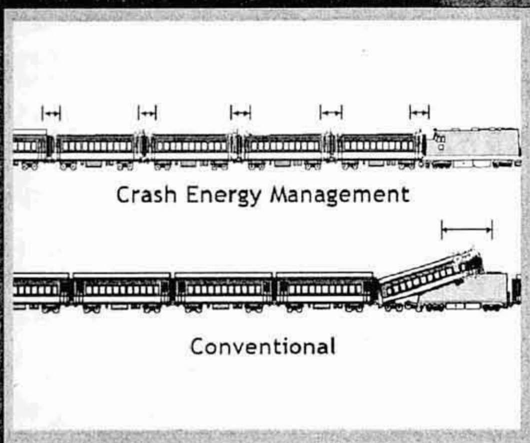
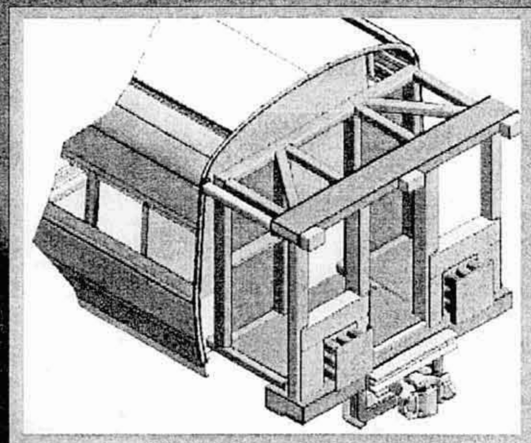
U.S. Department of Transportation
Volpe National Transportation Systems Center

# Crash Energy Management Technology Transfer Symposium

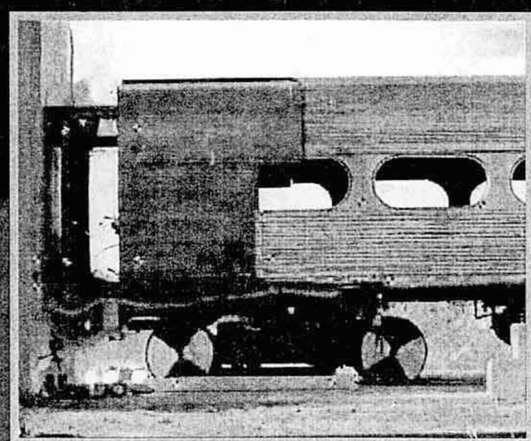



Effectiveness Studies



Design Studies

Retrofit



Full-scale Testing

## June 29 through July 1, 2005
## San Francisco, California

**Federal Railroad Administration**
**Office of Research and Development**

**Federal Transit Administration**
**Office of Research, Demonstration and Innovation**

Federal Railroad Administration
Office of Research and Development

Federal Transit Administration
Office of Research, Demonstration, and Implementation

# Crash Energy Management
# Technology Transfer Symposium
# June 29 through July 1,2005
# Sheraton Fisherman's Wharf
# San Francisco, California

Wednesday, June 29,2005

| | | |
|---|---|---|
| 1:00 pm | Opening | Jo Strang, FRA<br>Ron Hynes, FTA |

## ------ Session I: Overview of CEM ------

| | | |
|---|---|---|
| 1:20 pm | Rail Crashworthiness Research | David Tyrell, Volpe |
| 1:45 pm | Strategies for Improving Crashworthiness | Benjamin Perlman, Volpe |
| 2:10 pm | CEM Design, Build, and Test | Karina Jacobsen, Volpe |
| 2:35 pm | Occupant Protection | Dan Parent, Volpe |
| 3:00 pm | Break | |
| 3:15 pm | CEM Structural Standards and Specifications | Eloy Martinez, Volpe |

## ------ Session II: Supplier Capabilities ------

| | | |
|---|---|---|
| 3:40 pm | Bombardier CEM Equipment | Jacques Brassard, Bombardier |
| 4:05 pm | Kawasaki CEM Equipment | Toshi Hasegawa, Kawasaki |
| 4:30 pm | Talgo CEM Equipment | Gregg Sinn, Talgo |
| 4:55 pm | Indian Railway CEM Equipment | Steve Kirkpahick, ARA |
| 5:20 pm | Regulatory Perspective | Grady Cothen, FRA |

## Crash Energy Management
## Technology Transfer Symposium

Thursday, June 30,2005

| | | |
|---|---|---|
| 8:30 am | Opening | David Tyrell, Volpe |

### Session III: Service Experience with CEM ------

| | | |
|---|---|---|
| 8:40 am | Acela Service Experience | George Binns, Amtrak |
| 9:05 am | Hudson-Bergen Experience | Clive Thomes, Parsons-Brinkerhoff |

### ------ Session IV: CEM Effectiveness ------

| | | |
|---|---|---|
| 9:30 am | Full-scale Testing: Methodology | Kristine Severson, Volpe |
| 9:50 am | Full-scale Testing: Structural Crashworthiness | David Tyrell, Volpe |
| 10:10 am | Full-scale Testing: Occupant Protection | Dan Parent, Volpe |
| 10:30 am | Break | |
| 10:45 am | Train Crashworthiness Strategies | Kristine Severson, Volpe |
| 11:15 am | Parametric Studies of Train Crashworthiness | Michelle Priante, Volpe |
| 11:45 am | Lunch | |

### ------ Session V: CEM Design, Fabrication, and Evaluation ------

| | | |
|---|---|---|
| 1:00 pm | Features, Functions, and Requirements | Karina Jacobsen, Volpe |
| 1:25 pm | Concept Generation | Robert Rancatore, TIAX |
| 1:50 pm | Design Aspects of Crush Zones | Gabriel Amar, TRA&A |
| 2:15 pm | Retrofit of Test Cars | Eloy Martinez, Volpe |
| 2:40 pm | Break | |
| 3:00 pm | Component Crush Analysis and Testing | Rich Stringfellow, TIAX |
| 3:40 pm | Car Crush Analysis | Patricia Llana, TIAX |
| 4:00 pm | Train Crush Analysis | Rich Stringfellow, TIAX |
| 4:20 pm | Summary and Review | David Tyrell, Volpe |

# Crash Energy Management
# Technology Transfer Symposium

Friday, July 1, 2005

| | | |
|---|---|---|
| 8:30 am | Symposium Review and Summary | David Tyrell, Volpe |

## ------ Session VI: Panel Discussion -----

| | | |
|---|---|---|
| 9:15 am | Development of CEM Specifications for Passenger Rail Equipment | |
| | Steps for Developing Requirements | Jo Strang, FRA |
| | Equipment Specifications | Bill Lydon, Metrolink |
| | Industry Standards | Tom Peacock, APTA |
| | Funding Issues | Ron Hynes, FTA |
| | Operational Issues | George Binns, Amtrak |
| | Engineering Issues | David Tyrell, Volpe |
| 11:00 am | Close | Jo Strang, FRA<br>Ron Hynes, FTA |

# Session I - Overview of CEM

| | |
|---|---|
| Rail Crashworthiness Research | David Tyrell, Volpe |
| Strategies for Improving Crashworthiness | Benjamin Perlman, Volpe |
| CEM Design, Build, and Test | Karina Jacobsen, Volpe |
| Occupant Protection | Dan Parent, Volpe |
| CEM Structural Standards and Specifications | Eloy Martinez, Volpe |

Federal Railroad Administration

Federal Transit Administration

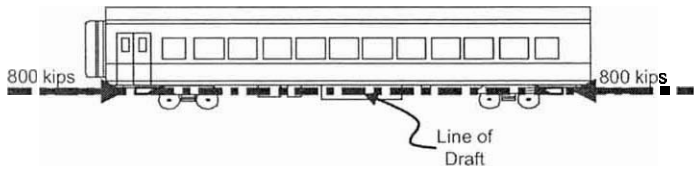
# Session I - Overview of CEM Rail Crashworthiness Research

**Crash Energy Management Technology Transfer Symposium**
**June 29 through July 1, 2005**
**San Francisco, California**

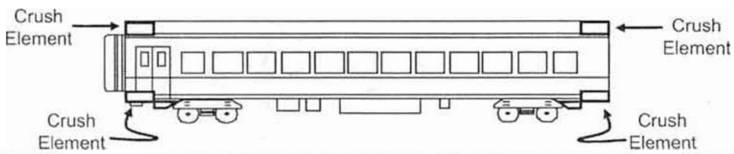
David Tyrell
Volpe Center
US Department of Transportation

## Crashworthiness Strategies

- Conventional
  - Static Strength




- Crash Energy Management
  - Crush Zones at Car Ends



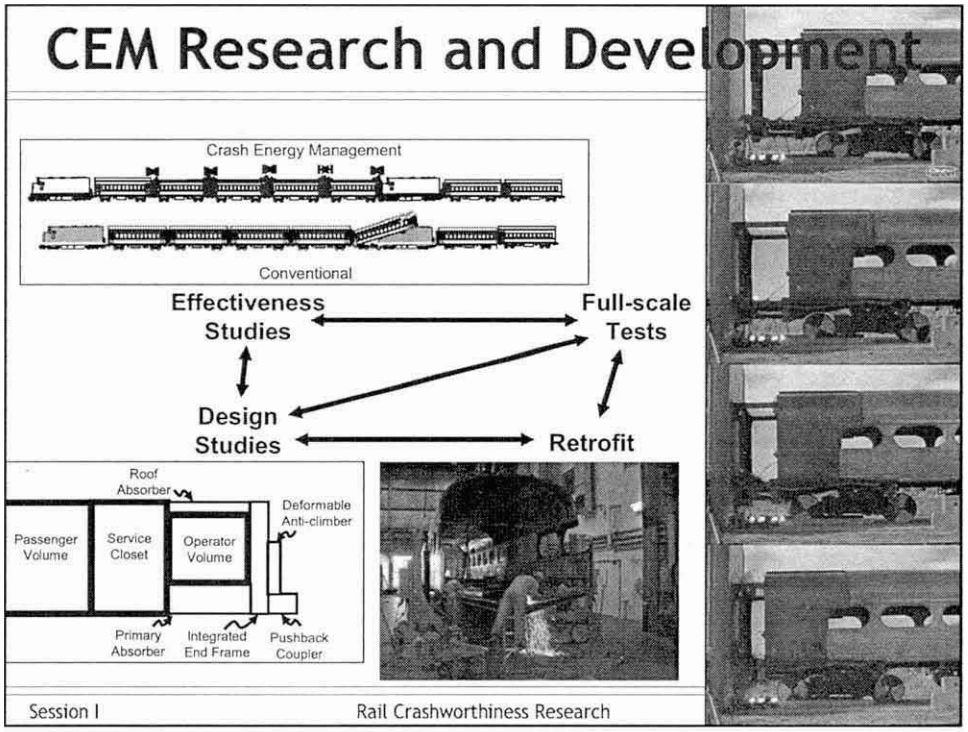

Session I Rail Crashworthiness Research Slide 2

## Objectives of Symposium

- Provide the Rail Industry with the Full Span of CEM Research Results
  - Effectiveness, Design, Build, Test

  Aid Planned Discussions of CEM Specification Issues, Options, and Alternatives
- Help the Commuter Railroads Develop CEM Specifications for Inclusion in Equipment Purchases

Session I Rail Crashworthiness Research Slide 3




# Symposium Organization

| | |
|---|---|
| **Session I** | **Overview of CEM** |
| **Session II** | **Supplier Capabilities** |
| **Session III** | **Service Experience with CEM** |
| **Session IV** | **CEM Effectiveness** |
| **Session V** | **CEM Design, Fabrication, and Evaluation** |
| **Session VI** | **Panel Discussion on Development of CEM Specifications** |

Session I Rail Crashworthiness Research Slide 5

## Crashworthiness

- **Preserve Occupant Volume**
  - Maintain Sufficient Space
  - Minimize Local Compartment Penetration
  - Ensure Occupant Containment
- **Limit Forces and Decelerations to Survivable Levels**
  - Limit Deceleration of Occupant Volume
  - Restrict Secondary Impact Forces
  - Secure Interior Fittings

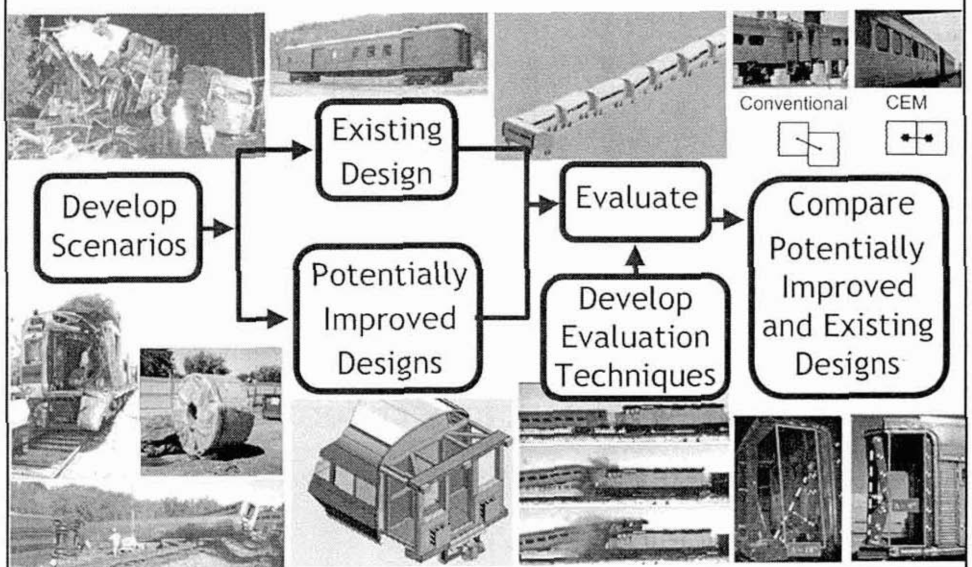
Session I | Rail Crashworthiness Research | Slide 6

## Passenger Rail Equipment Crashworthiness Research

- **Objective**
  - Development and Evaluation of Concepts for Improved Rail Equipment Crashworthiness
- **Major Outputs**
  - Definition of Scenarios of Concern
  - Evaluation of the Effectiveness of Modifications and New Approaches to Equipment Design
  - Analysis and Test Techniques
  - Information for Specifications and Regulations

Session I | Rail Crashworthiness Research | Slide 7

## Research Methodology




Session I | Rail Crashworthiness Research | Slide 8

## Categories of Collisions

- Collisions with Another Train, e.g.,
  - Beverly, Massachusetts - August 11, 1981
  - New York, New York - July 23, 1984
  - Secaucus, NJ - February 9, 1996
  - Silver Spring, Maryland - February 16, 1996
  - Bourbonnais, Illinois - March 15, 1999
  - et al
- Collisions with Objects, e.g., Grade Crossing Collision

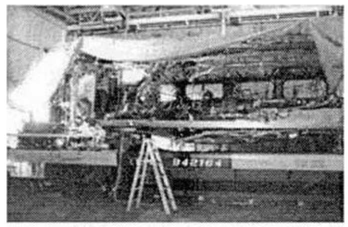
  Single Train Events, e.g., Derailment

Session I | Rail Crashworthiness Research | Slide 9

# Accident Observation

- **Structural Damage Focused on Impacting Equipment**

**Secaucus, NJ - February** 9, 1996

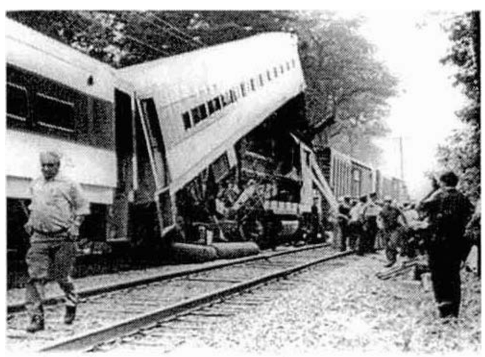



**Silver Spring, Maryland - February** 16, 1996



# Accident Observation

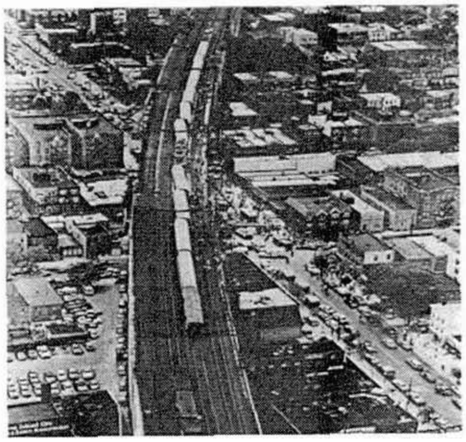
- **Impacting Equipment Can Override**

**Beverly, Massachusetts - August 11, 1981**

# Accident Observation

- Coupled Cars Tend to Laterally Buckle During Collisions



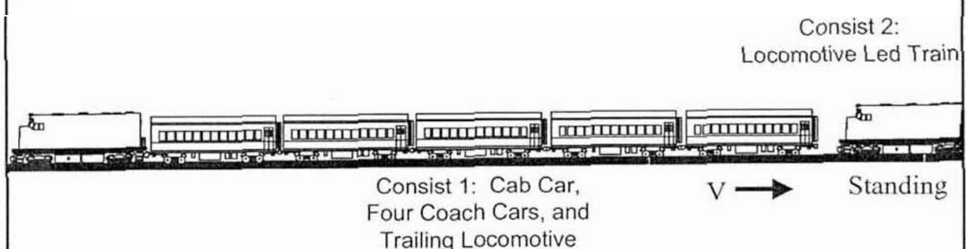
New York, New York - July 23, 1984

Bourbonnais, Illinois - March 15, 1999

Session I | Rail Crashworthiness Research | Slide 12

# Scenario: Collision with Another Train

- **Based on Accident History**
- **Developed to Allow Comparison of Alternative Crashworthiness Strategies**




Session I | Rail Crashworthiness Research | Slide 13

# Potentially Improved Design: CEM

- Sacrificial Crush Zones at Unoccupied Locations in Cars
- Crush Zones Designed with a Lower Initial Force and Increased Average Force
- Energy Absorption is Shared by Multiple Crush Zones
- Preserves the Integrity of the Occupied Areas


Session I | Rail Crashworthiness Research | Slide 14

# Comparison of Alternative Designs

- Conventional Trains Crashworthy up to **~13** mph
- CEM Trains Crashworthy up to **~32** mph
  - When Constrained by Floor Plan
  - Higher Speeds Possible if Cab Car Crush Zone is not Constrained
- CEM Cab Car with Conventional Coach Cars Crashworthy up to ~19 mph

*Note: Publications and videos available on the web at http://www.volpe.dot.gov/sdd*

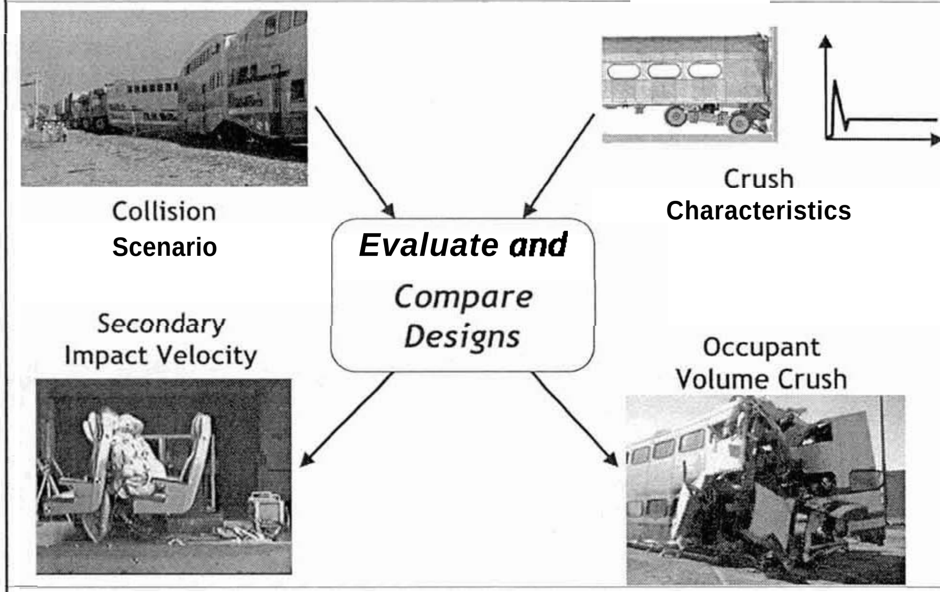
Session I | Rail Crashworthiness Research | Slide 15

# Session I - Overview of CEM Strategies for Improving Crashworthiness

**Crash Energy Management Technology Transfer Symposium**
**June 29 through July 1, 2005**
**San Francisco, California**

**Benjamin Perlman**
**Volpe Center**
**US Department of Transportation**

# Research Methodology





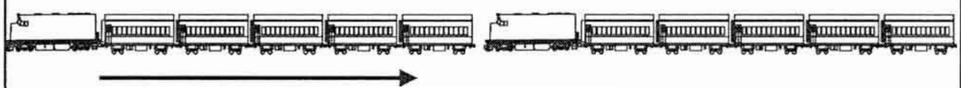

# Outline

- Scenario
- Train Collision Mechanics
  - Energy absorption mechanisms
  - Force-crush behavior
- Conventional vs. CEM Trains
  - Crush is focused in a conventional train
  - Crush is distributed in a CEM train
- Preview of Results

# Scenario

**Train to Train Collision**

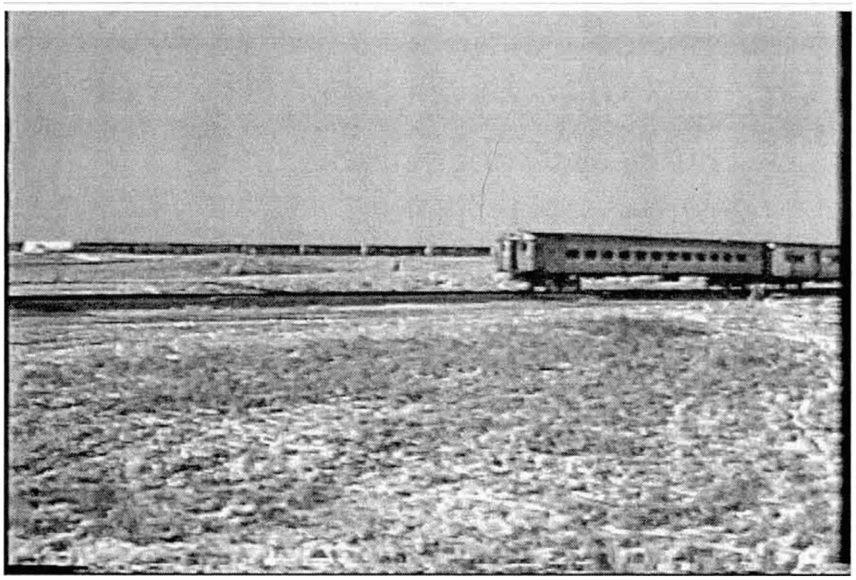
- Cab car
- **4 coach cars**
- **Locomotive**



**30 rnph closing speed**

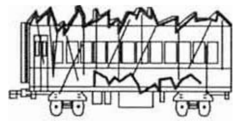


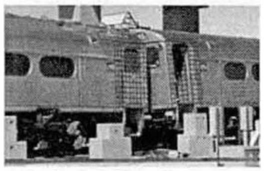
# Conventional Equipment: Train to Train Test



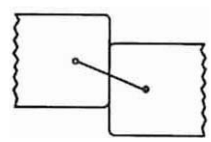
# Uncontrolled Energy Absorption

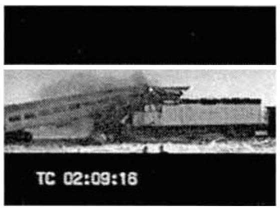
**In-line Crush**



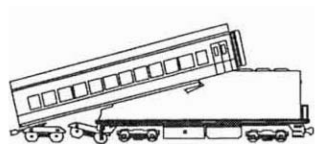


**Derailment**
**Lateral Buckling**



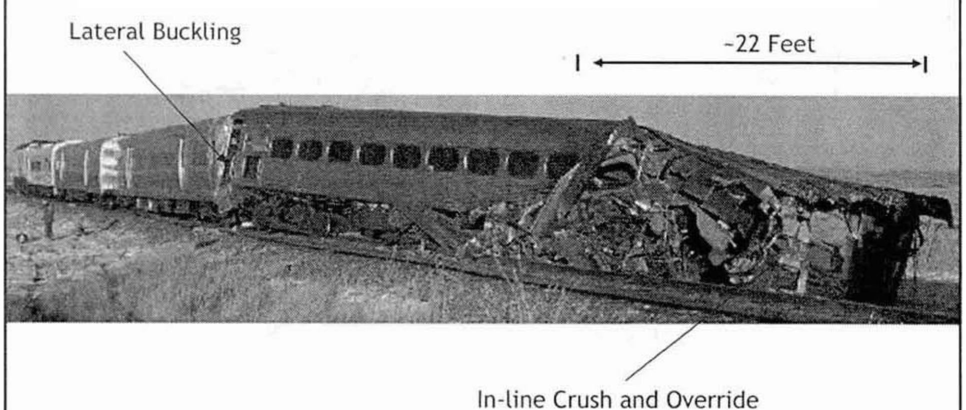



**Override**



Session I    Strategies for Improving Crashworthiness    Slide 6

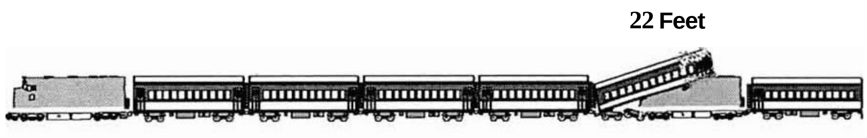
# Conventional Equipment: Focused Crush



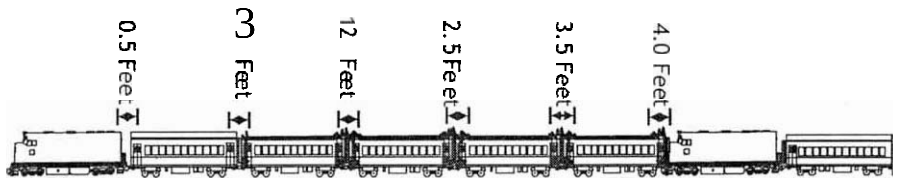

Session I    Strategies for Improving Crashworthiness    Slide 7

# Crush Distribution

Conventional: Crush Focused on Cab Car

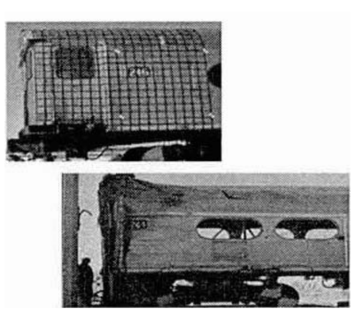



Crash Energy Management: Crush Distributed Among Cars



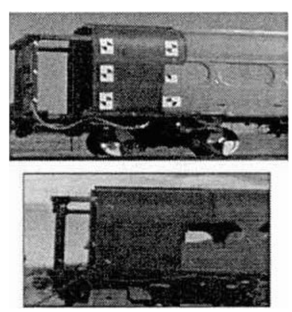



# Single Car Tests: 35 MPH

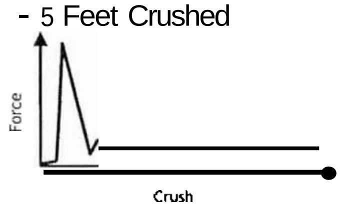


Before

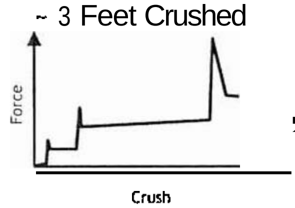
After

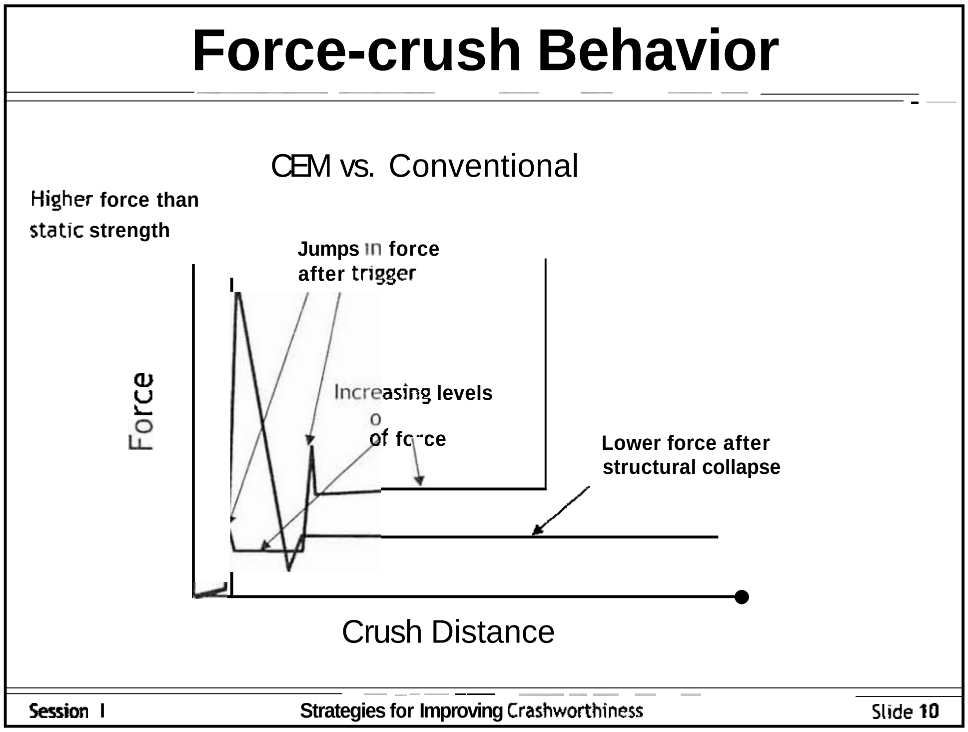


- 5 Feet Crushed

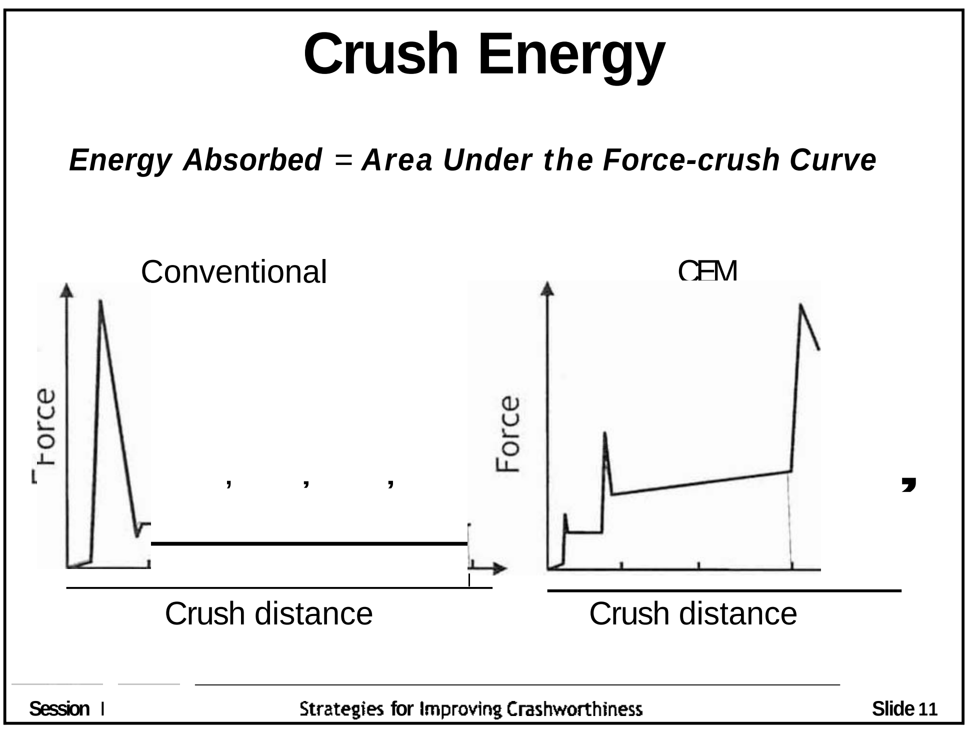



~ 3 Feet Crushed





Force-crush Behavior
CEM vs. Conventional
Higher force than
static strength
Jumps in force
after trigger
Force
Increasing levels
of force
Lower force after
structural collapse
Crush Distance
Session I
Strategies for Improving Crashworthiness
Slide 10

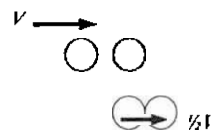



Crush Energy
Energy Absorbed = Area Under the Force-crush Curve
Conventional
CEM
Force
Force
Crush distance
Crush distance
Session I
Strategies for Improving Crashworthiness
Slide 11

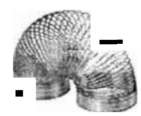
# Energy Transfer Mechanisms

- Superball
  - Elastic collision
  - Energy recovered

- Velcro
  - Plastic collision
  - Energy absorbed

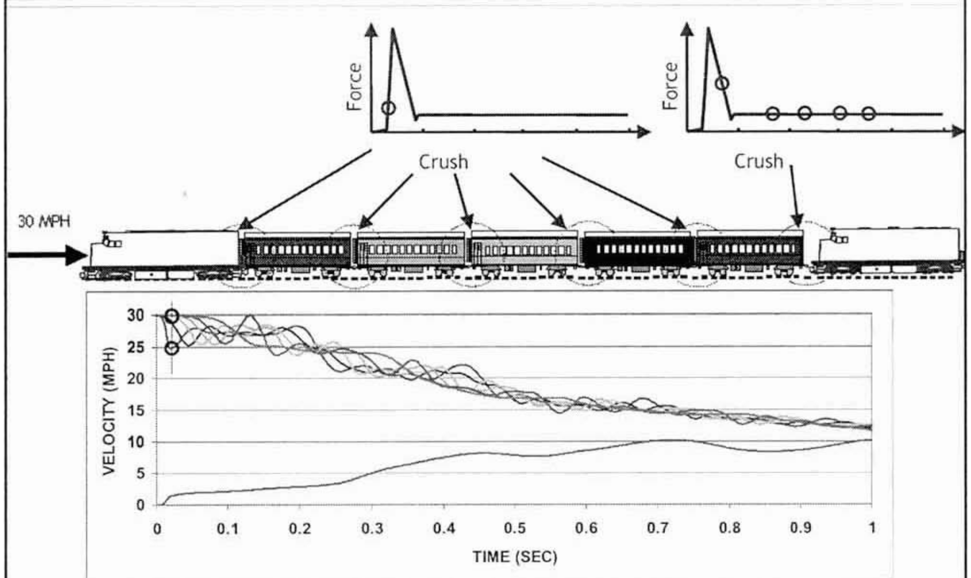



- Slinky
  - Elastic wave
  - Delay in time



Session I Strategies for Improving Crashworthiness Slide 12

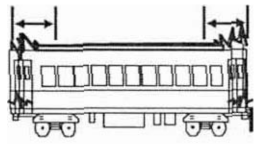
# Conventional Train Crashworthiness



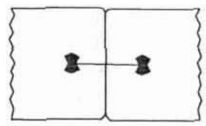

Session I Strategies far Improving Crashworthiness Slide 13

# Controlled Energy Absorption

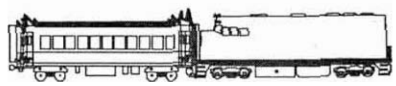
- Each car absorbs some of the train collision energy



- Crush is distributed through the train with no lateral buckling

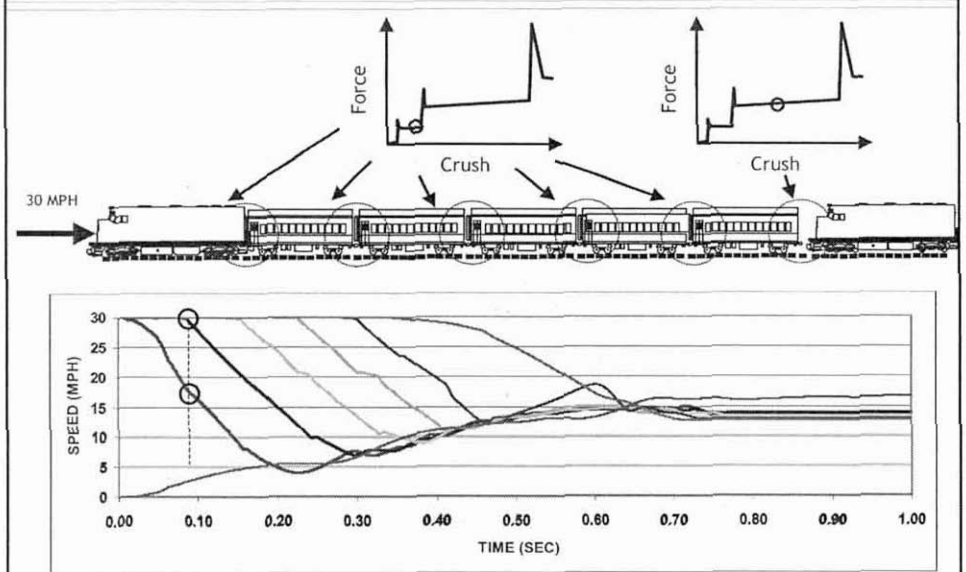


- Engagement is promoted at the colliding interface



Session I | Strategies for Improving Crashworthiness | Slide 14

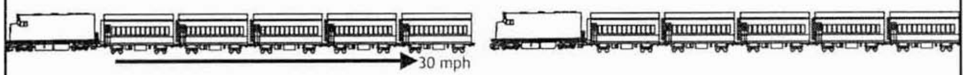
# CEM Train Crashworthiness



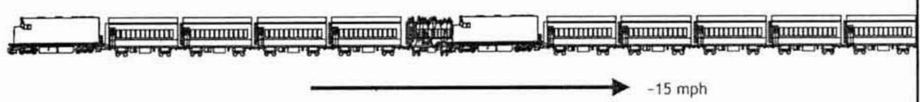

Session I | Strategies for Improving Crashworthiness | Slide 15

# Energy Budget

## Identical 6 Car Consists



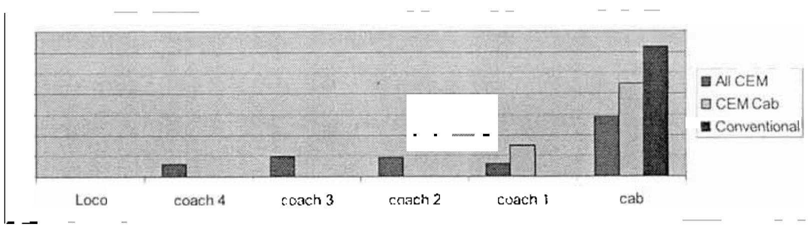

- Kinetic Energy,,,, = ½ m $V^2$
  - Typical masses of cab, coach k loco
  - At 30 MPH: approximately 25 million ft-lb

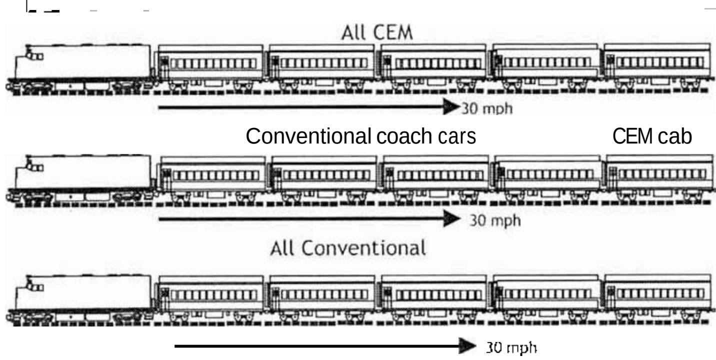



- Kinetic Energy$_{end}$ ~ ½ (2m) $(v/2)^2$ = ¼ m $v^2$
- More than half of the initial kinetic energy must be absorbed by crush



# Crash Energy Distribution



# Summary

- **Managed Energy Absorption**
  - **Prevent crush into the occupant volume**
  - **Control coupled car interactions**
  - **Control the mode of deformation at the colliding interface**
- **Structural Design**
  - **Force that increases with crush**
- **Interior Environment**
  - **Mitigate the effects of car acceleration**

# Session I - Overview of CEM
# CEM Design, Build, & Test

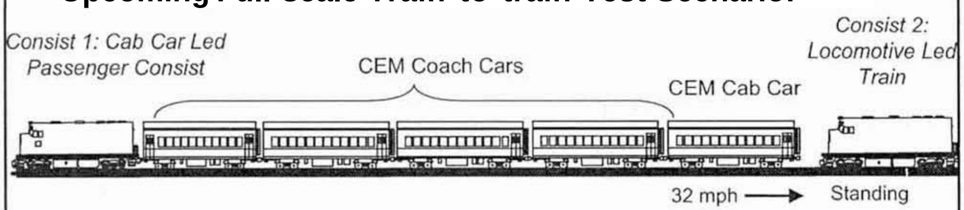
Crash Energy Management Technology Transfer Symposium
June 29 through July 1, 2005
San Francisco, California

Karina Jacobsen
Volpe Center
US Department of Transportation

# Collision Scenario

**Design Requirements are Dictated by the Impact Scenario.**

**Upcoming Full-scale Train-to-train Test Scenario:**




Session I | CEM Design, Build, & Test | Slide 2

# Design Overview Topics

DESIGN

Formulate Design Requirements

↓

Develop Design

↓

BUILD

Retrofit Existing Cars

↓

TEST

Full-scale Tests

↓

Compare Performance with Design Requirements

Session I | CEM Design. Build, & Tert | Slide 3

## Design Strategy

1. Develop Coach Car Crush Zone
   - Structural Components to Manage Energy Absorption for Coupled Cars
2. Develop Cab Car Crush Zone
   - Based upon Coach Car Design
   - Additional Structural Components to Manage Energy Absorption for Colliding Equipment
   - Preserves Operator's Volume

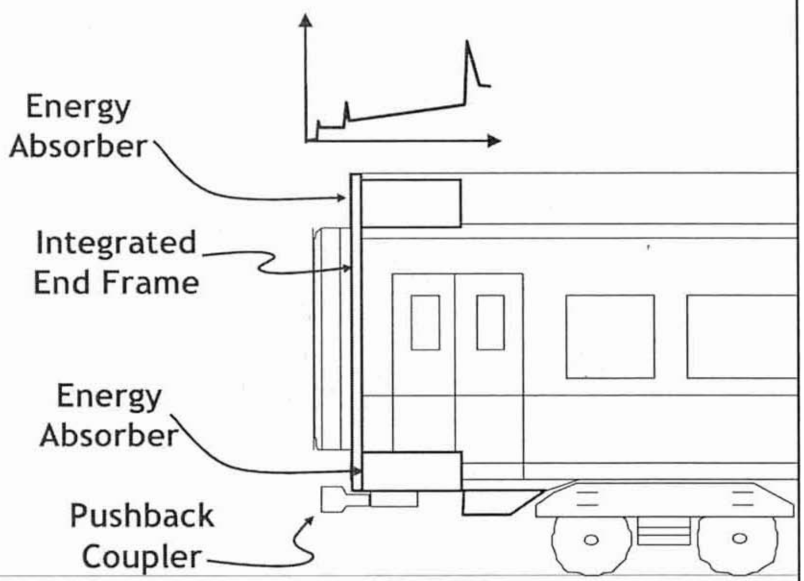
Session I | CEM Design. Build, & Test | Slide 4

## Design Requirements: Coach Car

- Protect Passenger Volume
  - Minimize Intrusion
- Energy Absorption
  - 2.5 Million ft-lbs Per Car End
- Graceful Deformation
  - Crush Zone Collapses in a Controlled Manner
  - Minimize Lateral and Vertical Motions

Session I | CEM Design, Build. 6 Test | Slide 5

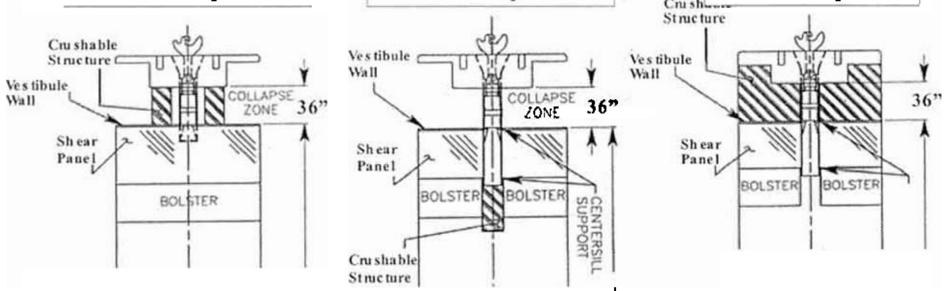
## Design Requirements: Coach Car




Session I | CEM Design. Build, & Test | Slide 6

## Preliminary Design Concepts

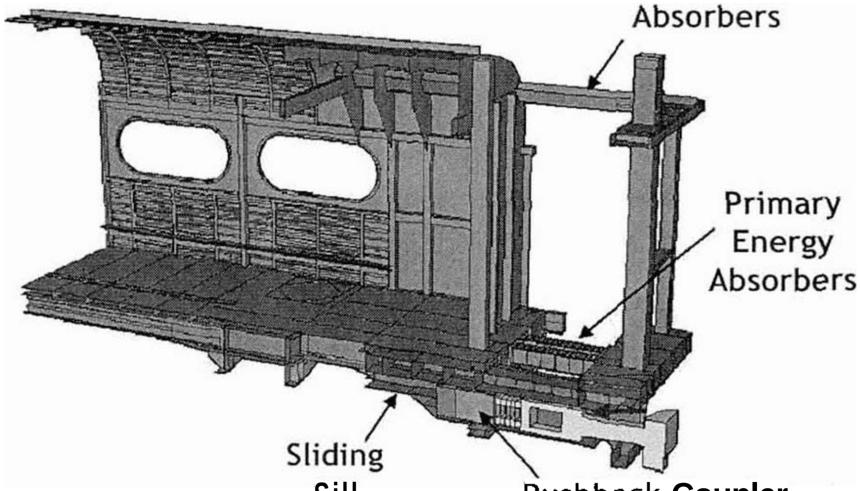
| Alternative Concept A | Alternative Concept B | Alternative Concept C |
|---|---|---|




| Double Energy Absorber | Sliding Sill & Energy Absorber | Distributed Energy Absorber |
|---|---|---|

Session I | CEM Design, Build, & Test | Slide 7

## Coach Car Crush Zone

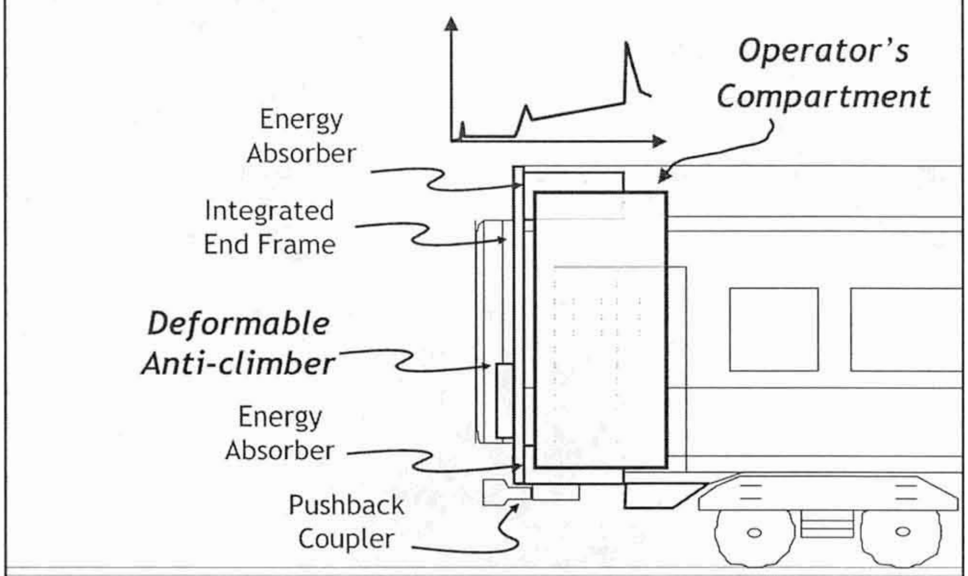





## Design Requirements: Cab Car

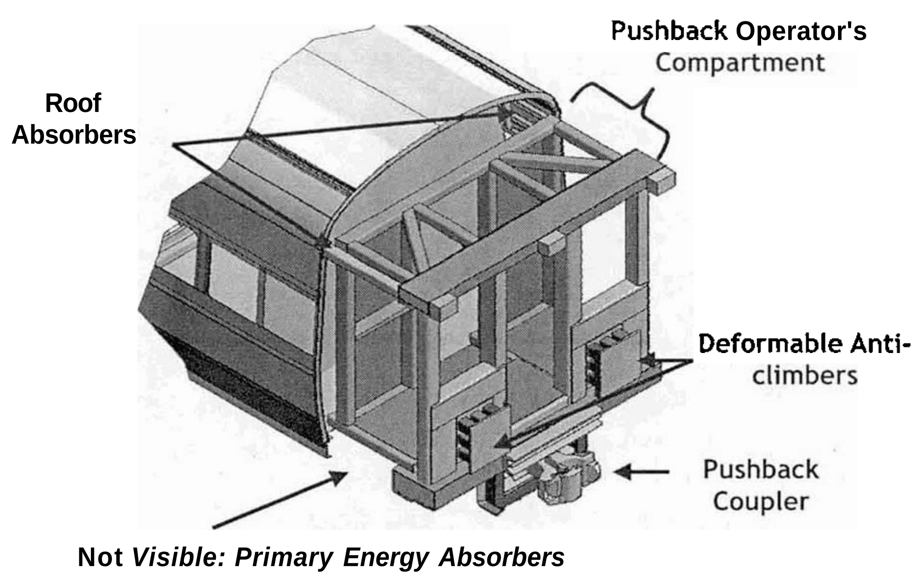
- **Protect Operator & Passenger Volume**
  - **Minimize Intrusion**
- **Energy Absorption**
  - **3.0 Million ft-lbs Per Cab End**
- **Manage Colliding Equipment**
  - **Crush Zone Collapses in a Controlled Manner**
  - **Prevent Override as Locomotive and Cab Car Collide**

## Design Requirements: Cab Car



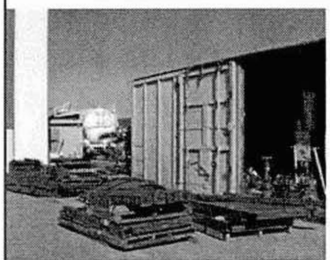

Session I CEM Design, Build, & Test Slide 10

## Final Cab Car Design



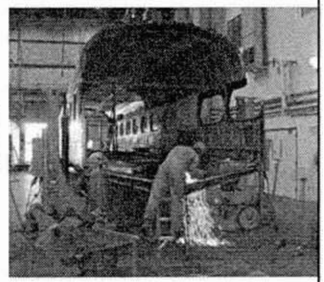

Session I CEM Design. Build, & Test Slide 11

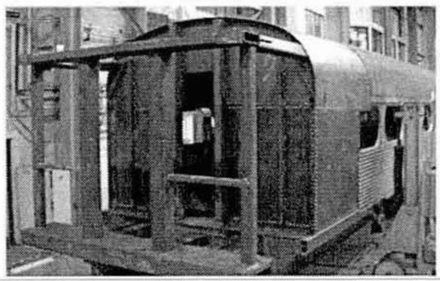
## Retrofit onto Existing Cars



Fabricate Components ↔ Prepare Cars

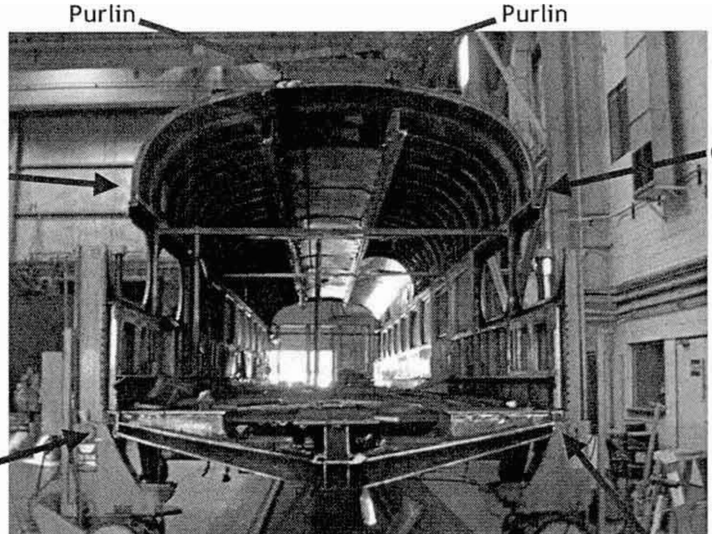
Install Components





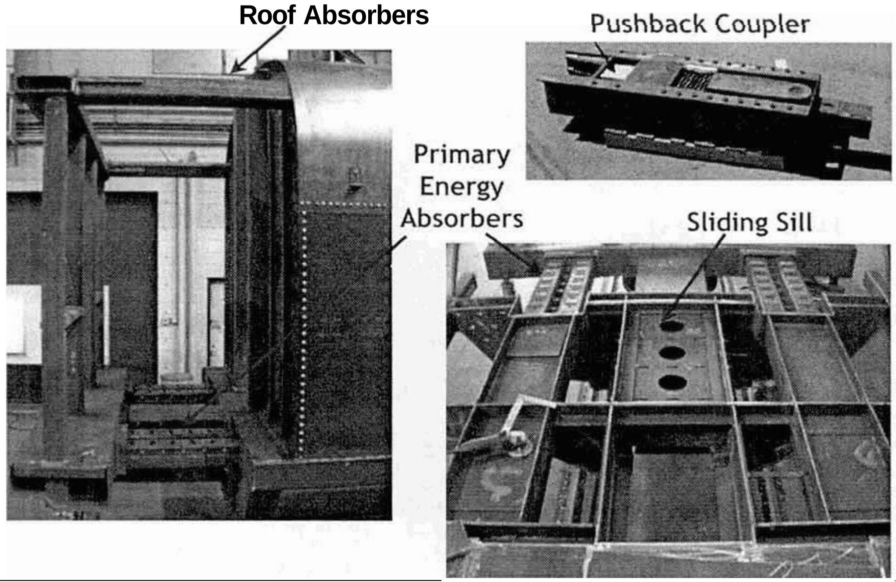
Session I | CEM Design, Build, & Test | Slide 12

## Existing Cars



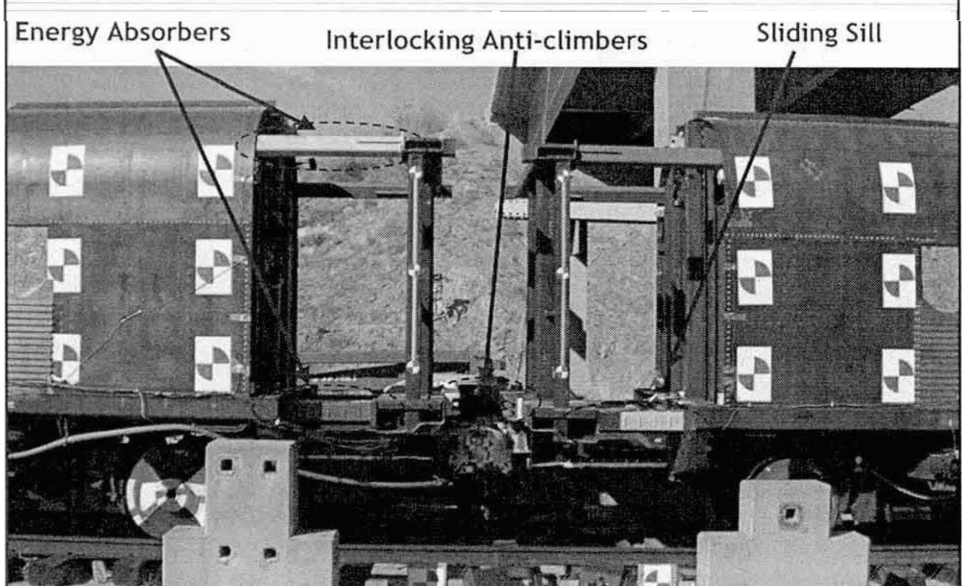

Session I | CEM Design, Build, & Tert | Slide 13

## Integrated CEM Components




Session I | CEM Design, Build, & Test | Slide 14

## Completed Test Car

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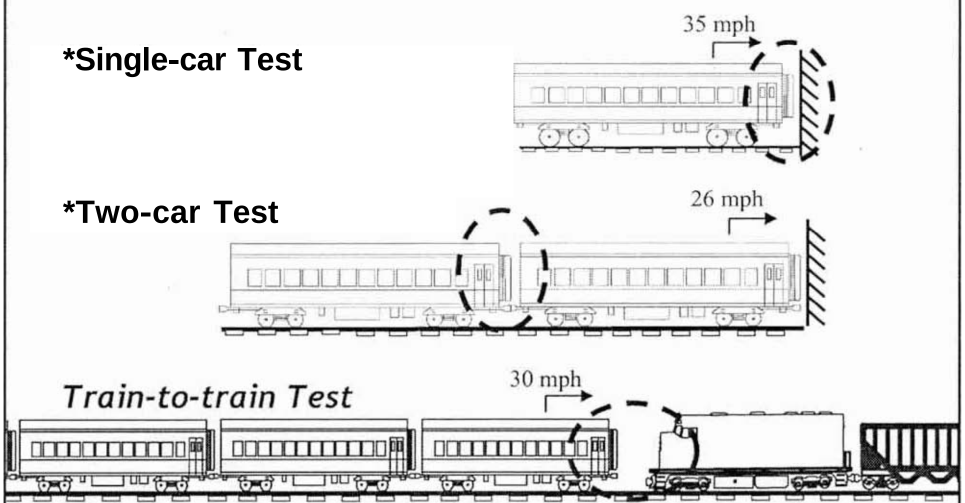
## Full-scale Tests




***Conventional and CEM Equipment Tested**

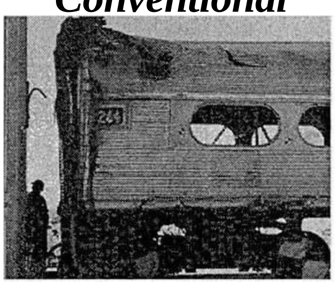
Session I | CEM Design, Build, & Test | Slide 16

## Single-car Test Principal Results

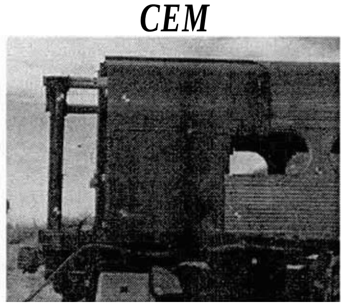
**For an Impact with Fixed Barrier at 35 mph**

- **CEM Design Performed as Intended**
  - **No Intrusion into the Occupant Compartment**
  - **Lateral and Vertical Motions Minimized**

*Conventional* | *CEM*



- 5 Feet Crushed



~ 3 Feet Crushed

**JImproved Preservation of Occupant Volume Under Similar Test Conditions.**

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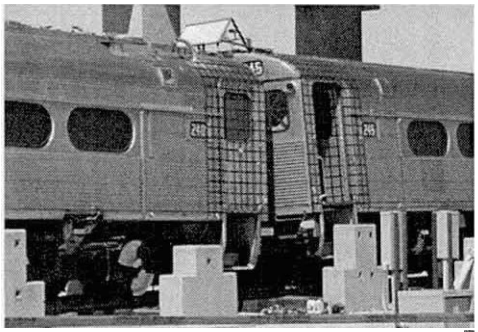
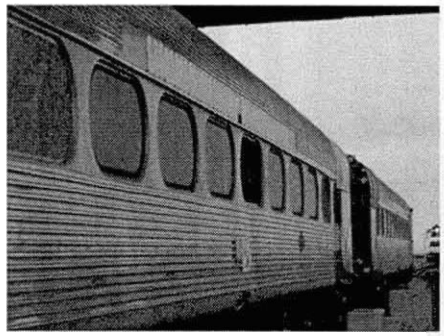
## Two-car Test Principal Results





Conventional

Pre-test
**Predictions**



## Conventional Train-to-train Test Principal Result

- **Crush Focused on Cab Car**

**"Volume for 46 Passengers & the Operator**
Destroyed.

# Federal Railroad Administration

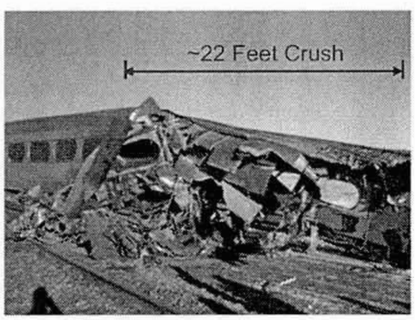
# Single Car Impact Tests

## 35 mph

**Transportation Technology Center**
**Pueblo, Colorado**
**November 16, 1999**
**December 3, 2003**

## Train-to-train Test Prediction

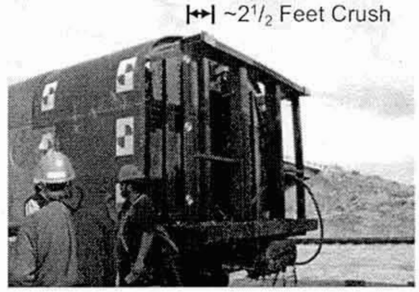
***Measured*** *Conventional*




***Expected*** *CEM*

**Note: Photo of Impact Coach Car,** Two-car **Test**

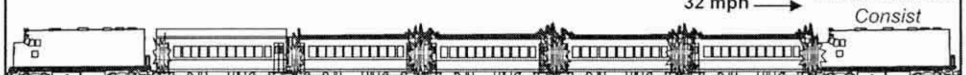
~$2^1/_2$ Feet Crush



**Crash Energy Management: Crush Distributed Among Cars (predicted)**

*Cab Car Led Consist*
32 mph →

*Standing Locomotive Led Consist*



## Technical Basis for Structural Specifications

- Design Studies Result in Requirements
- Retrofit Demonstrates Practicality
- Single-car and Two-car Tests Full-scale Impact Tests Confirm Effectiveness, Design and Retrofits
- Further Confirmation Expected from Train-to-train Full-scale Impact Test of CEM Equipment

Session I CEM Design, Build, & Test Slide 22

# Session I - Overview of CEM
# Occupant Protection

**Crash Energy Management Technology Transfer Symposium**
**June 29 through July 1, 2005**
**San Francisco, California**

**Dan Parent**
**Volpe Center**
**US Department of Transportation**

# Research Approach

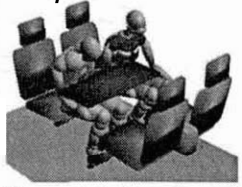
*Full-scale Testing*

*Occupant Response: Kinematics, Injury Risk*

*Field Study*

*Collision Scenarios, Occupant Injury*

*Computer Simulation*



*Occupant Response in Different Scenarios*

***Improvements to Occupant Protection***

Session I | Occupant Protection | Slide 2

# Occupant Protection Strategies

1. **Preserve occupant volume**
   - **Crash energy management system**

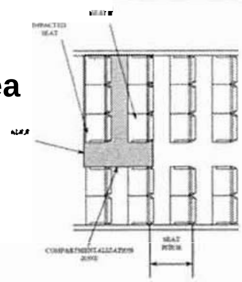
2. **Ensure compartmentalization**
   - **Seats and tables remain attached**
   - **Restrain occupants**

3. **Minimize severity of secondary impacts**
   - **Reduce secondary impact velocity**
     - **Rear-facing seats**
   - **Employ energy-absorbing elements**
   - **Padding, frangible materials**

Session I | Occupant Protection | Slide 3

# Critical Measurements

- Compartmentalization
  - Occupant remains within specified area

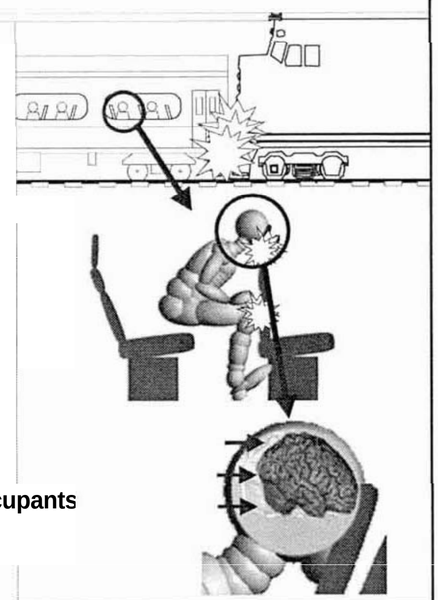


- Occupant Kinematics
  - Predictable interaction with seats
- Injury Risk - Maximum injury criteria values
  - Head Injury → HIC
  - Chest Injury → Cumulative 3ms
  - Neck Injury → Nij
  - Femur Load

Session I | Occupant Protection | Slide 4

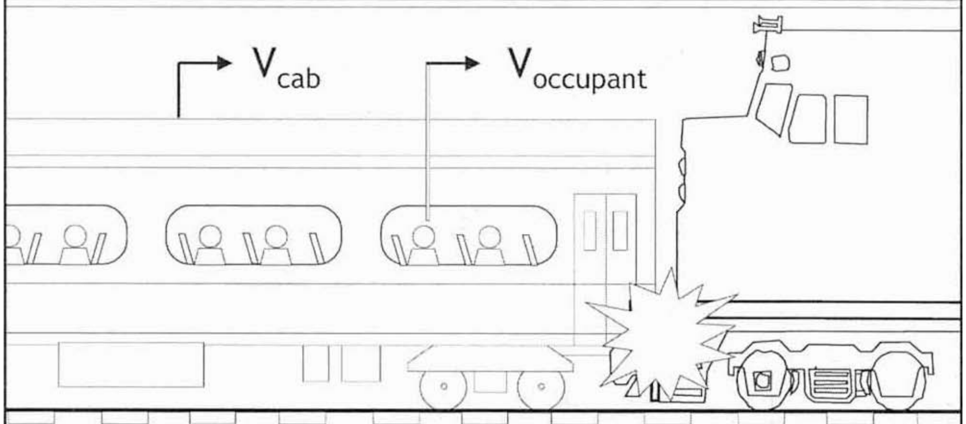
# Anatomy of a Collision

- Primary Impact
  - Severity determined by:
    - Closing speed
    - Structure
  - Measure of severity:
    - Occupied volume intrusion
    - Car body acceleration
- Secondary Impact
  - Severity determined by:
    - Secondary impact velocity
    - Interior configurations
  - Measure of severity:
    - Loads and accelerations on occupants
- Tertiary Impact



Session I | Occupant Protection | Slide 5

## Anatomy of a Collision - Primary Impact

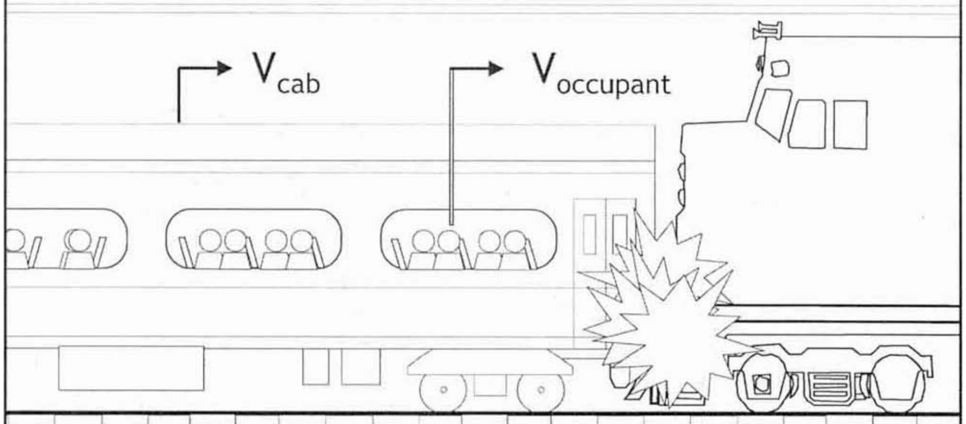



*Pre-impact* $V_{occupant} = V_{cab}$

$$\frac{dV_{cab}}{dt} = A_{cab}$$

Session I | Occupant Protection | Slide 6

## Anatomy of a Collision - Secondary Impact



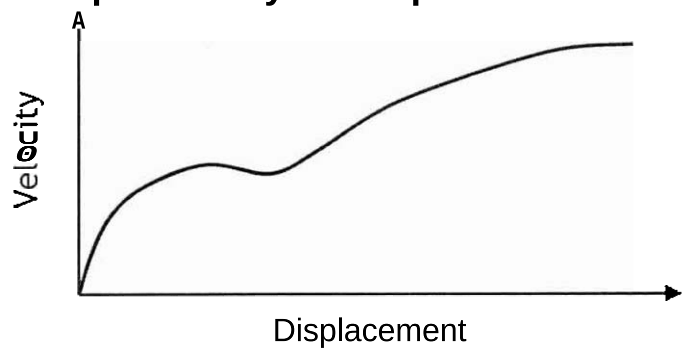

SIV = $\Delta$V at time of impact

***If cab is infinitely rigid*** SIV = $V_{cab}$

**Session I** | **Occupant Protection** | **Slide 7**

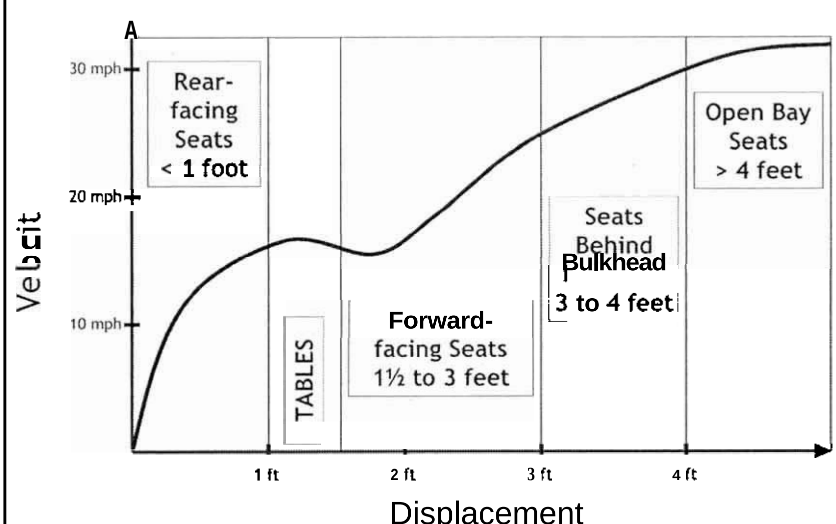
## Evaluation of Secondary Impact Velocity

- **For a known acceleration pulse**
  - **Integrate → relative velocity**
  - **Integrate → relative displacement**
  - **Graph velocity vs. displacement**



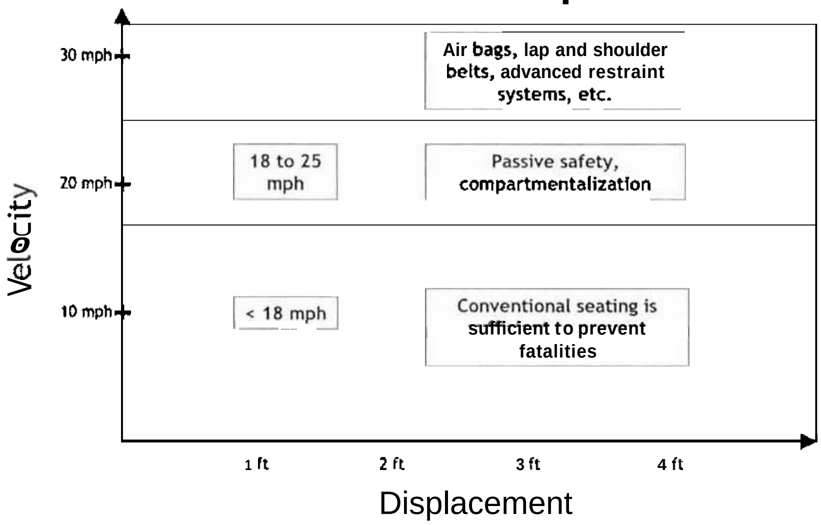



## Evaluation of Secondary Impact Velocity



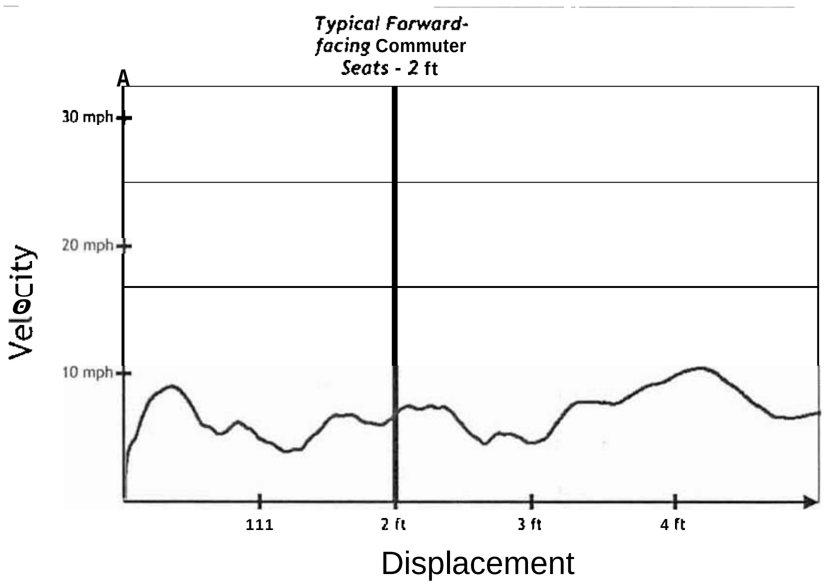
## Evaluation of Secondary Impact Velocity

- SIV determines level of protection

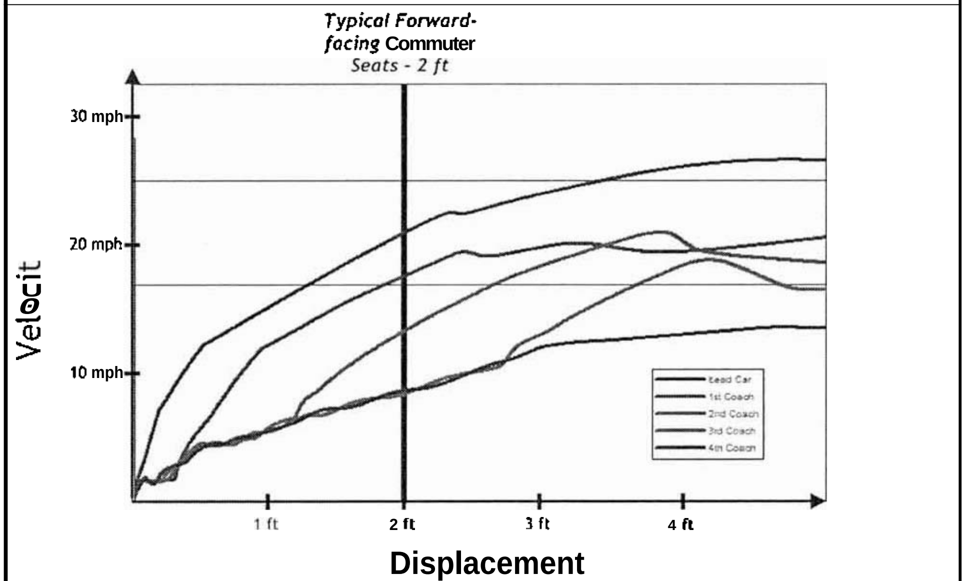





## SIV - Measured Conventional Train-to-train

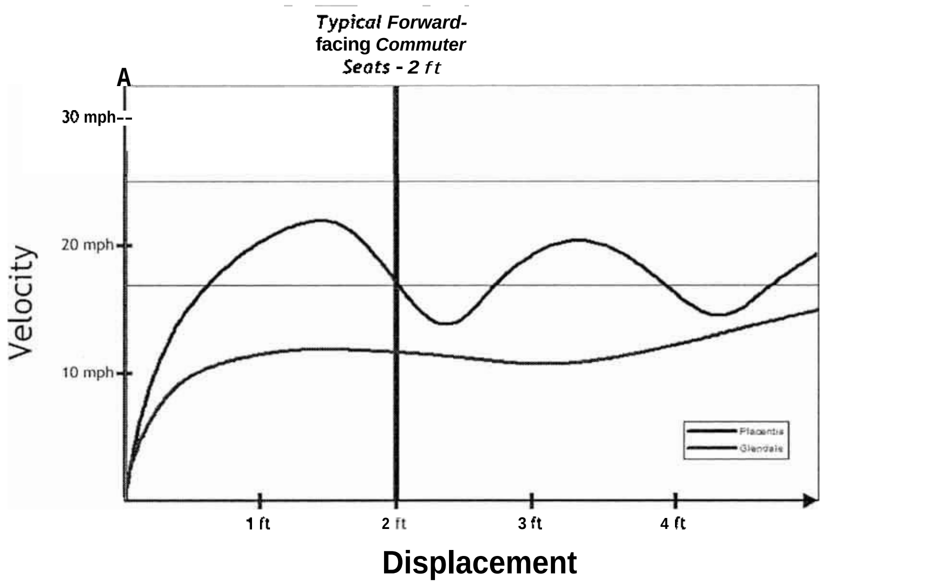


## SIV - Predicted CEM Train-to-train




Session I | Occupant Protection | Slide 12

## SIV - Estimated Placentia, Glendale CA

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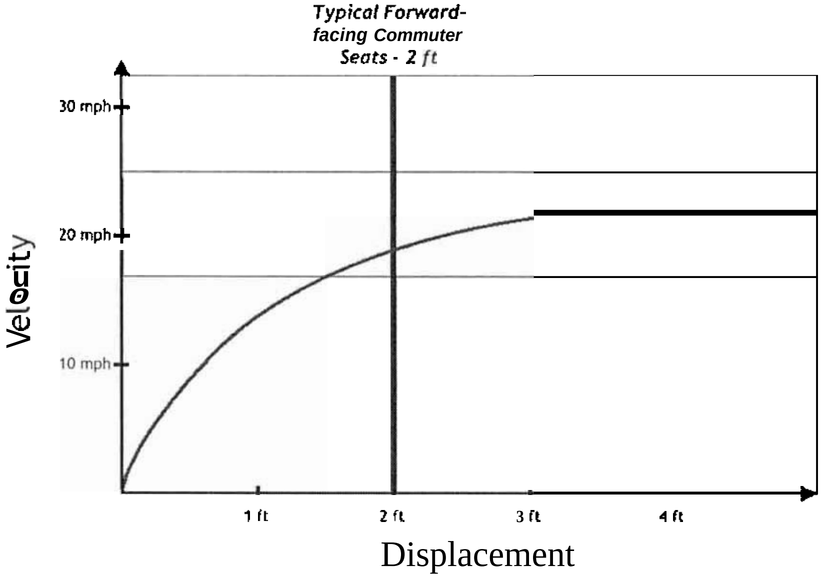
## SIV - 8G Test Pulse




Session I | Occupant Protection | Slide 14

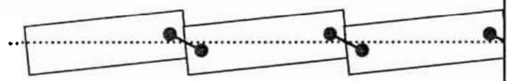
## Secondary Impact Environment

- **Large structural deformation = low SIVs**
  **BUT loss of occupant volume**
  **→ Injuries that cannot be prevented**
  **Stiffer occupant volume = higher SIVs**
  **NO loss of occupant volume**
  **→ Injuries that CAN be prevented**
- **Worst-case scenario is in cab car**
  - **Conventional - loss of occupant volume**
  - **CEM - highest SIVs - can be mitigated**
  - **Trailing cars have lower SIVs**

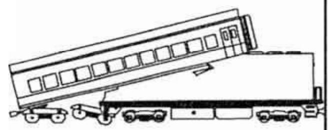
Session I | Occupant Protection | Slide 15

## Vertical and Lateral Acceleration

- Conventional cars are subject to lateral and vertical accelerations
  - Saw-tooth buckling
    - Lateral accelerations
    - Occupants thrown into/across aisle



  - Draft gear crushing
    - Vertical accelerations
    - Occupants thrown over seatbacks



- **CEM significantly reduces lateral and vertical accelerations**

Session I | Occupant Protection | Slide 16

## Conclusions

- **Crash Energy Management**
  - Preserves occupied volume
  - Minimizes lateral and vertical accelerations
  - Increases SIVs
- **Strategic interior modifications prevent injuries associated with increased SIVs**
  - Improved workstation tables
  - Optimized commuter seats
  - Rear-facing seats

  } Session IV
- **CEM combined with strategic interior modifications can significantly increase occupant protection**

Session I | Occupant Protection | Slide 17

# Session I - Overview of CEM
# CEM Structural Standards & Specifications

Crash Energy Management Technology Transfer Symposium
June 29 through July 1, 2005
San Francisco, California

Eloy Martinez
Volpe Center
US Department of Transportation

## Outline

- Background
- Specification Components
  - Train Level
  - Structural Crashworthiness
  - Occupant Protection
- Review Some Current CEM Equipment
- Specification Development

Session I | CEM Structural Standards & Specifications | Slide 2

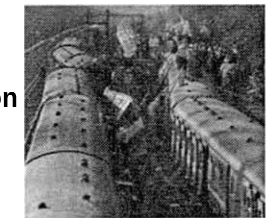
## Background

- CEM Concept and Specifications Not New
- Timeline for CEM Specifications
  - Established in Europe Since the Early 1980s
    - ORE Question B 165 Committee
    - Proposed to UIC Standards (not accepted)
    - High and Low Speed Technical Specifications for Interoperability (TSI) across Europe
  - Established in North America Since Early 1990s
    - Amtrak's High Speed Train Specification
    - FRA Passenger Equipment Safety Standards
    - APTA Manual of Standards and Recommended Practices

Session I | CEM Structural Standards & Specifications | Slide 3

## Background

- **Several Accidents Occurred that Motivated Development of CEM Specifications**
  - **U.K. Accidents**
    - **Head-on Accident: Clapham Junction**

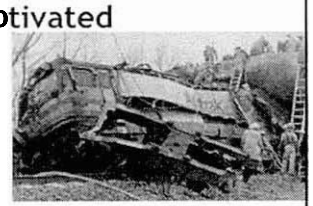


  - **French Accidents**
    - **Grade Crossing Accident: Voiron**

Session I | CEM Structural Standards & Specifications | Slide 4

## Background

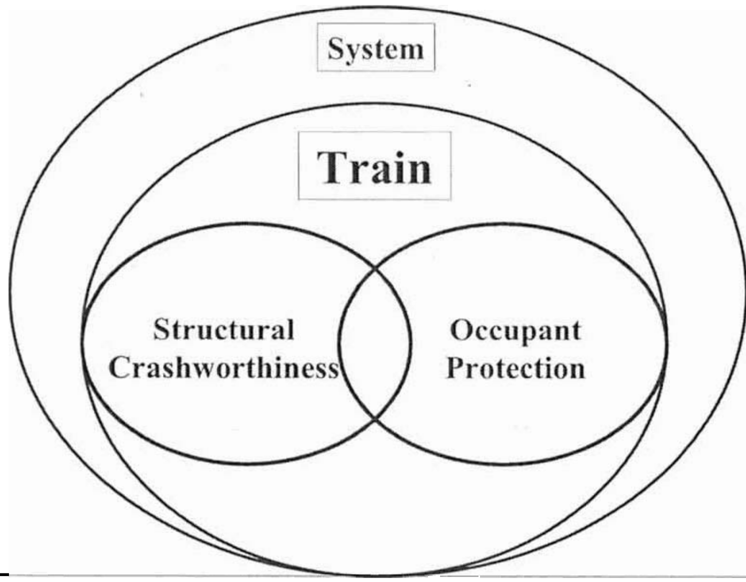
- **Several Accidents Occurred that Motivated Development of CEM Specifications**
  - **North American Accidents**
    - **Rear-end Collision: Chase, MD**



    - **Head-on Collision: Glendale, CA**

Session I | CEM Structural Standards & Specifications | Slide 5

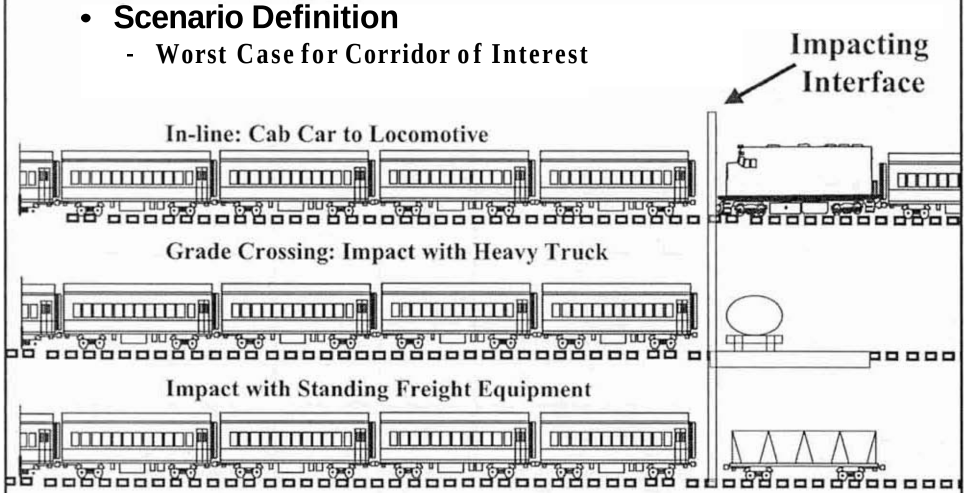
## Crashworthiness Specification Components




Session I | CEM Structural Standards & Specifications | Slide 6

## Train Level Specifications

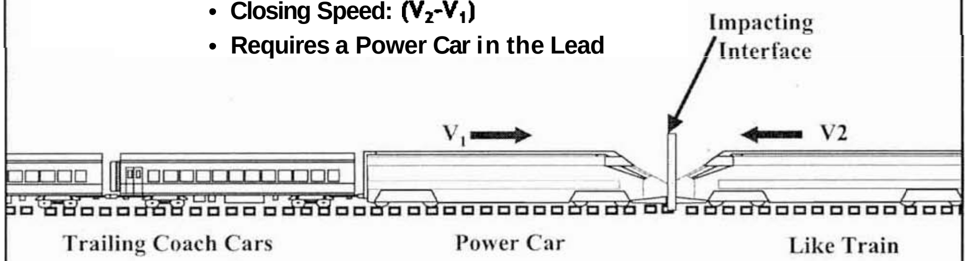
- **Scenario Definition**
  - Worst Case for Corridor of Interest




Session I | CEM Structural Standards & Specifications | Slide 7

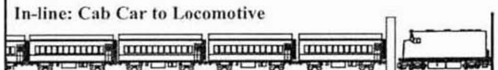
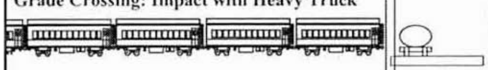
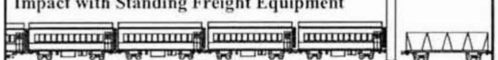
## Example: Train-Level Performance Specification

- **Tier II: 49 CFR Part 238 Subpart E**
  - **Scenario Definition**
    - **In-line Collision Between Identical Trains**
    - **Tangent Level Track**
    - **Closing Speed: ($V_2$-$V_1$)**
    - **Requires a Power Car in the Lead**






## Train Level Specifications

| Scenario Definition | APTA R.P. | Tier II | E.U. TSI | Proposed |
|---|---|---|---|---|
| In-line: Cab Car to Locomotive  | ✓ | ✓ | ✓ | ✓ |
| Grade Crossing: Impact with Heavy Truck  | ✓ | – – | ✓ | ? |
| Impact with Standing Freight Equipment  | ✓ | – – | ✓ | – – |

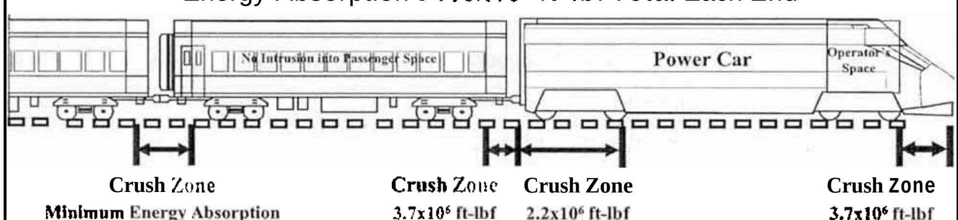
## Structural Crashworthiness

- Objectives:
  - Preserve Occupied Volume
    - Set Allowable Crush Stroke
  - Control Consist Behavior
    - Absorb Collision Energy in Controlled Manner
      - Prescribe Amount of Energy Absorption
    - Distribute Crush Along Consist **Length**
      - Characteristics of **Force/Crush**
    - Minimize Vertical k Lateral Motions
- CEM Requirements Are in Addition to Existing Load Requirements



## Example: Structural Crashworthiness

- Tier II: 49 CFR Part 238 Subpart E
  - Energy Absorption : $9.6 x 10^6$ ft-lbf Total Each End




- Crush Zones Must Be Placed on Either Side of Occupied Areas
- No Restriction on Crush Stroke Length

## Structural Crashworthiness

| | AQTA RQ. | Tier II | E.3 TSI | Proposed |
|---|---|---|---|---|
| Energy Absorption | ✓ | ✓ | ✓ | ✓ |
| Crush Stroke | -- | -- | ✓ | ✓ |



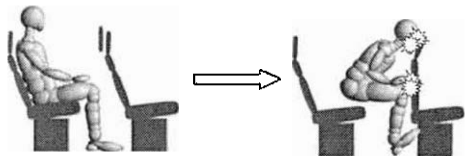
## Occupant Protection Requirements

- Define Survivable Secondary Impact Environment
  - Set Criteria for Passengers & Crew Members
    - Allowable SIV
    - Peak Acceleration Level
    - Average Acceleration Level
  - Additional Requirements*
    - Maintain Compartmentalization
    - Allow Quick Emergency Egress
    - Set Allowable Injury Criteria

* Additional Requirements Needed for Occupant Protection

## Occupant Protection Requirements

- Tier II: 49 CFR Part 238 Subpart E
  - Maximum Allowable SIV: 25 mph

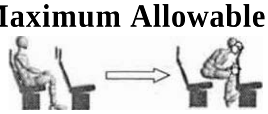


Prior to Impact — Secondary Impact

  - Peak Allowable Acceleration: 8 g's



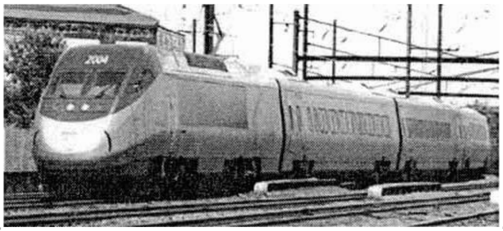
## Occupant Protection Requirements

| | APTA R.P. | Tier II | E.3 TSI | Proposed |
|---|---|---|---|---|
| Maximum Allowable SIV  Prior to Impact — Secondary Impact | ✓ | ✓ | -- | * |
| Peak Acceleration | ✓ | ✓ | -- | -- |
| Allowable Mean Acceleration | -- | -- | ✓ | -- |

* Alternative Requirements Needed

## Example:
## Tier II Compliant Equipment

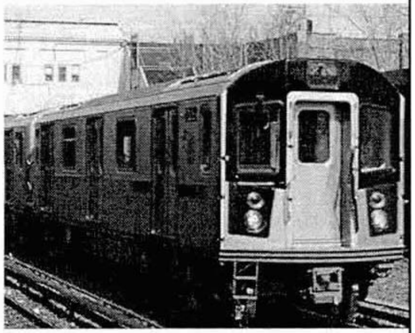
- Acela Express - High Speed Trainset
- Manufactured by Bombardier/Alstom
- Trainset ~$9.6 \times 10^6$ ft-lbf Energy Absorption Per End
  - Power Car Plus First Trailing Coach





## Example:
## Domestic Subway with CEM Features

- New York City Transit R142 - Rapid Transit Car
- Qualified Designs By:
  - Bombardier
  - Kawasaki
- Both Designs - $1 \times 10^6$ ft-lbf of Energy Absorption



http://www.kawasakirailcar.com/rapidTransit.htm

## Example:
## Domestic LRV with CEM Features

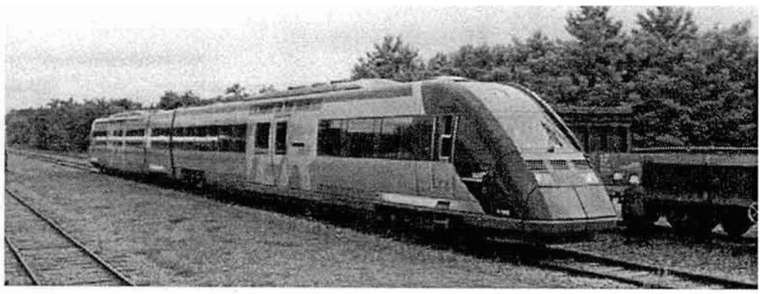
- New Jersey Transit Hudson-Bergen Line - Light Rail Vehicle
- Manufactured by Kinkisharyo
- Total Energy Absorption ~$0.4 \times 10^6$ ft-lbf

http://www.railfanwindow.com/gallery/HBLR/hblr004

Session I | CEM Structural Standards & Specifications | Slide 18

## Example:
## Overseas Service

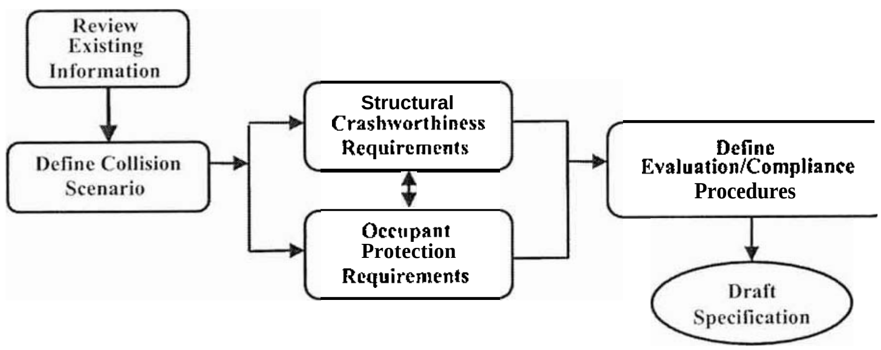
- XTER - Diesel Multiple Unit (DMU) (France)
- Manufactured by Alstom
- Energy Absorption ~$4.3 \times 10^6$ ft-lbf



Session I | CEM Structural Standards & Specifications | Slide 19

## Summary

- Objective of Working Group is to Use Information Presented to Develop a Specification for Inclusion of CEM Features for the Commuter Railroad Industry




Session I CEM Structural Standards & Specifications Slide 20

# Session II - Supplier Capabilities

| | |
|---|---|
| Bombardier CEM Equipment | Jacques Brassard, Bombardier |
| Kawasaki CEM Equipment | Toshi Hasegawa, Kawasaki |
| Indian Railway CEM Equipment | Steve Kirkpatrick, ARA |
| Regulatory Perspective | Grady Cothen, FRA |

DEPARTMENT OF TRANSPORTATION UNITED STATES OF AMERICA

# Single Rail Vehicle Crashworthiness Study

(Reference: Proceedings of the 2001 IEEE/ASME Joint Railroad Conference, pp.251-257)

Kawasaki Rail Car, Inc. — Toshi Hasegawa, Kenneth Mannen

Kawasaki Heavy Industries Ltd. — Toshinori Kimura

Single Rail Vehicle Crashworthiness Study
Contents





Single Rail Vehicle Crashworthiness Study
Introduction

Background

FRA has instituted regulations for operation of Rail Vehicles of speed above 125 mph, and is considering Crash Energy Management (CEM) for lower speed operations, which could be adopted as regulations.

However, in terms of cost, it is relatively expensive to use actual models for crash tests of rail vehicles.

One reasonable method is to evaluate crashworthiness using numerical simulations.

Single Rail Vehicle Crashworthiness Study
Introduction

## Kawasaki Approach to Numerical Simulations

There are some reports that have attempted to prove analytical accuracy by comparing their results with the results of actual experiments.

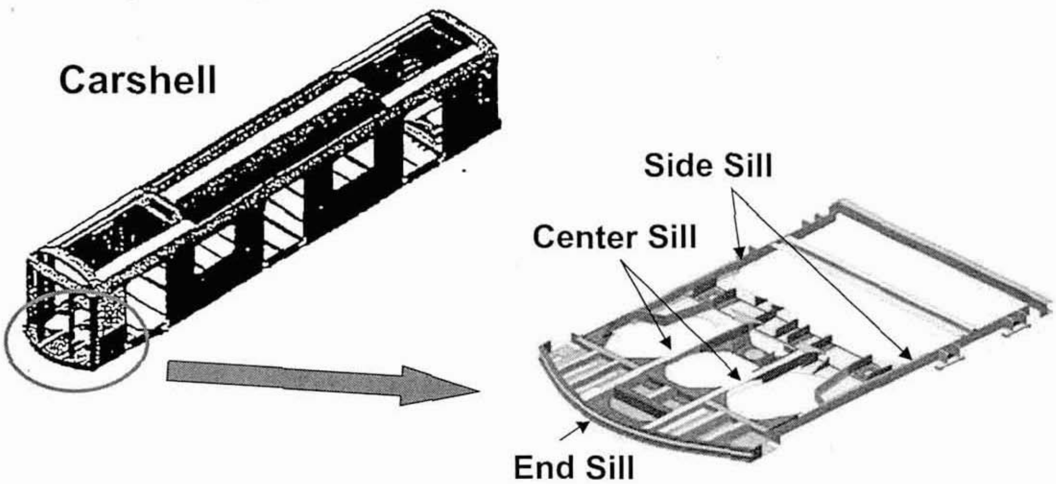
However, reports that discuss to what extent it is possible to evaluate the crashworthiness based on numerical simulations, and what points should be taken into consideration in the analysis, are relatively rare.

Numerical simulation was implemented before the experiment. We showed simulation results of the behaviors of the rail vehicle during collision, which could not be known by experiment.

Kawasaki KRC/th D506061-4

Single Rail Vehicle Crashworthiness Study
Crash Analysis Preparation

## Structure Design of Single Rail Vehicle




End Underframe

Crushable **Zones:** End Sill, Center Sill, and Side Sill

## Evaluation of Strength at End Underframe

Requirements for a structure to absorb the energy exerted on the **carshell** structure include the following:

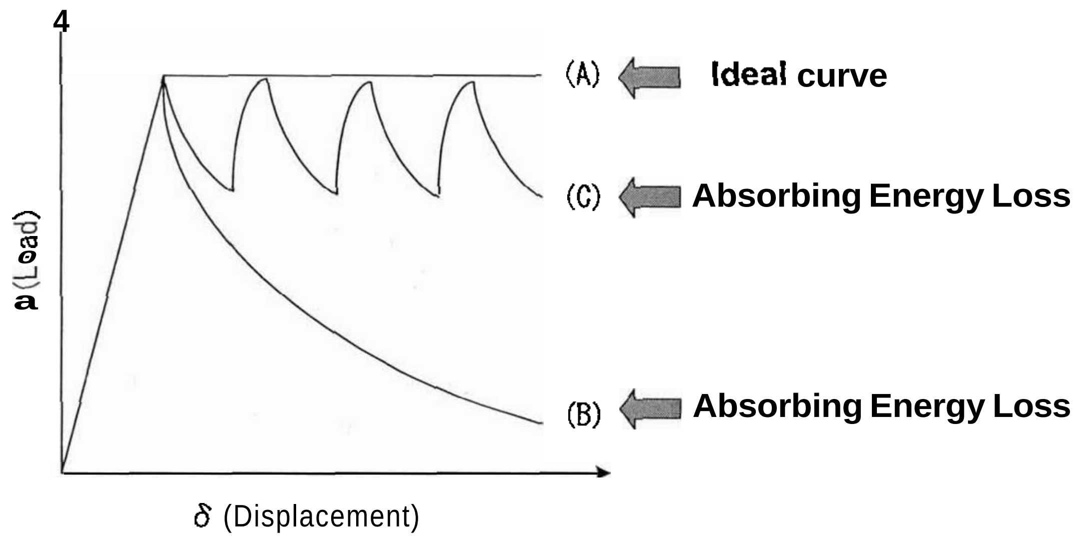
1. To avoid deformation occurring at any other section, especially the compartments for the crew and passengers.
2. To be able to absorb the largest possible crash energy.

In order to meet these contradictory requirements, relationship between the reaction force and displacement during the crash of energy absorbing members is shown in next slide.





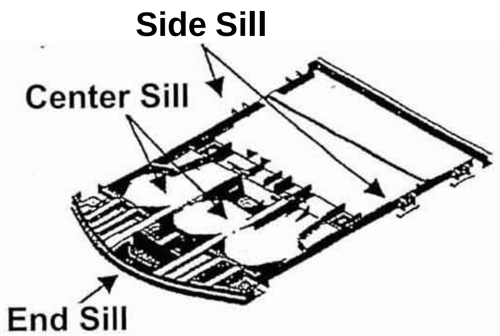
## Evaluation of Strength at End Underframe

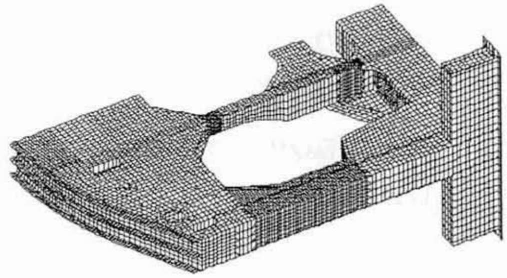



Idealized Load-Displacement Curve of Energy Absorbed Member

## Single Rail Vehicle Crashworthiness Study
## Crash Simulation (LS-DYNA)

### LS-DYNA (Finite Element Dynamic Analysis program)



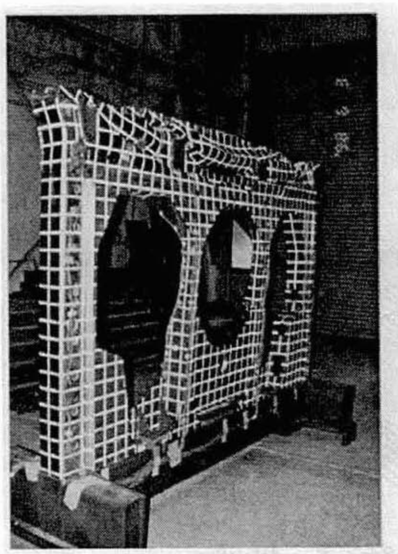
**Design** **Model (Mesh)**

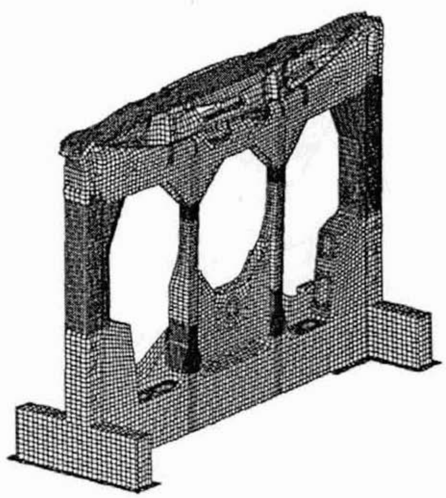
**End Underframe**



## Single Rail Vehicle Crashworthiness Study
## Quasi-Static Analysis

### End Underframe Results

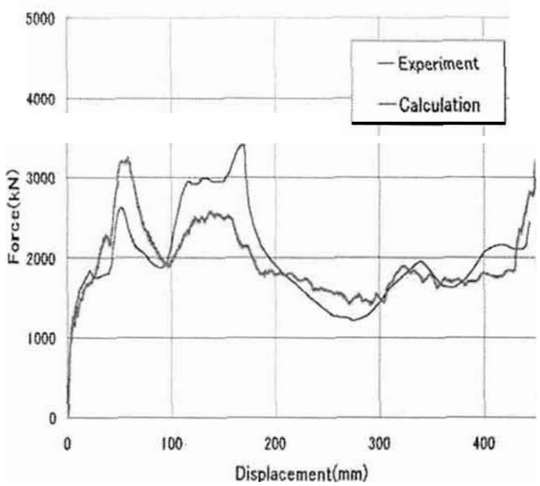




**Experiment** **Calculation**

## **Single** Rail Vehicle Crashworthiness Study
## **Quasi-Static** Analysis

### End Underframe Results



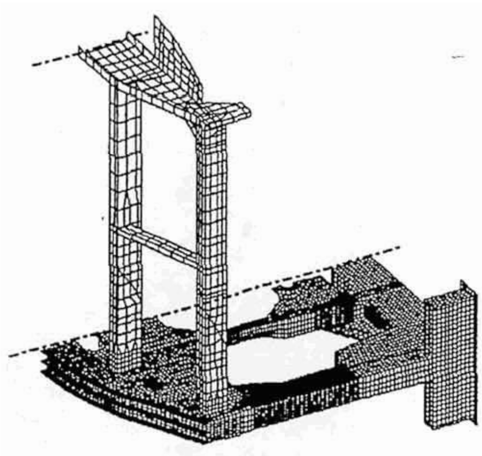

Relationship between Load and Compressive **Displacement**



## Single Rail Vehicle Crashworthiness Study
## **Carshell** Structure Crash Analysis

### Dynamic Analysis

Actual crash is dynamic, therefore the dynamic strain rate effect & inertia effect should be considered.

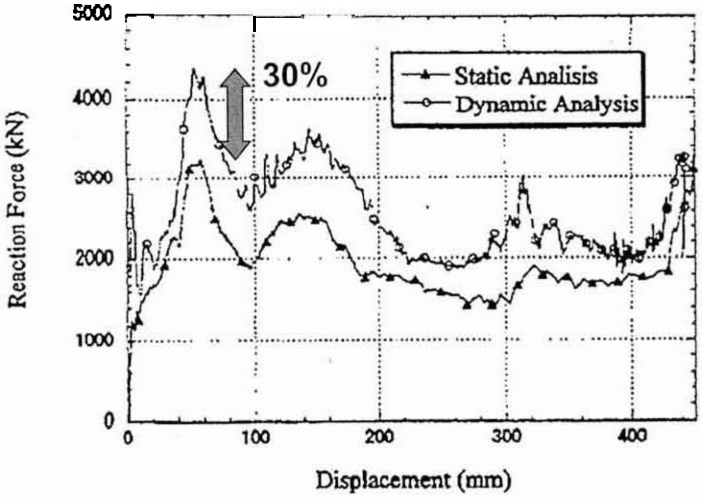


Strain rate effect: Cowper-Symonds equation

AT plate, Collision Posts, and End Underframe Model

## Single Rail Vehicle Crashworthiness Study
## Carshell Structure Crash Analysis

### Dynamic Analysis Results

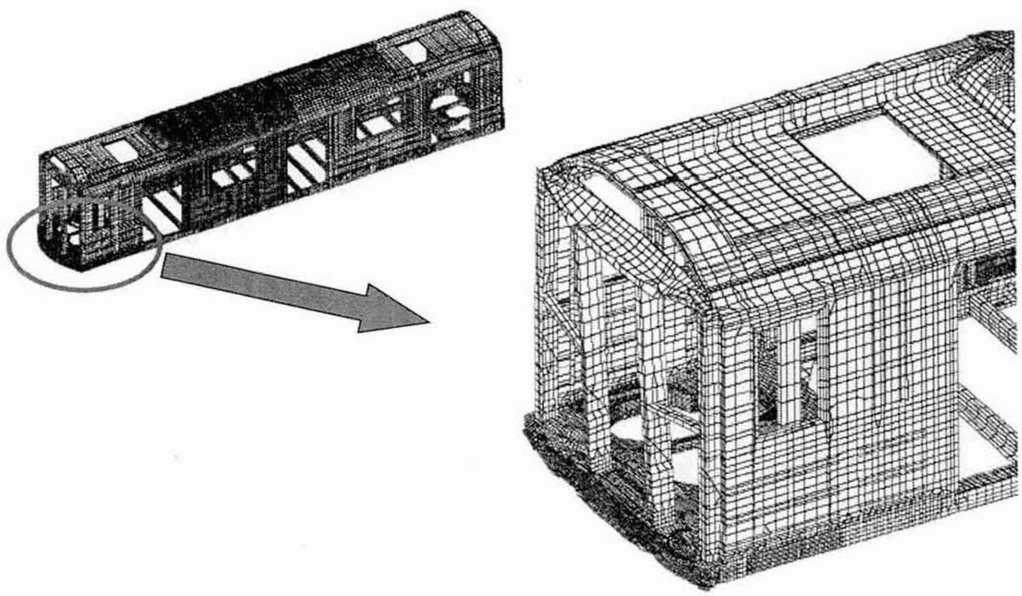



**Dynamic Effect on Load-Desplacement Relation**



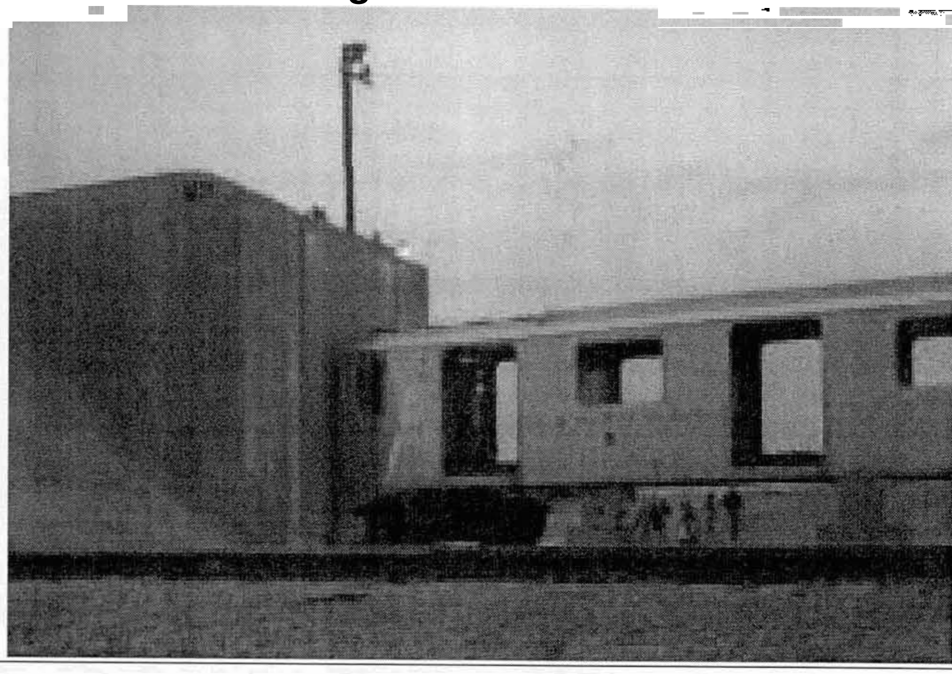
## Single Rail Vehicle Crashworthiness Study
## Carshell Structure Crash Analysis

### Carshell Crash Simulation Results



## Single Rail Vehicle Crashworthiness Study
## Carshell Structure Crash Analysis

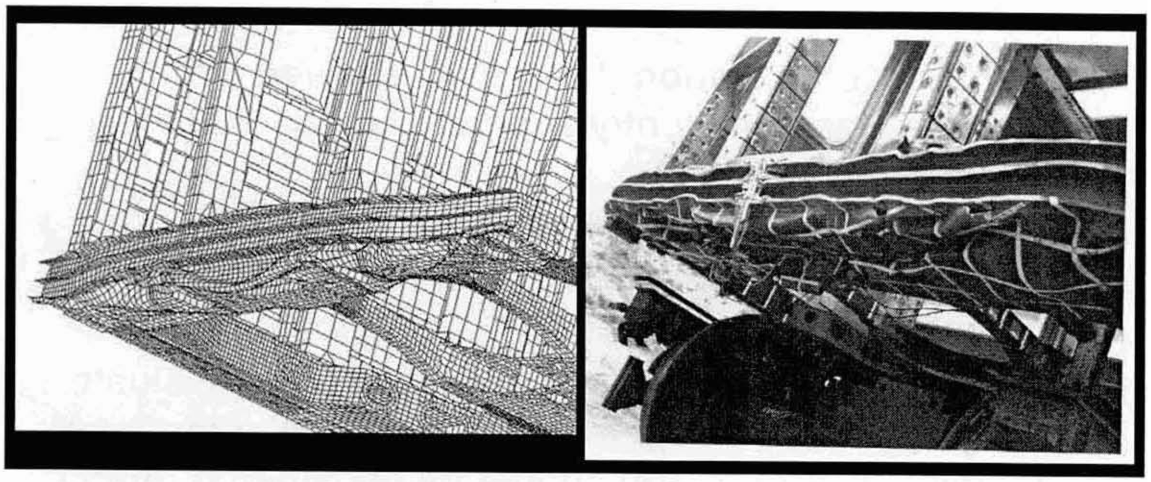
### Carshell Crash Testing





## Single Rail Vehicle Crashworthiness Study
## Carshell Structure Crash Analysis

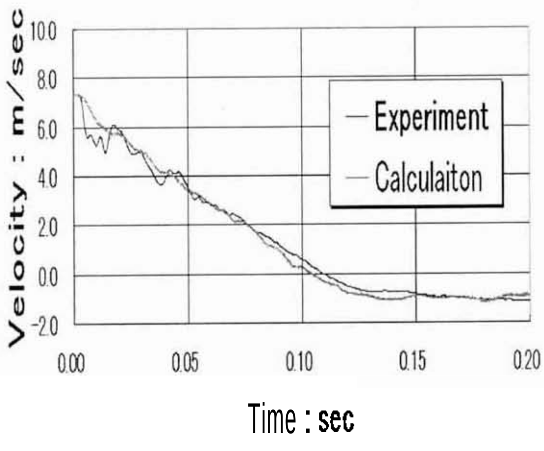
### Carshell Calculation vs. Experiment

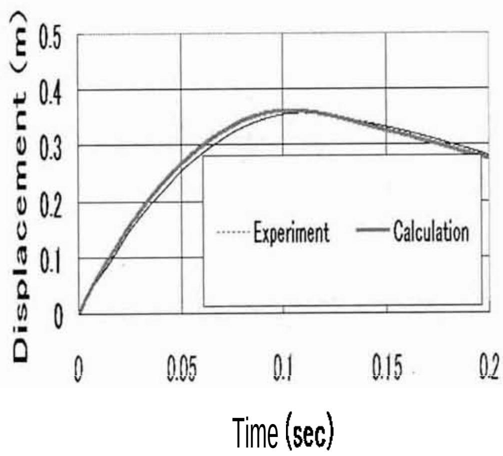


Calculation Experiment

## Single Rail Vehicle Crashworthiness Study
## **Carshell** Structure Crash Analysis

Correlation between calculation and Experiment






## Single Rail Vehicle Crashworthiness Study
## Conclusion

1. Single Rail Vehicle Crashworthiness has been achieved.
2. Numerical Simulation (LS-DYNA) showed that the calculations sufficiently accurate compared to the experiment results.
3. **Carshell** crash testing was implemented and deformation by crash energy absorption was visualized.
4. Numerical Simulation is a powerful tool to evaluate Crash Energy Management. However, assumptions (especially strain rate) should be considered. Also, quasi-static test is very important for successful crash testing.

# DEVELOPMENT OF CRASHWORTHY COACH CARS FOR THE INDIAN RAILWAYS

## Crash Energy Management Technology Transfer Symposium

**June 29 through July 1,2005**
**San Francisco, California**

Transportation Technology Center, Inc.

## Crashworthiness Development

- **Program is a partnership of:**
  - Indian Railways (IR)
    - Collaboration on all aspects of program.
  - RITES Ltd.
    - Program Management (India), Design & Engineering.
  - Transportation Technology Center, Inc. (TTCI)
    - Program Management (US), Testing, Design Consulting.
  - Applied Research Associates, Inc. (ARA)
    - CEM Design, Analysis.

ARA — TTCI

12Nov03 2

## Indian Railways

- One of the largest railway operations under one administration.
- 64,000 route kilometers.
- 1.5 million employees.
- 16 percent of worlds rail passenger kilometers.
- Fleet with 35,000 coach cars.
- Manufacturing 2,000+ coach cars/year.

ARA — TTCI Transportation Technology Center, Inc.

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# Operating Environment

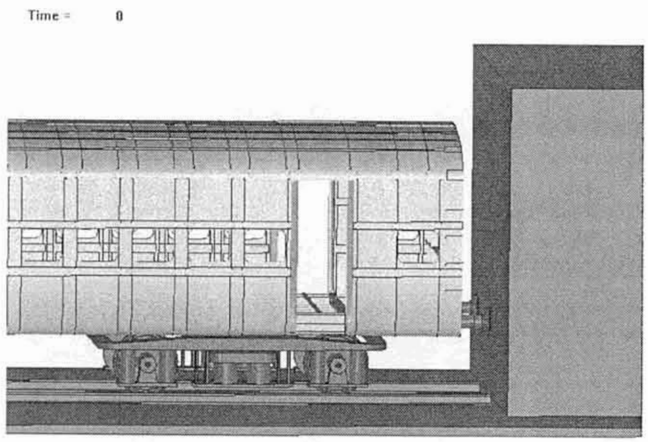
- Long distance travel is the normal condition (up to 48 hour journeys).
- Significant number of sleeper cars.
- Typical consist is locomotive hauled with **17-24 coaches.**
  - GS and SLR coaches at end of the consist.
- Broad gage (1676 **mm).**
- Low cost equipment (less than **$100K/coach).**
- Low cost mode of travel (GS - $511000 km).



# Unmodified GS Impact Analysis

- Detailed Crash Analyses:
  (40 kmph impact into a rigid wall)
  - Baseline crush behavior analyzed.
  - Baseline GS crush strength needed for development of lumped mass models.
  - Effects of the side buffers analyzed.

# Unmodified GS Impact Analysis




Baseline GS coach crush behavior (with buffers)

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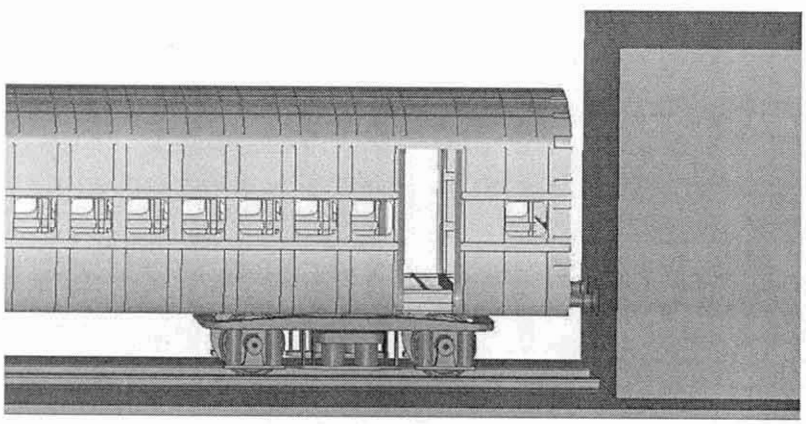
# Unmodified GS Impact Analysis



Baseline GS coach crush behavior

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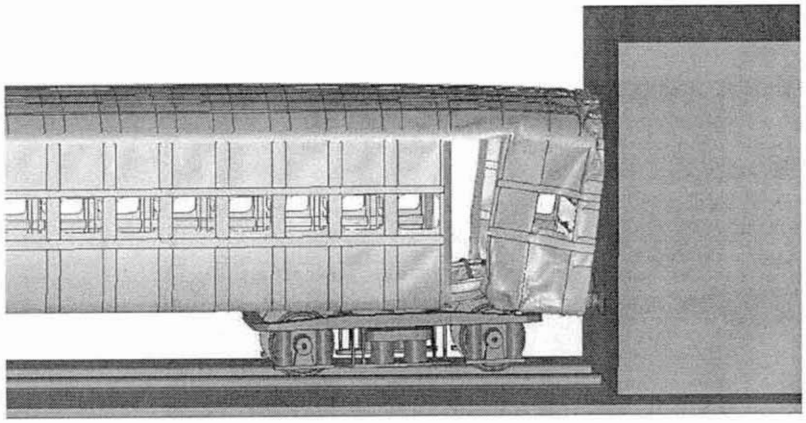
## Unmodified GS Impact Analysis



Baseline GS coach crush behavior

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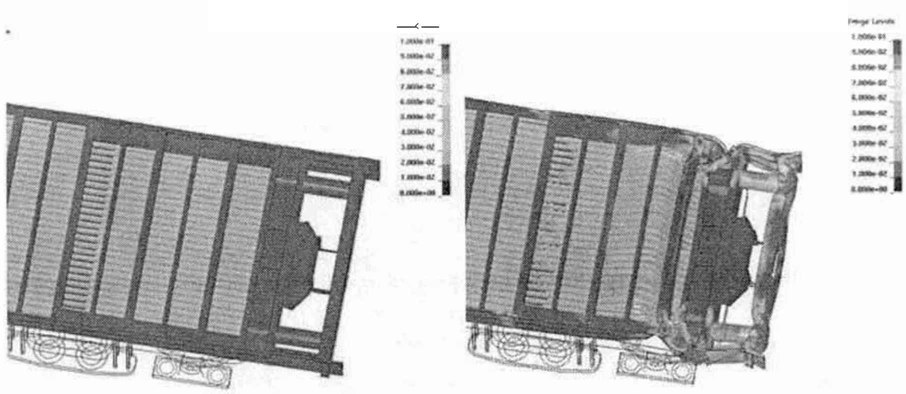
## Unmodified GS Impact Analysis



Baseline GS coach crush behavior

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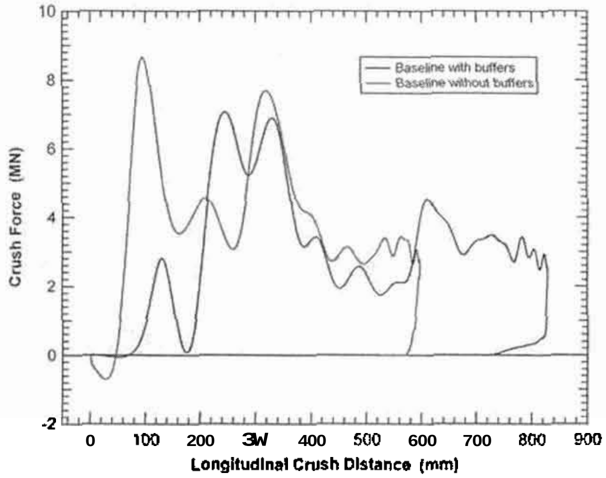
# Detailed Impact Analyses




Baseline GS coach crash behavior

06Feb04 10

# Baseline GS Crash Behavior

- Side buffers produce undesirable behavior:
  - Vaulting of car in collision–override potential.
  - localized underframe loading with uncontrolled crush response.
  - Space between car ends not utilized in energy absorption.
- Collapse localizes to end door regions
  - May prevent egress after collision.
  - Door zone is a weak point in the structure.
- Peak GS car crush force is 7-9 MN.
  - Uniform car body strength is probably higher.

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RITES

# Crashworthy GS Coach Design

- Requirements of crashworthy GS Coach design.
  - Controlled energy absorption at car end crush zone.
  - Collision energy distributed along length of consist.
  - Improved control of train collision dynamics.
- Approach selected is a CBC design with shear away buff stop and energy absorption in push back response.
  - Approach meets requirements and is well suited to IR environment with long consists.
  - Proven technology.

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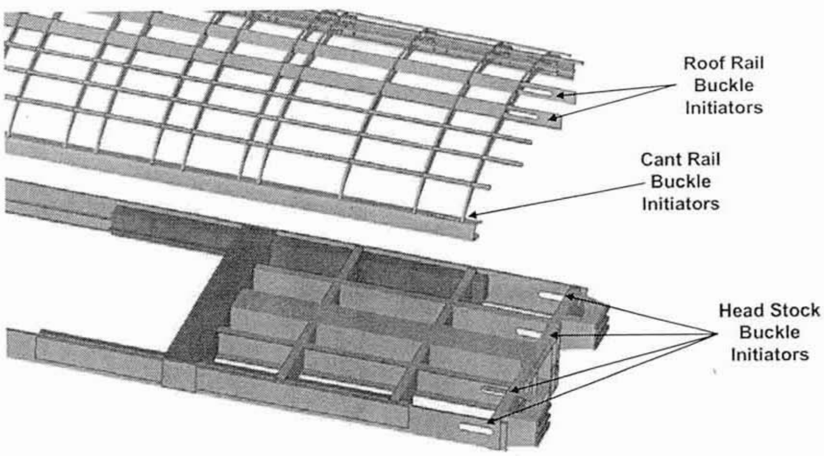
# Crashworthy GS Coach




New Crashworthy GS Coach Design

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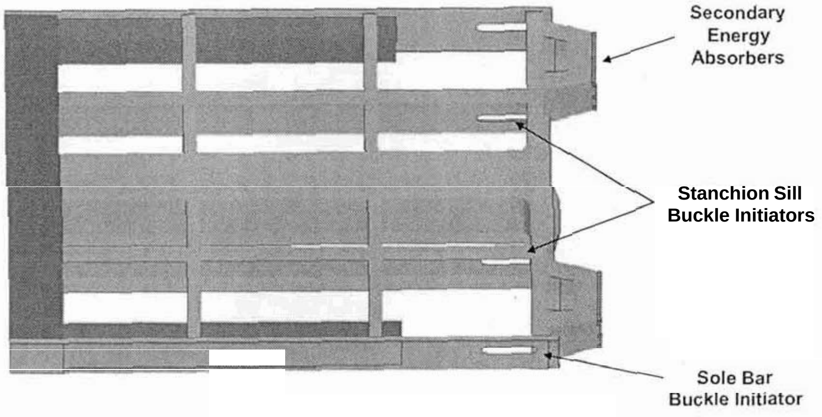
## Crashworthy GS Coach




**New Crashworthy GS Coach Design**

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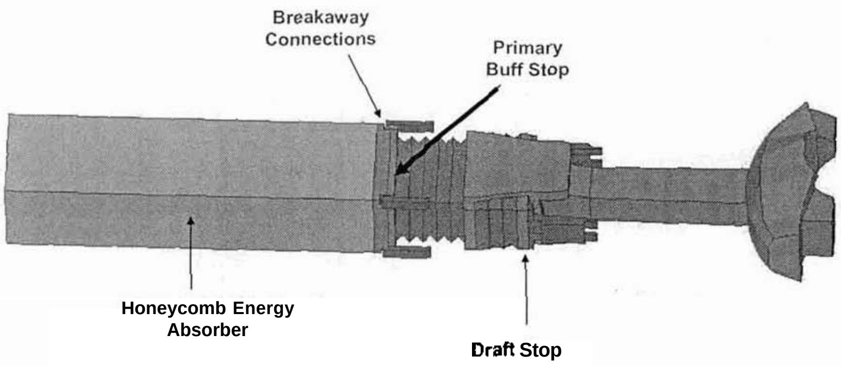
## Crashworthy GS Coach




**Crashworthy CBC Draft Gear and Primary Energy Absorber**

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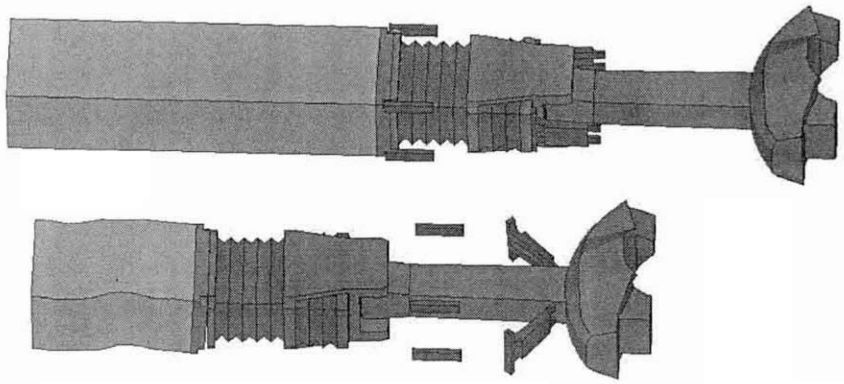
## Crashworthy GS Coach



**Crashworthy CBC Draft Gear and Primary Energy Absorber**

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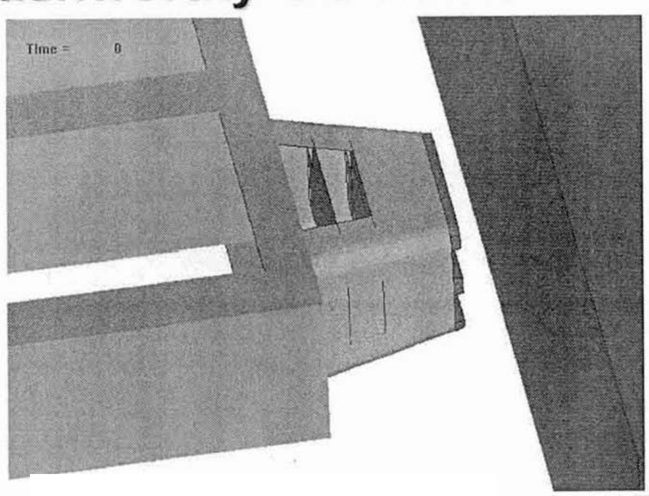
## Crashworthy GS Coach




**Secondary Energy Absorber**

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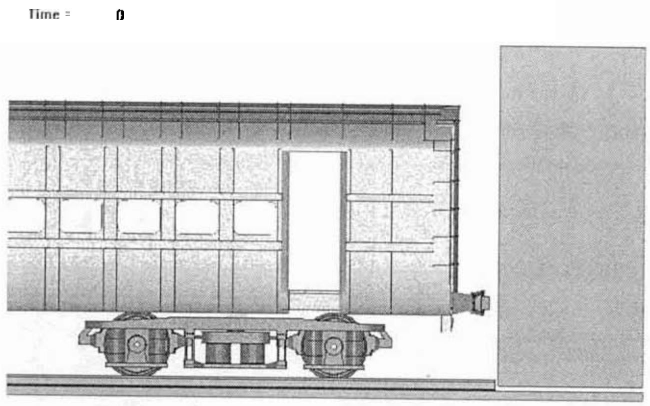
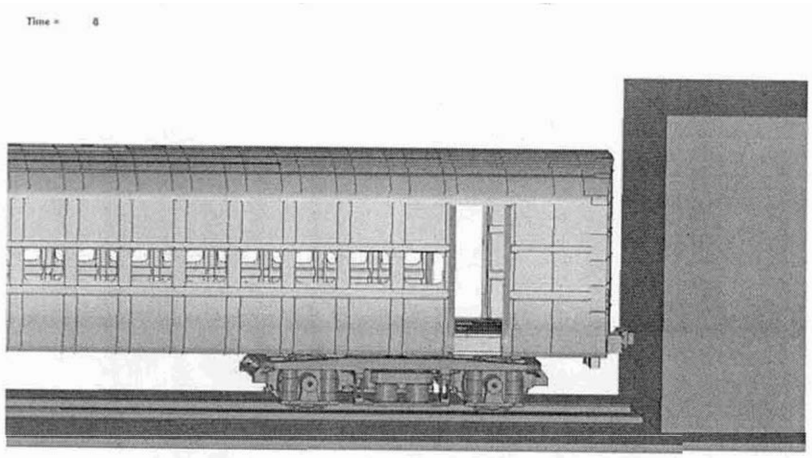
## 40 kmph Impact Analysis




Crashworthy GS coach crush behavior

## 40 kmph Impact Analysis




Crashworthy GS coach crush behavior

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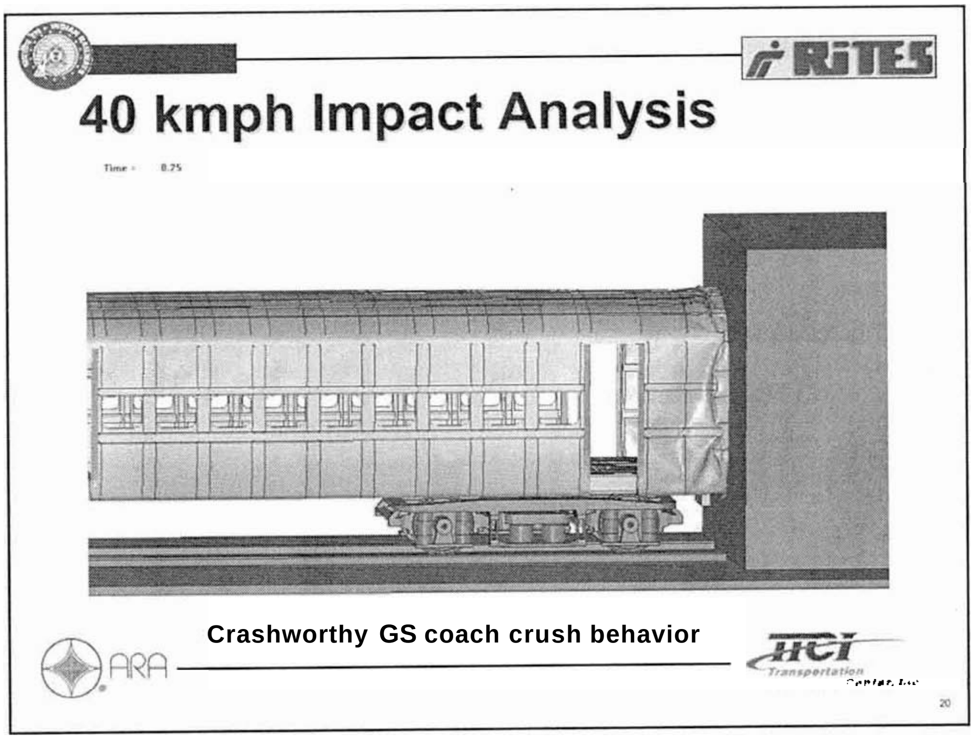
RITES
40 kmph Impact Analysis
Crashworthy GS coach crush behavior
ARA
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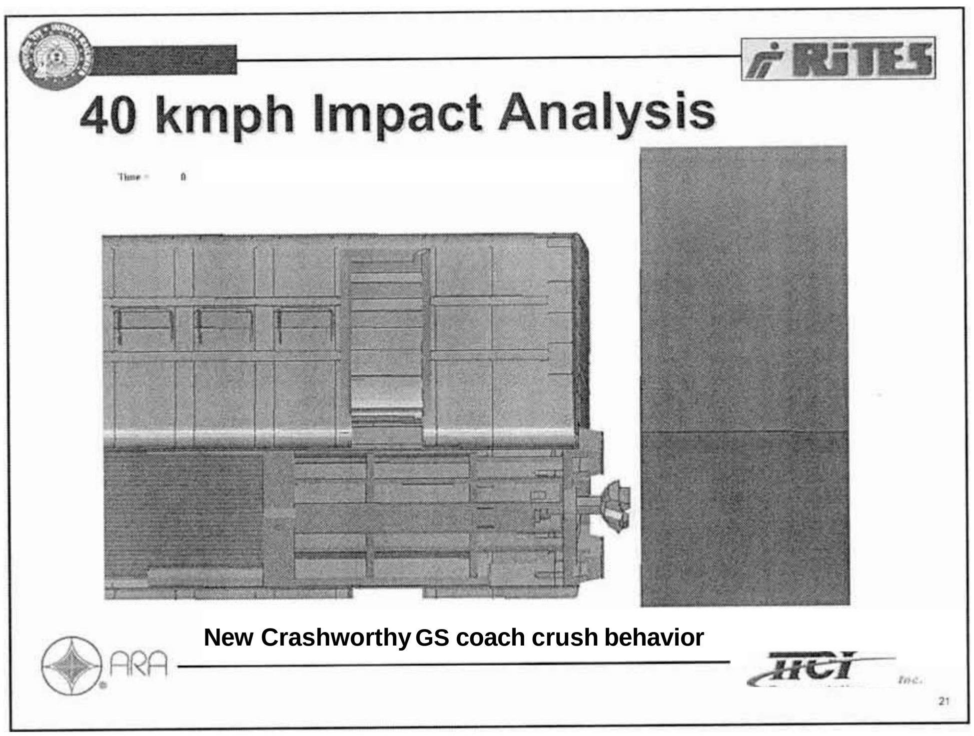
RITES
40 kmph Impact Analysis
New Crashworthy GS coach crush behavior
ARA
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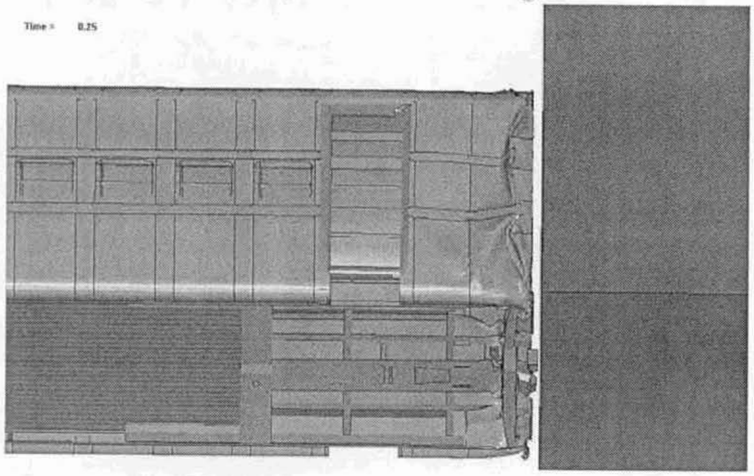
# 40 kmph Impact Analysis



New Crashworthy GS coach crush behavior

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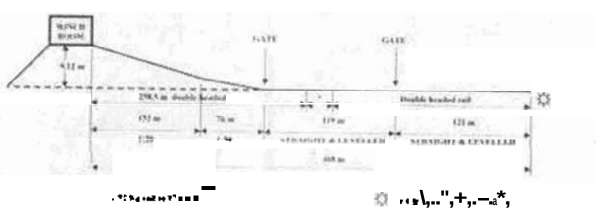
# Ramp Platen Crash Test

- The intermediate test was performed at RDSO, **Lucknow**
- The test utilized the VCF ramp facility to accelerate the cars to speed.



TEST TRACK GEOMETRY OF VCF LABORATORY

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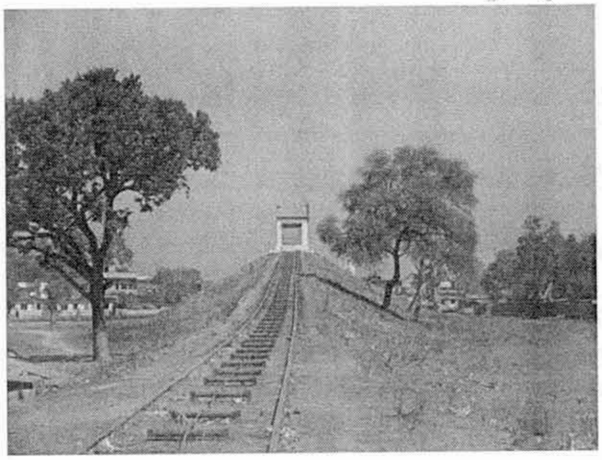
## Vehicle Crash Facility (VCF)



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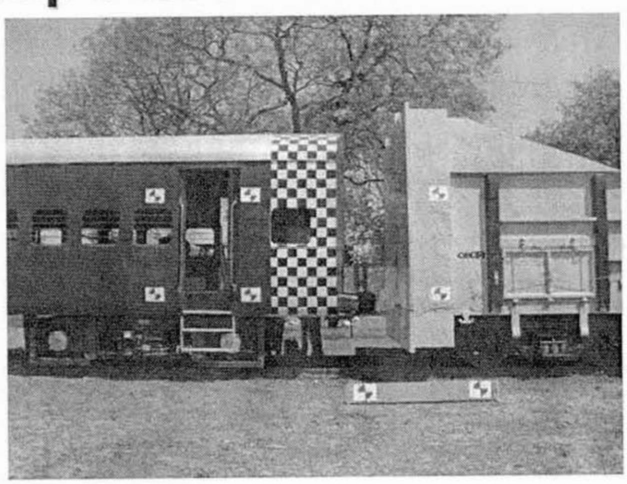
## Ramp Platen Crash Test



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# Ramp Test of Crashworthy GS

- Impact Conditions.
  - 42 kmph impact speed.
  - 39 t crashworthy GS coach test vehicle.
  - 110 t platen car.
  - Approximately 1.8 MJ of energy absorbed in the crashworthy GS coach.

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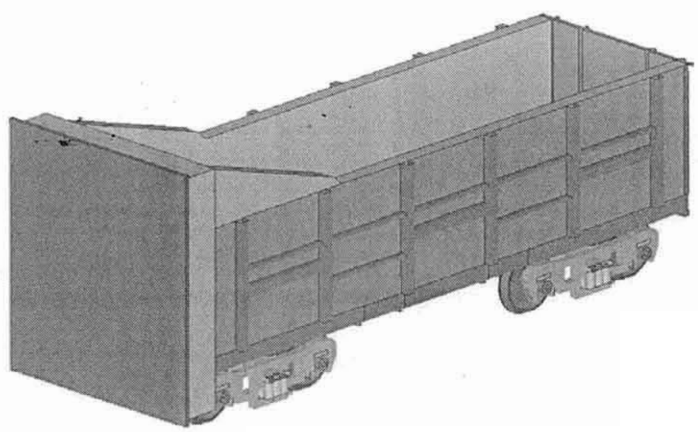
# Platen Car Ramp Test



Platen Car Model

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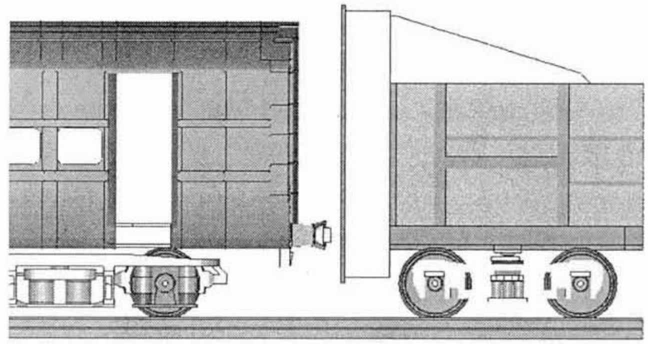
# Platen Car Ramp Test

Time = 0



38 kmph GS and Platen Car Impact Analysis

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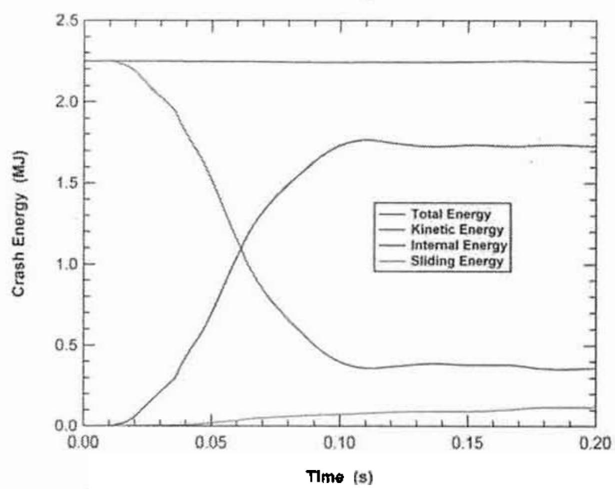
# Platen Car Ramp Test




38 krnph GS and Platen Car Impact Analysis

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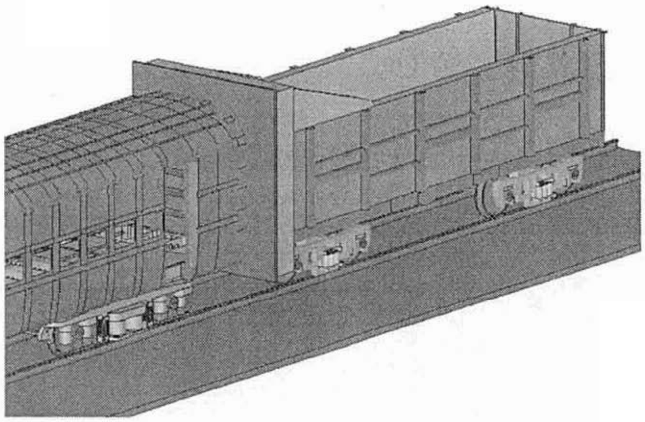
## Platen Car Ramp Test

Time = 0



38 kmph GS and Platen Car Impact Analysis

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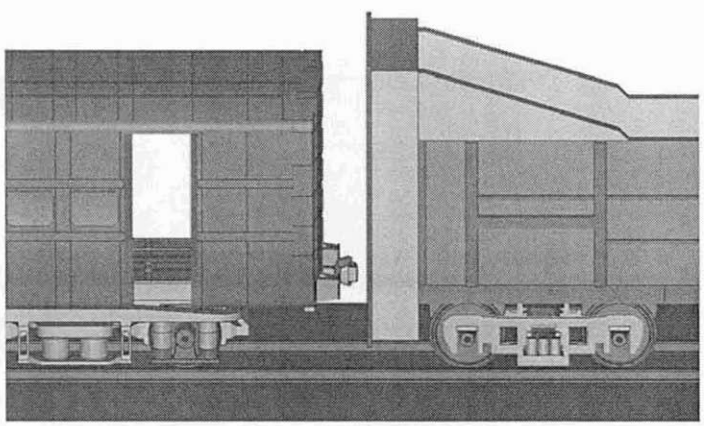
## Platen Car Ramp Test

Time = 0



38 kmph GS and Platen Car Impact Analysis

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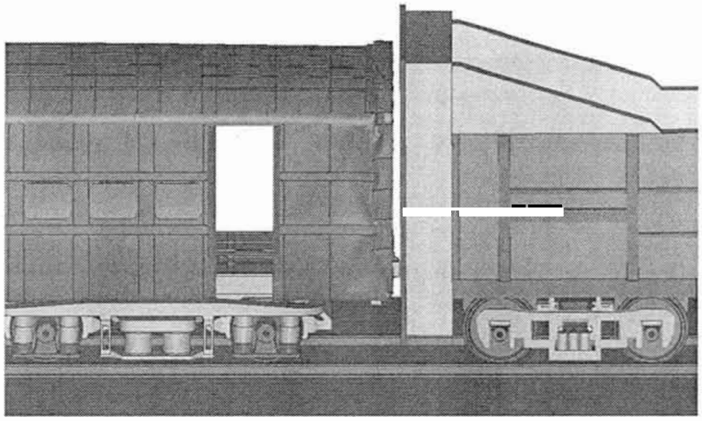
## Platen Car Ramp Test

Time = 0.2



38 kmph GS and Platen Car Impact Analysis

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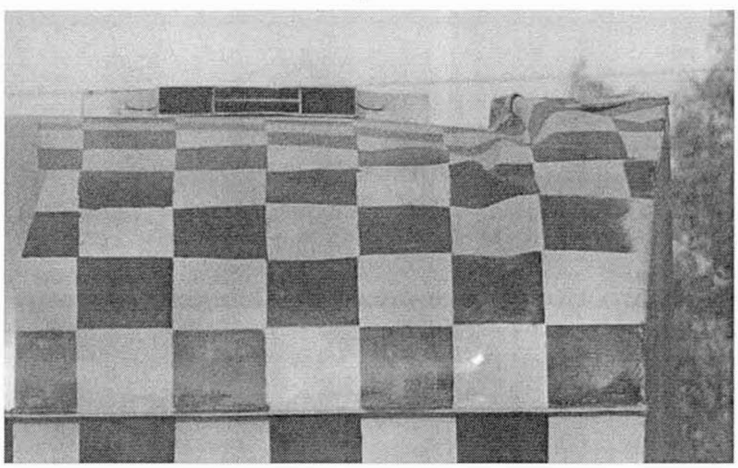
## Platen Car Ramp Test



Measured Behavior

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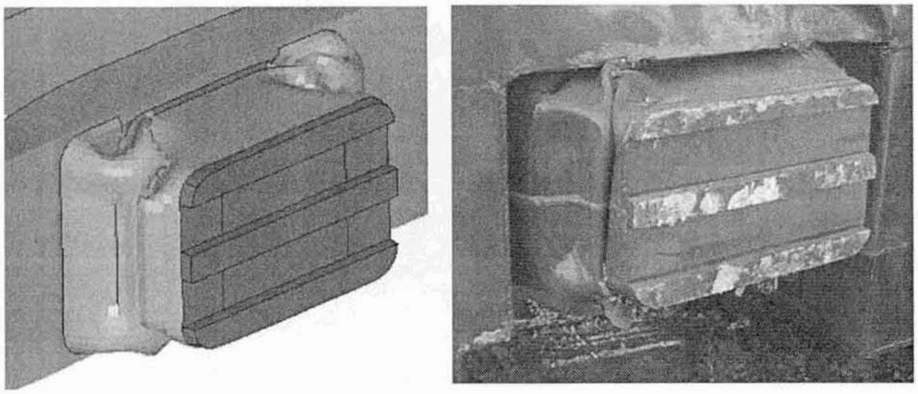
RITES

# Platen Car Ramp Test



Measured Behavior

ARA

TTCI Transportation Technology Center, Inc.

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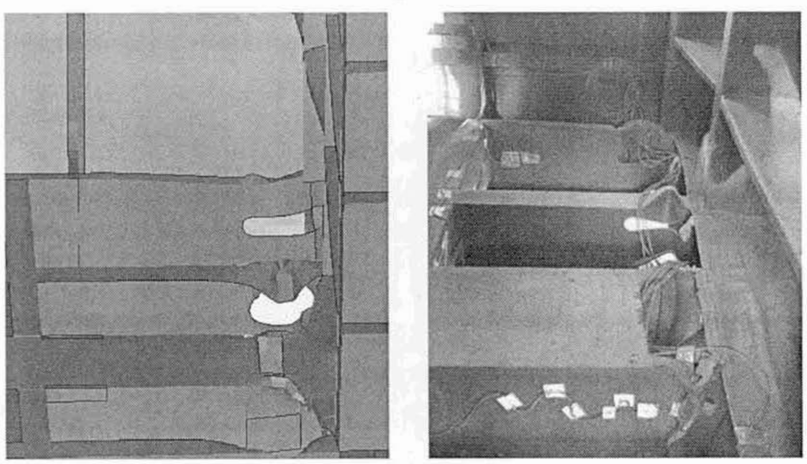
RITES

# Platen Car Ramp Test



Under Frame Crush Mode

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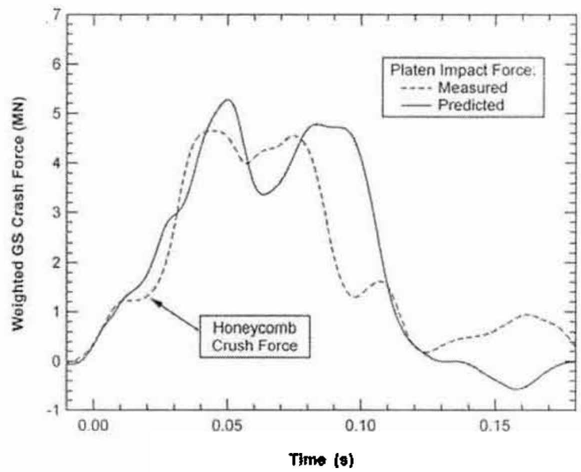
# Platen Car Ramp Test




Platen Car Impact Force



# Summary

- **Ongoing Program to redesign GS and SLR Coaches.**
  - **GS design complete and prototype cars to be placed in service in 2005.**
    - **Additional 2-car crash test scheduled for October 2005.**
- **SLR Design following similar design approach.**
  - **SLR located at end of consist**
  - **Higher energy absorption requirements (–5 MJ).**
  - **Test scheduled for October 2005.**

Transportation Technology Center, Inc.

# Session III - Service Experience with CEM

Acela Service Experience — George Binns, Amtrak

Hudson-Bergen Experience — Clive Thomas, Parsons-Brinkerhoff

**Crash Energy Management Technology Transfer Symposium**
**June 29 through July 1, 2005**
**San Francisco, California**

# CRASH ENERGY MANAGEMENT TECHNOLOGY TRANSFER SYMPOSIUM SAN FRANCISCO, CA

SESSION III
SERVICE EXPERIENCE WITH CEM
HUDSON BERGEN EXPERIENCE

Clive Thornes
Manager Rail Vehicles
PB Transit & Rail Systems, Inc.

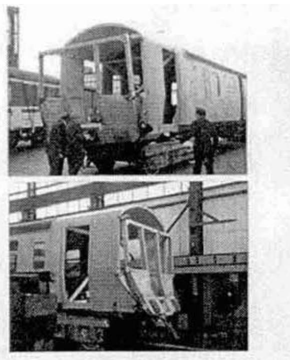
June 30th, 2005

## Where did it Start?

BRITISH RAIL RESEARCH

60 MPH COLLISION TEST

- CONTROLLED DAMAGE
- NO DERAILMENT
- NO OVERRIDING



## Preliminary Work

- 70% Light Rail Low Floor Car
- NJ Transit desired a lighter car with CEM
- Concern with amount of metal in underframe
- Structural Requirements Study performed in 1994/1995
  - Evaluation of dynamics of collisions
  - Evaluation of buff load and overall structural design
  - Effect of difference in height and buff load on car shell weight
- Technical Paper presented at APTA Rapid Transit Conference June 1996

## NJ Transit Specification and Technical Provisions

Based on a two 40,000 kg car train in collision with unbraked two 40,000 kg car train at a closing speed of 20 km/h.

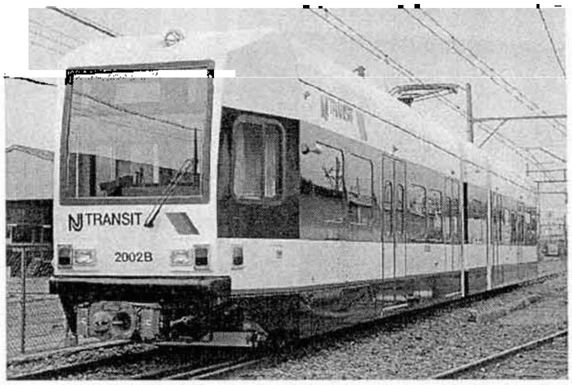
- Buff load at anticlimber 392 kN
- Buff load at coupler bracket 431 kN
- Absorb 308 kJ distributed between coupler, anticlimber and end underframe
- 600 to 1000 mm controlled collapse
- Coupler 8 km/h closing speed

## NJ Transit Light Rail Vehicle

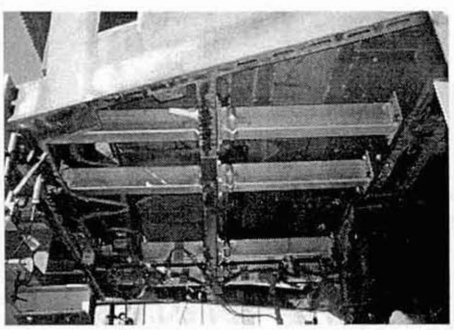
Based on two car train in collision with unbraked two car train at a closing speed of 20 km/h.

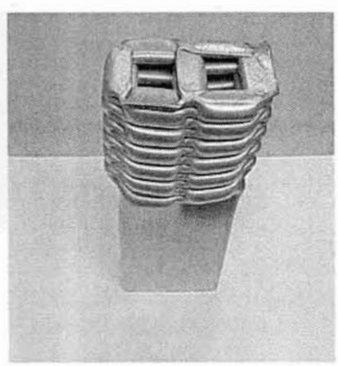
- Each car 45,000 kg
- Buff Load at Anticlimber 441 kN
- Buff Load at Coupler Bracket 490 kN
- Absorb 347 kJ distributed between coupler, and end underframe
- 600 to 1000 mm controlled collapse
- Coupler 14.5 km/h closing speed

## The NJ Transit Light Rail Car – HBLRTS and NCS

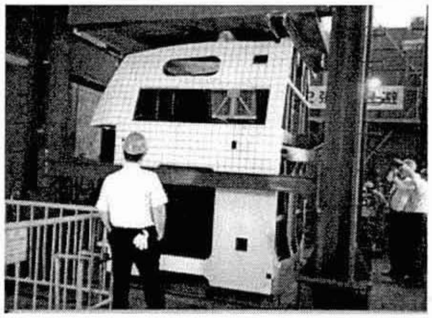


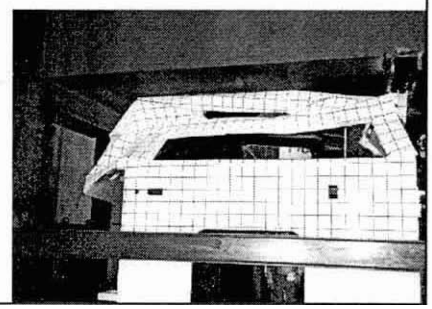

## CEM Aluminum Tubes



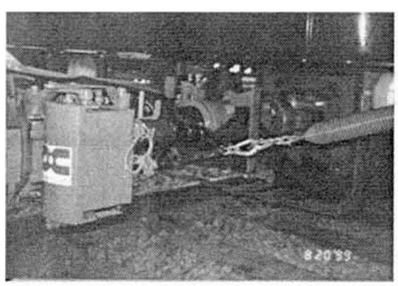


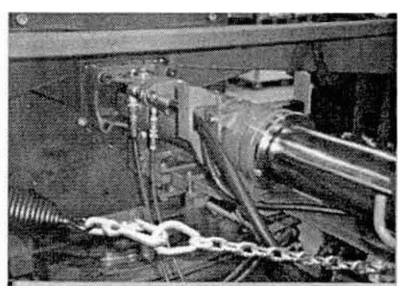
## Static Test of Cab





## Coupler Energy Absorbing Unit





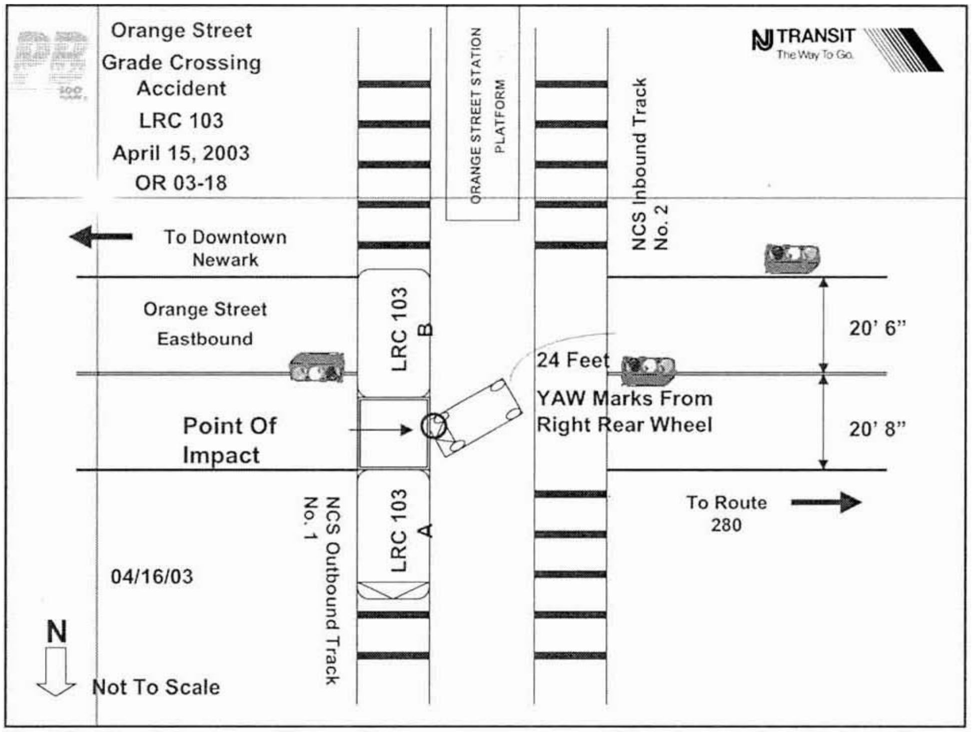
## Unscheduled testing

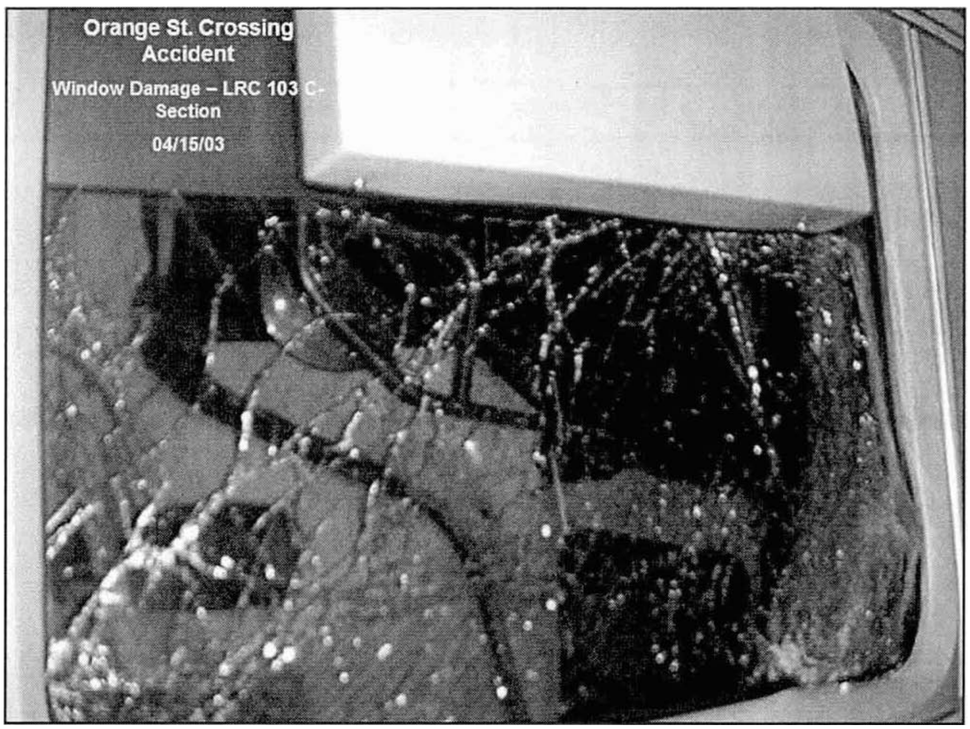
Two Major Collisions:

- Car 103 T- Bone by Heavy Truck
  - April 15th, 2003
- Car 2003 Head on with Heavy truck
  - May 12th 2003

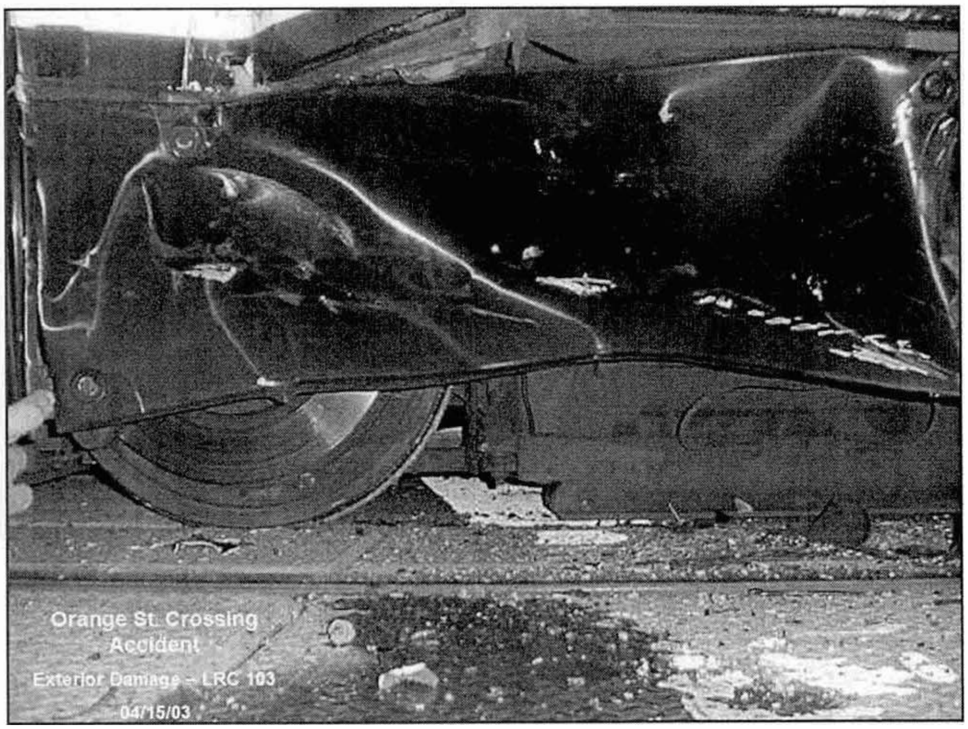
## CAR 103

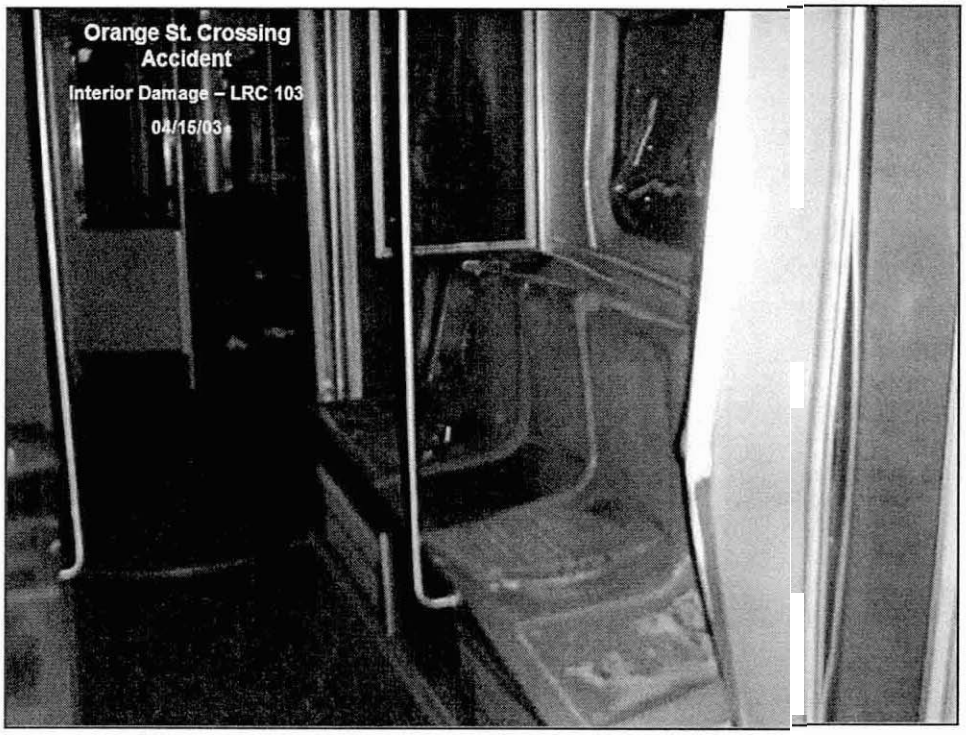
- System – Newark City Subway
- Location – Orange Street Crossing
- Date - April 15th, 2003
- Estimated LRV Speed – 10 mph
- Estimated Truck Speed – 35 mph
  Truck Weight – 30,000 lb
- Movement - 6 ft


Orange Street
Grade Crossing
Accident
LRC 103
April 15, 2003
OR 03-18
NJ TRANSIT
The Way To Go.
ORANGE STREET STATION
PLATFORM
NCS Inbound Track
No. 2
To Downtown
Newark
Orange Street
Eastbound
LRC 103
B
24 Feet
YAW Marks From
Right Rear Wheel
20' 6"
20' 8"
Point Of
Impact
LRC 103
A
NCS Outbound Track
No. 1
To Route
280
04/16/03
N
Not To Scale


Orange St. Crossing
Accident
Window Damage – LRC 103 C-
Section
04/15/03


Orange St. Crossing
Accident
C-Section Damage – LRC 103
04/15/03

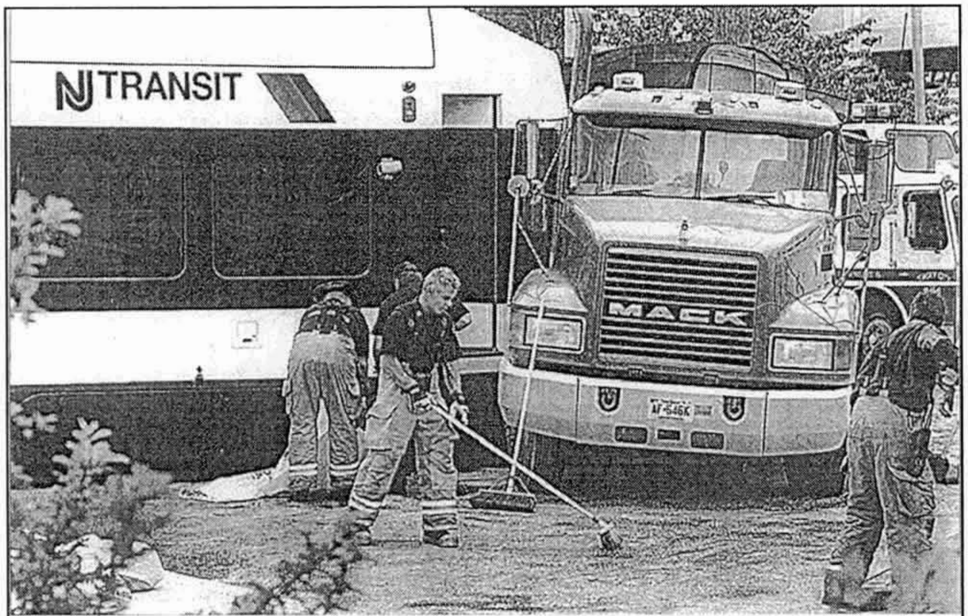

Orange St. Crossing
Accident
Exterior Damage – LRC 103
04/15/03




## Car 2003

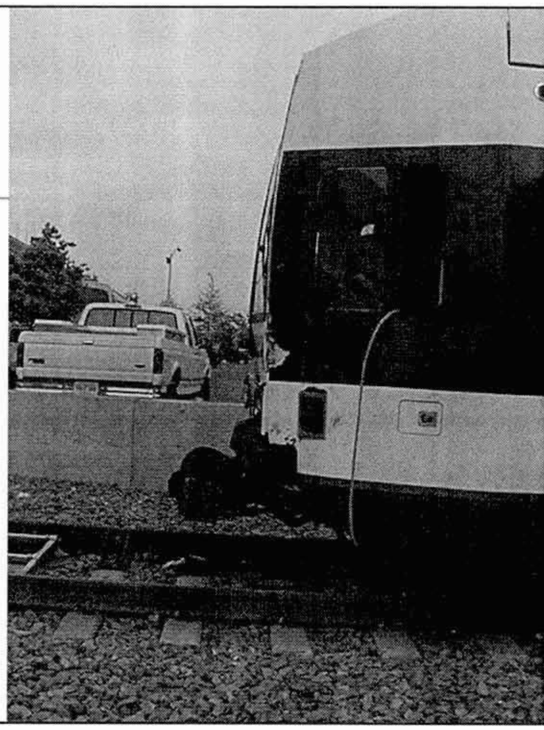
System – Hudson Bergen
- Location – Newport
- Date – May 12th, 2003
- Estimated LRV Speed – 12mph

Estimated Truck Speed – 25 mph
- Truck Weight - 60 ton
- Movement 10 ft (into catenary pole)


NJ TRANSIT
MACK

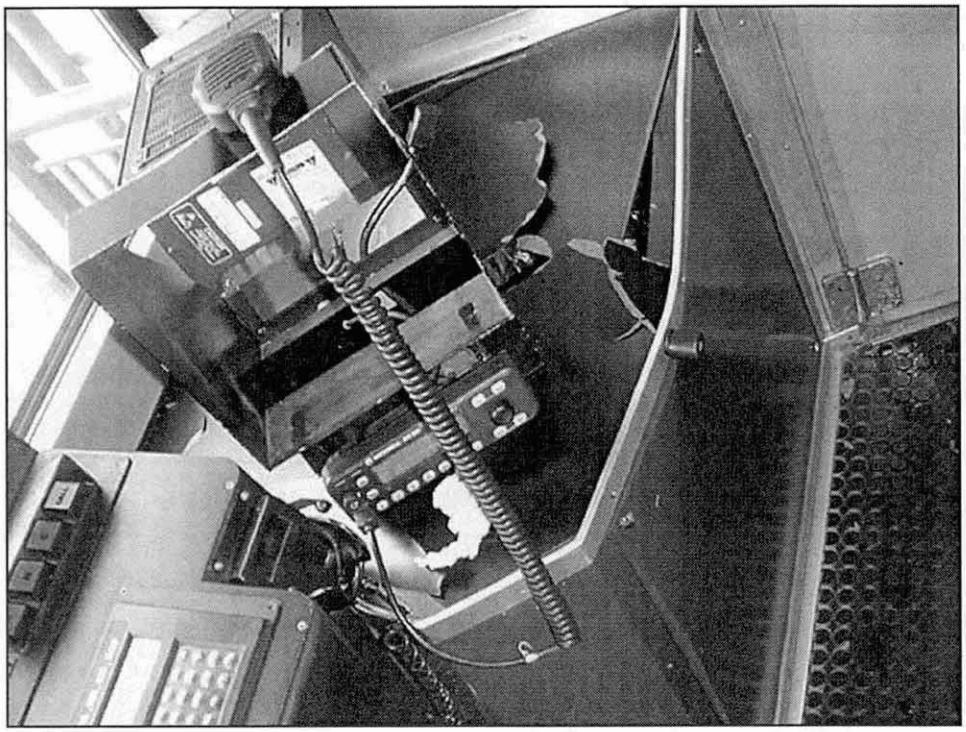

NJ TRANSIT
NJ TRANSIT
2003B


NJ TRANSIT
2003B




NJ TRANSIT
NJ TRANSIT
2003B


DO NOT
STOP ON
TRACKS
POLICE LINE DO NOT CROSS
POLICE LINE DO NOT CROSS
POLICE LINE DO NOT CROSS
POLICE LINE DO NOT CROSS



# Inferences from Major Collisions

- Designed Carbody Side Structure performs satisfactory in side swipe
- End of car with CEM performs in a satisfactory manner in head on collision
- No sharp objects enter interior of car
- Carbody structure does not disintegrate
- Low Cost to Repair

## NJ Transit Experience Summary

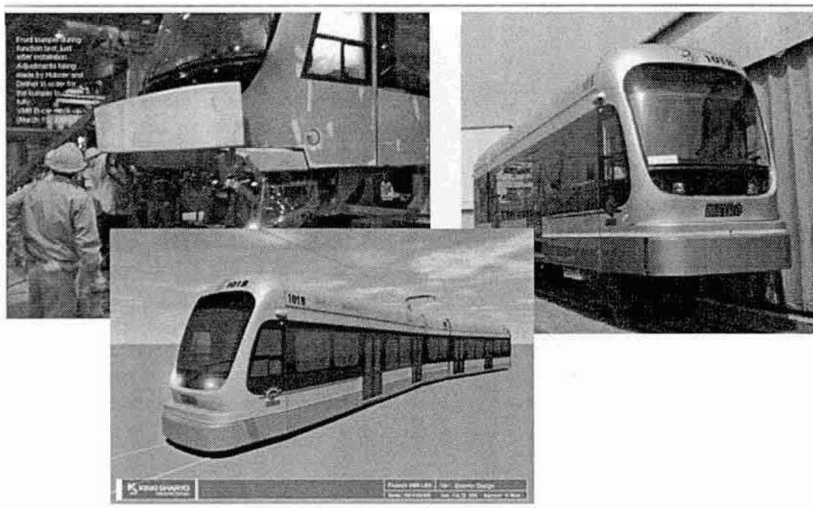
- Over Five Years of Operation in Revenue Service HBLRTS and NCS cars have Performed Very Well
- Lightweight car with CEM
- Proven Very Successful Design
- Several Minor Collisions with Automobiles
- Two Major Collisions with Heavy Trucks
- Structure Remains Intact
- All Cars Quickly Repaired at Low Cost with Localized Damage

## Moving On

Phoenix Valley Metro LRV designed to ASME RT-1 Revision 5, Draft Safety Standard for Structural Requirements for Light Rail Vehicles

- Same scenario as HBLRTS
- Buff Load at anticlimber 400 kN
- Buff Load at coupler Bracket 450 k N
- End underframe absorbs 350 kJ
- Absorption zone 500 mm to 700 mm
- Energy Absorbing Bumper 8 km/h
- Folding Coupler with Energy Absorbing Element
- "Friendly" design for all road users and pedestrians

# Phoenix Valley Metro LRV



THANK YOU

**Federal Railroad Administration**

**Federal Transit Administration**

# Session IV - CEM Effectiveness

| | |
|---|---|
| **Full-scale Testing: Methodology** | **Kristine Severson, Volpe** |
| **Full-scale Testing: Structural Crashworthiness** | **David Tyrell, Volpe** |
| **Full-scale Testing: Occupant Protection** | **Dan Parent, Volpe** |
| **Train Crashworthiness Strategies** | **Kristine Severson, Volpe** |
| **Parametric Studies of Train Crashworthiness** | **Michelle Priante, Volpe** |

DEPARTMENT OF TRANSPORTATION UNITED STATES OF AMERICA

**Crash Energy Management Technology Transfer Symposium**
**June 29 through July 1, 2005**
**San Francisco, California**

Federal Railroad Administration

Federal Transit Administration

# Session IV - CEM Effectiveness Full-scale Testing: Research Methodology

Crash Energy Management Technology Transfer Symposium
June 29 through July 1, 2005
San Francisco, California

Kristine Severson
Volpe Center
US Department of Transportation

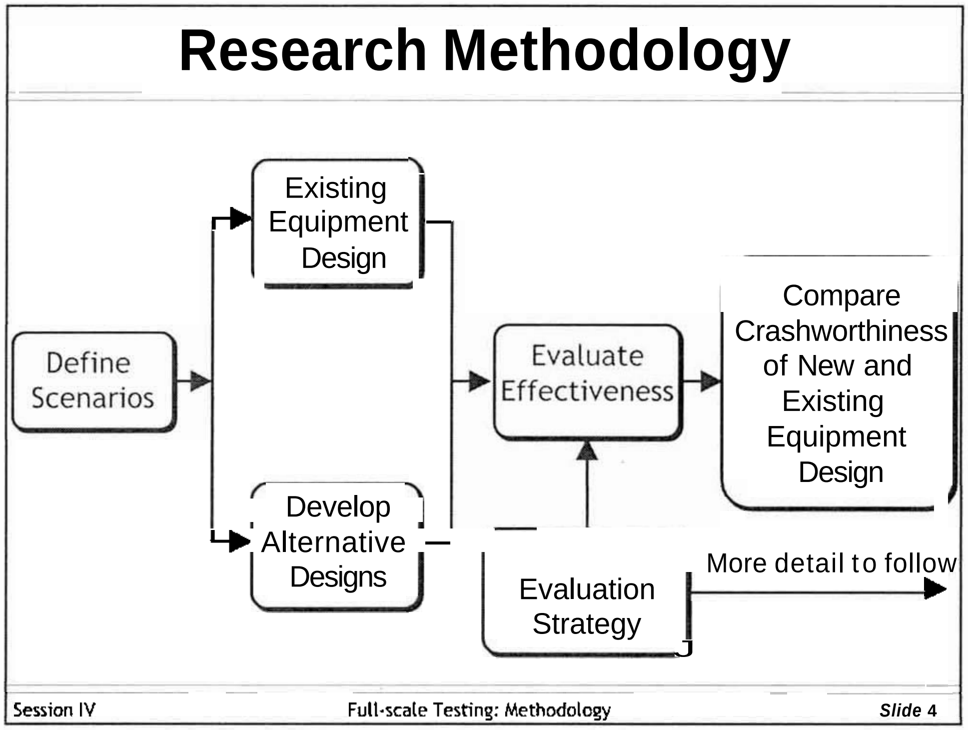
## Outline

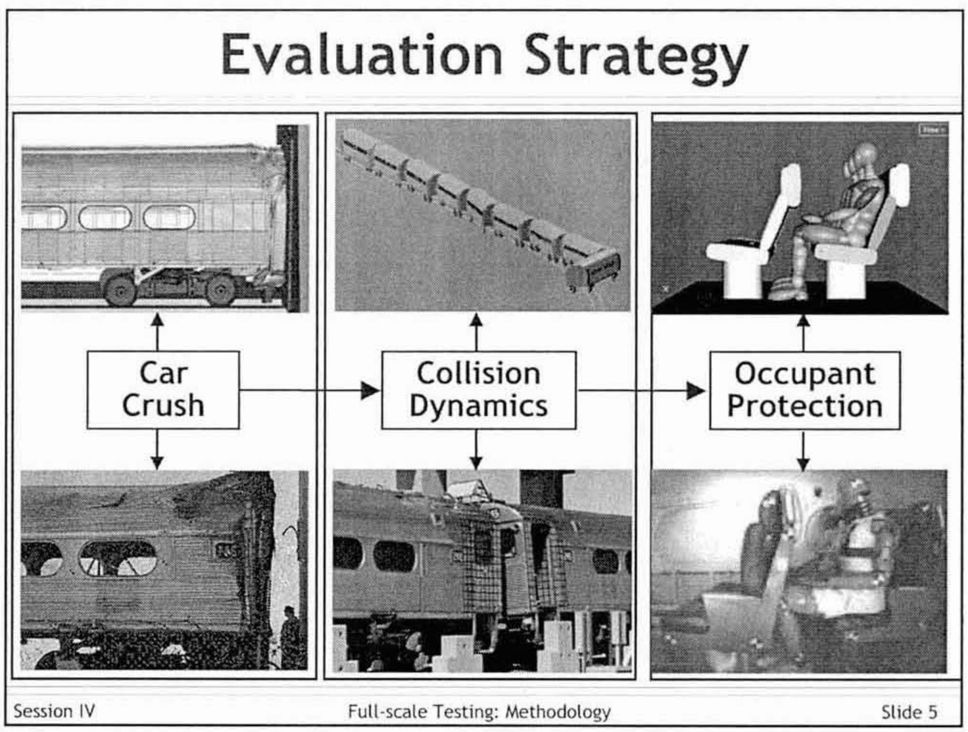
- Crashworthiness Objectives
- Research Methodology
- Evaluation Strategy
  - Crush Analysis
  - Collision Dynamics Analysis
  - Occupant Protection Analysis
- Analytical Evolution

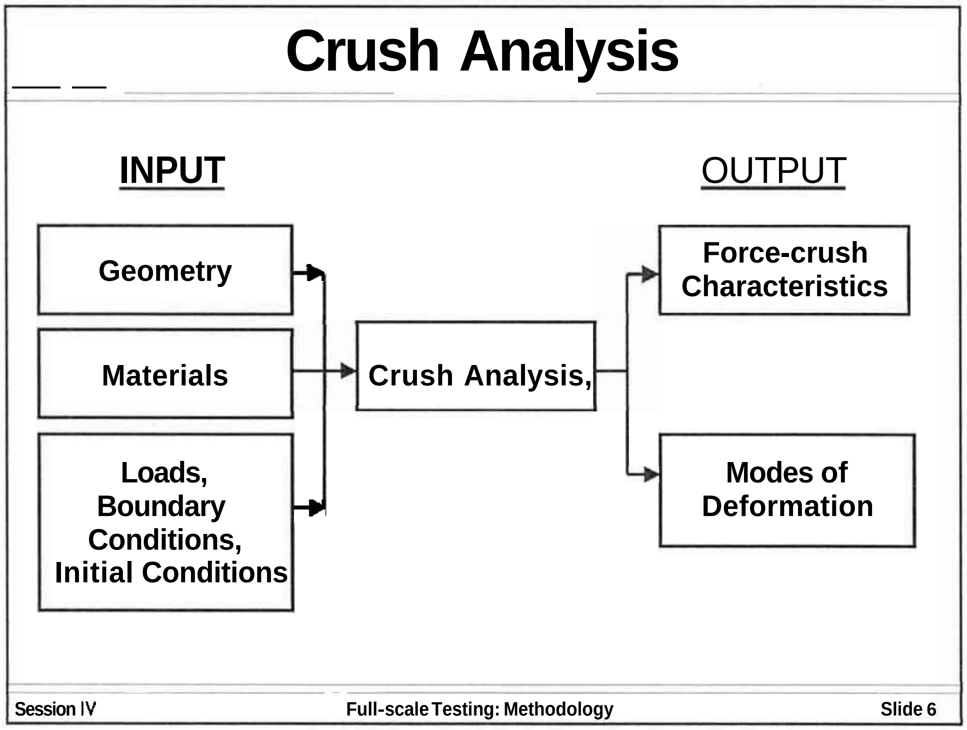


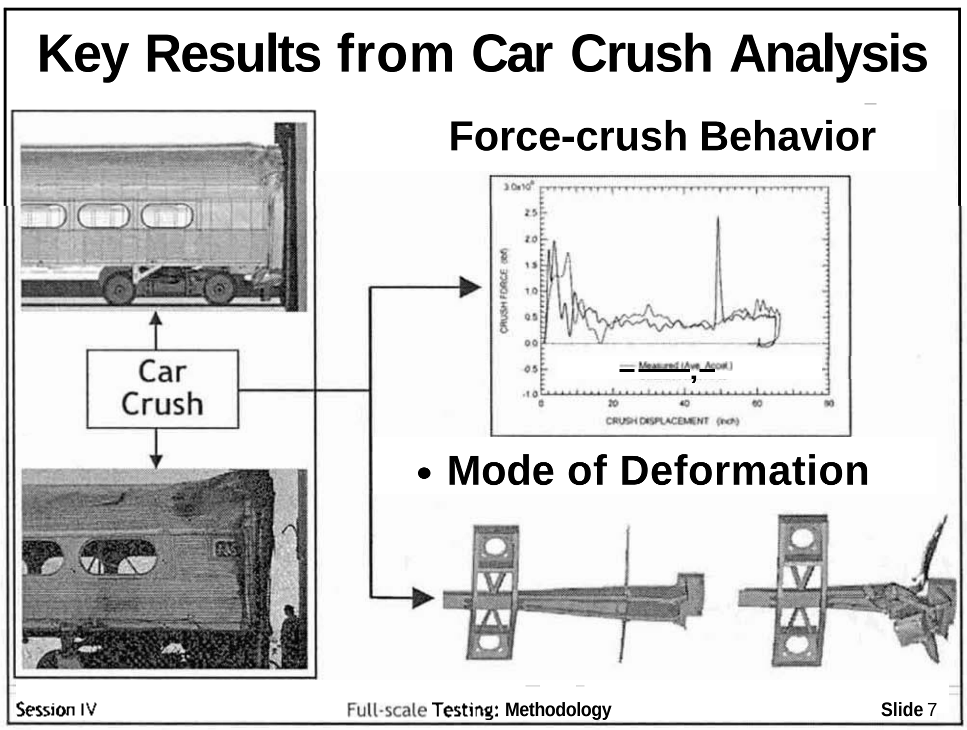
## Crashworthiness Objectives

- Preserve integrity of occupied areas
  - Maintain sufficient space
  - Minimize local compartment penetration
  - Ensure occupant containment
- Limit Occupant forces/decelerations to survivable levels
  - Limit deceleration of occupant compartment
  - Limit secondary impact forces
  - Interior fittings remain attached

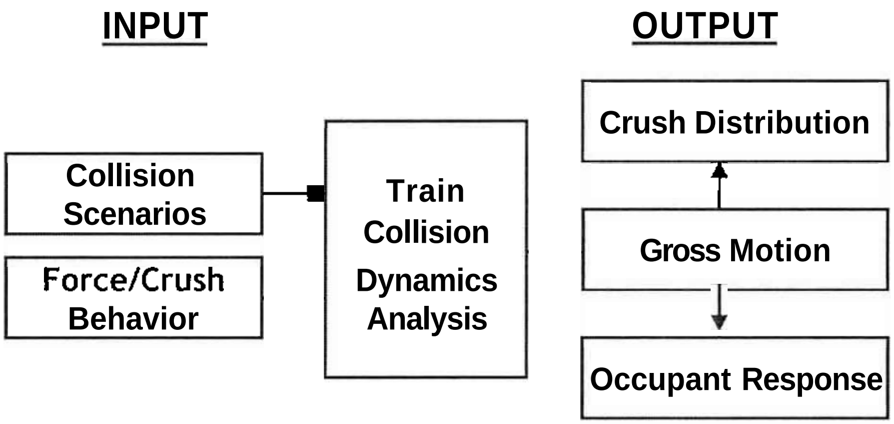

Research Methodology
Define Scenarios
Existing Equipment Design
Develop Alternative Designs
Evaluate Effectiveness
Compare Crashworthiness of New and Existing Equipment Design
Evaluation Strategy
More detail to follow
Session IV
Full-scale Testing: Methodology
Slide 4


Evaluation Strategy
Car Crush
Collision Dynamics
Occupant Protection
Session IV
Full-scale Testing: Methodology
Slide 5


Crush Analysis
INPUT
OUTPUT
Geometry
Materials
Loads, Boundary Conditions, Initial Conditions
Crush Analysis,
Force-crush Characteristics
Modes of Deformation
Session IV
Full-scale Testing: Methodology
Slide 6

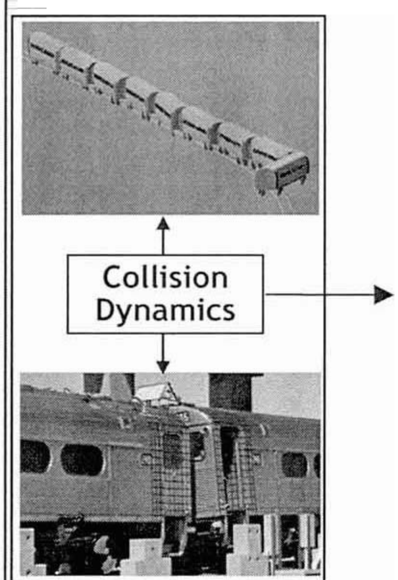

Key Results from Car Crush Analysis
Force-crush Behavior
Car Crush
• Mode of Deformation
Session IV
Full-scale Testing: Methodology
Slide 7

## Collision Dynamics Analysis

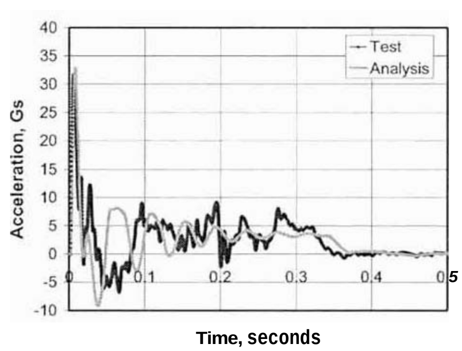




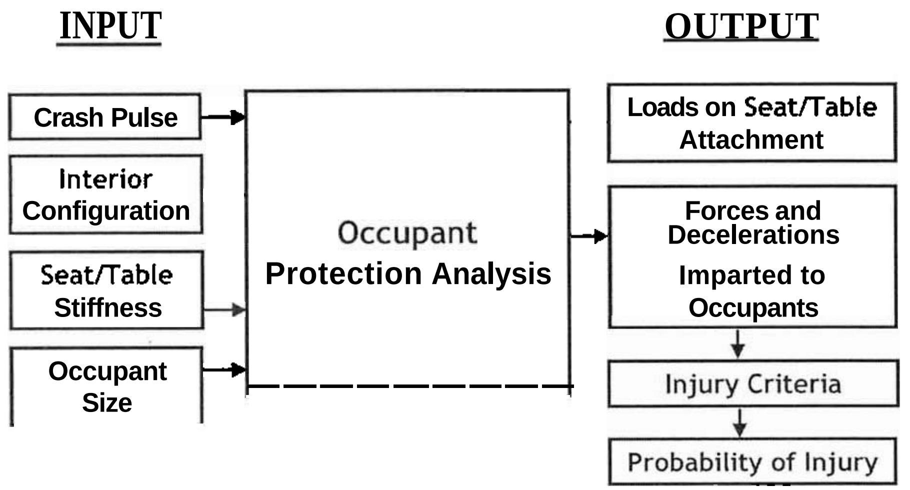

## Key Results from Collision Dynamics Analysis




- Gross Car Motion

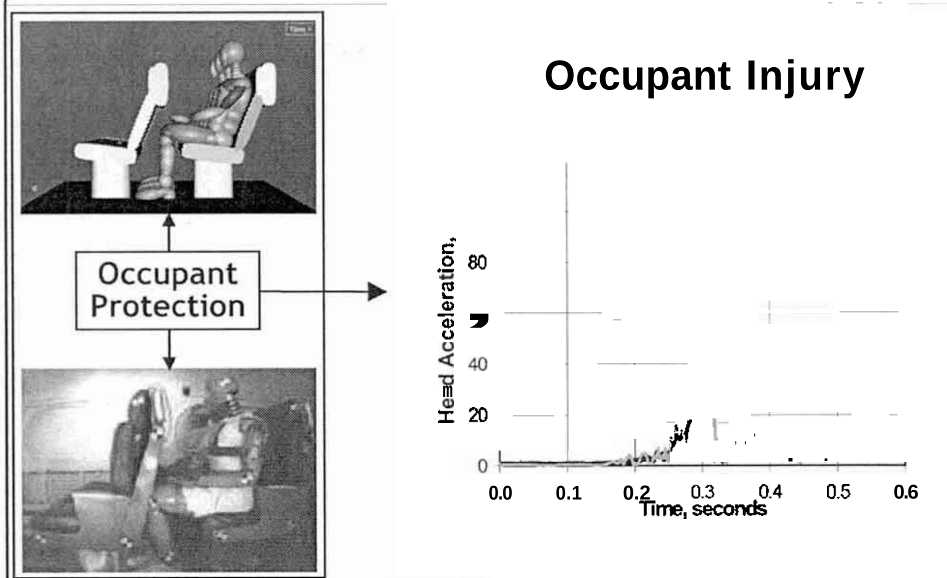


# Occupant Protection Analysis



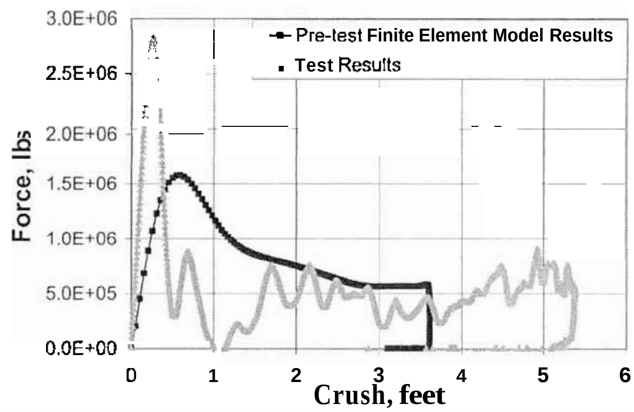



# Key Results from Occupant Analysis



## Analytical Evolution

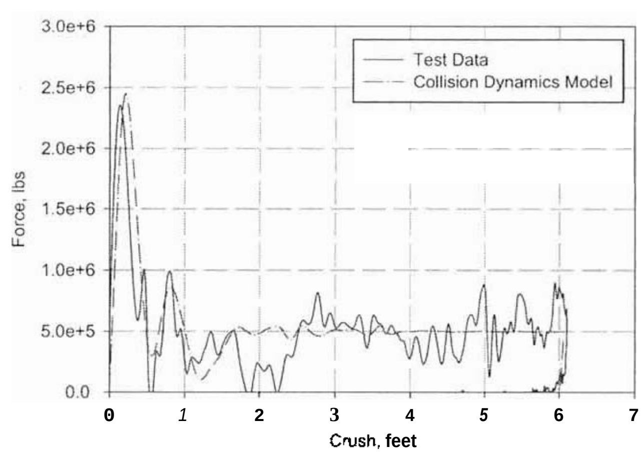
- **Test 1 - Moderate Agreement, Significant Post-test Model Refinements**





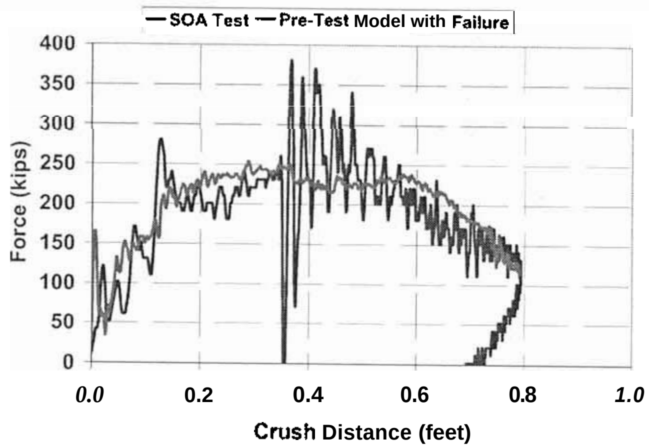

## Analytical Evolution

- **Tests 2 and 3: Closer Agreement, Incremental Model Refinements**



# Analytical Evolution

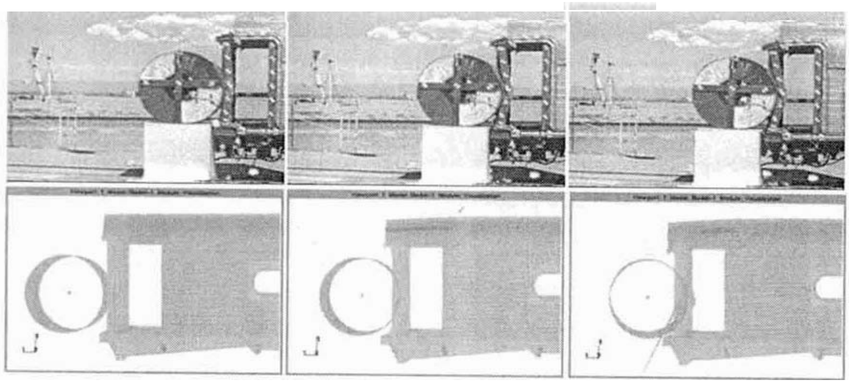
- Tests 4, 5, 6, and 7: Model Predictions within Repeatability of Tests




Session IV | Full-scale Testing: Methodology | Slide 14

# Analytical Evolution

- Mode of Deformation:



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## Analytical Evolution

Data from each test enables further refinement of the computer models

- Refined analytical models can be used to extrapolate beyond test cases to evaluate variables such as:
  - Train length
  - Car weight
  - Push/pull
  - Mixed consists



## Summary

Strategy developed to evaluate crashworthiness
- integrity of occupied areas
- Forces, decelerations imparted to occupants

- Strategy consists of three parts:
  - Car crush
  - Train collision dynamics
  - Occupant protection
- Strategy can be applied to evaluate influence of:
  - Train characteristics
    - Car crush behavior, car weight, train length, et al
  - Collision conditions
    - Speed, train-to-train, train-to-highway vehicle, et al

Federal Railroad Administration

Federal Transit Administration

# Session IV - CEM Effectiveness

# Full-scale Testing: Structural Crashworthiness

Crash Energy Management Technology Transfer Symposium
June 29 through July 1, 2005
San Francisco, California

David Tyrell
Volpe Center
US Department of Transportation

## Full-scale Test Objectives

- Measure and Compare Structural Crashworthiness of Conventional and Alternative Rail Passenger Equipment Under Impact Conditions
- Measure and Compare Occupant Protection Capabilities of Conventional and Alternative Interior Arrangements
- Provide Information for Refining Analytical Models
- Provide Reference for Extrapolations with Analytical Models

Session IV Full-scale Testing: Structural Crashworthiness Slide 2

## Full-scale Test Approach

- Arrange Tests to Minimize Reliance on Analytical Models to Compare the Crashworthiness of Alternative Equipment

Session IV Full-scale Testing: Structural Crashworthiness Slide 3

# Pre-test Analysis

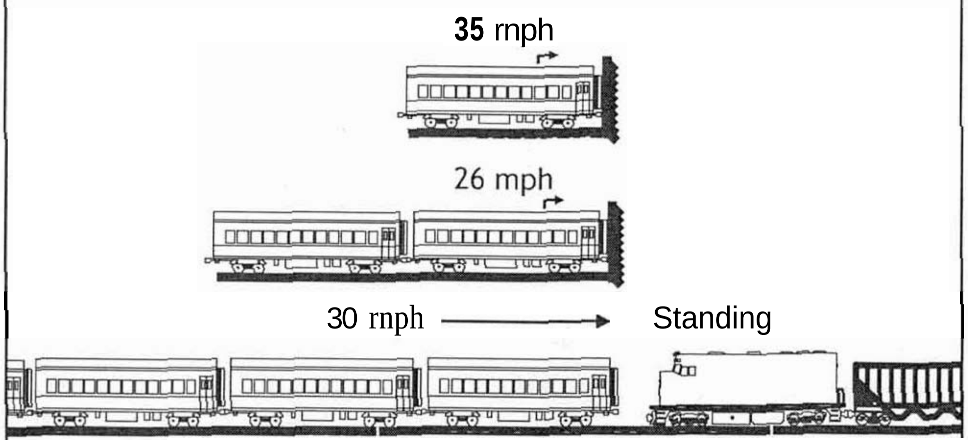
- **Critical for Defining Test Conditions, e.g.,**
  - **Too Low an Impact Speed -> Little Damage**
  - **Too High an Impact Speed -> Not Survivable with Incremental Improvements**
- **Critical for Defining Size and Location of Instrumentation, e.g.,**
  - **Views and Locations of Cameras**
  - **Ranges and Locations of Accelerometers**



# Full-scale Tests

| *Test Conditions* | *Conventional Equipment* | *Improved Equipment* |
|---|---|---|
| *Single-carimpact with fixed barrier* | *November* 16.1999<br>**35 mph impact speed** | *December* 3,2003<br>**34 mph impact speed** |
| *Two-coupled-car impact with fixed barrier* | **April** 4,2000<br>**26 mph impact speed** | *February* 26.2004<br>**29 mph impact speed** |
| *Cab car-led train impact with locomotive-led train* | *January* 31.2002<br>*30* **mph impact speed** | *February* 2006 *(Target)*<br>**32 mph impact speed** |
| *Single cab car impact with steel coil* | *June* 4.2002<br>***t4*** **mph impact speed** | *June* 7,2002<br>**14 mph impact speed** |

# In-line Tests




Consist 1: **Cab** Car. Coach **Cars,** and Trailing Locomotive

Consist **2:** Locomotive and Two Ballasted Freight Cars

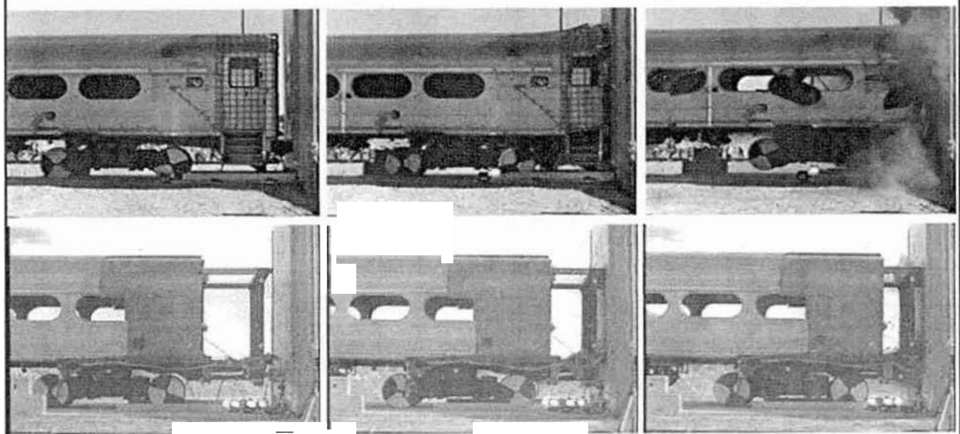


# Objectives of In-line Tests

| *Test Description* | *Key Observations* |
|---|---|
| Single-car Test | -Modes of deformation<br>-Dynamic force-crush behavior<br>-Gross motions of vehicle<br>-Minimized vertical and lateral motions |
| Two-car Test | -Interactions of coupled cars<br>-*Cars* remain in-line<br>-Distribution of crush to the trailing car |
| Train-to-train Test | -Interactions of colliding equipment<br>-Override of the colliding vehicles<br>-Lateral buckling of coupled cars<br>-Distribution of crush along consist<br>-No override and no *lateral* buckling |

# Results of Single-car Tests

Conventional: Occupant Volume Lost, Vertical Motion



CEM: Occupant Volume Preserved, Remained In-line

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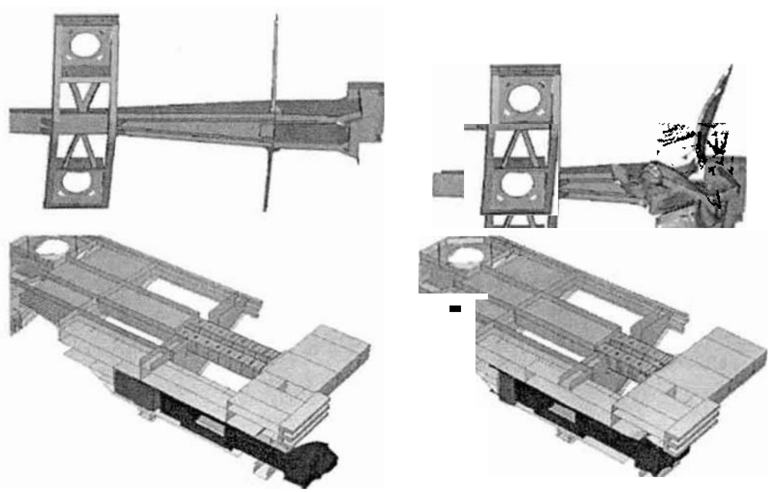
# Underframe Crush Comparison

**Pre-impact** | **Post-impact**

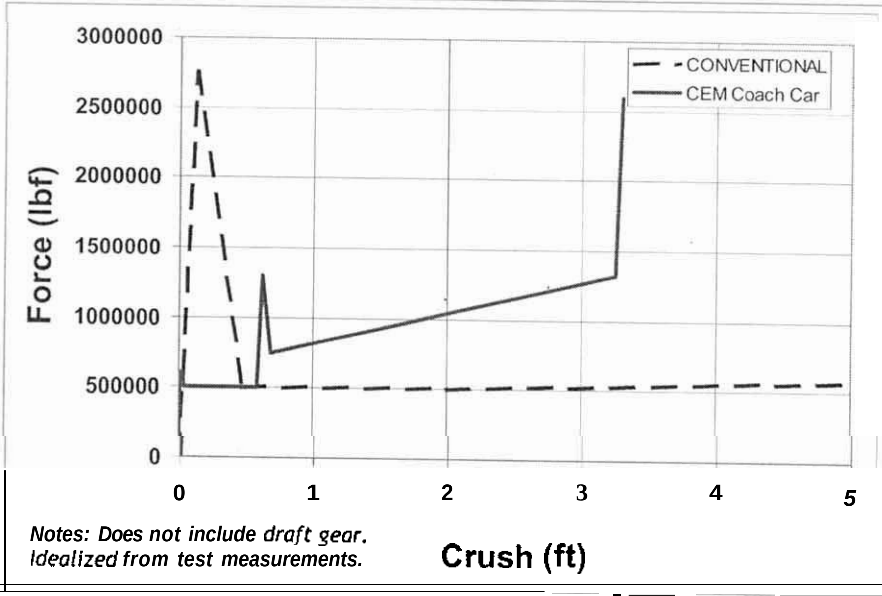
Conventional

CEM



Session IV | Full scale Testing Structural Crashworthiness | Slide 9

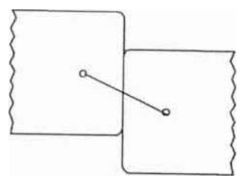
## Single-car Tests
## Principal Results



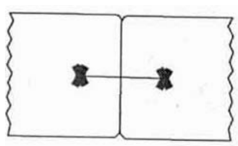

*Notes: Does not include draft gear.*
*Idealized from test measurements.*

Session IV | Full-scale Testing: Structural Crashworthiness | Slide 10

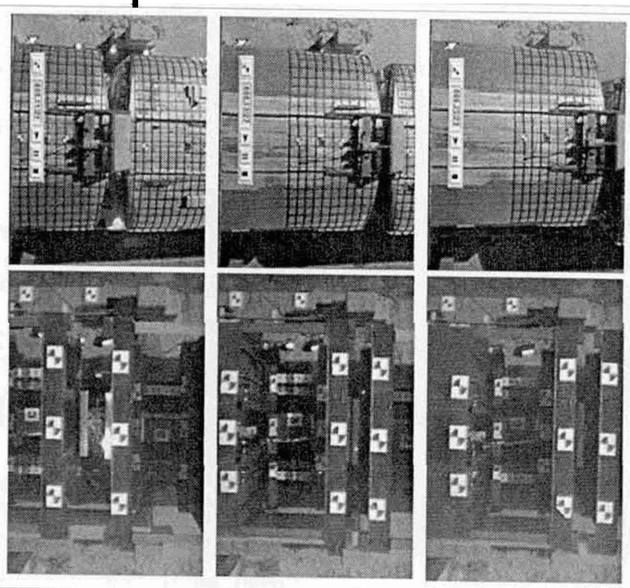
## Two-car Tests
## Principal Results



**Conventional**



**CEM**



Session IV | Full-scale Testing: Structural Crashworthiness | Slide 11

## Summary of Results
## for In-line Tests of CEM Equipment

- Increasing Force-crush Characteristic
  Coupled Cars Remain In-line
- Structural Damage Distributed Among Cars in the Train, Preserving Occupant Volume



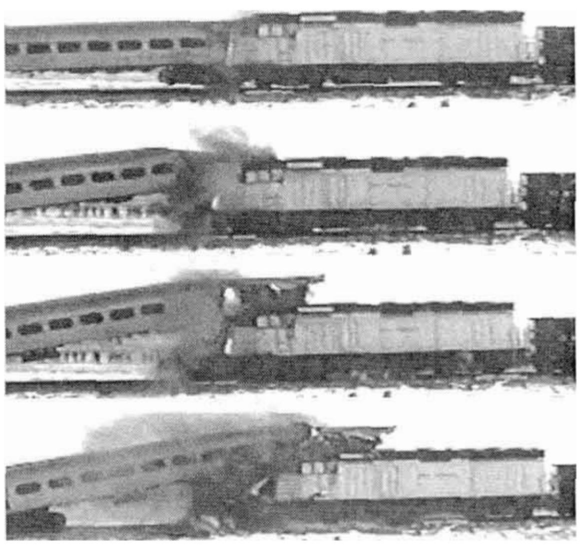
## Sequence of Events
## Train-to-train Test of Conventional Equipment

Crush 5 to 6 feet, Similar to One-car and Two-car Tests

Cab Car Body Folds
Body Bolster Fails

Maximum Vertical Displacement

Maximum Crush



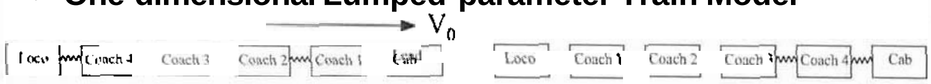
## Train-to-train Test of Conventional Equipment
## Energy–Budget

- Conservation of Energy and Momenta
  - Initial Kinetic Energy ~ 19.2 x $10^6$ ft-lbs
  - Plastic (Crushing) Energy ~ 9.6 x $10^6$ ft-lbs
  - Override Energy ~0.20 x$10^6$ ft-lbs

Session IV | Full-scale Testing: Structural Crashworthiness | Slide 14

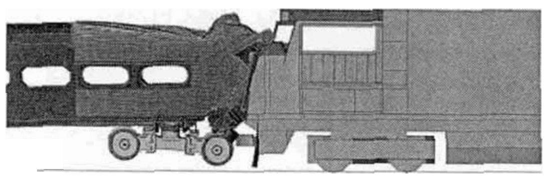
## Train-to-train Test of Conventional Equipment
## Analysis Models

- One-dimensional Lumped-parameter Train Model




- Three-dimensional Lumped-parameter Train Model

- Three-dimensional Non-linear Finite-element Train Model



  - Post-test; Used to Develop Cab Car Crush Zone

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## Summary of Results for In-line Tests of Conventional Equipment

- Decreasing Force-crush Characteristic
- **Coupler/Draft** Gear Arrangement Promotes Lateral Buckling
- Structural Damage Focused on Impacting Car, Resulting in Significant Loss of Occupant Volume

Session IV | Full scale Testing Structural Crashworthiness | Slide 16

## Train-to-train Test of CEM Equipment Key Measurements

- Colliding Cab Car and Locomotive Interaction
- Interactions of Coupled Cars
- Structural Responses
- Car Body Gross Motions
- Measure Test Dummy Response in Selected Interior Configurations

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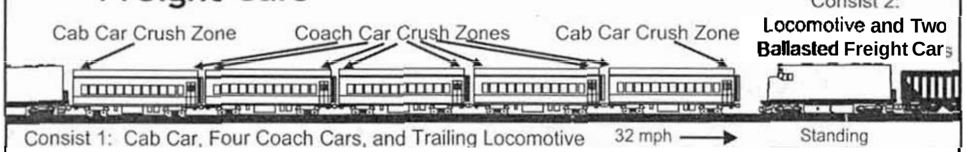
## Train-to-train Test of CEM Equipment

- In-line Collision Between a Cab Car led Passenger Train and a Locomotive led Freight Train
- Both Consists of Equal Mass
  Target Impact Speed of 32 mph
- Five Passenger Cars Retrofitted with CEM Crush Zones, Trailing Conventional Locomotive
- Conventional Locomotive and Two Ballasted Freight Cars

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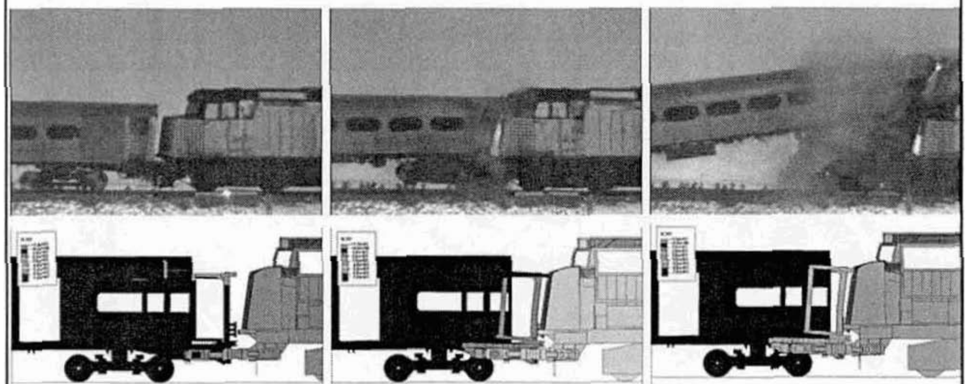
## Cab Car Crush
## Train-to-train Test and Analysis

Conventional Test: Occupant Volume Lost, Override



CEM Analysis: Occupant Volume Preserved, Engagement

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## Full-scale Tests
## Summary

- Test Results Show CEM Equipment Significantly More Crashworthy than Conventional Equipment
- Tests Also Used to Compare the Occupant Protection Capabilities of Conventional and Alternative Interior Arrangements
- Tests Also Used as a Reference Point for Extrapolations
  - Train Collision Dynamics
  - Car Crush
  - Occupant Protection

# Session IV - CEM Effectiveness

# Full-scale Testing: Occupant Protection

Crash Energy Management Technology Transfer Symposium
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San Francisco, California

Dan Parent
Volpe Center
US Department of Transportation

# Objective

- Measure the occupant protection capabilities interior arrangements
  - Conventional } *Compare*
  - Alternative
- Demonstrate the effectiveness of occupant protection strategies
  - Compartmentalization
  - Rear-facing seats
  - Strategic interior modifications
- Refine computer simulations

Session IV | Full-scale Testing: Occupant Protection | Slide 2

# Occupant Protection Experiments

- Background
  - Acceleration of occupant volume determined by specific structural full-scale test
- Approach
  - Measure 3-D accelerations of occupant volume
  - Implement Anthropomorphic Test Devices (ATDs)
  - Arrange tests to minimize reliance on analysis to determine effectiveness of occupant protection strategies
- Pre-test Analysis
  - Define instrumentation, expected outcomes
- Post-test Analysis
  - Evaluate occupant protection strategies

Session IV | Full scale Testing Occupant Protection | Slide 3

# Previous/Planned Occupant Experiments

| Test / Seating Arrangement | Conventional | | |
|---|---|---|---|
| | One-car | Two-car | Train-to-train |
| Forward-facing Commuter | ✓ | ✓ | ✓ |
| Rear-facing Commuter | ✓ | ✓ | |
| Unrestrained Intercity | ✓ | ✓ | ✓ |
| Lap Belt and Shoulder Harness Intercity | ✓ | ✓ | ✓ |
| Workstation Table | | | |
| Locomotive/Cab Operator | | | ✓ |

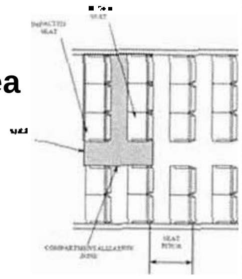


# Previous/Planned Occupant Experiments

| Test / Seating Arrangement | Conventional | | | CEM | |
|---|---|---|---|---|---|
| | One-car | Two-car | Train-to-train | Two-car | Train-to-train |
| Forward-facing Commuter | ✓ | ✓ | ✓ | ✓ | ✓ |
| Rear-facing Commuter | ✓ | ✓ | | ✓ | ✓ |
| Unrestrained Intercity | ✓ | ✓ | ✓ | ✓ | ✓ |
| Lap Belt and Shoulder Harness Intercity | ✓ | ✓ | ✓ | | |
| Workstation Table | | | | ✓ | ✓ |
| Locomotive/Cab Operator | | | ✓ | | ◆ |

# Critical Measurements

- **Compartmentalization**
  - **Occupant remains within specified area**



- **Occupant Kinematics**
  - **Predictable interaction with seats**
- **Injury Risk - Maximum injury criteria values**
  - **Head Injury → HIC**
  - **Chest Injury → Cumulative 3ms**
  - **Neck Injury → Nij**
  - **Femur Load**

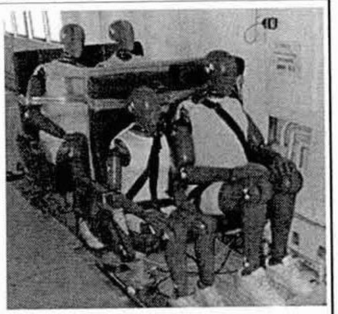
Session IV | Full-scale Testing: Occupant Protection | *Slide* 6

# Occupant Protection Strategies

- **Effectiveness has been demonstrated:**
  - **Lap belt and shoulder harness**
  - **Rear-facing seating**
  - **Energy-absorbing elements**
- **Effectiveness to be demonstrated on the CEM Train-to-train test**
  - **Improved workstation table**
  - **Optimized commuter seat**

Session IV | Full-scale Testing: Occupant Protection | Slide 7

# Lap Belt and Shoulder Harness



- Ensures compartmentalization
  - Vertical, lateral accelerations
- Prevents secondary impacts
  - Head, chest, knees

→ Reduces overall injury risk

- *Implementation Issues*
  - Seat modifications
  - Increase in potential injury modes
    - Abdominal Injury
    - Loss of survival space
  - Misuse

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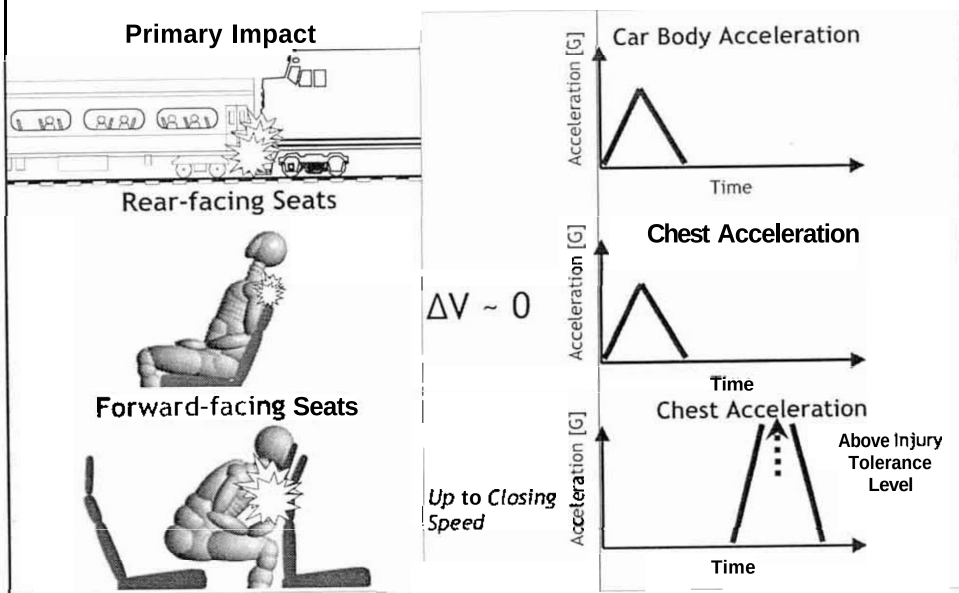
# Rear-facing Seats

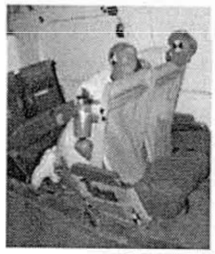


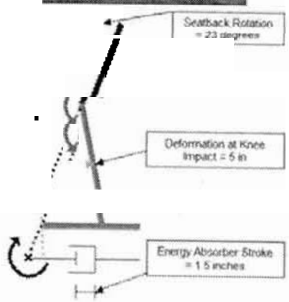

Session IV | Full-scale Testing: Occupant Protection | Slide 9

# Energy-absorbing Elements

- **Passive protection strategy**
  - **Absorbs kinetic energy of occupant**
  - **Arrests motion of occupants over a longer period of time**
    - **Reduces loads and accelerations**
  - **Protects for wide range of impact velocities while compartmentalizing occupants**

→ **Reduces overall injury risk**

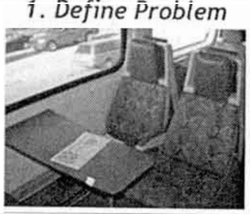




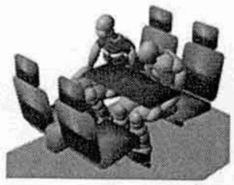

Session IV | Full-scale Testing: Occupant Protection | Slide 10

# Interior Modification Strategy

*1. Define Problem*



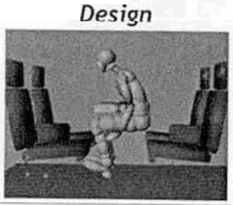
*2. Analyze Problem*



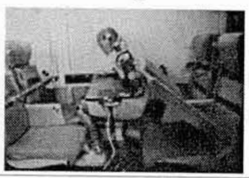
*3. Test Baseline Design*

*4. Refine Simulation*

*5. Develop Improved Design*

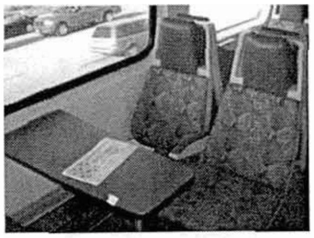


*6. Test Improved Design*



Session IV | Full-scale Testing: Occupant Protection | Slide 11

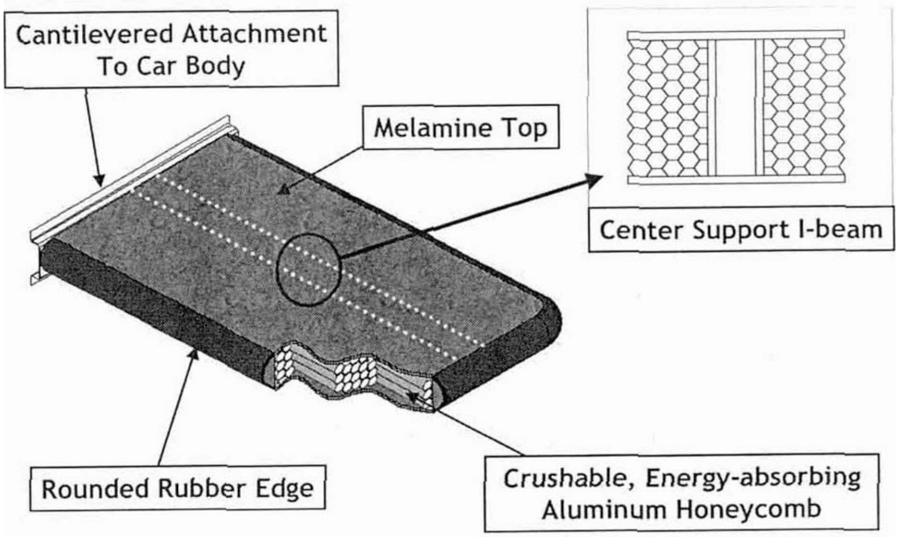
# Improved Workstation Table



- **Impetus - High injury risk**
  - Placentia, CA
  - Burbank, CA
  - Confirmed by analysis
  - Confirmed by baseline test
- **Improved design will:**
  - Compartmentalize the occupant
  - Limit abdominal load
  - Distribute load over larger area
  - Absorb impact energy
  - Protect aisle, window occupants equally

Session IV Full-scale Testing: Occupant Protection Slide 12

# Improved Workstation Table




Session IV Full-scale Testing: Occupant Protection Slide 13

# Improved Workstation Table

- **Schedule**
  - Design completed by September
  - Four tables fabricated by December
  - One table will be quasi-statically tested
  - One table will be sled tested
  - Two tables included on CEM Train-to-train Full-scale Test



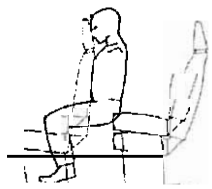
# Optimized Commuter Seat

- **Improved design will:**
  - Compartmentalize the occupant
  - Limit head, chest acceleration
  - Limit femur loads
  - Absorb impact energy
  - Protect forward- and rear-facing occupants equally
- **Design Requirements**
  - Crashworthiness performance
  - Strength under service loads
  - Geometry

## Optimized Commuter Seat

**Design Concepts**

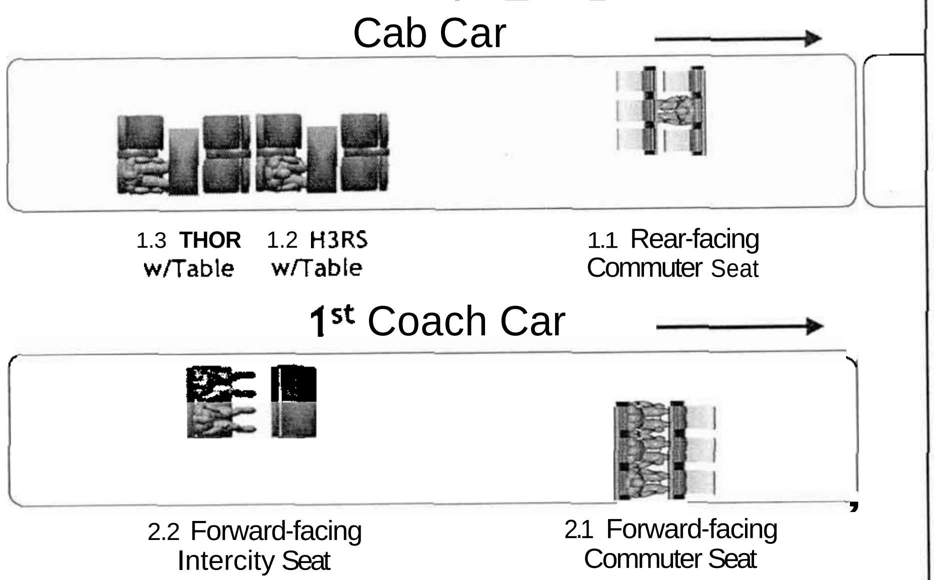
- Energy absorbers in seat back, pedestal, attachment to car body, or combination of all three
- Energy-absorbing impact surfaces
- Increased seat back height



- **Compliant with**
  - APTA SS-C&S-016-99, Rev 1, Standard for Row-to-row Seating in Commuter Rail Cars
  - Code of Federal Regulations, Title 49, Part 238, Section 233: Interior Fittings and Surfaces
- **Schedule**
  - Design completed by September
  - Eight seats fabricated by December
  - Four seats included on CEM Train-to-train Full-scale Test

Session IV | Full-scale Testing: Occupant Protection | Slide 16

## CEM Train-to-train Full-scale Test

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## CEM Train-to-train Full-scale Test

**Objectives**

Measure occupant response in five (5) seating arrangements

- Evaluate overall injury risk
- Compare results to conventional seating
- Demonstrate effectiveness of strategic interior modifications
  - Improved workstation table
  - Optimized commuter seats
  - Rear-facing seats
- Measure operator environment for future research

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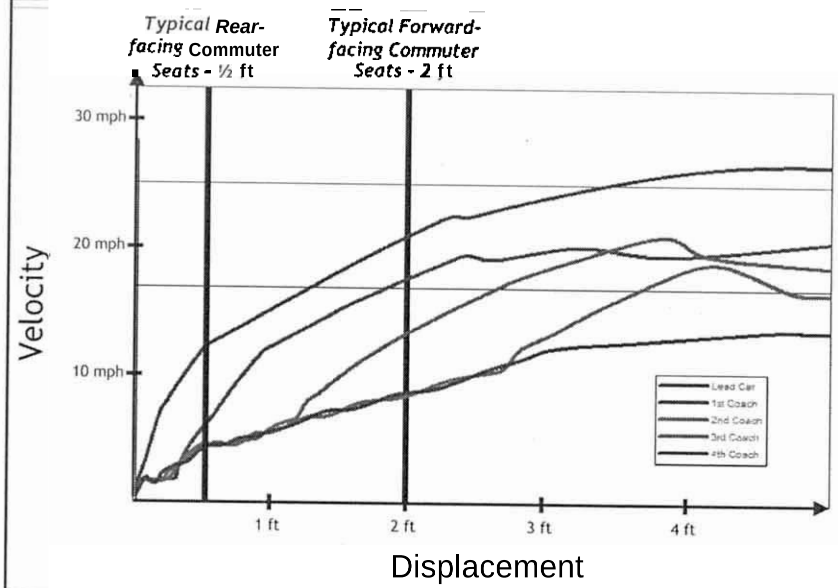
## CEM Train-to-train Predicted Environment

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# Conclusions

- Modifications to the car end structures are being made to prevent loss of occupant volume-related injuries
  - Crash energy management system
- Modifications to the interior are being made to prevent secondary impact-related injuries
  - Improved workstation tables
  - Optimized commuter seats
  - Rear-facing seats

Combined, these modifications can significantly increase occupant protection

Federal Railroad Administration

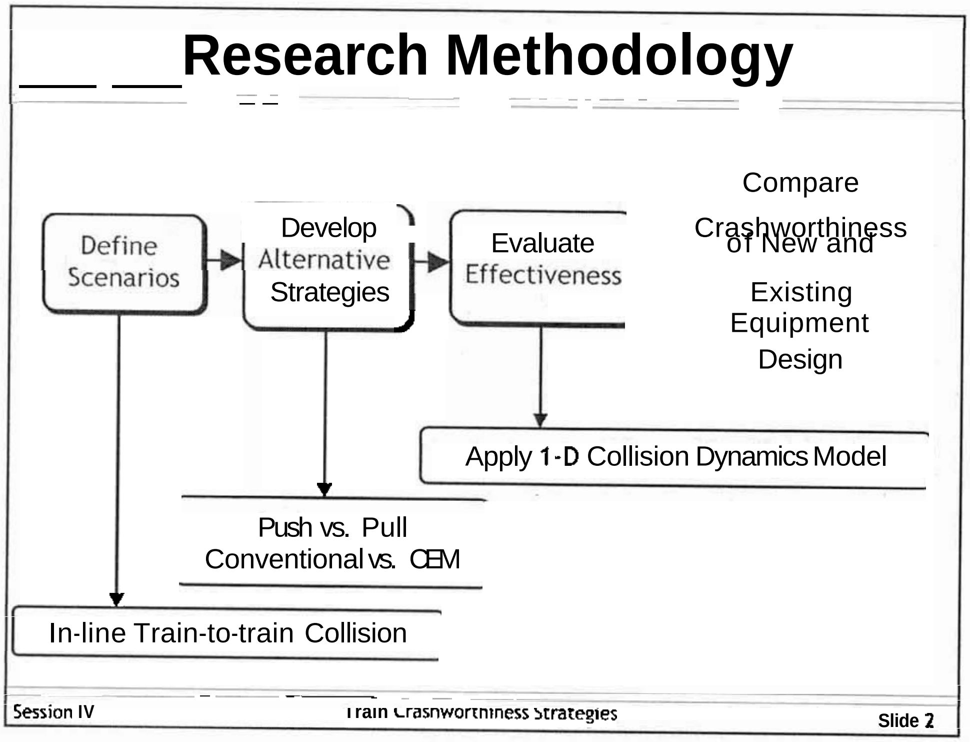
Federal Transit Administration

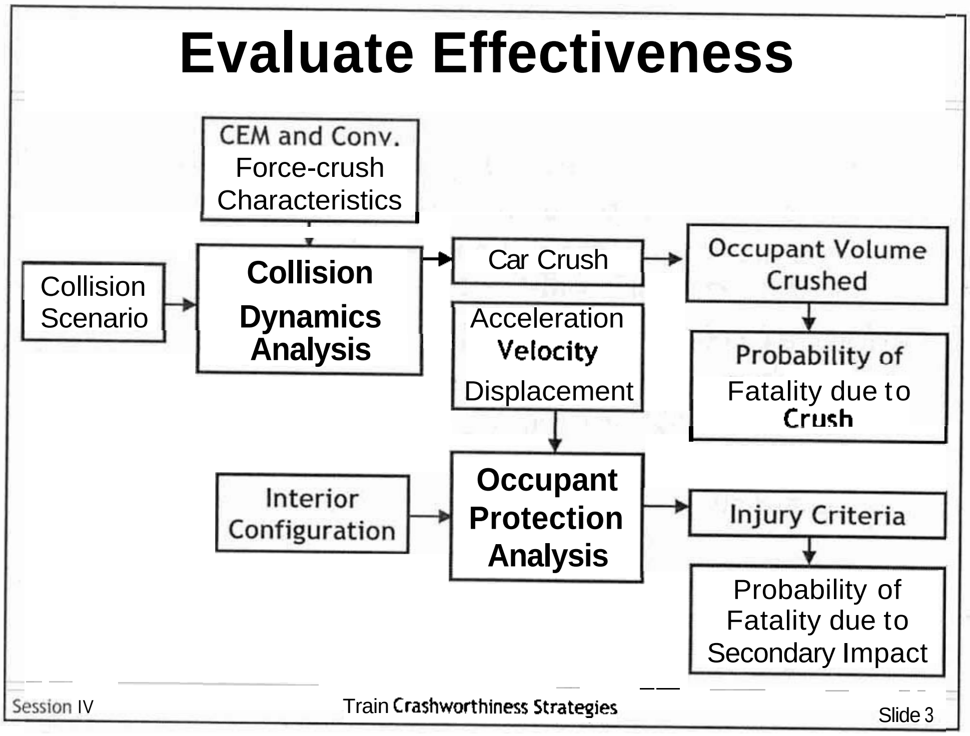
# Session IV - CEM Effectiveness

# Train Crashworthiness Strategies

**Crash Energy Management Technology Transfer Symposium**
**June 29 through July 1, 2005**
**San Francisco, California**

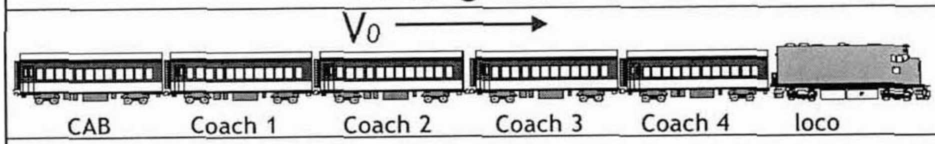
Kristine Severson
Volpe Center
US Department of Transportation


Research Methodology
Define Scenarios
Develop Alternative Strategies
Evaluate Effectiveness
Compare Crashworthiness of New and Existing Equipment Design
Apply 1-D Collision Dynamics Model
Push vs. Pull
Conventional vs. CEM
In-line Train-to-train Collision
Session IV
Train Crashworthiness Strategies
Slide 2


Evaluate Effectiveness
CEM and Conv. Force-crush Characteristics
Collision Scenario
Collision Dynamics Analysis
Car Crush
Occupant Volume Crushed
Probability of Fatality due to Crush
Acceleration
Velocity
Displacement
Interior Configuration
Occupant Protection Analysis
Injury Criteria
Probability of Fatality due to Secondary Impact
Session IV
Train Crashworthiness Strategies
Slide 3

# Collision Scenario

## Moving Train




**Standing Train**

6 Car locomotive led consist
(identical to moving consist)

**Moving Train (30 mph)**

6 Car consist:
- Conventional train, cob car leading
- Conventional train, loco leading
- CEM train, cab leading
- CEM train, loco leading

Session IV | Train Crashworthiness Strategies | Slide 4

# Collision Dynamics Analysis

## One-dimensional lumped-mass model

- Masses connected by non-linear springs
- Idealized force-crush behavior developed from FEA models and full-scale test results

## Model used to evaluate:

- Car crush
- Gross motion of occupant compartment
- Relative velocity vs. relative displacement for occupant


**Moving Consist** | **Stationary Consist**

Session IV | Train Crashworthiness Strategies | Slide 5

## Occupant Analysis

- Simplified occupant analysis used to estimate:
  - Secondary impact velocity (SIV)
  - Injury Criteria for head, chest, neck and femur
  - Probability of fatalities and serious injuries based on crush and SIV

Session IV | Tram Crashworthiness Strategies | Slide 6

## Analysis Results

- Occupant volume crushed
- Secondary impact velocity
- Injury criteria
- Probability of fatality due to car crush and secondary impact

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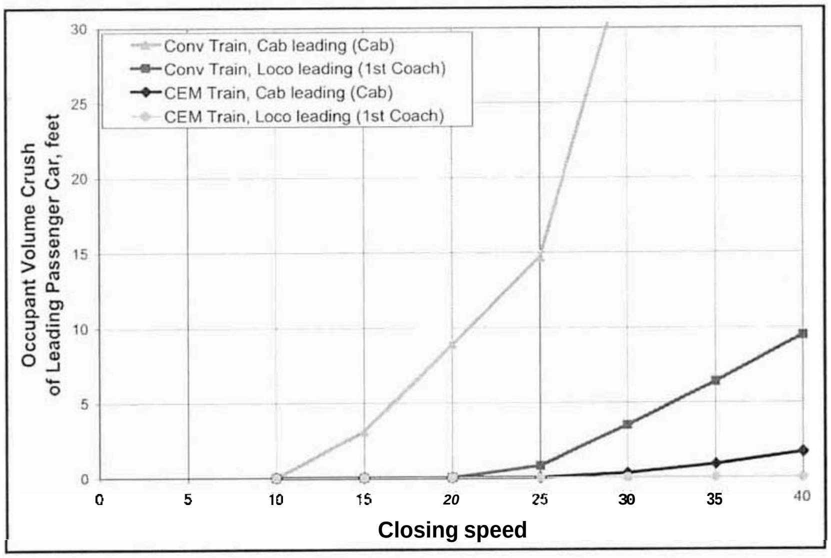
# Occupant Volume Crushed

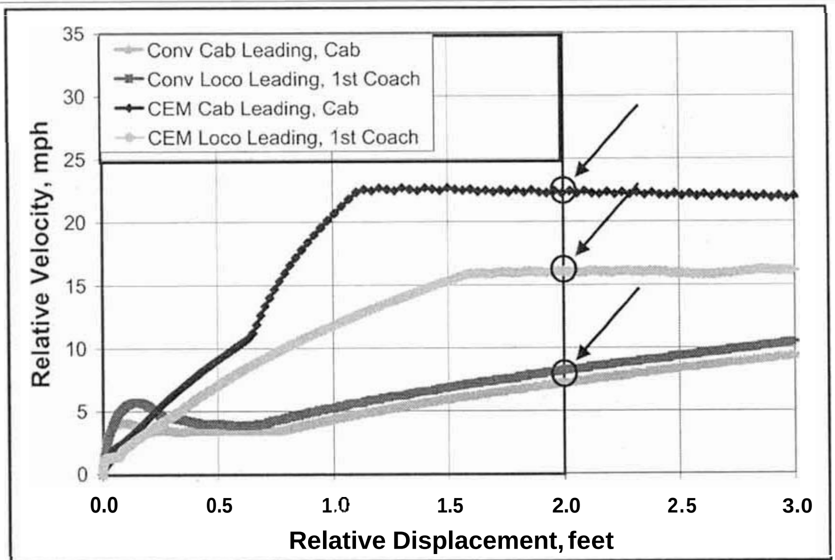





# Interpreting Occupant Injury

- **Calculate SIV at 2.0 feet of travel (corresponds to forward-facing commuter seat configuration)**
- **Correlate SIV to HIC, Chest G, Nij and Femur load**
- **Calculate probability of injury >= AIS 5**

## Interpreting Occupant Injury




* *Closing speed is 30 mph*

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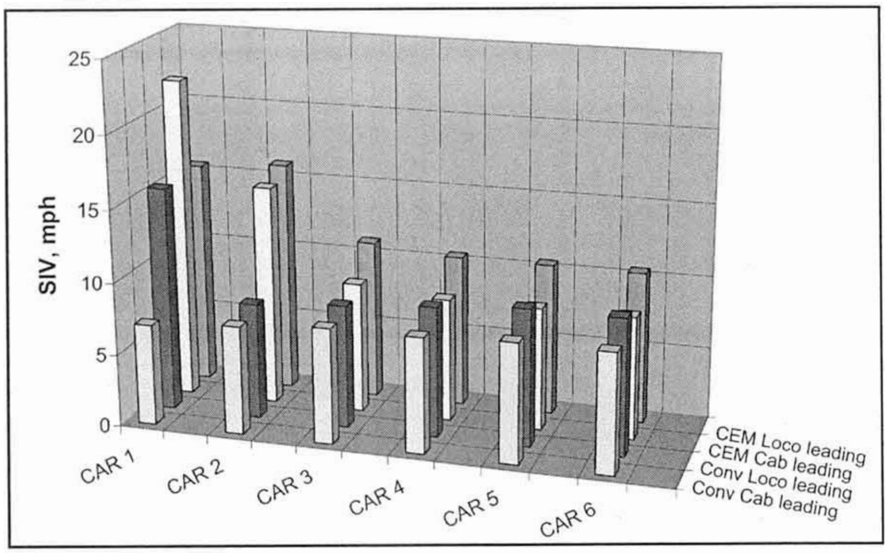
## SIV Results




* *Closing speed is 30 mph*

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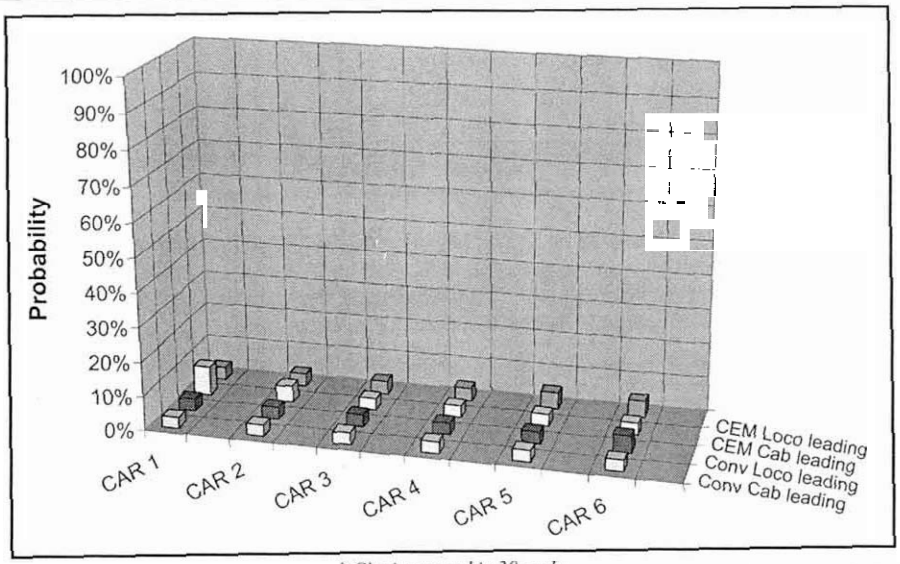
## Probability of Fatality due to Secondary Impact




* *Closing speed is 30 mph*

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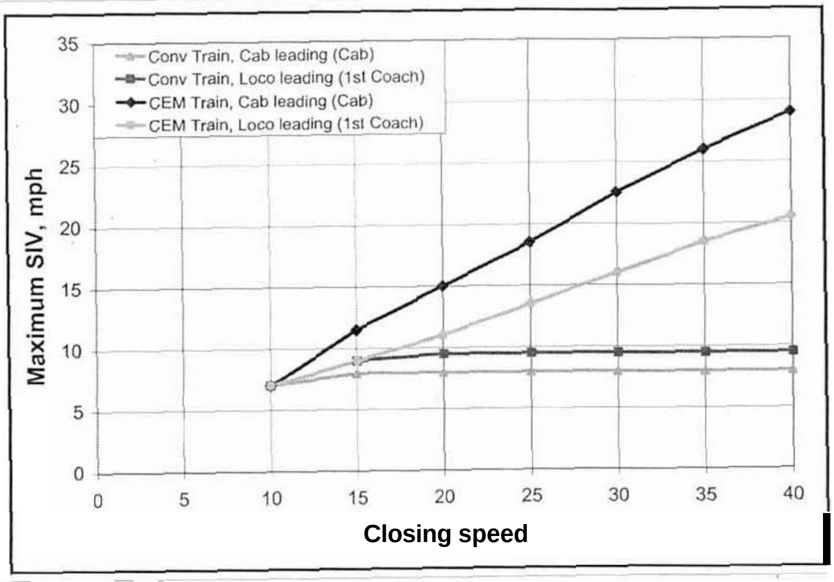
## Maximum SIV for passenger car




Session IV | Train Crashworthiness Strategies | Slide 13

# Conclusions

- Conventional Cab Car-led Train
  - Maximum Crashworthy Speed **-13** mph
  - Relatively Rapid Loss of Occupant Volume with Increased Closing Speed
- Conventional Locomotive-led Train
  - Maximum Crashworthy Speed **-25** mph
  - Relatively Rapid Loss of Occupant Volume with Increased Closing Speed
- CEM Cab Car-led Train
  - Maximum Crashworthy Speed with existing interior **-25** mph
  - Maximum Crashworthy Speed with modified interior **-32** mph
  - Relatively Slow Loss of Occupant Volume with Increased Closing Speed
- CEM Locomotive-led Train
  - Maximum Crashworthy Speed with existing interior **-30** mph
  - Maximum Crashworthy Speed with modified interior **-40** mph
  - Provides a Very High Level of Crashworthiness

# Session IV - CEM Effectiveness Parametric Studies of Train Crashworthiness

Crash Energy Management Technology Transfer Symposium
June 29 through July 1, 2005
San Francisco, California

Michelle Priante
Volpe Center
US Department of Transportation

## Operating Parameters

- Train Length
- Car Weight
- MU Train
- Push/Pull Train
- Mixing Conventional and CEM Cars

Session IV | Parametric Studies of Train Crashworthiness | Slide 2

## Train Length, Weight, Type

- Trains run:
  - With different numbers of cars
  - With light and heavy loads
  - Powered differently (w/ or w/o locomotive)
- How will crashworthiness be affected for these different operating conditions?
- Will having a CEM consist ever decrease crashworthiness?
- What are the potential benefits?

Session IV | Parametric Studies of Train Crashworthiness | Slide 3

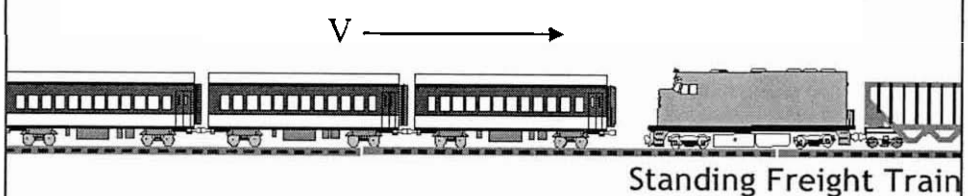
# Train Length, Weight, Type

- Train type
  - MU or Push/Pull
- Number of coach cars
  - (1 Locomotive) — 2 Coach cars / 4 Coach cars / 6 Coach cars — 1 Cab leading
- Weight of cars
  - 75, 100, 125 and 150 Kips



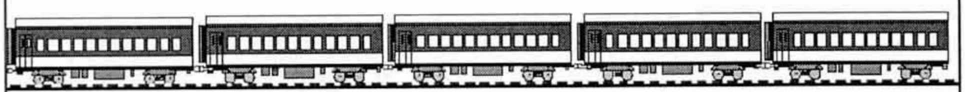
# Collision Scenario

- Initially standing train
  - Locomotive led freight train
- Initially moving train
  - Cab car led passenger train
  - All CEM or all conventional end structures



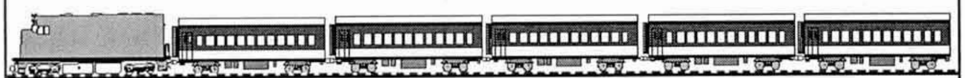
## Baseline Scenario

100 Kip Cars



MU Crashworthy Speed:

CEM (33 mph) Conventional (14 mph)



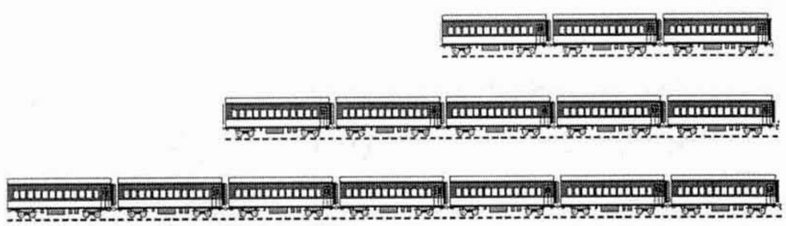
Push/Pull Crashworthy Speed:

CEM (32 mph) **Conventional (13 mph)**

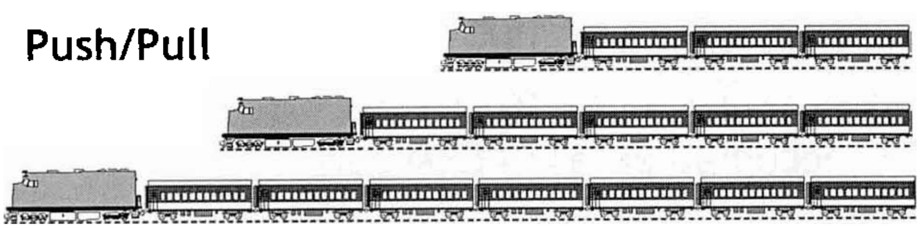


## Train Length

MU

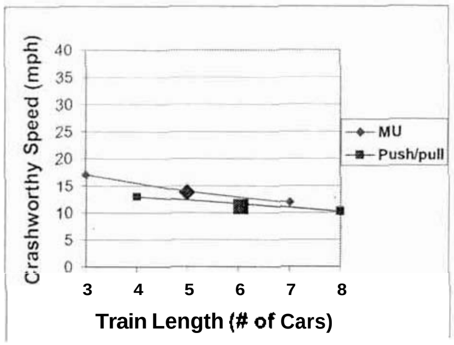


Push/Pull

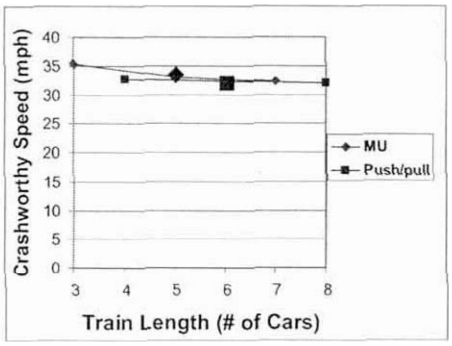


# Train Length

**Conventional**




**CEM**




◆, ■ = Baseline Scenario



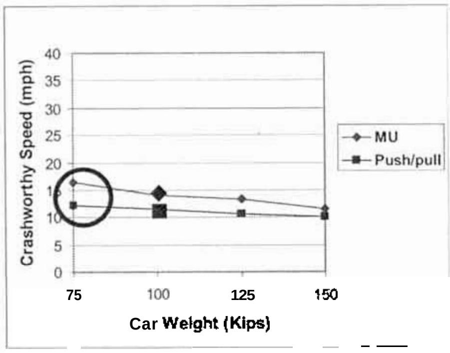
# Train Length: Observations

- CEM trains have double the crashworthy speeds of conventional trains

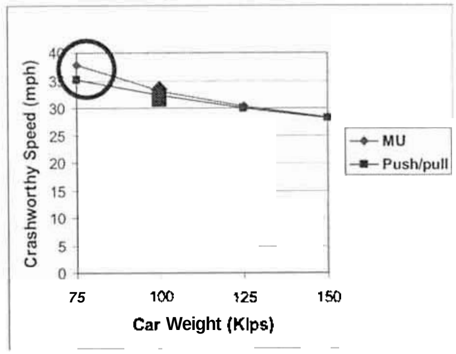
  For CEM trains, crashworthy speed is less sensitive to train length
- CEM is effective for MU and Push/Pull
- Potential benefits: Less crush in occupied areas in CEM cars

# Car Weight

## Conventional




## CEM




◆, ■ = Baseline Scenario ◯ = Full-scale Test Car Weight



# Car Weight: Observations

- For conventional trains, crashworthy speed is less sensitive to car weight
  CEM trains have twice the crashworthy speed of conventional trains
- Benefits are equal for MU and Push/Pull trains
- Potential benefits: Less crush in occupied areas with CEM trains

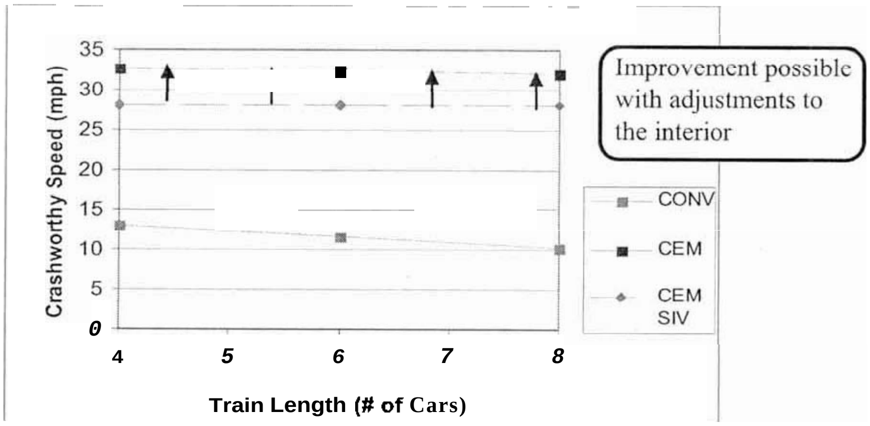
# What About SIV?

- In CEM cab cars, SIV is more severe
- Taking SIV into account
  - Lowers CEM crashworthy speed
  - Does not effect conventional crashworthy speed
- CEM performance can be further improved by strategic modifications to the occupant environment



# What About SIV?

**Example of the effect of the interior:**



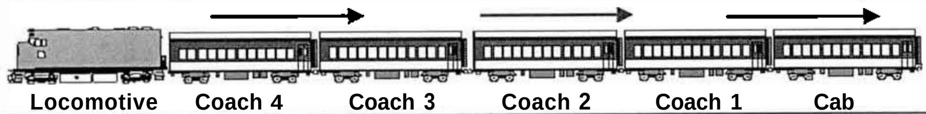

**Push/Pull, 100 Kip Cars**

# Mixing CEM and Conventional Cars

- The transition to CEM likely to take place by changing individual cars
- How will crashworthiness be affected if the consists are mixed?
- If only some cars can be CEM, which one(s) should be CEM?
- What are the potential benefits?

Session N | Parametric Studies of Train Crashworthiness | Slide 14

# Train to Train Collision Scenario



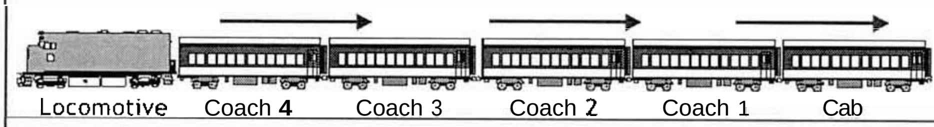

**Standing Train**
6 Car locomotive led consist

**Moving Train**
6 Car cab led consist
- All conventional
- Leading Cab CEM, rest conventional
- All CEM

Session IV | Parametric Studies of Train Crashworthiness | Slide 15

## Leading Conventional Cab

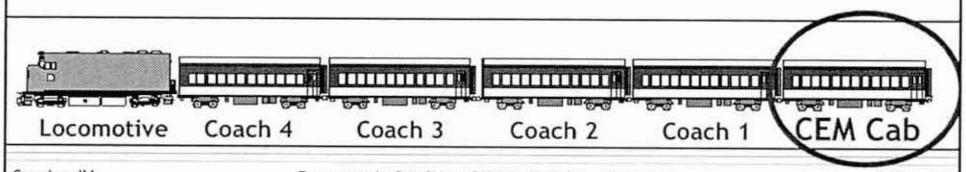
- **Putting CEM cars behind a conventional cab is not beneficial**
- **These three train make-ups behave similarly**
  - All conventional
  - 1st coach CEM, rest conventional
  - Leading cab conventional, rest CEM




Session IV | Parametric Studies of Train Crashworthiness | Slide 16

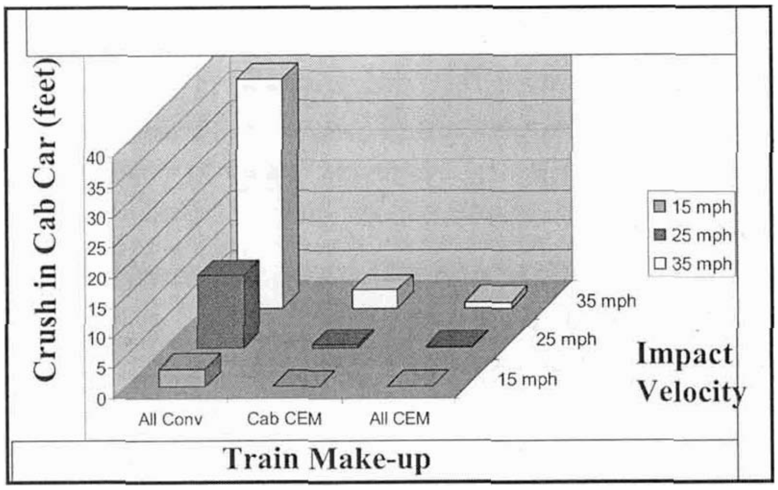
## Leading CEM Cab

- **Adding a CEM cab to a conventional consist improves crashworthiness**
- **An entirely CEM train performs the best**
- **CEM performance can be further improved by strategic modifications to the occupant environment**




Session IV | Parametric Studies of Train Crashworthiness | Slide 17

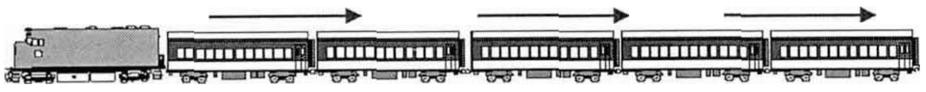
# Damaged Occupant Volume in Cab Car






# Summary of Expected Fatalities

| Total Number of Fatalities (Seats lost + SIV estimates) | Makeup of Moving Train | | |
|---|---|---|---|
| | All Conv | Cab CEM | All CEM |
| 15 mph | *5* | *0* | *0* |
| *25* mph | *20* | *5* | *0* |
| 35 mph | *60* | *29* | *15* |



## Mixed Consist Observations

- Replacing any conventional car with a CEM car does not put passengers at greater risk
- CEM cars should be put at the front of the train
  - Putting a CEM car behind a conventional car does almost nothing
- Potential benefits: Less crush in occupied areas in most cases

Session IV | Parametric Studies of Tram Crashworthiness | Slide 20

## Effectiveness Conclusions

- CEM structure is beneficial for weight and length variations
- CEM structure is beneficial for both MU and Push/Pull operations
- Consists of mixed CEM and conventional equipment always perform at least as well as an all conventional equipment consist
- Improving the interior configurations of a train can further improve crashworthiness

Session IV | Parametric Studies of Train Crashworthiness | Slide 21

# Questions?

More information can be found at:

**http://www.volpe.dot.gov/sdd**

Priante, Michelle, Tyrell, David and A. Benjamin Perlman. 'The Influence of Train Types, Car Weight, and Train Length on Passenger Train Crashworthiness", IEEE/ASME Joint Rail Conference, Pueblo, CO, March 16-18, 2005. RTD2005-70042.

Severson, K. Tyrell, D, Perlman, B., "Analysis of Collision Safety Associated with Conventional and Crash Energy Management Cars Mixed Within a Consist," American Society of Mechanical Engineers, Paper No. IMECE2003-44122, November 2003.

# Session V - CEM Design, Fabrication, and Evaluation

| | |
|---|---|
| Features, Functions, and Requirements | Karina Jacobsen, Volpe |
| Concept Generation | Robert Rancatore, TIAX |
| Design Aspects of Crush Zones | Gabriel Amar, TRA&A |
| Retrofit of Test Cars | Eloy Martinez, Volpe |
| Component Crush Analysis and Testing | Rich Stringfellow, TIAX |
| Car Crush Analysis | Patricia Llana, TIAX |
| Train Crush Analysis | Rich Stringfellow, TIAX |

Federal Railroad Administration

Federal Transit Administration

Session V - CEM Design, Fabrication, & Evaluation

# Features, Functions, 8 Requirements

Crash Energy Management Technology Transfer Symposium
June 29 through July 1, 2005
San Francisco, California

Karina Jacobsen
Volpe Center
US Department of Transportation

# Conventional Equipment

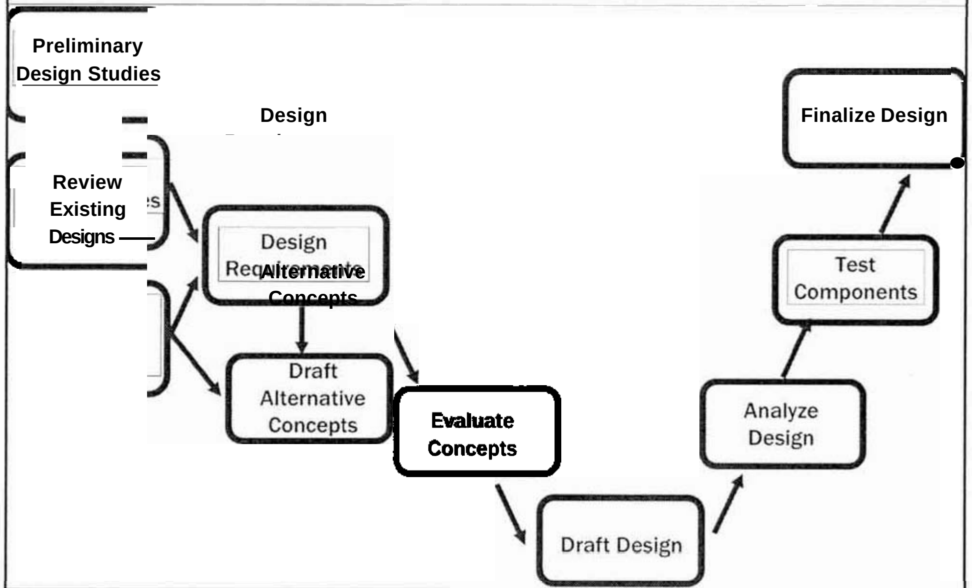
Session V Features, Functions, & Requirements Slide 2

# Objective: Develop Prototype Design

- Coach Car Crush Zone
  - Total Energy Absorption of 2.5 Million ft-lbs
  - Structural Crush of 30"
- Cab Car Crush Zone
  - Based on Coach Car Design
  - Total Energy Absorption of 3.0 Million ft-lbs
  - Structural Crush of 30" Crush
  - Operator Protection Features
  - Anti-climbing Features
  - Capable of Functioning as Coach Car

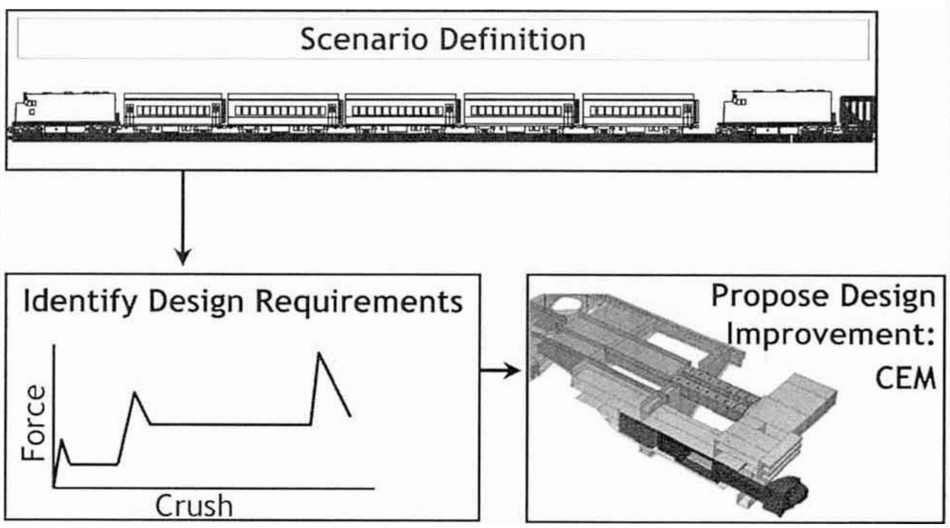
Session V Features. Functions, & Requirements Slide 3

# Design Process



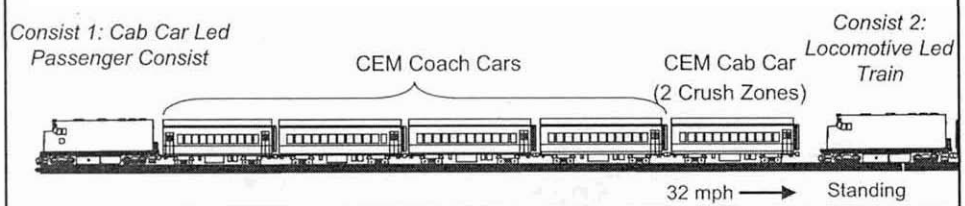



# Scenario: Train-to-train Collision



## Train-to-Train Test Scenario

- Accident Investigations Help Identify Scenarios of Concern
- Collision Behavior
  - Car Crushing: Bulk vs. Controlled
  - Lateral Motions: Lateral Buckling vs. In-line
  - Vertical Motions: Override vs. Engagement

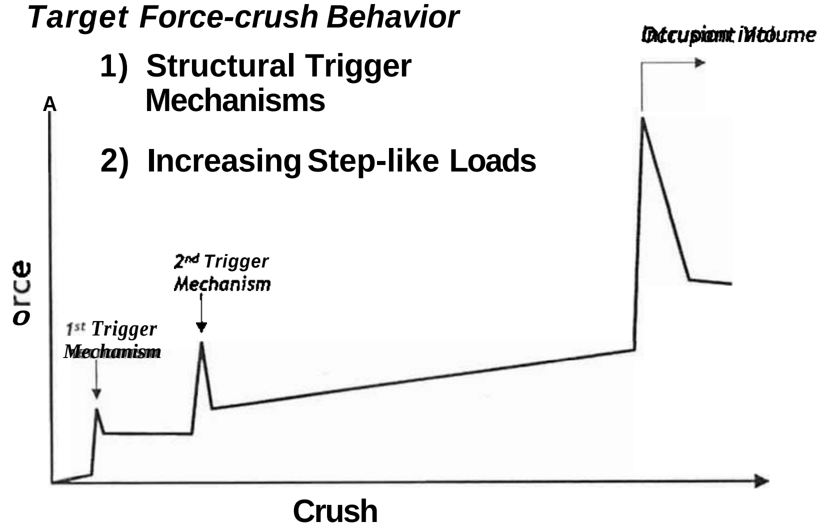





## Design Requirements: CEM Coach Car

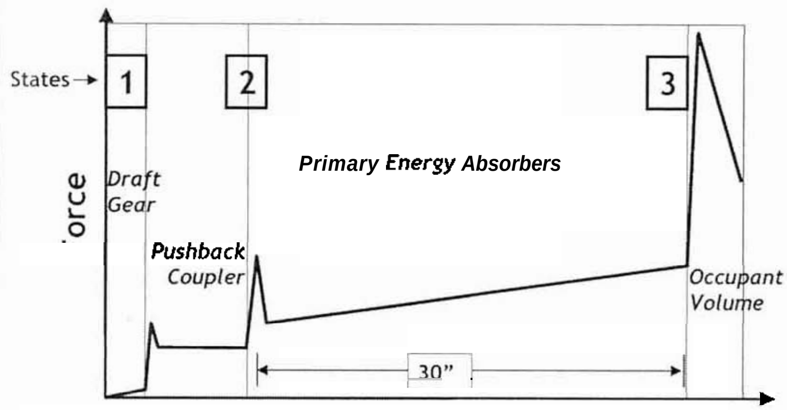
*Target Force-crush Behavior*

1) Structural Trigger Mechanisms
2) Increasing Step-like Loads



## Design Requirements: CEM Coach Car

**Key Components**



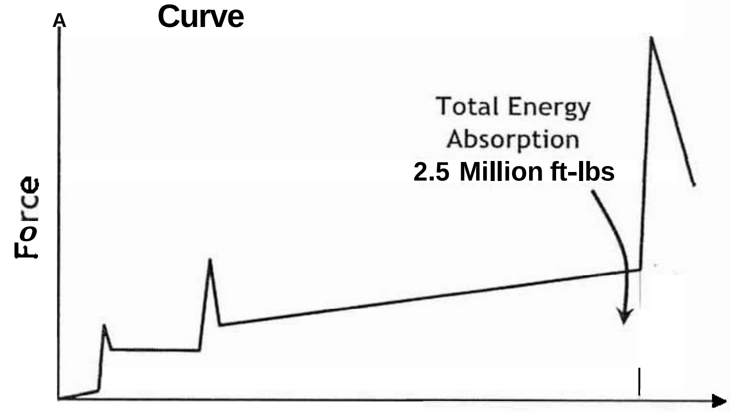

**Crush**

Session V | Features. Functions. & Requirements | Slide 8

## Design Requirements: CEM Coach Car

**Energy Absorbed**

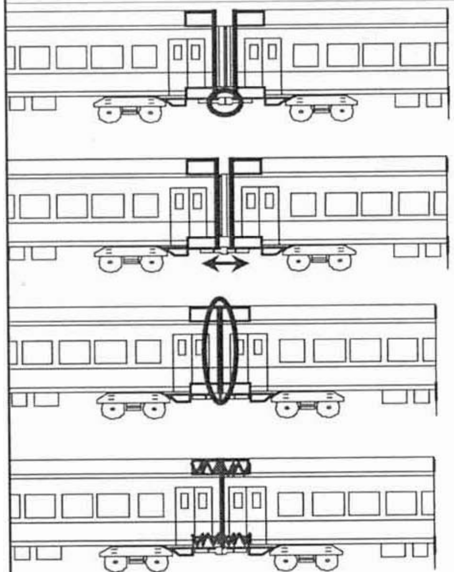
**= Area Under the Force-crush Curve**




**Crush**

Session V | Features, Functions, & Requirements | Slide 9

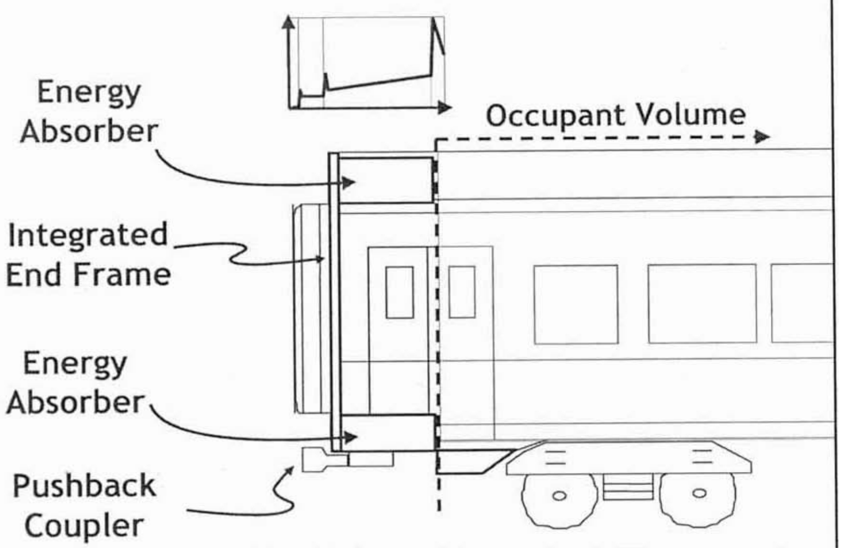
## Design Requirements: Desired Kinematics



1) *Coupled Coach Cars*
2) *Pushback Couplers Trigger*
3) *End Frames Come Together and Sliding Sills Trigger*
4) *Energy Absorbers Crush*

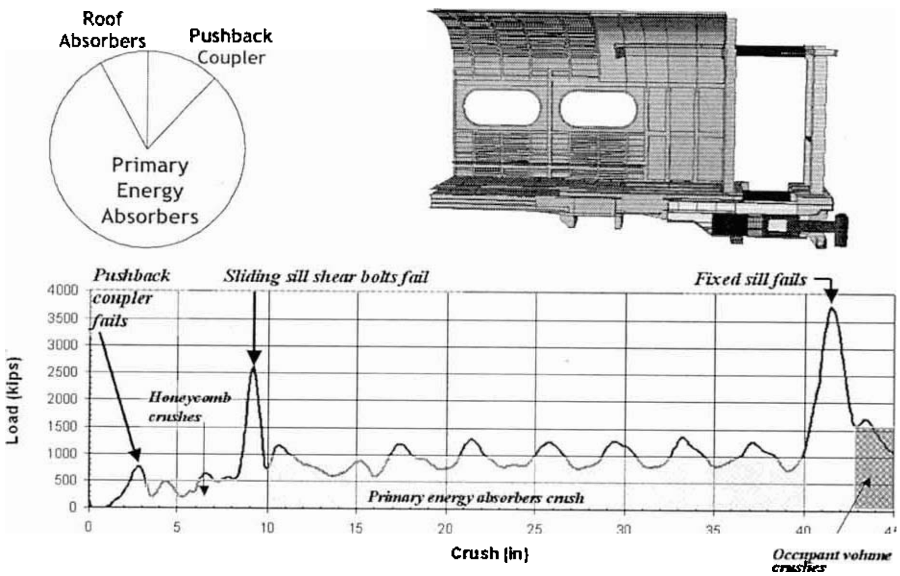
Session V Features, Functions, & Requirements Slide 10

## Necessary Components: CEM Coach Car



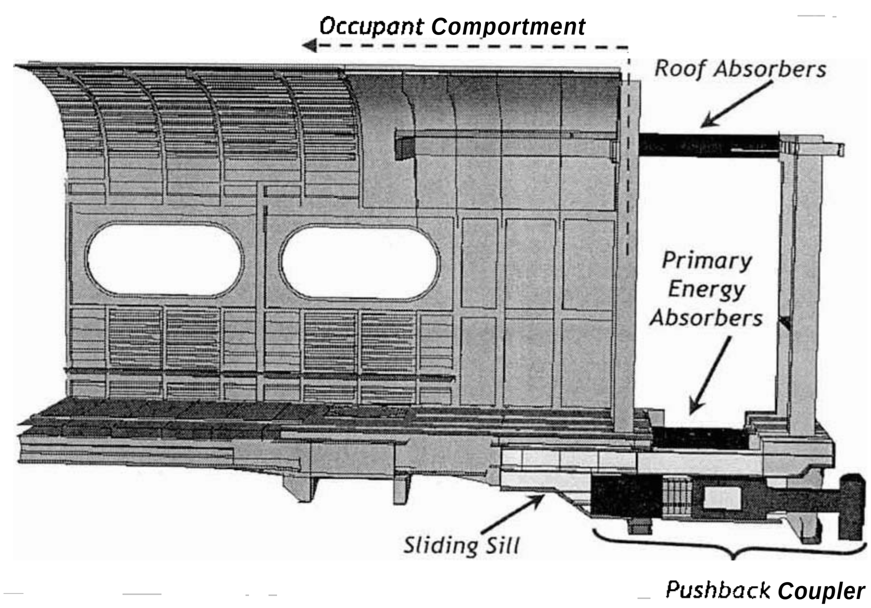

Session V Features, Functions, & Requirements Slide 11

## Energy, Components, and Force-crush






## CEM Coach Car Design

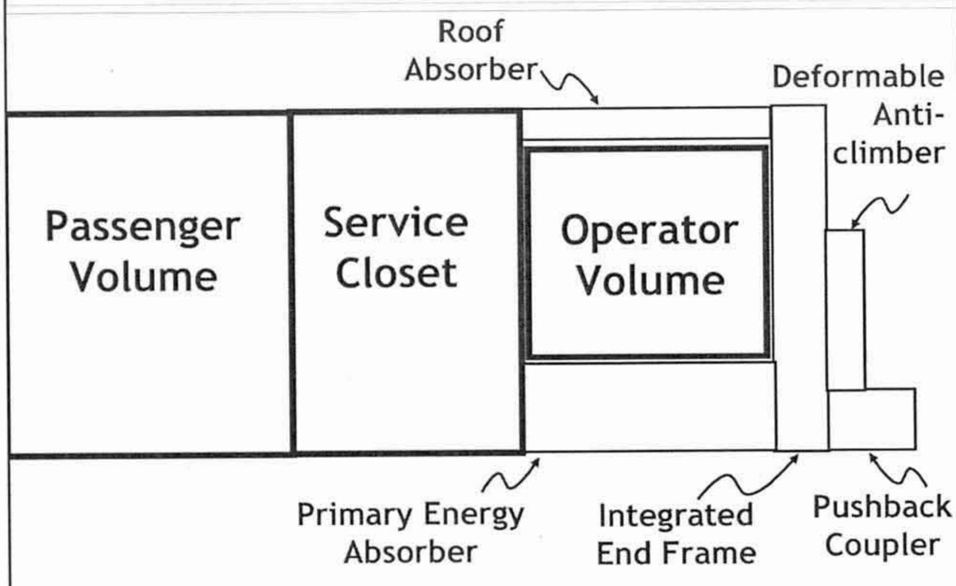


## Benefits of Coach Car Design Features

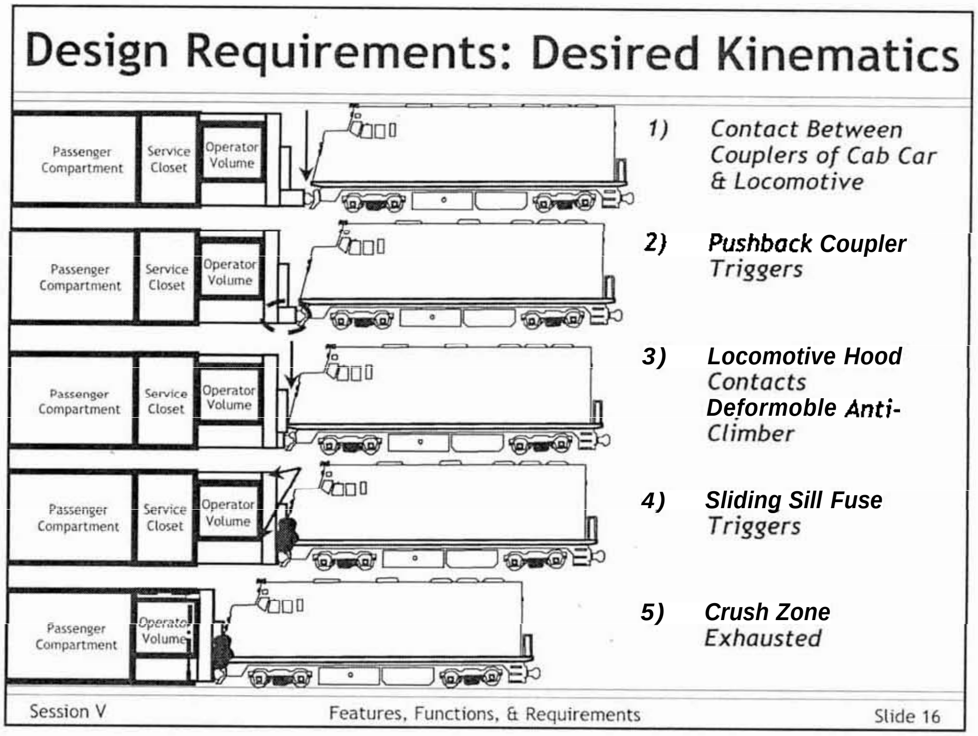
- Pushback Coupler
  - Promotes Full Contact of Main Structures of Coupled Equipment
  - Absorbs Modest Amount of Energy
  - Triggers at Lower Speeds
  - Minimizes Vertical Motions
- Interlocking Anti-climber
  - Promotes Engagement of Coupled Vehicles
  - Minimizes Vertical Motions
- Energy Absorbers
  - Promote Controlled, Progressive Crush
  - Absorb Large Amount of Energy
- Integrated End Frame
  - Supports the Loads Required to Trigger Energy Absorbers

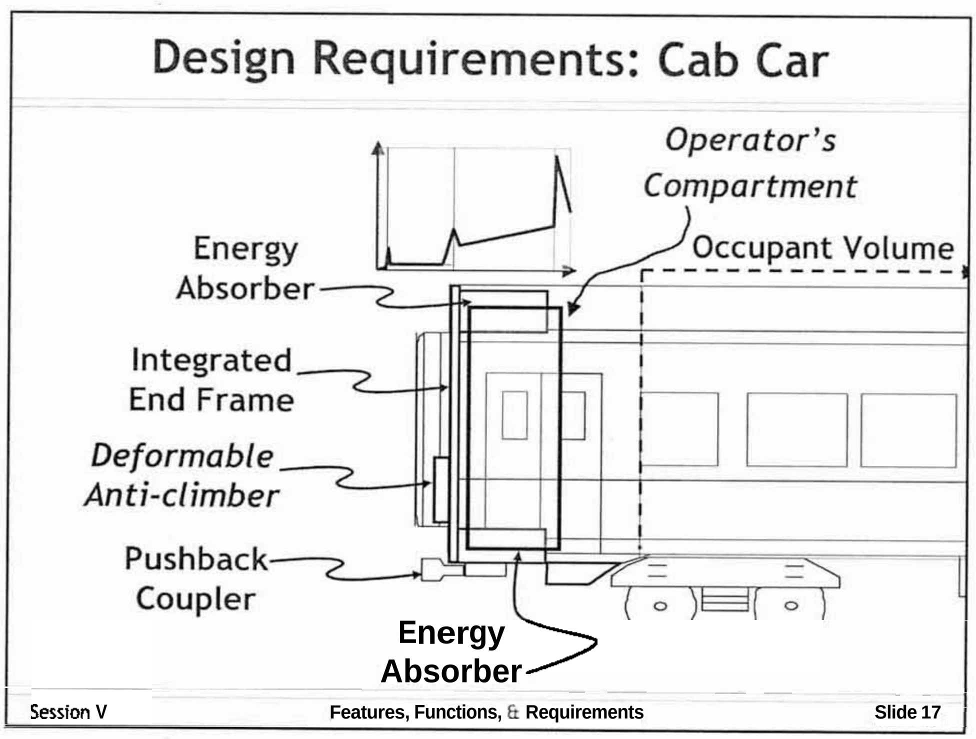
Session V | **Features.** Functions, k **Requirements** | **Slide 14**

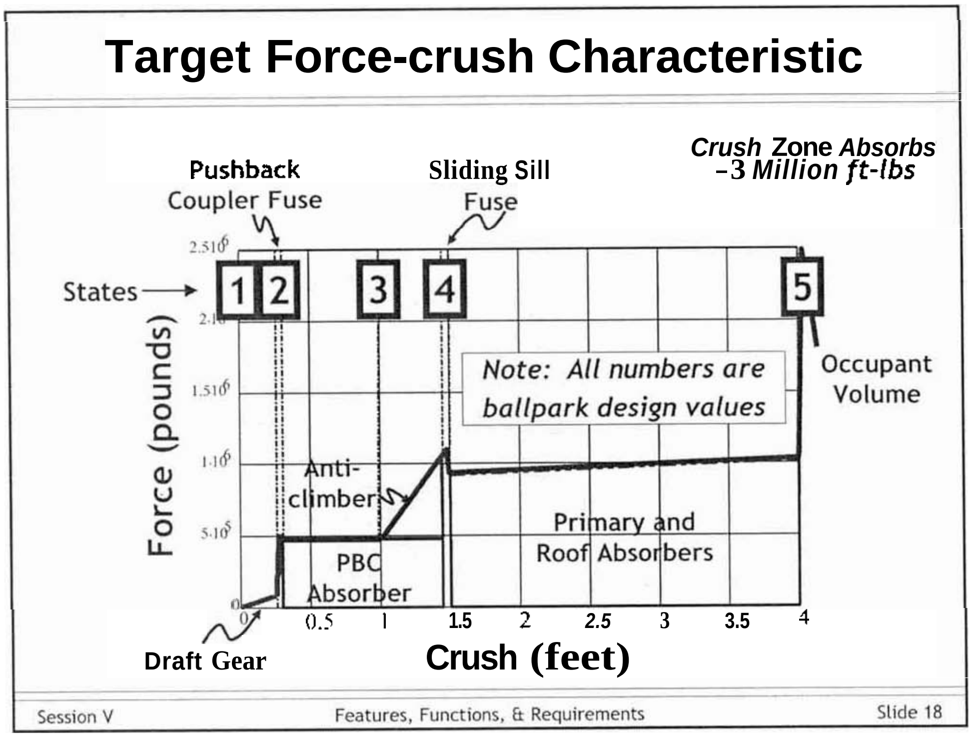
## Conceptual Cab Car

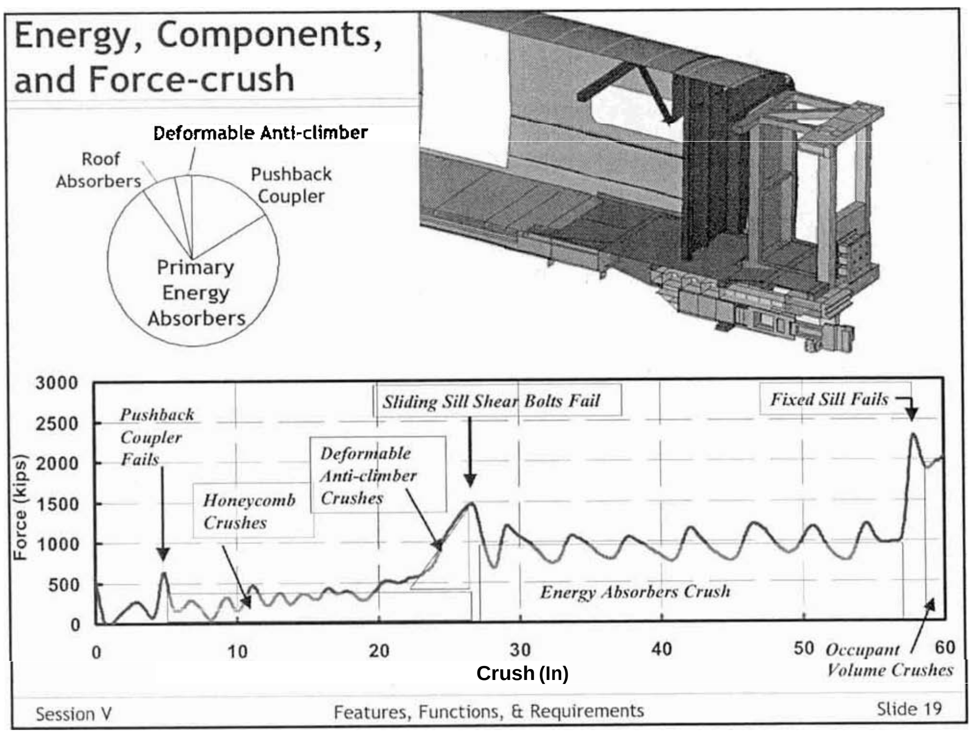



Session V | Features, Functions, & Requirements | Slide 15

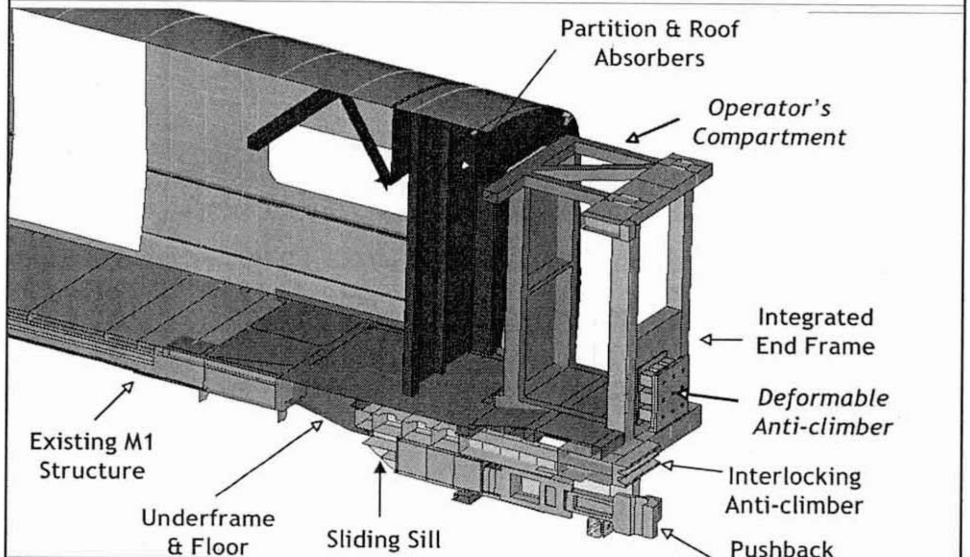

Design Requirements: Desired Kinematics
Passenger Compartment
Service Closet
Operator Volume
1) Contact Between Couplers of Cab Car & Locomotive
2) Pushback Coupler Triggers
3) Locomotive Hood Contacts Deformoble Anti-Climber
4) Sliding Sill Fuse Triggers
5) Crush Zone Exhausted
Session V
Features, Functions, & Requirements
Slide 16


Design Requirements: Cab Car
Operator's Compartment
Occupant Volume
Energy Absorber
Integrated End Frame
Deformable Anti-climber
Pushback Coupler
Energy Absorber
Session V
Features, Functions, & Requirements
Slide 17


Target Force-crush Characteristic
Crush Zone Absorbs
~3 Million ft-lbs
Pushback
Coupler Fuse
Sliding Sill
Fuse
States
1
2
3
4
5
Force (pounds)
Note: All numbers are
ballpark design values
Occupant
Volume
Anti-
climber
Primary and
Roof Absorbers
PBC
Absorber
0
0.5
1
1.5
2
2.5
3
3.5
4
Draft Gear
Crush (feet)
Session V
Features, Functions, & Requirements
Slide 18


Energy, Components,
and Force-crush
Deformable Anti-climber
Roof
Absorbers
Pushback
Coupler
Primary
Energy
Absorbers
3000
2500
2000
1500
1000
500
0
Force (kips)
Pushback
Coupler
Fails
Honeycomb
Crushes
Deformable
Anti-climber
Crushes
Sliding Sill Shear Bolts Fail
Fixed Sill Fails
Energy Absorbers Crush
0
10
20
30
40
50
60
Occupant
Volume Crushes
Crush (In)
Session V
Features, Functions, & Requirements
Slide 19

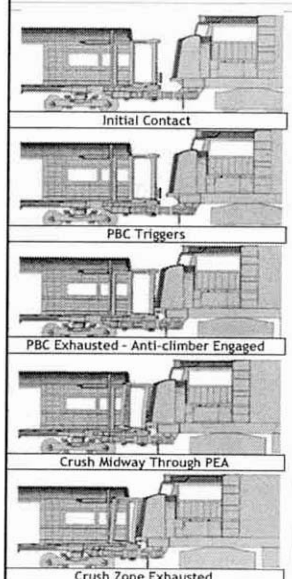
# Retrofitted Cab Car Design




Not Visible: Primary Energy Absorbers

Session V | Features, Functions, & Requirements | Slide 20

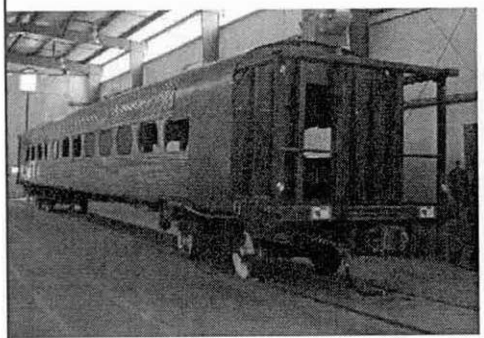
# Benefits of Design Features

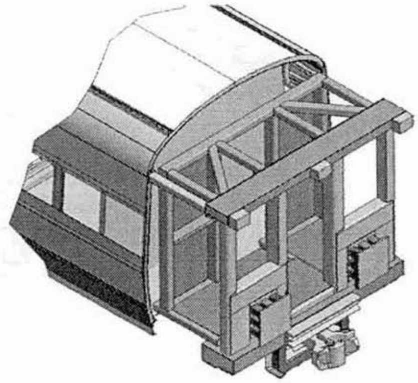



- Pushback Coupler
  - Accommodates the Locomotive Coupler
- Deformable Anti-climber
  - Conforms to Locomotive
  - Distributes Load into the Integrated End Frame
  - Helps Limit Vertical Motion
- Integrated End Frame/Operator's Compartment
  - Limits Intrusion into Operator's Compartment
  - Supports Anti-climber
- Energy Absorbers
  - Absorb a Large Amount of Energy
  - Promote Controlled Progressive Crush

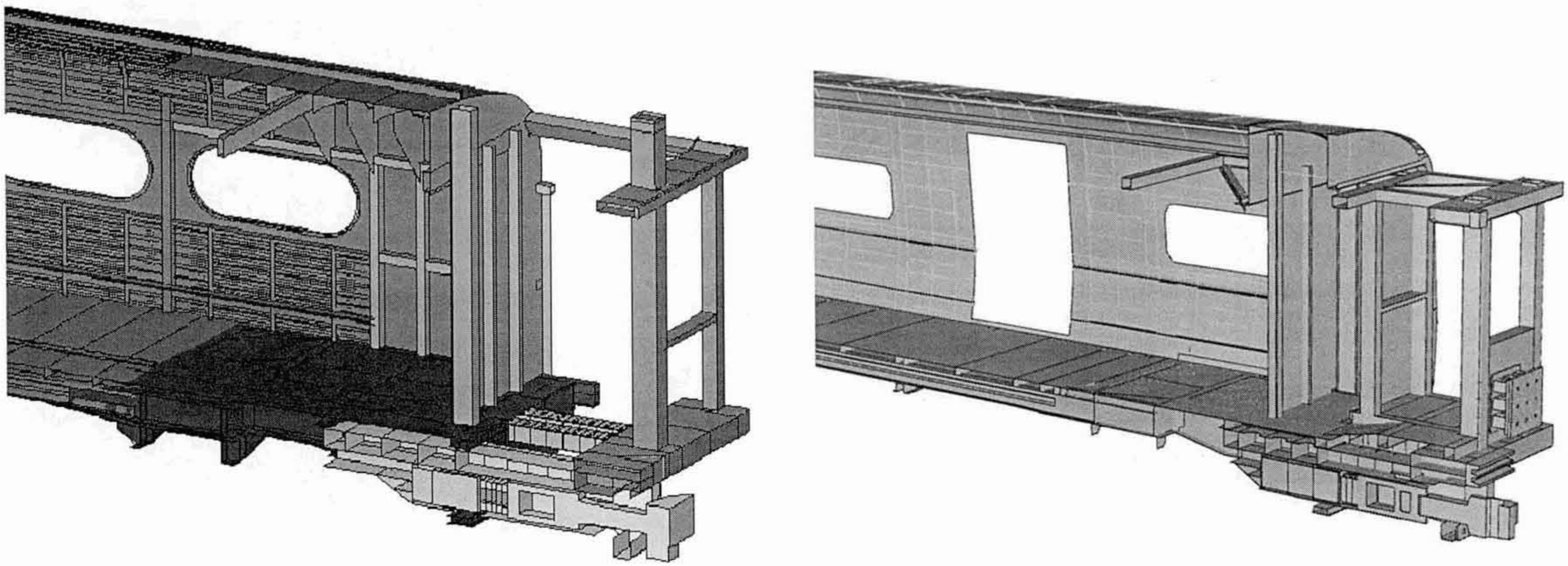
Session V | Features, Functions, & Requirements | Slide 21

# Coach and Cab Designs





Session V | Features, Functions, & Requirements | Slide 22



# Concept Generation

## Session V: CEM Design, Fabrication & Evaluation

Crash Energy Management Technology Transfer Symposium
29 June - 1 July 2005
San Francisco, California

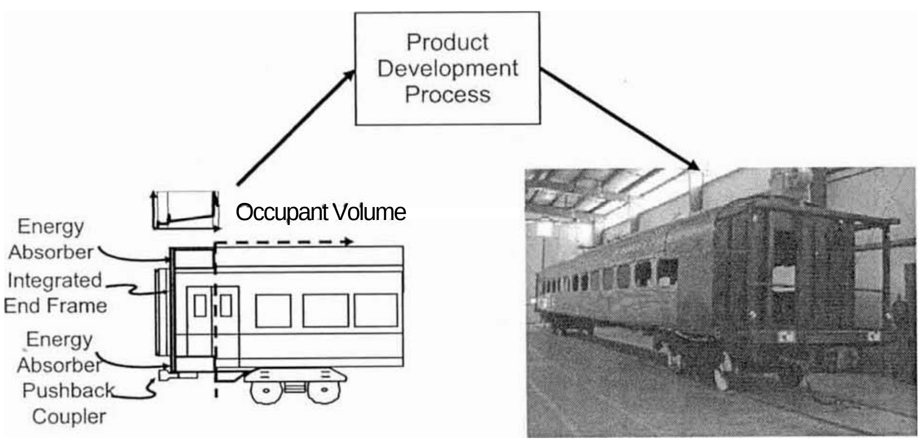
Robert Rancatore
TIAX LLC
Cambridge, Massachusetts

Overview of Presentation

- Objective
- introduction to TIAX
- Description of our Product Development Process
  - Phase 1 – Product Definition
    - Requirements Definition
    - Concept Generation
    - Preliminary Analyses
  - Phase 2 – Preliminary Design
  - Phase 3 – Detailed Design



The overall objective of the projects is to investigate and demonstrate the feasibility of Crash Energy Management for heavy rail passenger service.



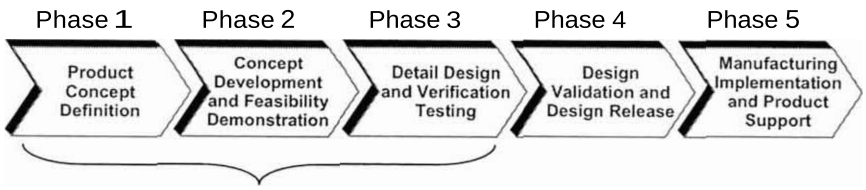
Formed out of Arthur D. Little's Technology & Innovation business, TIAX builds on more than a century of breakthrough innovation and client success using collaborative RBD.

- The TIAX Team members contributed to the development of the coach and cab car crush zones:
  - TIAX LLC – Program management, non-linear crush analyses, collision dynamics analyses, design and engineering support
  - Taylor, Raynauld, Amar & Associates – Detailed design
  - R.A. **Mayville** and Associates – Engineering support
  - Transportation Technology Systems – Detailed design
  - Premier Engineering – Detailed design
  - **Simula** Aerospace and Defense Group, Inc. – Testing
  - Ebenezer Railcar **Services** Inc. – Fabrication





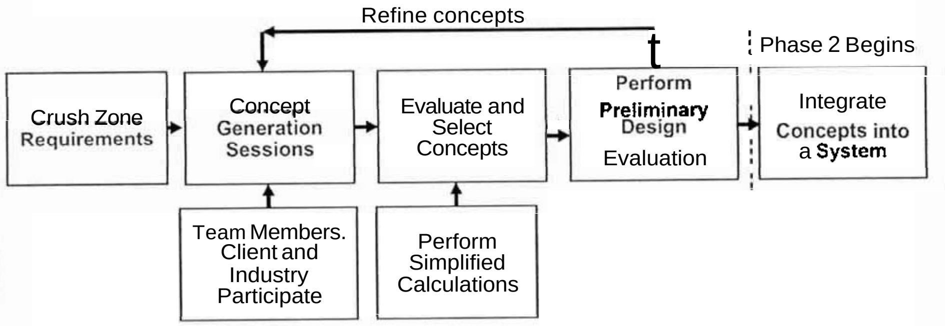
We followed **TIAX's** Product Development Process (PDP) during the design of each of the crush zones.




We applied these Phases of the process for these projects.

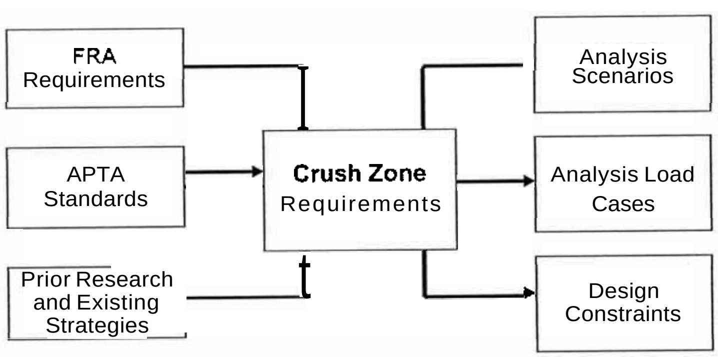
CEM Technology Transfer Symposium *Phase 1 – Product Concept Definition*

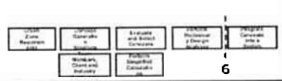
Phase 1 includes the Requirements and Concept Definition Tasks.




CEM Technology Transfer Symposium *Phase* 1 Requirements Definition

Requirements definition is an important activity in the PDP because it helps to identify critical constraints and analyses early in the design process.



6

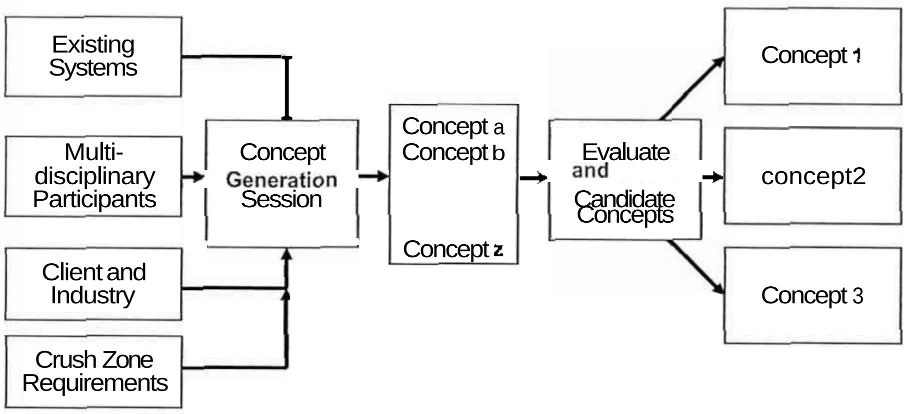
Several critical requirements must be met by the crush zone design.

| Critical Crush Zone Design Requirement Areas |
|---|
| Meeting the 800,000 **lbf** static buff strength. |
| Absorbing the required energy in the defined crush distance. |
| Providing space for the **pushback** coupler, the operator's compartment and the crush zone given the existing car geometry. |
| Limiting intrusion into the operator's compartment. |
| Integrating the crush zone into the existing car structures such that loads are distributed without overloading the those structures. |



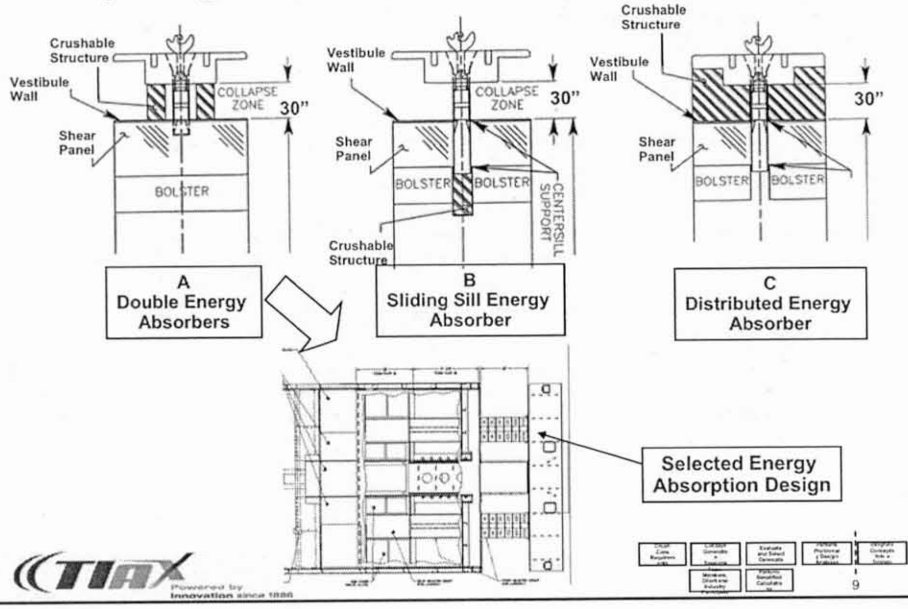


Developing concepts includes a review of existing systems, holding concept generation sessions, and categorizing and evaluating the concepts.




Two examples of using this process include the location and type of energy absorber designs.

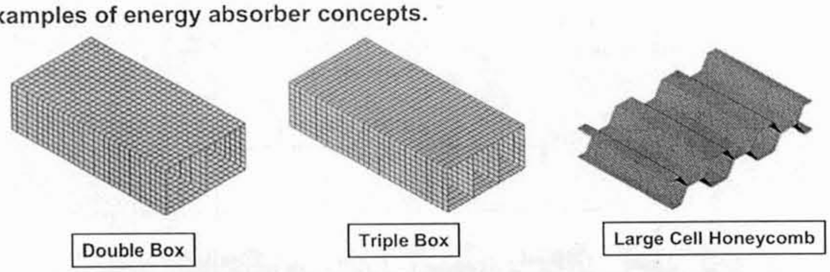
## Example energy absorption strategy concepts that were evaluated.








## Examples of energy absorber concepts.




Selected Primary Energy Absorber

CEM Technology Transfer Symposium *Phase 1* Concept Selection

An example concept ranking to help select the concept to be carried forward to preliminary design.

| | | Crush Zone Concept | | | | | |
|---|---|---|---|---|---|---|---|
| Criterion | Weight | A | | B | | C | |
| | | Score | Weighted | Score | Weighted | Score | Weighted |
| 1. Weight | 1 | 1 | | 2 | | 3 | |
| 2. Ability to carry operating loads | 3 | 3 | | 2 | | 1 | |
| 3.Complexity to operate as a crush zone | 2 | 1 | | 3 | | 1 | |
| 4. Offset/vertical load sensitivity | 3 | 2 | | 3 | | 1 | |
| 5. Compatibility w/conventional layouts | 3 | 1 | | 2 | | 3 | |
| 6. Ease of manufacturing | 1 | 1 | | 2 | | 2 | |
| 7. | | | | | | | |
| Total | | | 9 | | 14 | | 11 |

EXAMPLE

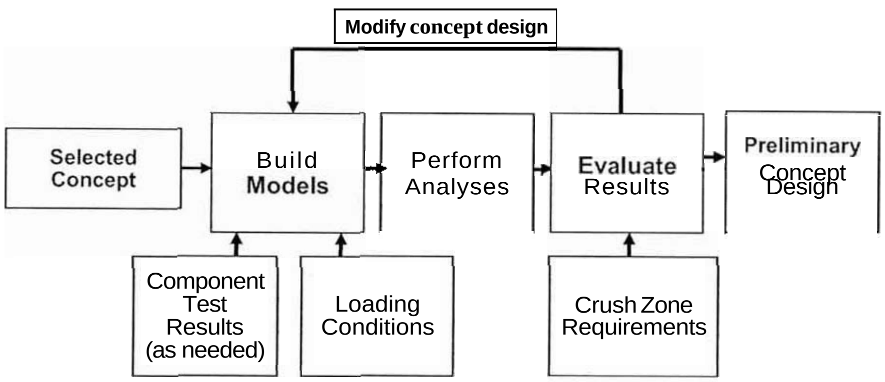
1=best; 2-intermediate; 3-worst

TIAX Innovation since 1886

11

CEM Technology Transfer Symposium *Phase 1* Preliminary Evaluation

The preliminary analyses guide the design of the concept to ensure its planned response is met.




TIAX Innovation since 1886

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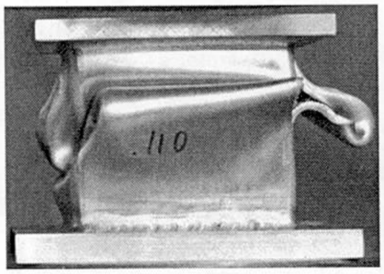
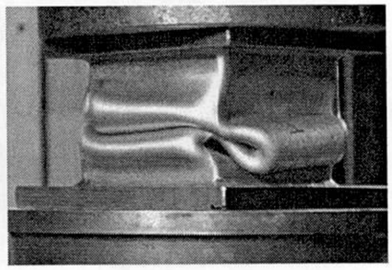
**Understanding the response of the components is key to developing a system that meets the requirements.**



As-received

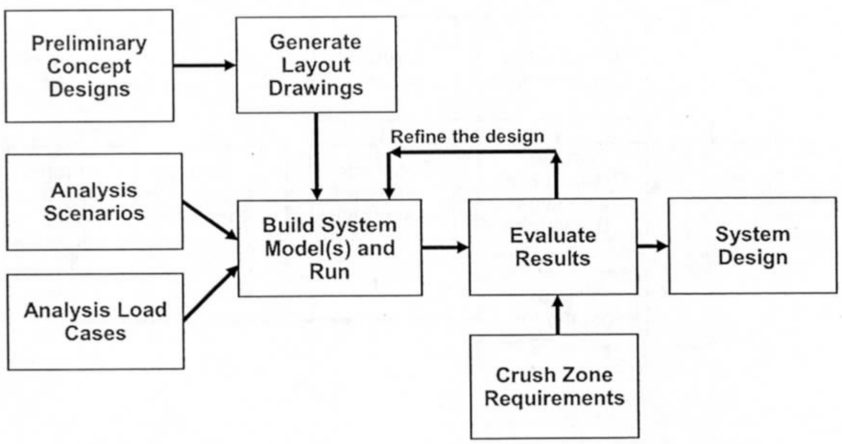


Annealed



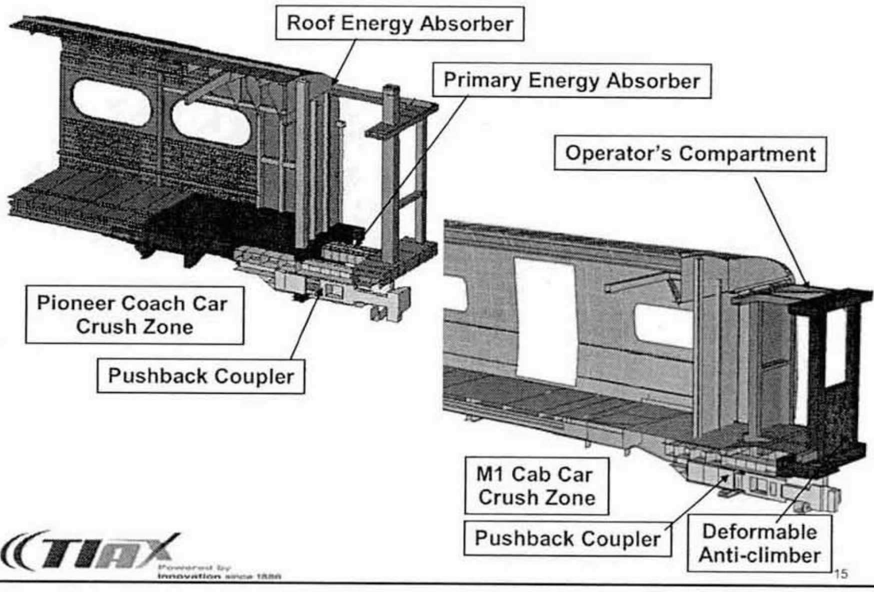


**The preliminary design of the system begins with the creation of the layout drawings based on the concept designs.**



CEM Technology Transfer Symposium *Phase* 2 Preliminary Design

The component concepts are integrated into a system concept.

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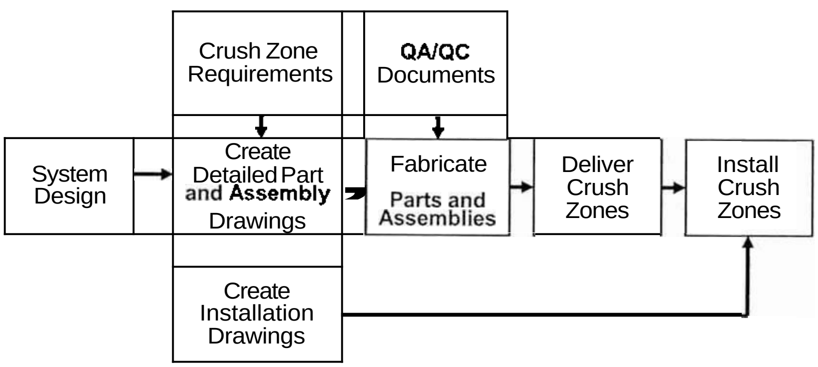
CEM Technology Transfer Symposium *Phase* 3 Detailed Design & Fabrication

Phase 3 includes specifying connection and fastener details for fabrication.

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CEM Technology Transfer Symposium — Conclusions

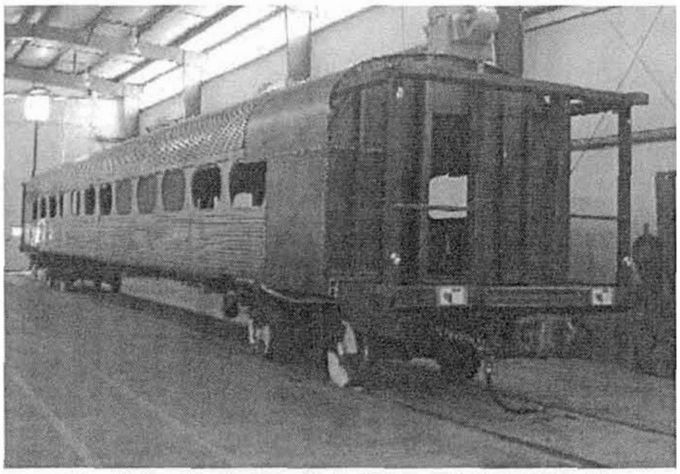
The Product Development Process was successfully used to guide the design of the prototype crush zones.

- Defining the requirements early in the design process leads to system designs that perform as desired.
- Critical components were identified, concept designs generated and analyzed, and the designs integrated into the system design.
- The strength and energy-based requirements were compared against the analysis results throughout the design process to ensure the appropriate response of the crush zones.
- Fabrication of the designs is underway for the remaining six vehicle ends.

TIAX — Innovation since 1886 — 17

CEM Technology Transfer Symposium — Ready for Testing

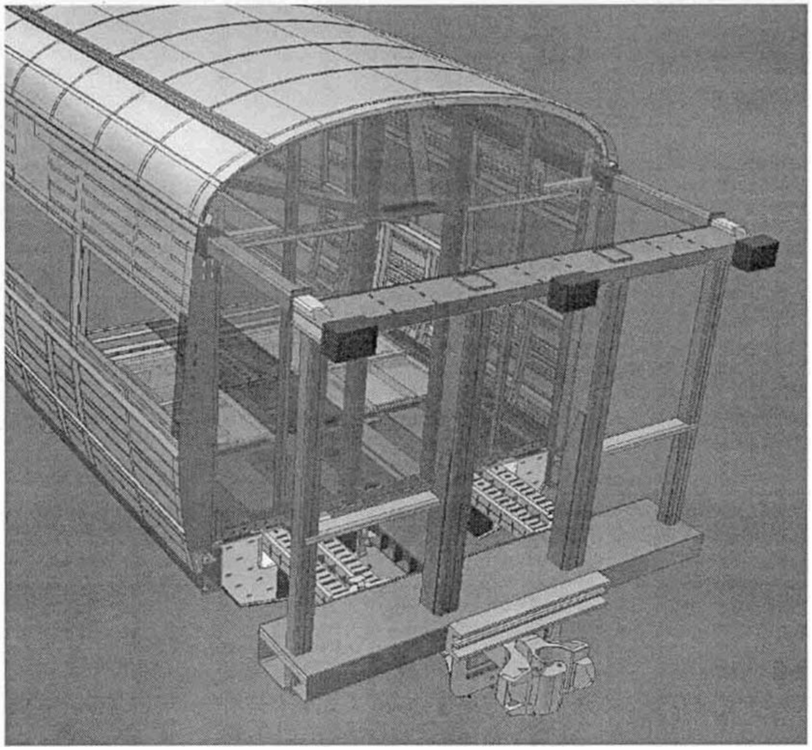
Once completed, the crush zone components and assemblies are delivered to TTCI in Pueblo to be installed on the prepared cars.



Coach Car Crush Zone Installed on a Budd Pioneer Car

TIAX — Innovation since 1886 — 18

# Design Aspects of Crush Zones



SESSION V: CEM Design, Fabrication & Evaluation

Crash Energy Management Technology Transfer Symposium

San Francisco, CA 29 June – 1 July 2005

Taylor Raynauld Amar & Associates Inc.
1751 Richardson, Suite 6.110, Montreal, QC, Canada H3K 1G6
Tel: (514) 933-1083 Fax: (514) 933-3533

Gabriel Amar

## Taylor Raynauld Amar & Associates Inc.

TRANSPORTATION VEHICLE CONSULTING ENGINEERS

- David D. Taylor - President
- Bernard Raynauld VP - Systems
- Gabriel Amar VP - Structures

Specification and design of rail passenger and transit vehicles, locomotives and freight cars.

Company established in 1985 (DDT&A)

- Involved with Volpe & TIAX since 2002



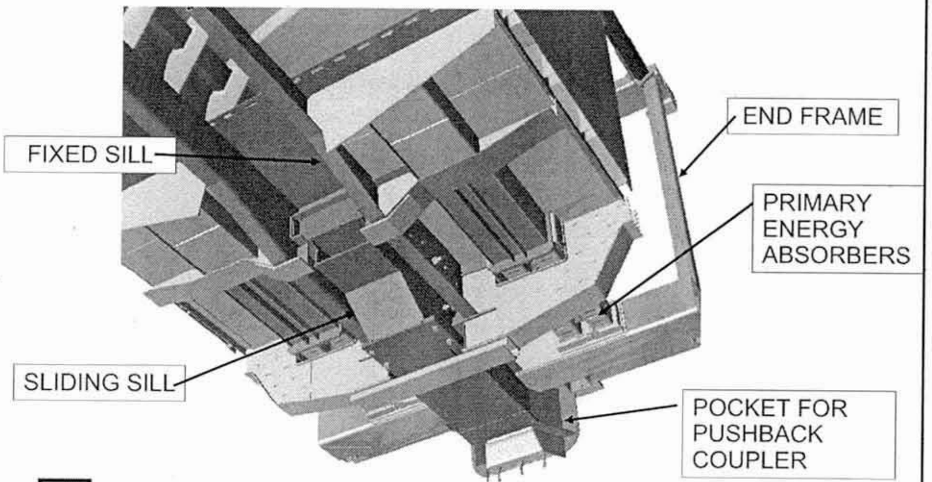


## Items covered in this presentation:

- Pioneer Coach Overall Arrangement
- M1 Coach Car Overall Arrangement
- M1 Cab Car Overall Arrangement
- Key Crush Zone Details

Design Aspects of Crush Zones | Pioneer Coach

## Pioneer Coach - Underframe

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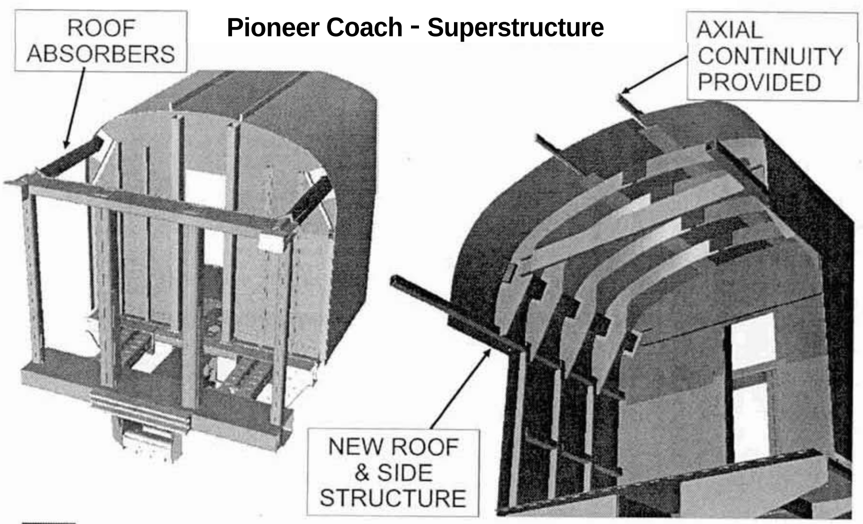
Design Aspects of Crush Zones | Pioneer Coach

## Pioneer Coach - Superstructure




TRA

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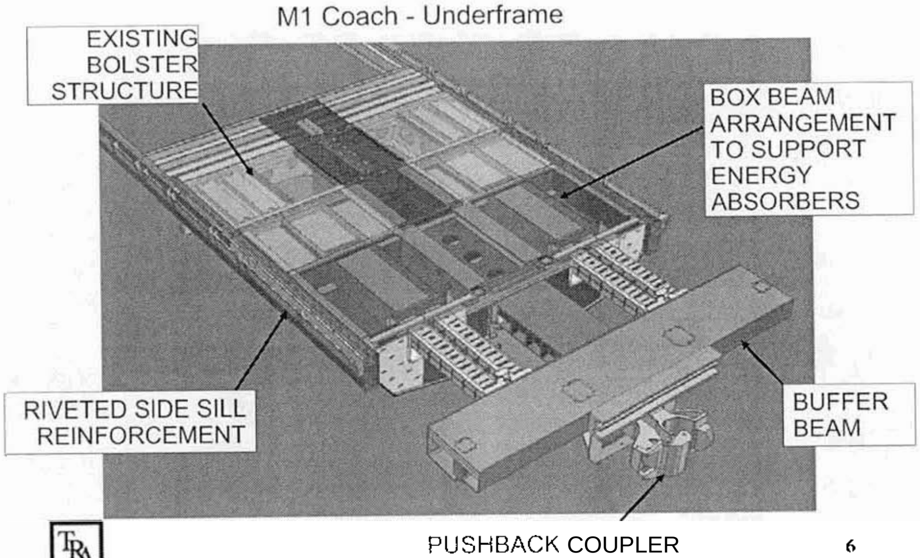
Design Aspects of Crush Zones M1 Coach

## M1 Coach - Underframe

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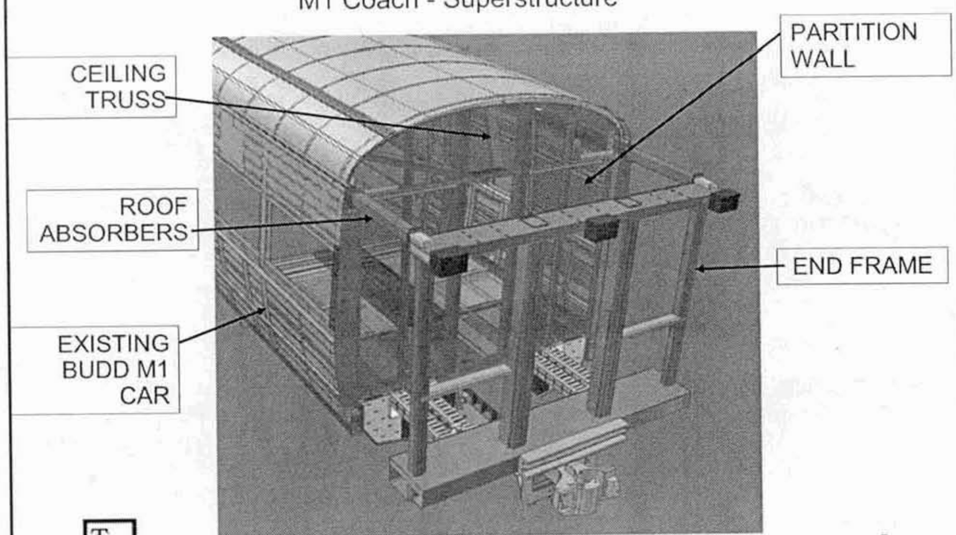
Design Aspects of Crush Zones M1 Coach

## M1 Coach - Superstructure

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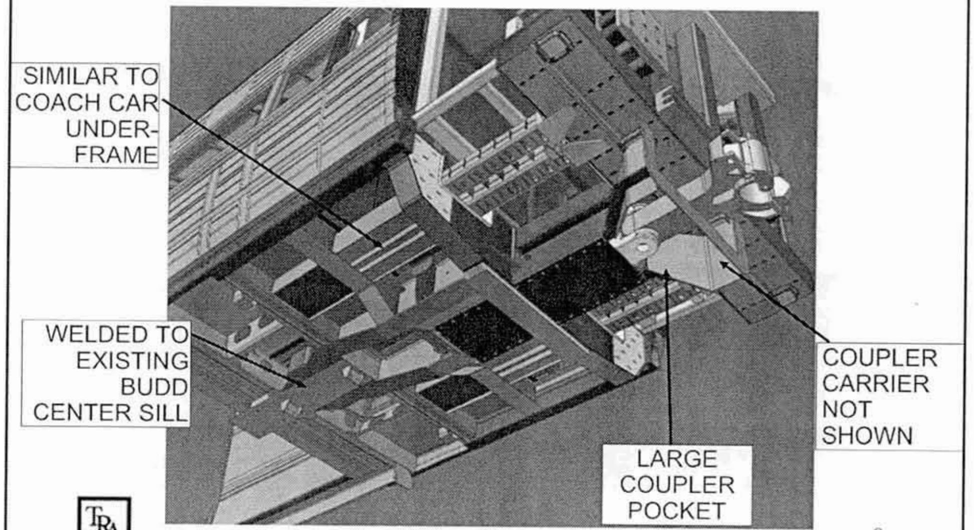
Design Aspects of Crush Zones

M1 Cab Car

## M1 Cab Car - Underframe

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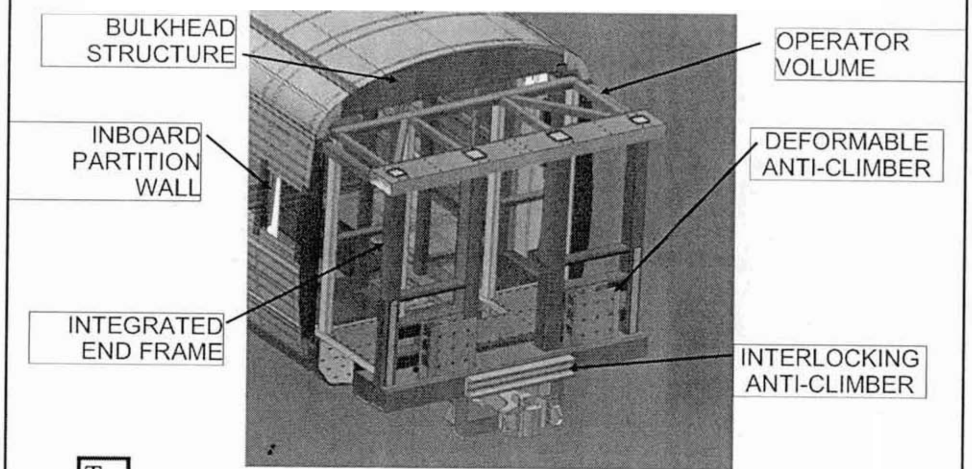
Design Aspects of Crush Zones

M1 Cab Car

## M1 Cab Car - Superstructure

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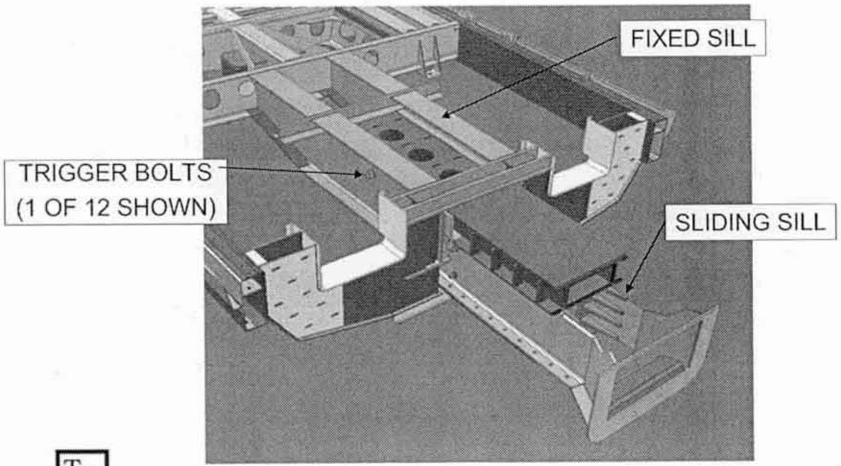
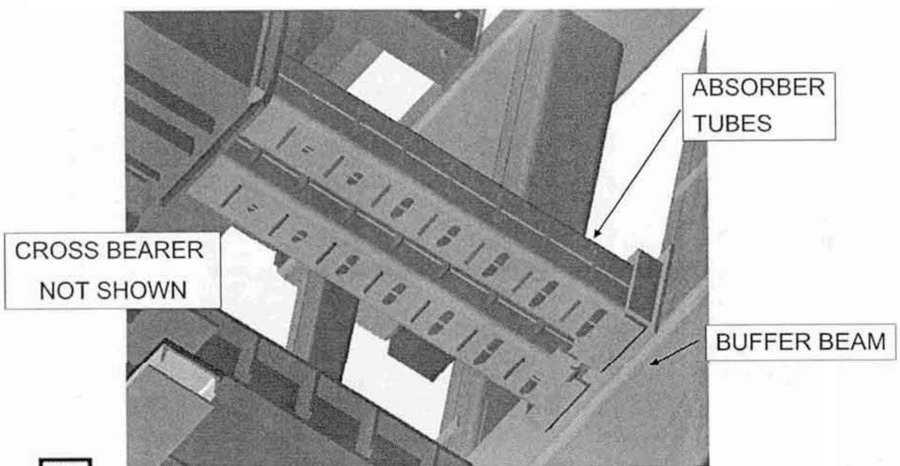
The CEM test cars feature a Fixed Sill & Sliding Sill arrangement with trigger bolts



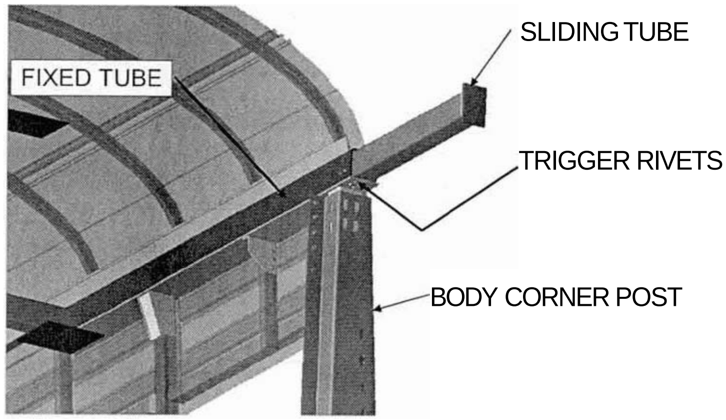





The Primary Energy Absorbers are composed of built-up welded tubes that deform by progressive local buckling



The Roof Energy Absorbers are composed of telescoping steel tubes that crush confined aluminum honeycomb units

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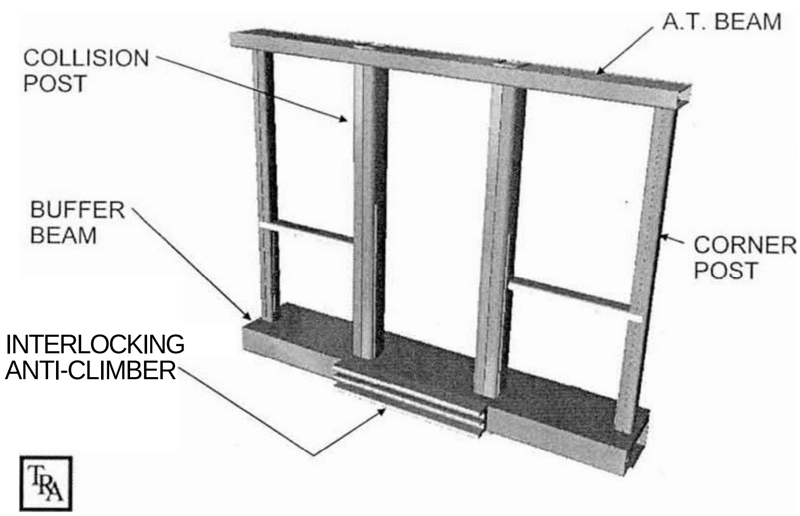
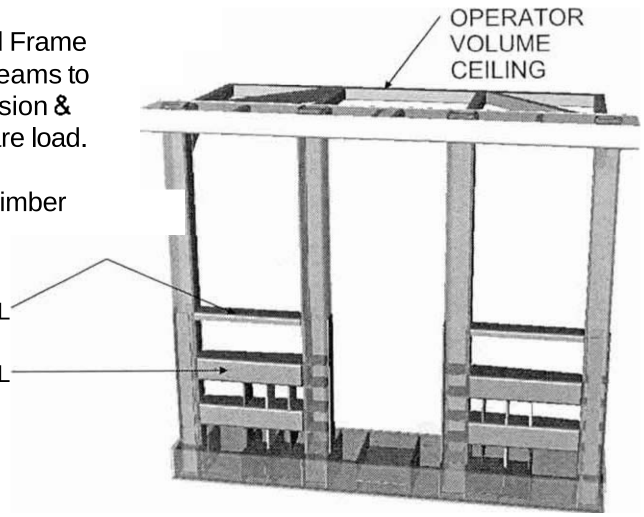
The Coach Car End Frame employs ASTM A710 built-up tubes and box sections with ductile connections




13

The Cab Car End Frame includes lateral beams to integrate the collision & corner posts, share load. andsupporta deformable anticlimber (not shown)

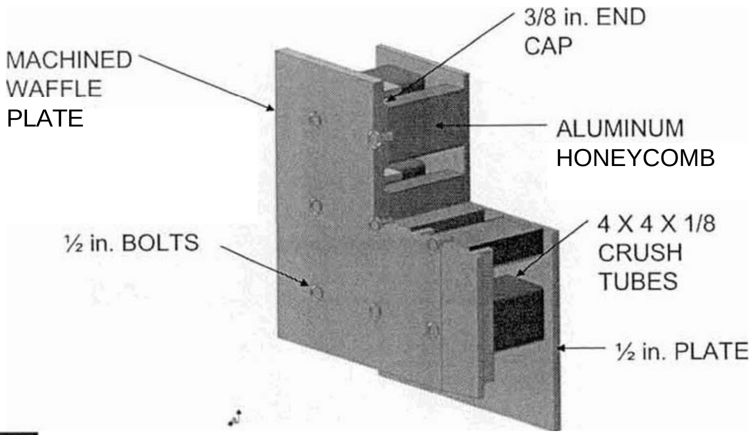



TRA

14



The cab car's Deformable Anti-climber includes a thick plate supported by stainless steel crushable tubes filled with aluminum honeycomb

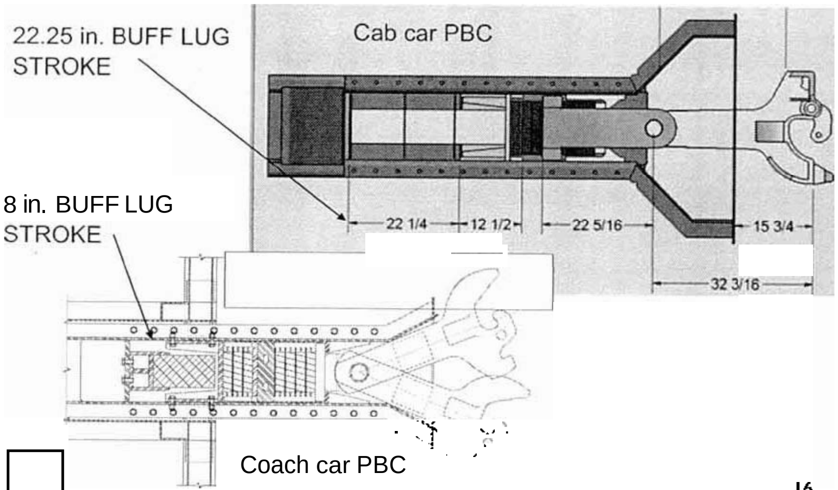



TRA

IS

**Design Aspects of Crush Zones** — **Key** Crush **Zone Details**

The Pushback Couplers (PBC) are AAR standard components supported by a break-away rear buff lug that crushes different lengths of aluminum honeycomb on the coach and cab cars

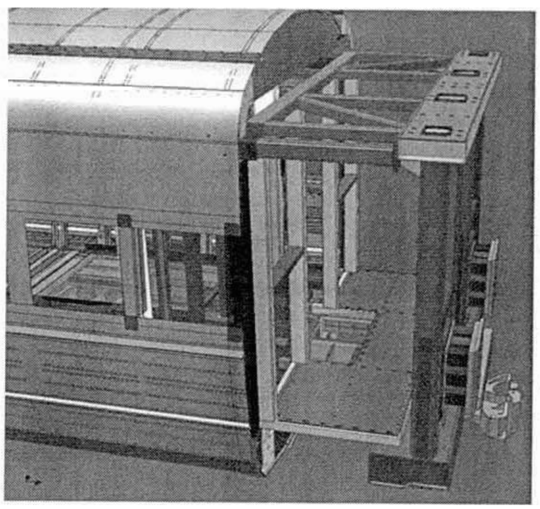



16

**Design Aspects of Crush Zones** — **Key** Crush **Zone Details**

The Cab Car Crush Zone offered several other design challenges such as:

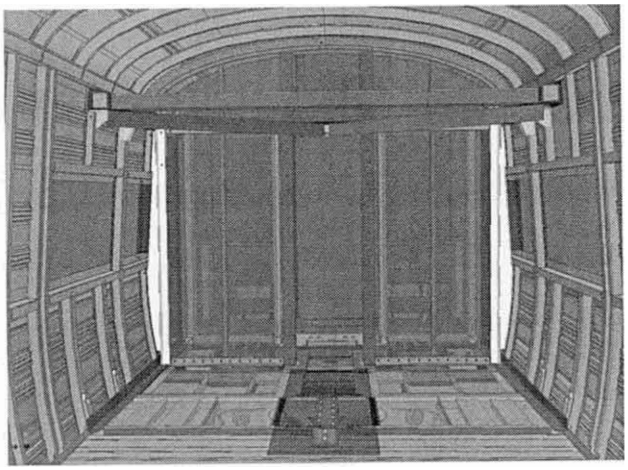
PROVISION OF AN OPERATOR VOLUME THAT MOVES INTO CAR WITHOUT INTERFERENCE WHILE UNDERGOING LARGE DEFORMATIONS



17

Other Cab Car Crush Zone design challenges:

INTEGRATION INTO AN EXISTING M1 CAR SHELL WITHOUT OVER STRESSING THE STRUCTURE



IS

## Session V - CEM Design, Fabrication, & Evaluation

# Retrofit of Test Cars

**Crash Energy Management Technology Transfer Symposium**
**June 29 through July 1, 2005**
**San Francisco, California**

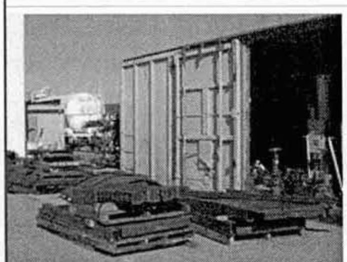
**Eloy Martinez**
**Volpe Center**
**US Department of Transportation**

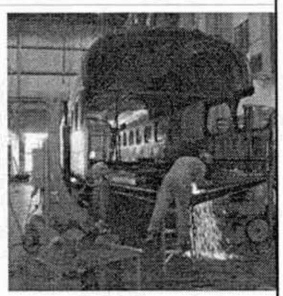
## Background

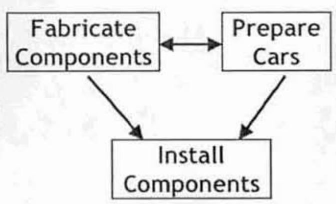
- **Objectives:**
  - **Retrofit Crush Zone Designs Onto Existing Cars in Preparation for Full-scale Train-to-train Test**
    - **SEPTA Budd Pioneer Cars**
    - **LIRR Budd M1 Cars**
  - **Show Existing Car Designs Can React Crush Zone Loads**
  - **Demonstrate Feasibility of Retrofitting Cars**

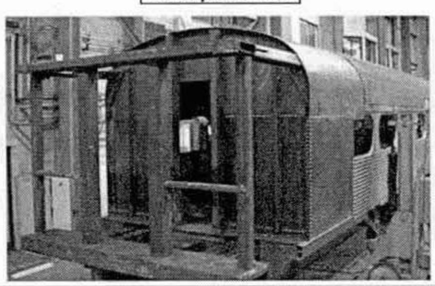
Session V | Retrofit of Test Cars | Slide 2

## Process to Retrofit Crush Zones Onto Existing Cars







Session V | Retrofit of Test Cars | Slide 3

## Fabricate Components

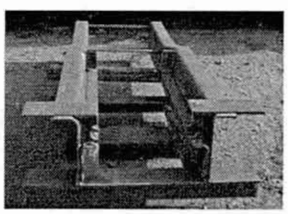
- **Fabrication Experience**
  - End Beam Design Tests
  - End Frame Designs for Grade Crossing Tests
  - End Frame Designs for In-line Tests
  - Coach Car Crush Zone Design

- **Fabrication Requirements - Use Typical:**
  - Materials
  - Fabrication Techniques

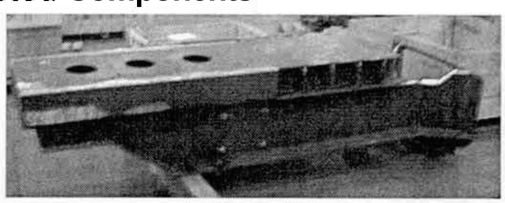
Session V | Retrofit of Test Cars | Slide 4

## Fabricate Components

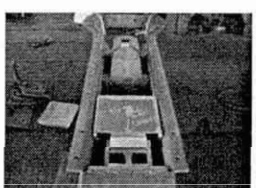
### Selected Components



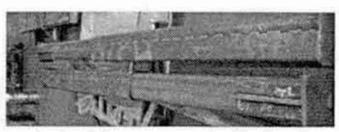
Fixed Sill



Sliding Sill



Push-Back Coupler

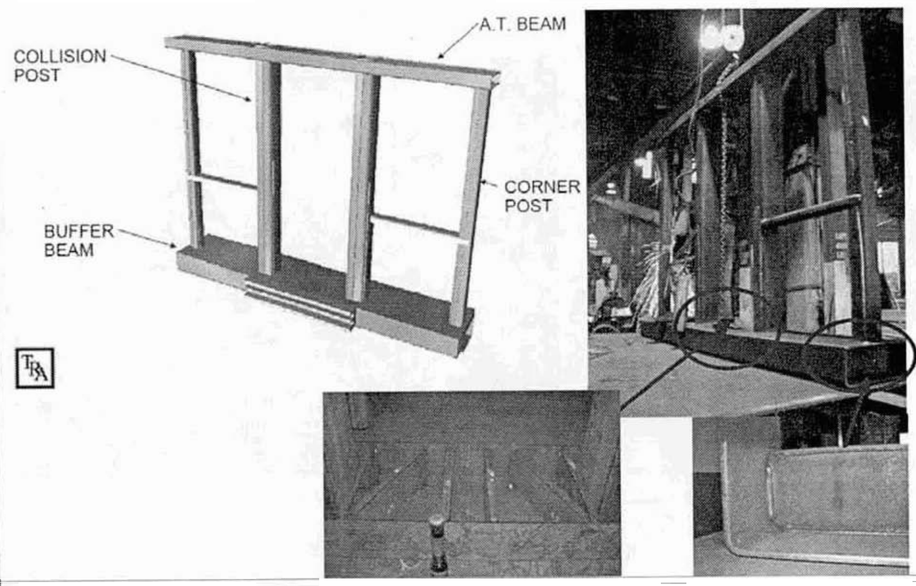


Roof Absorbers

Reaction Group With Primary Energy Absorber (PEA)

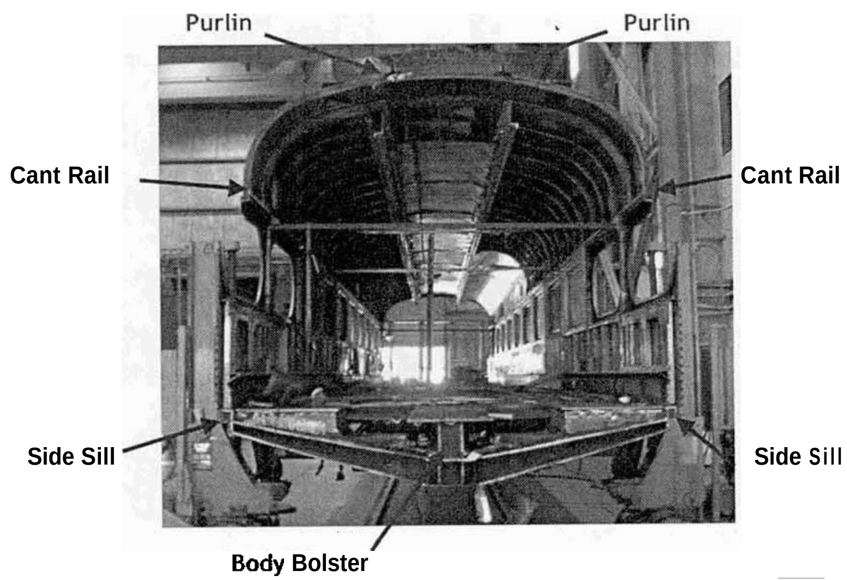
Session V | Retrofit of Test Cars | Slide 5

## Fabricate Components



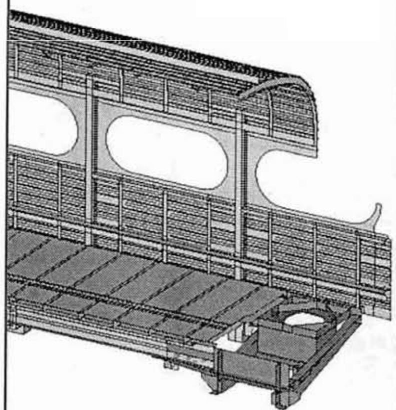

Session V | Retrofit of Test Cars | Slide 6

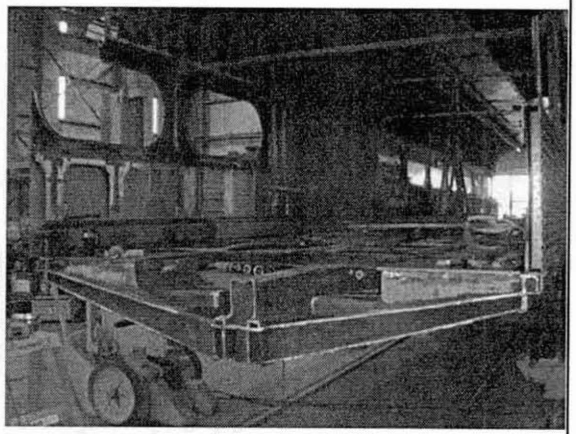
## Budd Pioneer Car Preparation




Session V | Retrofit of Test Cars | Slide 7

## Budd Pioneer Car Preparation

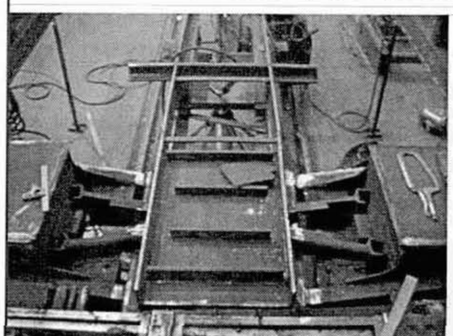


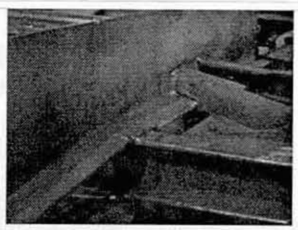


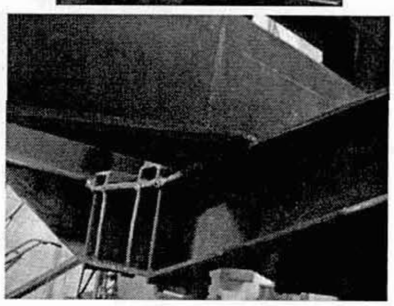
**Prepare Body Bolster**

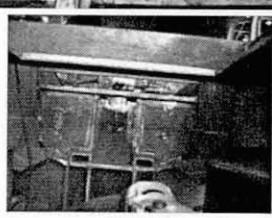
Session V | Retrofit of Test Cars | Slide 8

## Budd Pioneer Car Preparation





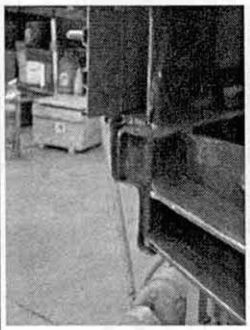
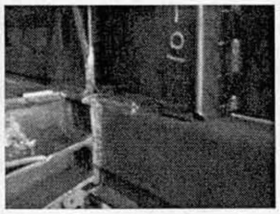
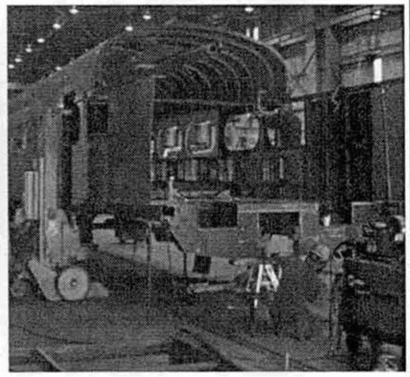




Stiffen Body Bolster & Integrate Fixed Sill

Session V | Retrofit of Test Cars | Slide 9

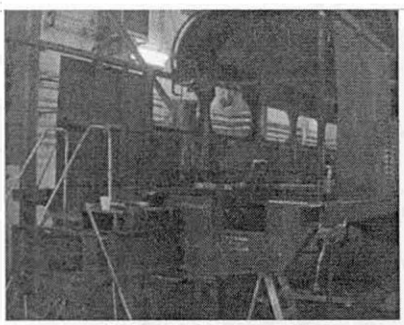
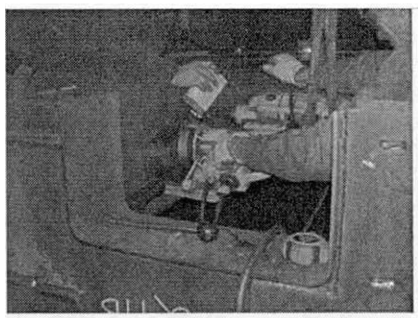
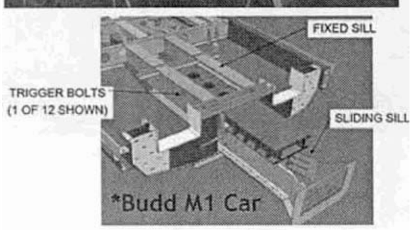
## Budd Pioneer Car Preparation

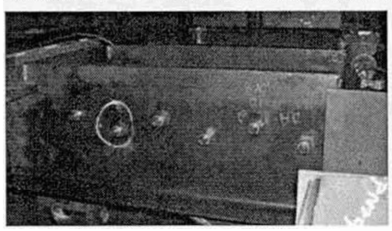




**Build Up Side Sills & Position Cross Bearer Assemblies**



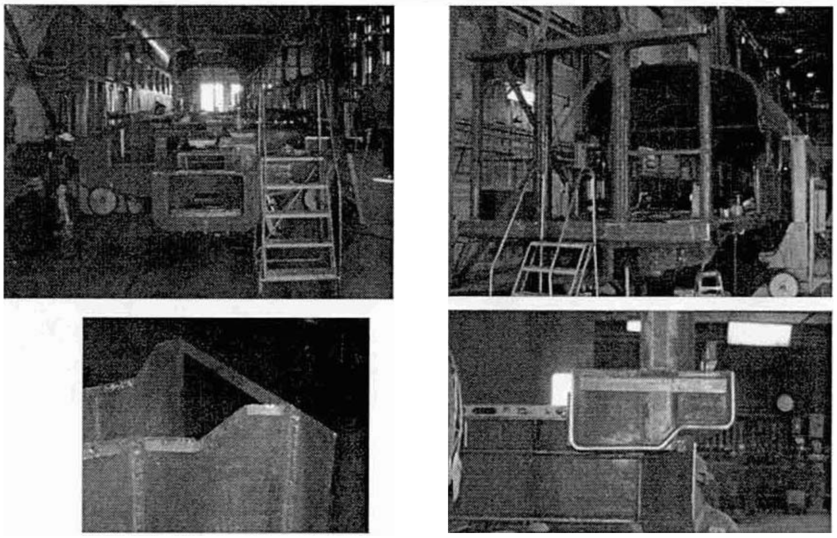
## Budd Pioneer Car Preparation



**Insert Sliding Sill and Drill Holes**

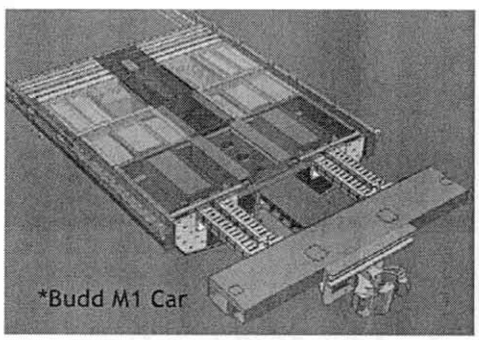
## Budd Pioneer Car Preparation

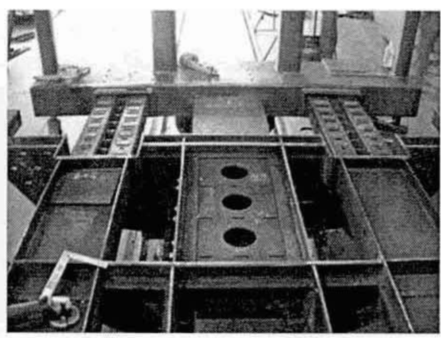


Attach End Frame Assembly



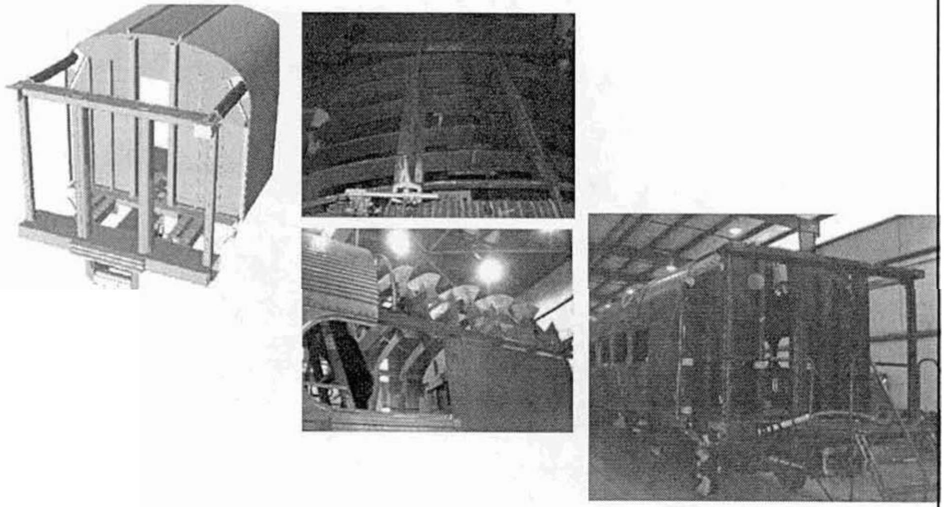
## Budd Pioneer Car Preparation



Attach Front and Rear Reaction Groups
Along with Primary Energy Absorbers

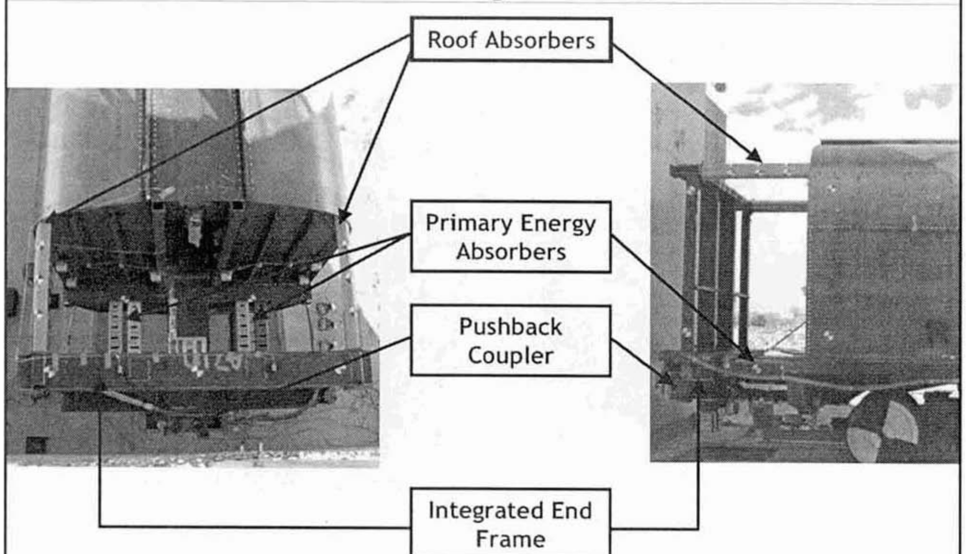
## Budd Pioneer Car Preparation



**Attach Roof Absorber and the Rest of the Roof Structure**

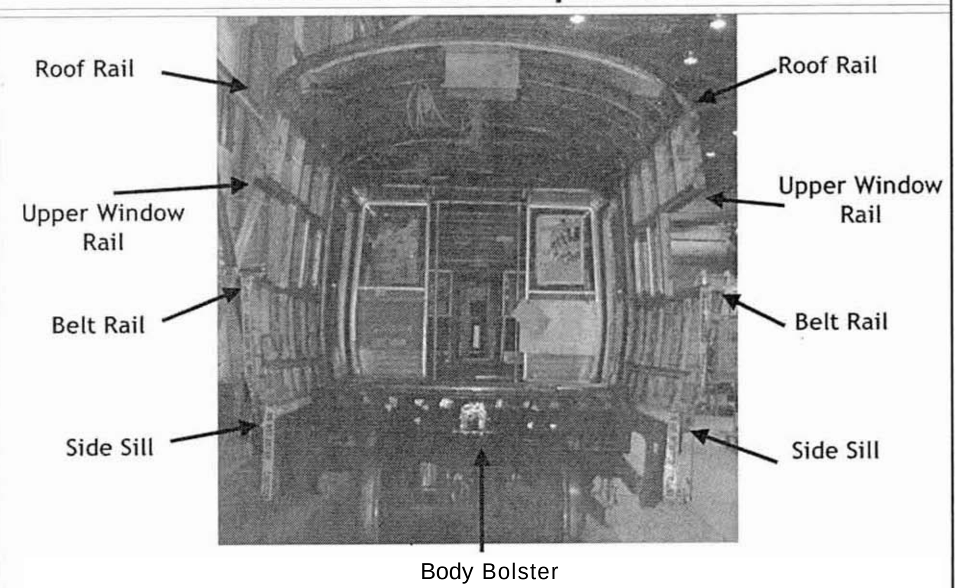
Session V | Retrofit of Test Cars | Slide 14

## Final Design Retrofitted Onto Budd Pioneer Passenger Coach Cars



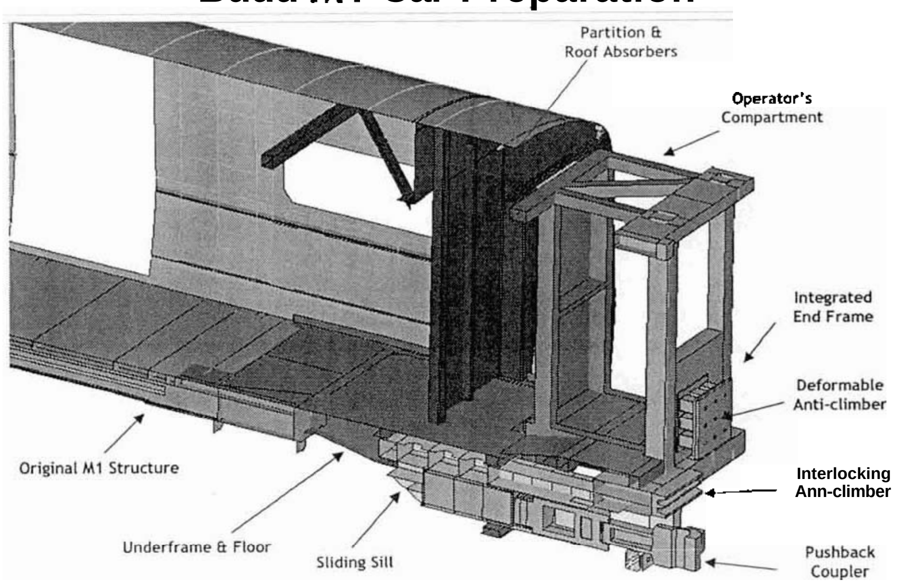

Session V | Retrofit of Test Cars | Slide 15

## Budd M1 Car Preparation




Session V | Retrofit of Test Cars | Slide 16

## Budd M1 Car Preparation




Session V | Retrofit of Test Can | Slide 17

## Summary

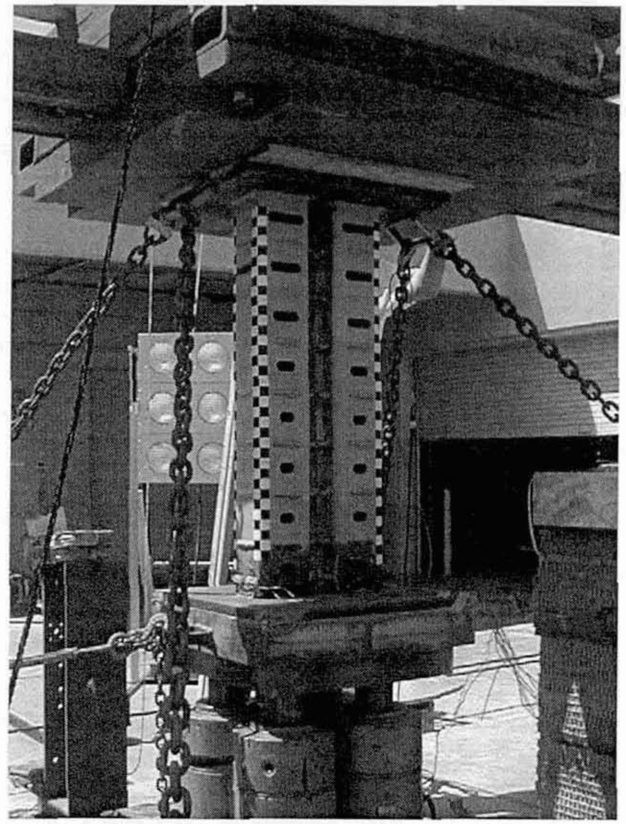
- CEM Crush Zone Designs Will Be Retrofitted onto Existing Car Bodies for Next Full-scale Train-to-train Test
  - **Budd Pioneer Coach Cars -- Completed**
  - **Budd M1 Coach Cars -- Parts Being Fabricated**
  - **Budd M1 Cab Car -- Final Design Completed, Materials To Be Ordered**
- One & Two Car CEM Full-scale Tests and Analyses Verified Existing Car Body Structure Able to Withstand Loads Introduced Through Crush Zones
- The Feasibility of Retrofitting Cars with Crush Zones Demonstrated



## Participating Organizations

- Federal Organizations
  - **Federal Railroad Administration**
  - **Volpe National Transportation Systems Center**
- Contractors
  - **Transportation Technology Center, Inc.**
  - **TIAX LLC**
    - **Taylor, Raynauld, Amar & Associates**
    - **Ebenezer Railcar Services, Inc.**
    - **R. A. Mayville & Associates**
- APTA
  - **SEPTA**
  - **LIRR**
  - **Bombardier**

# Component Crush Analysis and Testing



**Session V: CEM Design, Fabrication & Evaluation**

**Crash Energy Management Technology Transfer Symposium**
**29 June - I July 2005**
**San Francisco, California**


**Rich Stringfellow**
**TIAX LLC**
**Cambridge, Massachusetts**

## Overview

- Introduction
- Summary of Component Analysis & Testing Program
- Review of Primary Energy Absorber Analysis and Testing
- Review of Cab Car Deformable Anti-climber Analysis & Testing
- Summary and Conclusions





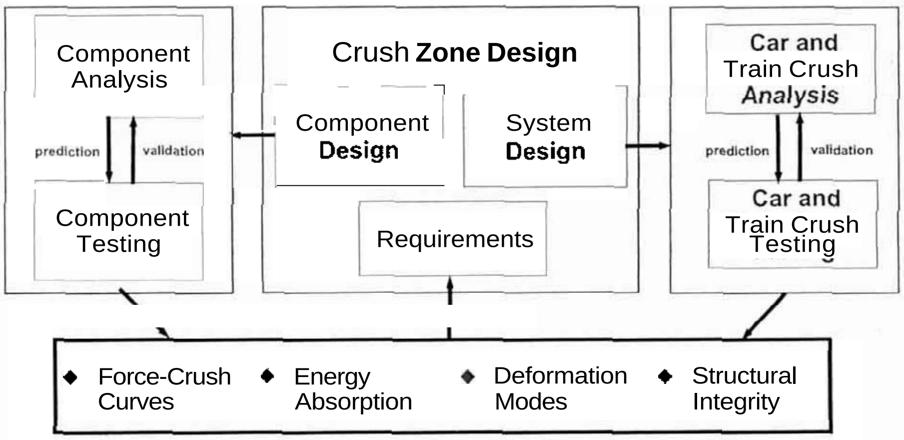
## Objectives:

The objective of component crush analysis and testing is to assure that the components meet design requirements.

- Analyses provide:
  - Rapid evaluation of design alternatives
  - A framework for any needed tests
- Tesling:
  - Assures that critical components function as designed
  - Resolve uncertainties with analyses

Component Crush Analysis and Testing — Introduction

The design of a crush zone for CEM coach and cab **cars** has been greatly aided by analysis and component testing.

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Component Crush Analysis and Testing — Analysis and Testing Summary

A comprehensive component analysis and testing program was conducted to assure that the key crush zone components meet design requirements.

| Component | Detailed Analysis | | Testing |
|---|---|---|---|
| | Component Level | Car Level | |
| Primary Energy Absorber | Yes | Yes | Dynamic |
| Pushback Coupler | Yes | Yes | Dynamic |
| Sliding Sill/Fixed Sill | Yes | Yes | Static & Dynamic |
| Combined Pushback Coupler/Sliding Sill/Fixed Sill | Yes | Yes | Yes |
| Roof Absorber | No | Yes | No |
| Deformable Anti-climber | Yes | Yes | No |
| Honeycomb-filled Tubes | Yes | Yes | Static |

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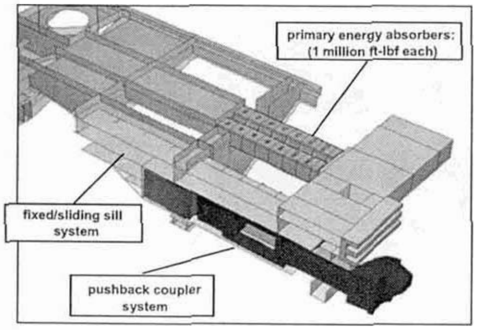
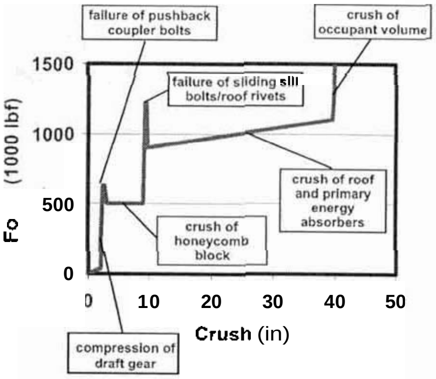
## Component Crush Analysis and Testing

Coach Car Testing/Analysis

Component testing for the coach car was aimed at validating the mechanical behavior of key contributors to the the crush response of the CEM crush zone.




ey Coach Car Crush Zone Components

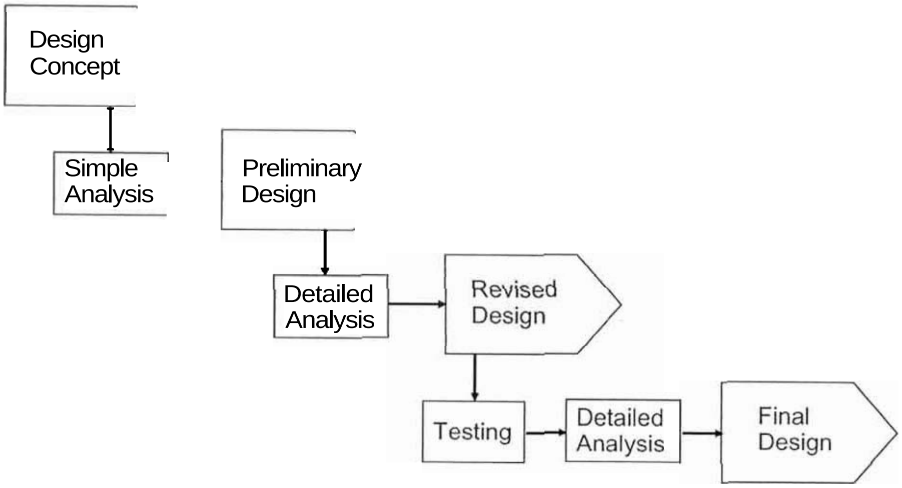



arget Coach Car End Crush Response

## Component Crush Analysis and Testing

**Primary Energy Absorbers**

The primary energy absorbers provide an excellent example of the use of testing and analysis in the design development process.

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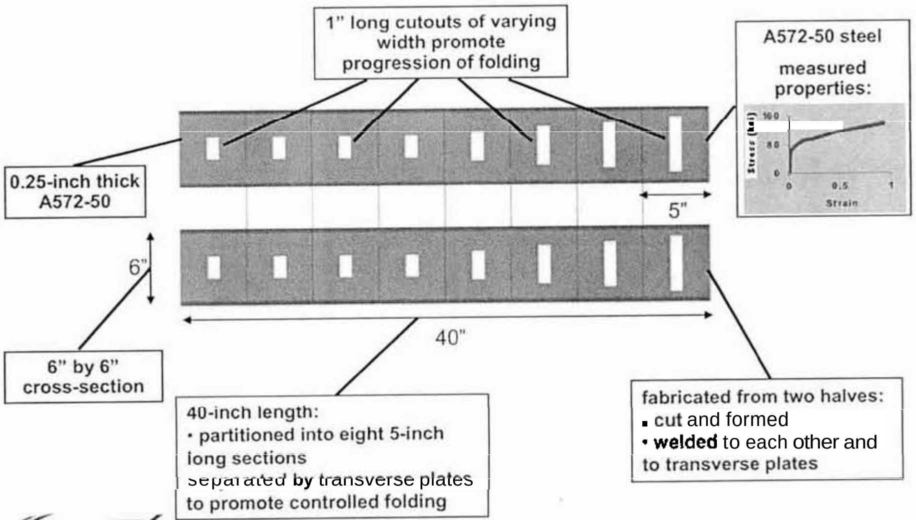
## Component Crush Analysis and Testing

Primary Energy Absorbers

The preliminary design for the primary energy absorbers was chosen to satisfy force, energy absorption, and deformation requirements.

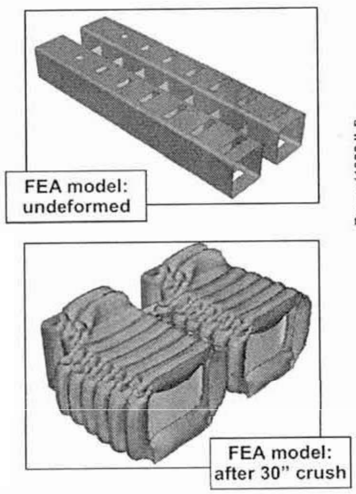


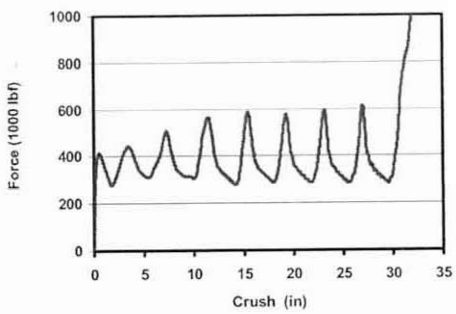



## Component Crush Analysis and Testing

Primary Energy Absorbers

Preliminary analvsis showed that this design deforms in a desirable manner and absorbs the required 1.0 million ft-lbf of energy.



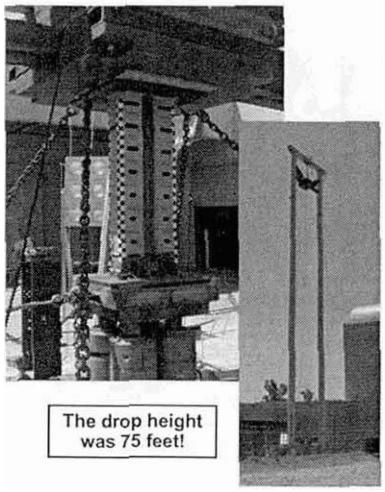




Calculated force-crush curve

Component Crush Analysis and Testing **Primary Energy Absorbers**

Drop tower tests were conducted on the primary energy absorbers to confirm key performance requirements

- ◆ The primary test delivered 800.000 ft-lbf of energy at about 47 mph
- ◆ Key Results:
  - – The force-crush characteristics satisfied requirements.
  - – The mode of deformation did not completely satisfy requirements
- +The unsatisfactory mode of deformation led to redesign of the absorbers

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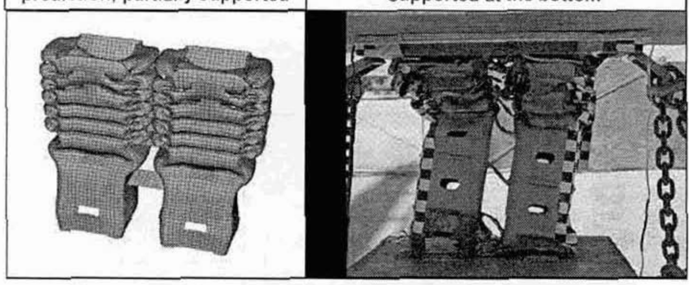
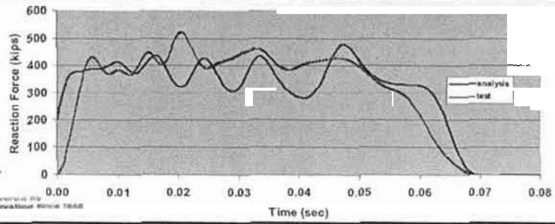
Component Crush Analysis and Testing **Primary Energy Absorbers**

In spite of the initiation of crush at the supported end, analysis predictions of reaction force are in generally good agreement with measured forces.

| Finite element analysis prediction; partially supported | Full-length test article; partially supported at the bottom |
| --- | --- |



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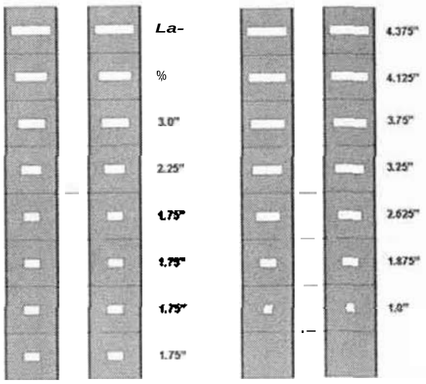
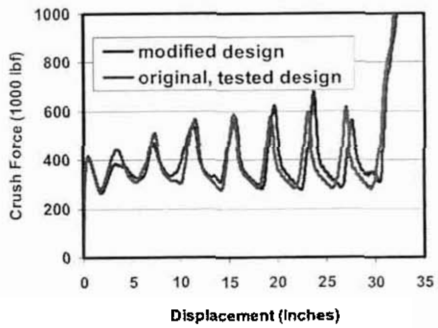
## Component Crush Analysis and Testing

**Primary Energy Absorbers**

As a direct result of the tests, the trigger hole geometry was modified to make it less likely that the absorber will deform at its supported end.



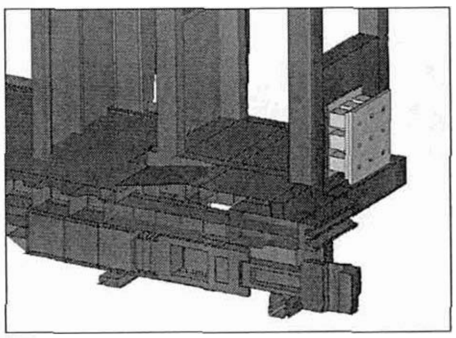

The modification had little effect on the overall forcecrush behavior or energy absorption



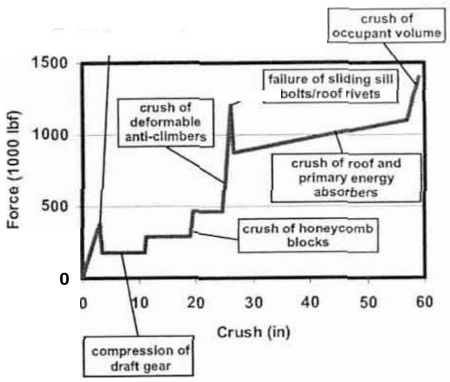
## Component Crush Analysis and Testing

**Cab Car Testing/Analysis**

Additional component analysis and testing for the cab car was aimed at validating the mechanical behavior of the deformable anti-climber.



Cab Car End with Deformable Anti-climber Highlighted

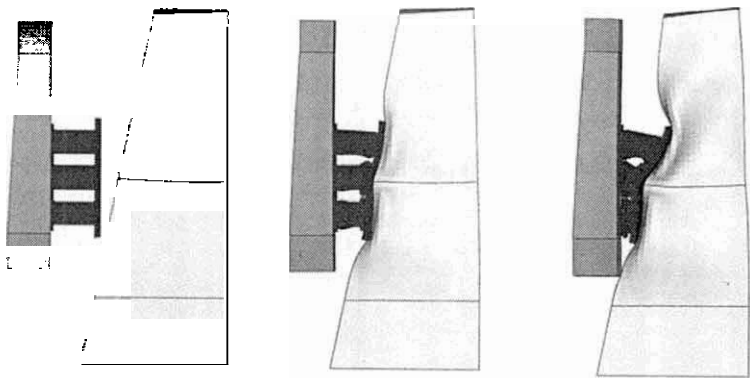



**Target** Cab Car **End** Crush Response

## Component Crush Analysis and Testing

**Deformable Anti-climber**

Component analyses and testing for the cab car were focused on the development of the design of the cab car deformable anti-climber.




Deformation results from deformable anti-climber component-level analyses

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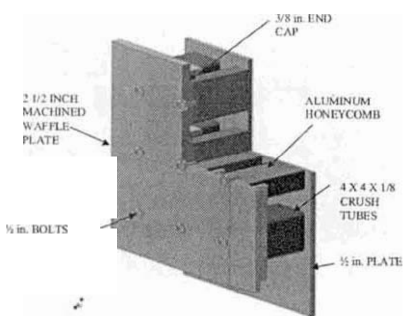
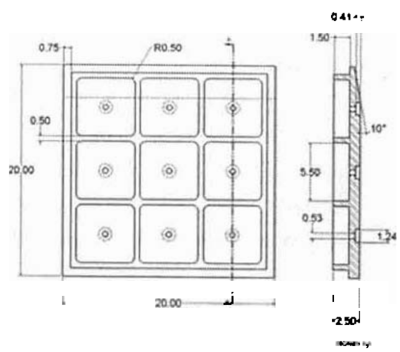
## Component Crush Analysis and Testing

**Deformable Anti-climber**

This analysis effort contributed significantly to the specification of a 3x3 pattern of honeycomb-filled tubes as the principal energy absorbing elements of the deformable anti-climber.



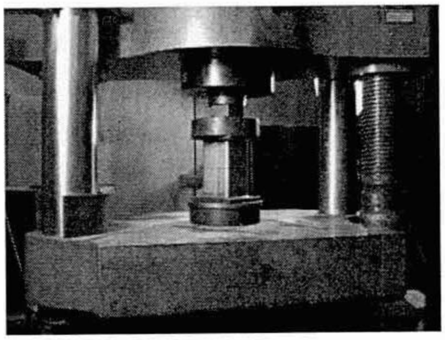

14

Component Crush Analysis and Testing — Tube Crush Tests

Concerns about the crush characteristics of the tubes and especially their tendency to fracture led us to conduct a series of quasi-static tube crush tests.

Key results from the tube testing:

- Annealing is necessary to remove the risk of material fracture.
- Strength is greatly reduced by annealing.
- Required strength levels are reached by selecting:
  - 301 stainless steel as the tube material
  - filling the tubes with 2150 psi aluminum honeycomb

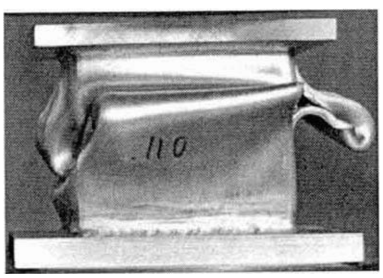


Tests were conducted on a 300.000 ibf hydraulic compression machine.

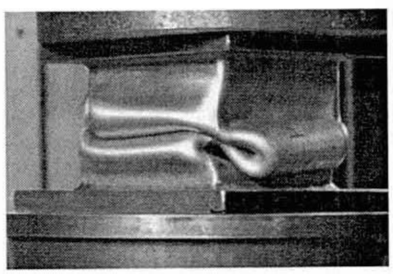
15

Component Crush Analysis and Testing — Tube **Crush** Tests

A key result of the testing is that annealing of the tubes is necessary **to** prevent cracking, particularly for filled tubes.



As-received

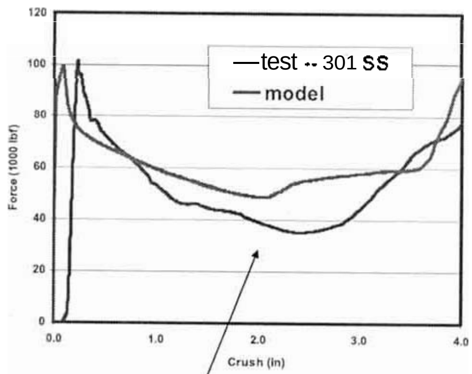


Annealed

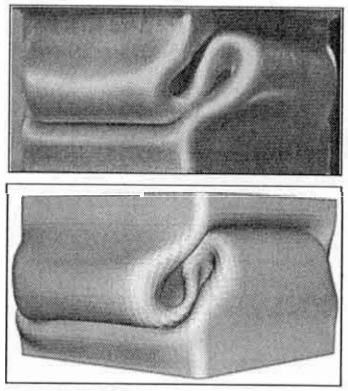
16

Component Crush Analysis and Testing — Tube Crush Tests

Tube testing results were used to verify model behavior. Agreement between the **force-crush** behaviors and deformation modes provides confidence in the manner in which the tube crush behavior is modeled.




The model is nor able la capture the full extent of the drop in load that ls likely caused by the reductlon of the effective crush area of the honeycomb.



The model is able to predict the deformation mode quite well.

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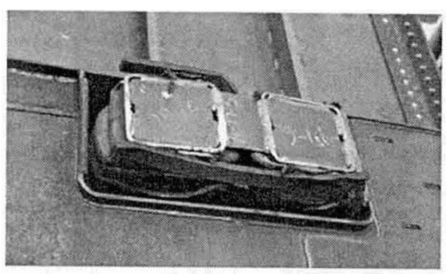
Component Crush Analysis and Testing — Summary

Summary:

- Design uncertainties were resolved with both analyses and tests.
  - The critical components were tested.

+Analyses and tests show that components meet design requirements.



Coach car crush zone components performed as designed in the single-car and two-car full-scale tests.

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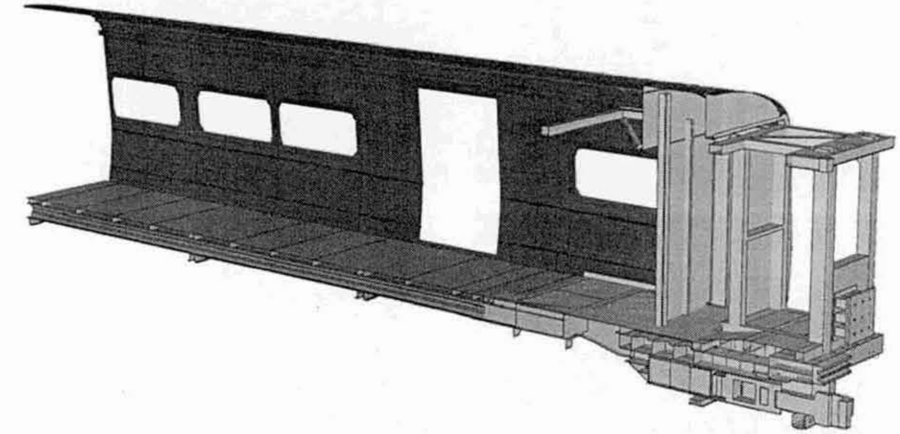
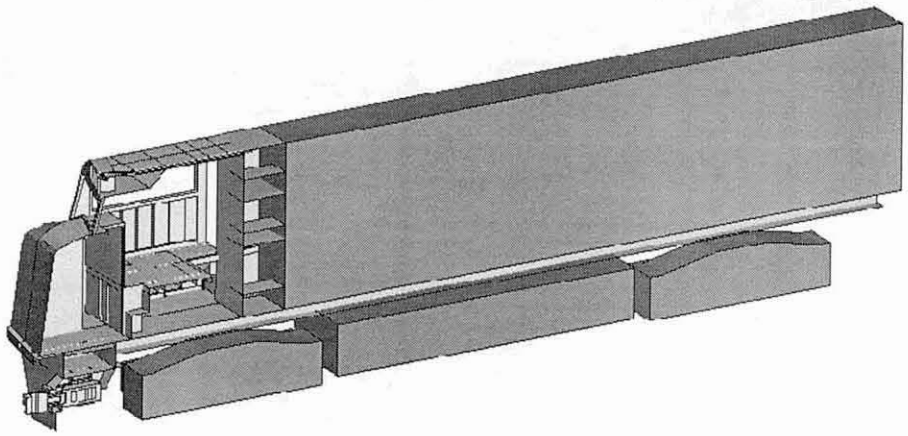
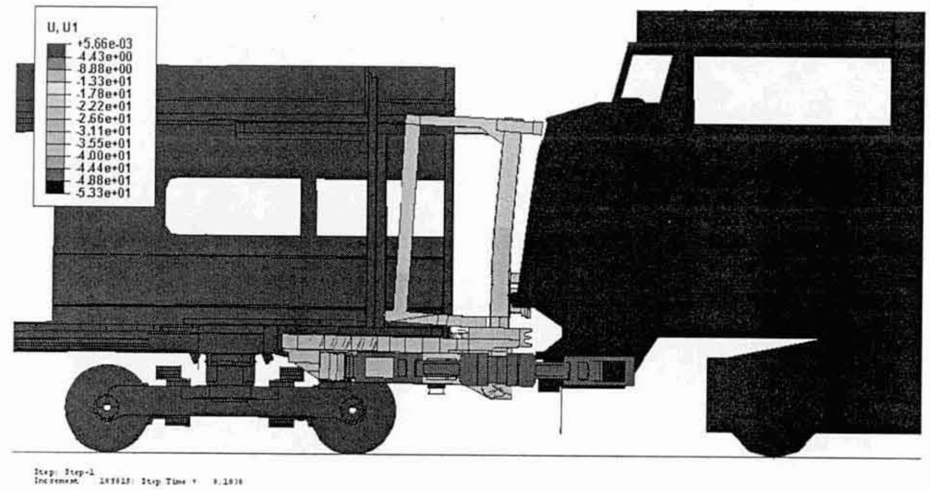







# Car Crush Analysis

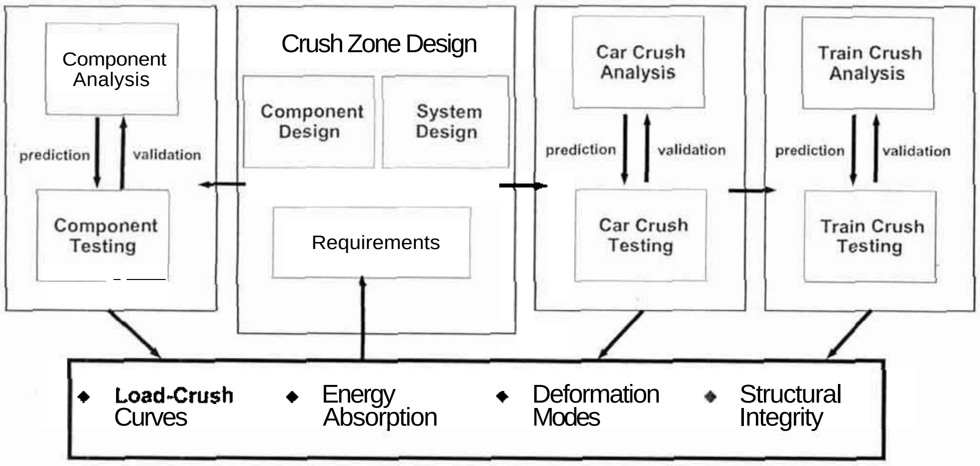
## Session V: CEM Design, Fabrication & Evaluation

**Crash Energy Management Technology Transfer Symposium**
**29 June - 1 July 2005**
**San Francisco, California**

**Patricia Llana**
**TIAX LLC**
**Cambridge, Massachusetts**

CEM Crush Zone Design Process — Crush Zone Design Overview

Afler conducting the component analysis and testing and seeing that the components behave well individually, the integrated system design must be analyzed for both the coach car and cab car CEM structures.




1

CEM Crush Zone Design Process — FEA Models and Analysis Overview

The objective of this presentation is to review the finite element models generated for the single car crush analyses. The results from these analyses will also be discussed.

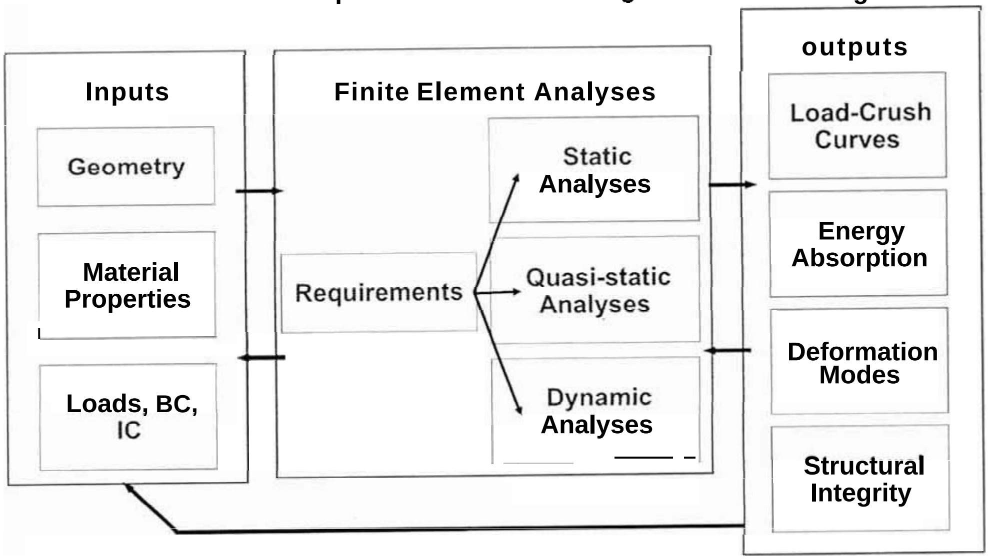
Overview of Presentation

- FEA Process
- FEA Model Development
  - Pioneer-based Coach Car
  - MI-based Cab Car
  - MI-based Coach Car
  - F40PHM-based Locomotive
- Coach Car Analyses
  - Static Analyses
  - Dynamic Crush Analysis
- Cab Car Analyses
  - Static & Quasi-static Analyses
  - Dynamic Crush Analysis – Ideal Case
  - Dynamic Crush Analysis – Non-ideal & Offset Conditions

2

CEM Crush Zone Design Process | FEA Process

**The finite element analysis process is an iterative undertaking. Feedback between steps is critical to achieving a successful design.**

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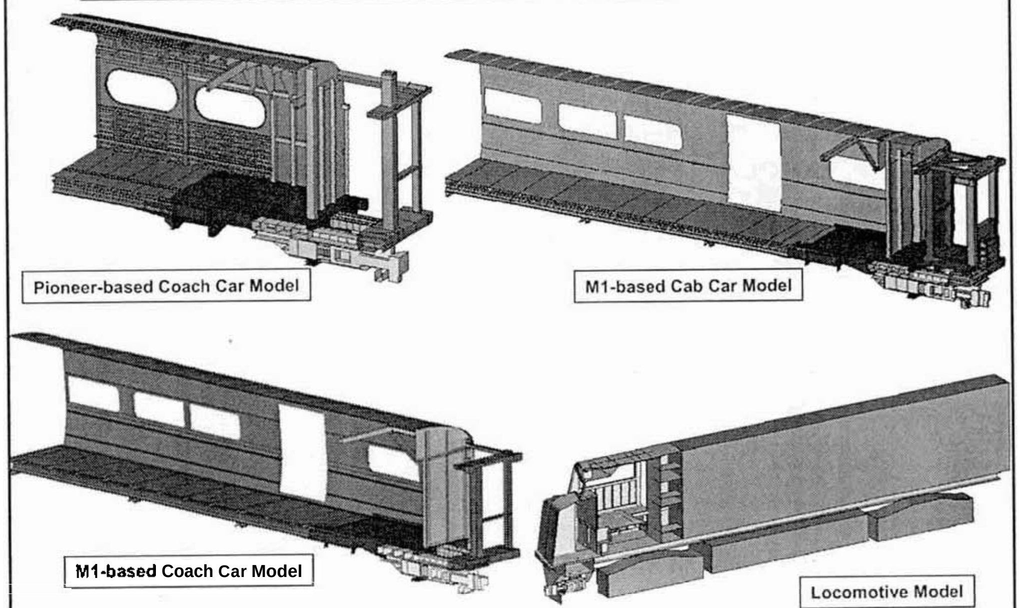
FEA Model Development | Car and Locomotive FEA Models

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## Coach Car Analyses

Summary of Analyses

One dynamic and nine static loading conditions were analyzed for the M1 coach car. All stresses were below yield in each of the static analyses. The dynamic analysis results satisfied the requirements.

Mi-based Coach Car Analyses

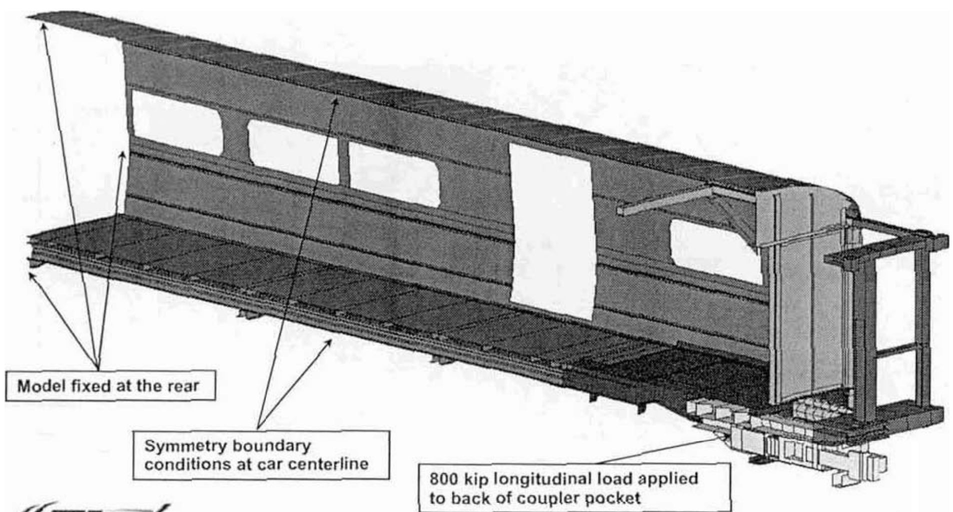
- Static Analyses
  - 60 kip longitudinal load on collision post midway between gusset 8 AT beam
  - 30 kip longitudinal load on comer post 18 inches above buffer beam
  - 20 kip longitudinal load on comer post midway between gusset 8 AT beam
  - 30 kip lateral load on comer post 18 inches above buffer beam
  - 20 kip lateral load on corner post midway between gusset & AT beam
  - 800kip longitudinal load on back of coupler pocket
  - 800 kip longitudinal load on buffer beam behind anticlimber
  - 100 kip vertical load on buffer beam behind anticlimber, before crush
  - 100 kip vertical load on buffer beam behind anti-climber, after 30 inches of crush
- Dynamic Crush Analysis
  - Rigid barrier analysis

5

## Coach Car Analyses

Static Analysis Set-up

One static analysis investigated whether an 800 kip linear longitudinal load applied to the back of the coupler pocket could be supported without yield in any part of the structure.

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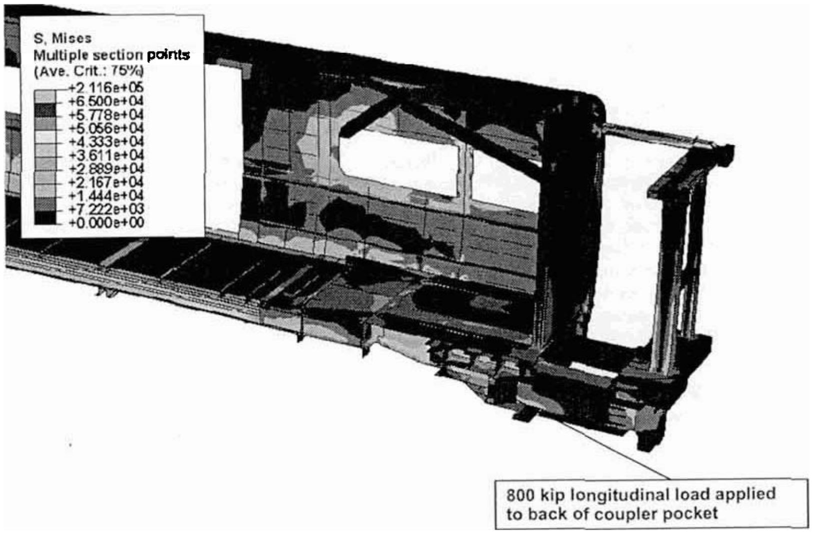
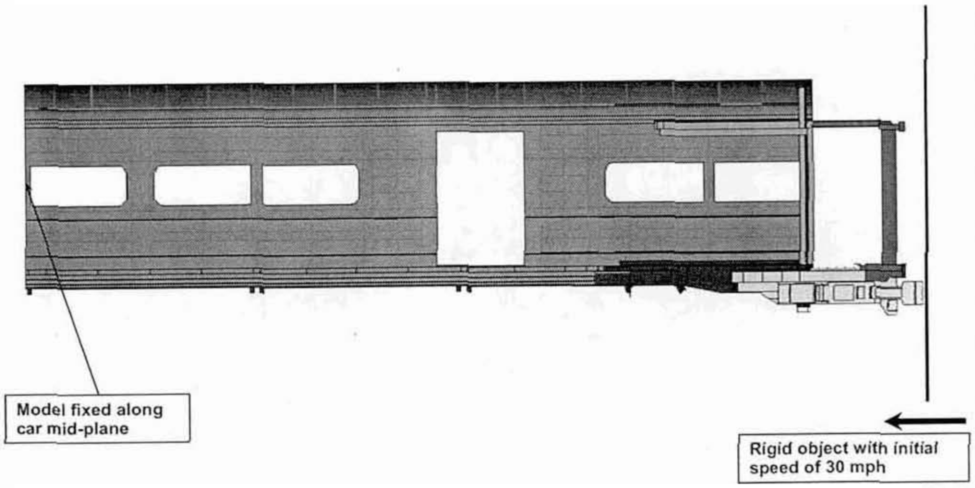
The 800 kip linear longitudinal load on the back of the coupler pocket resulted in no stresses above yield.





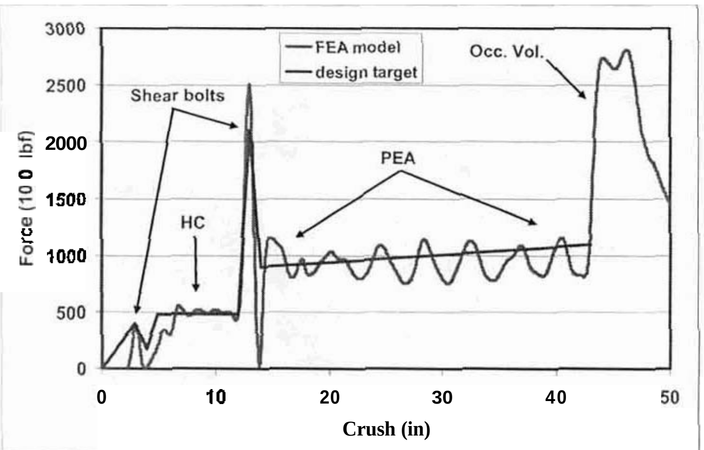



In the dynamic crush analysis, the coach car model was fixed at the rear and the rigid object had an initial speed of 30 mph.



Coach Car Analyses — Dynamic Analysis Results

The calculated load-crush curve for the rigid barrier dynamic analysis of the **M1** coach car is consistent with the design target. The required energy absorption of **$2.5 \times 10^6$** ft-lbf is achieved.




Video Clip
Iso view, barrier POV

Video Clip
Side view

Video Clip
Side view: sliding sill

Video Clip
Iso view, coach car POV

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Cab Car Analyses — Summary of Analyses

Nineteen loading conditions were analyzed for the cab car design. All stresses were below yield in each of the static analyses and the dynamic and quasi-static analysis results satisfied the requirements.

- **Static Analyses**
  - **60 kip longitudinal** load on **collision post** midway **between gusset** 6 AT beam
  - 100 **kip longitudinal** load on corner port 18 **inches above** buffer beam
  - 45 **kip longitudinal** load on corner **post midway between gusset & AT** beam
  - 100 **kip** lateral load on corner post18 **inches above** buffer beam
  - 45 **kip lateral** load on corner post **midway** between **gusset &** AT beam
  - **800kip longitudinal** load on back of coupler **pocket**
  - 800 kip longitudinal load on **buffer** beam behind **anti-climber**
  - 100 **kip** vertical load on **buffer** baam behind anti-climber. before **crush**
  - 100 **kip vertical load on buffer beam behind anti-climber, after 30 inches of crush**
- **Quasi-static Analyses**
  - 200 kip **longitudinal** load on the **collision port30 inches** above **the** buffer beam
  - 100 kip **longitudinal** load on **the** corner post 18 **inches above** the buffer beam
- Dynamic **Crush** Analyses
  - Ideal Case
  - Load only **through deformable anti-climber**
  - Load only **through coupler**
  - vertical offset – **locomotive raised** by **6** inch—
  - **Vertical offset – locomotive** lowered by 6 **inches**
  - **Lateral offset – locomotive shifted** by **+6 inches**
  - **Lateral** offset **– locomotive** shined by **r 6 inches**
  - **Combined lateral** and **vertical offset – locomotive lowered** 8 **inches and shifted** laterally by -6 inches

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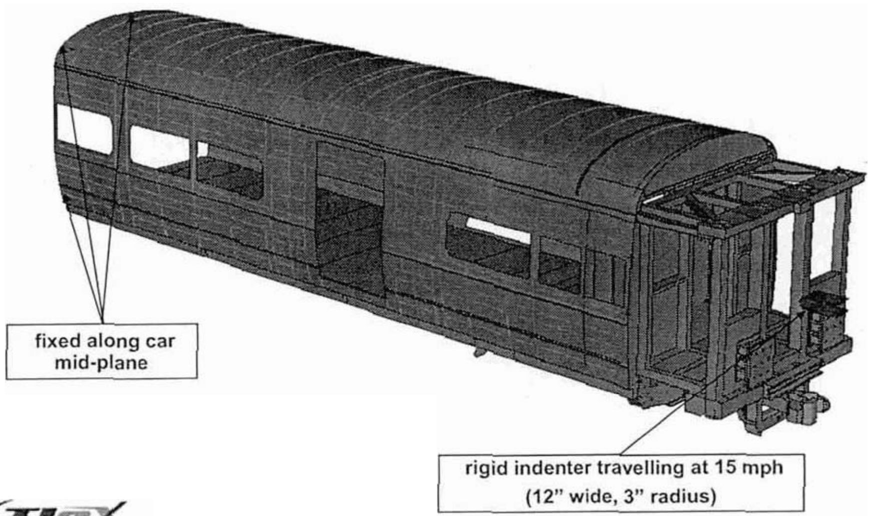
Cab Car Analyses

Quasi-Static Collision Post Crush

A full-width version of the model was used to evaluate whether the cab car can support a 200 kip longitudinal load on the collision post, 30" above the floor.

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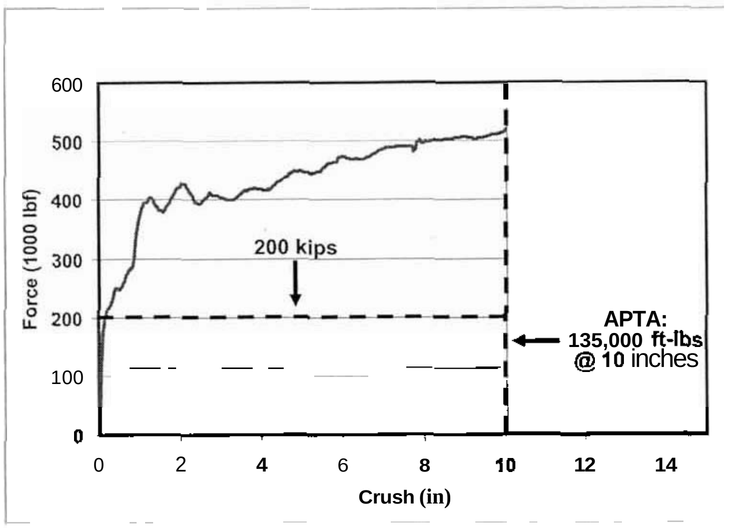
Cab Car Analyses

Quasi-Static Collision Post Crush

The calculated force-crush curve indicates that the 200 kip ultimate strength requirement is easily met.

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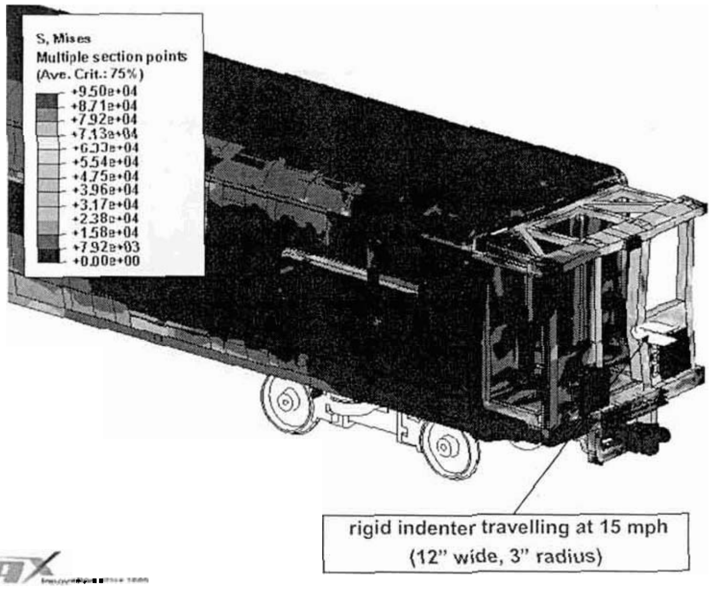
Cab Car Analyses — Quasi-Static Collision Post Crush

After 6 inches of crush, some parts of the end frame have plastically deformed. However, the ultimate strength has not been reached.

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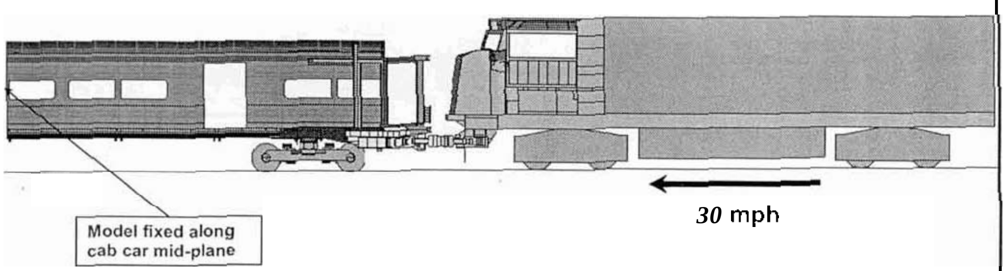
Cab Car Analyses — Ideal Dynamic Analysis Set-up

In the ideal dynamic crush analysis, the cab car model was fixed at the car mid-plane and the locomotive had an initial speed of 30 mph.

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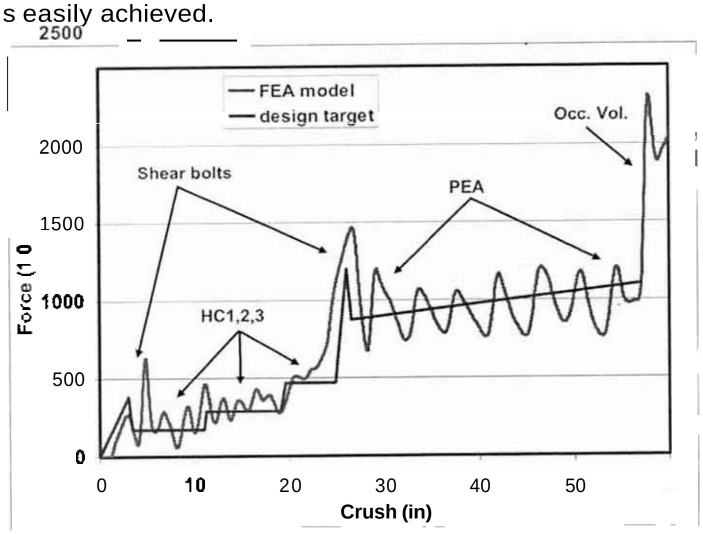
The calculated load-crush curve for the ideal case compares favorably with the design target. The required energy absorption of $3.0 \times 10^6$ ft-lbf is easily achieved.




Video Clip
Side view

Video Clip
Side view: sliding sill

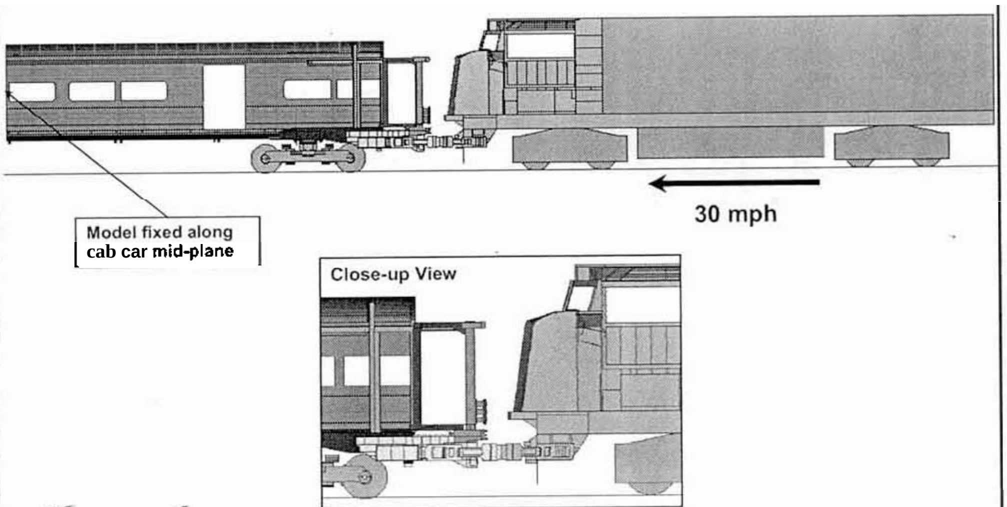
Video Clip
Iso vie*. loco POV

Video Clip
Iso view, coach car POV



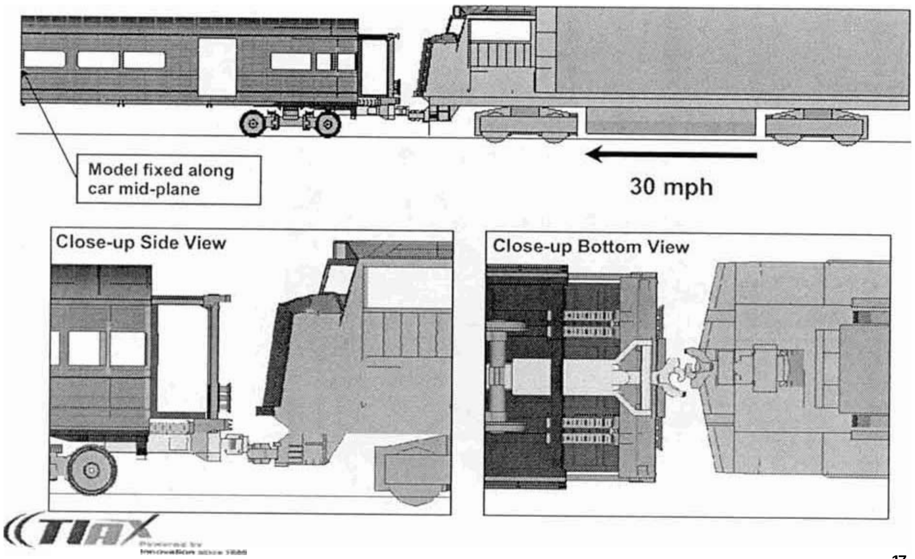


In the anti-climber only dynamic crush analysis, contact between the couplers is turned off so that all of the load goes through the deformable anti-climber.



## Cab Car Analyses — Combined Offset Dynamic Analysis Set-up

In the combined offset dynamic crush analysis, the locomotive is moved laterally 6 inches, and lowered 6 inches with respect to the cab car.

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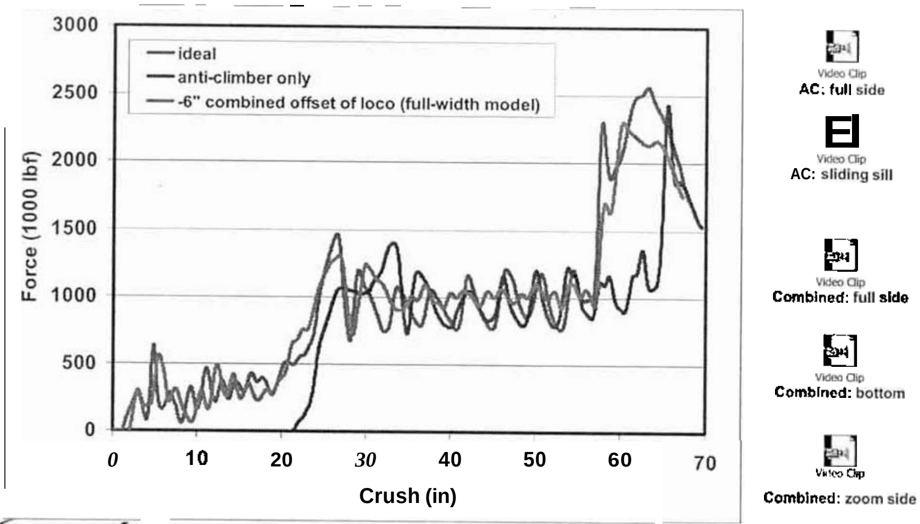
## Cab Car Analyses — Nan-ideal Cases

The calculated load-crush curve for these two non-ideal cases compare favorably with the ideal case. The required energy absorption of $2.5 \times 10^6$ **ft-lbf** is achieved in both cases.

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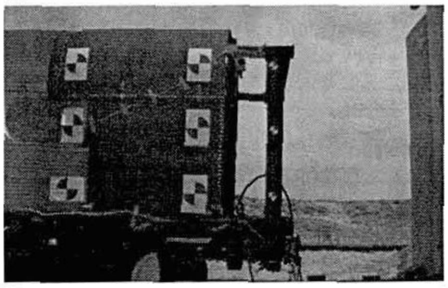
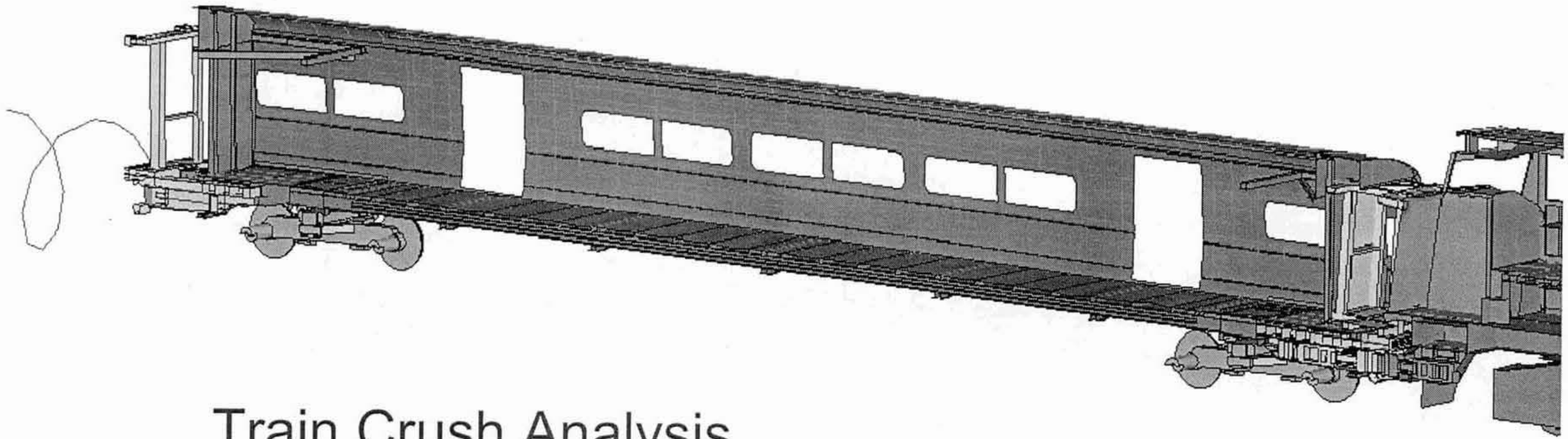
**Summary:**

- Coach car crush analyses indicated that the crush zone would perform as designed.
  - The single-car and two-car CEM full-scale tests demonstrated that the design requirements were met.
- Cab car crush analyses predict that the cab car crush zone will also meet the design requirements.



Coach car crush zone performed as designed in the single-car and two-car full-scale tests.



Train Crush Analysis

**Session V: CEM Design, Fabrication & Evaluation**

**Crash Energy Management Technology Transfer Symposium**
**29 June - 1 July 2005**
**San Francisco, California**


**Rich Stringfellow**
**TIAX LLC**
**Cambridge, Massachusetts**

## Train Crush Analysis — Overview

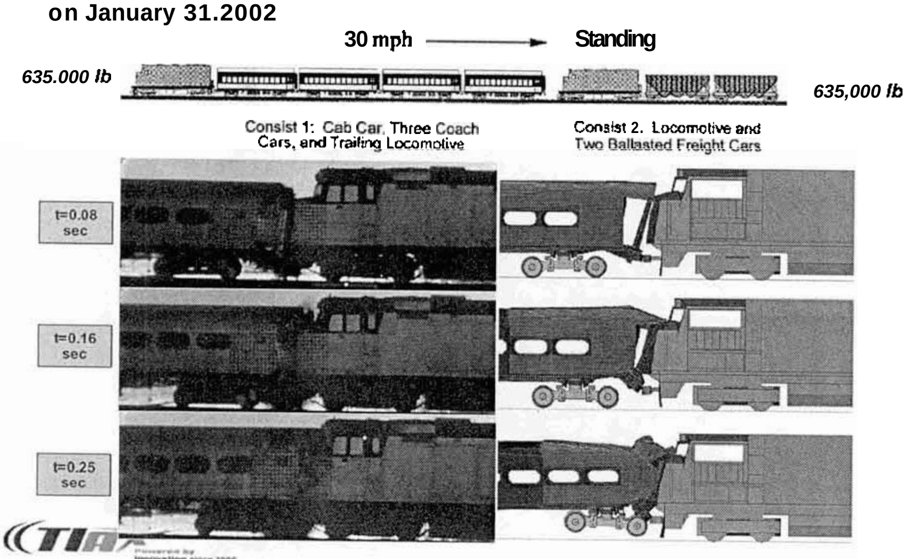
**Overview:**

- **Introduction**
- **Review of Model Development**
- **Review of Selected Model Results**
- **Summary and Conclusions**

1

## Train Crush Analysis — Introduction

**A full-train crush model was developed to simulate the full-scale train-to-train collision test that was performed at TTCI in Pueblo, Colorado on January 31.2002**

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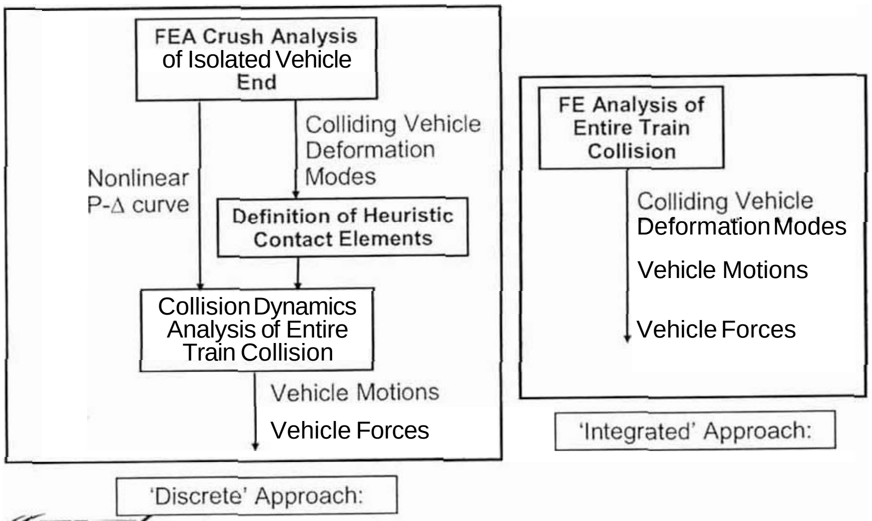
## Train Crush Analysis

Introduction

Full-train crush analysis integrates the function of collision dynamics models and car crush models.

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## Train Crush Analysis

Introduction

Objective:

The objective of full-train crush analysis is to assure that the CEM cab car interacts with locomotive as designed

- Advantages:
  - Provides an analytic representation of colliding interface
  - Models the influence of impacting car motions
- Limitations:
  - Requires voluminous input
  - Time intensive — several days are required for each analysis case

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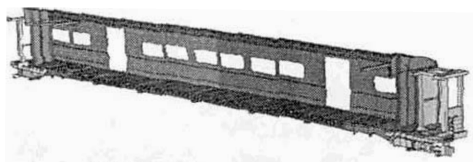
## Train Crush Analysis

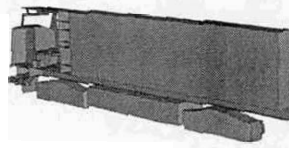
Model Development

The full-train finite element model brings together sub-models of four key elements:

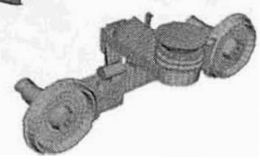
- ◆ Cab Car Body:



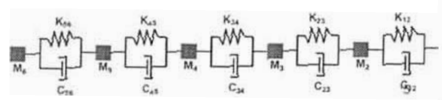
- *Standing Locomotive:



- ◆ Cab Car Truck and Truck-to-Body Connectors:



- *Trailing Vehicle and Vehicle-to-Vehicle Connections:



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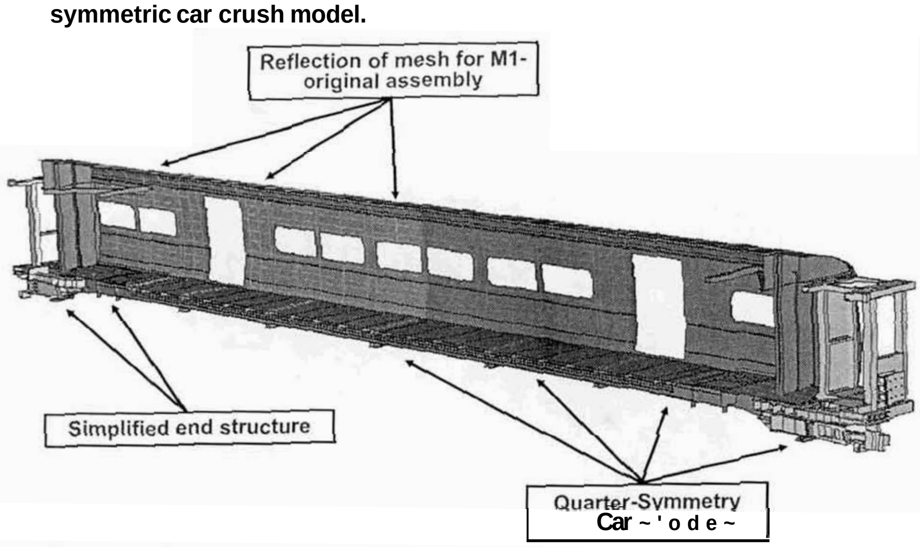
## Train Crush Analysis

Model Development

The model for the cab car body is an extension of the quarter-symmetric car crush model.

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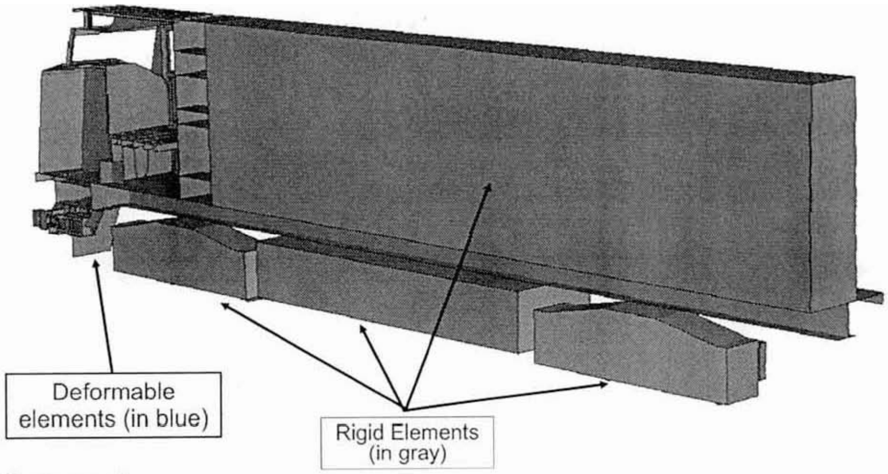
Train Crush Analysis — Model Development

The locomotive model consists of deformable and rigid elements.

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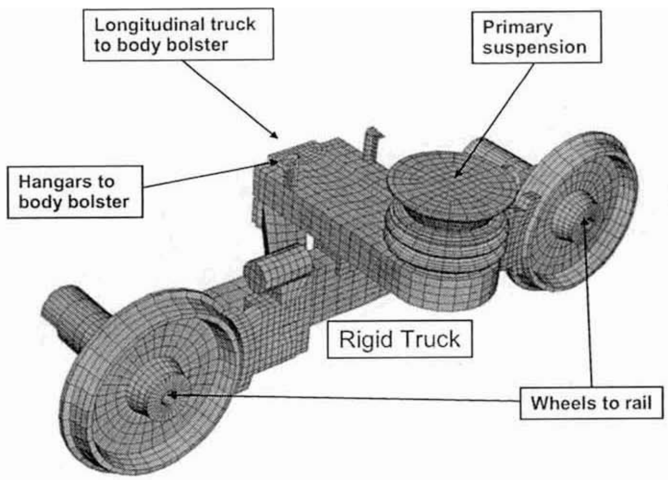
Train Crush Analysis — Model Development

An existing model for the cab car trucks has been further developed using connector features in ABAQUS:

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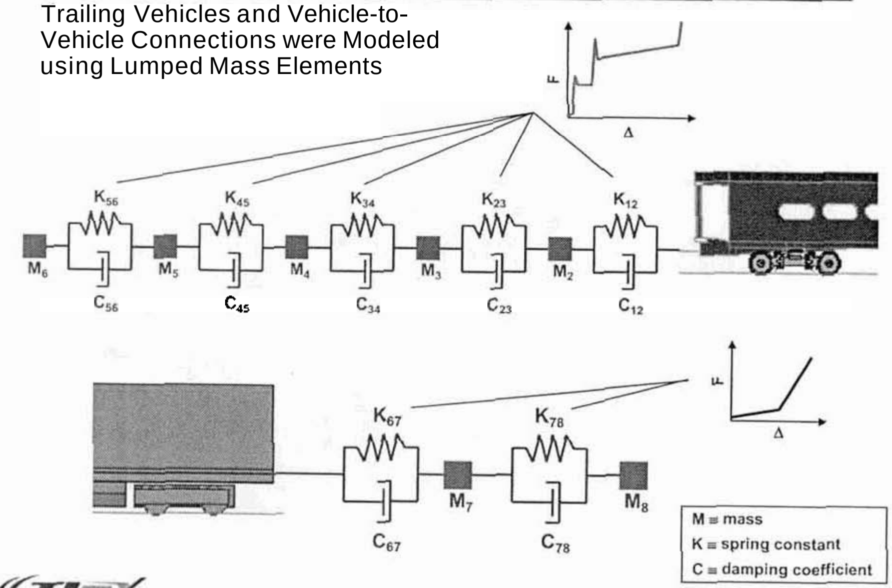
Train Crush Analysis

Model **Development**

## Trailing Vehicles and Vehicle-to-Vehicle Connections were Modeled using Lumped Mass Elements

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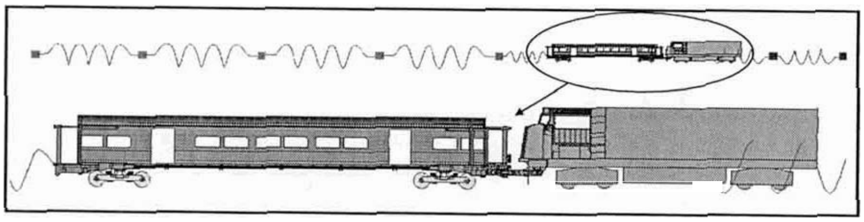
Train Crush Analysis

**Model Development**

## Analysis of the Full Train Collision Model was Performed with **ABAQUS/Explicit**

- An initial velocity of 32 mph was assigned to the moving passenger train
- The first 0.4 seconds of the collision were simulated
- 260 hours of CPU time (5+ days using 2 parallel CPUs) on a high-performance PC-workstation were required

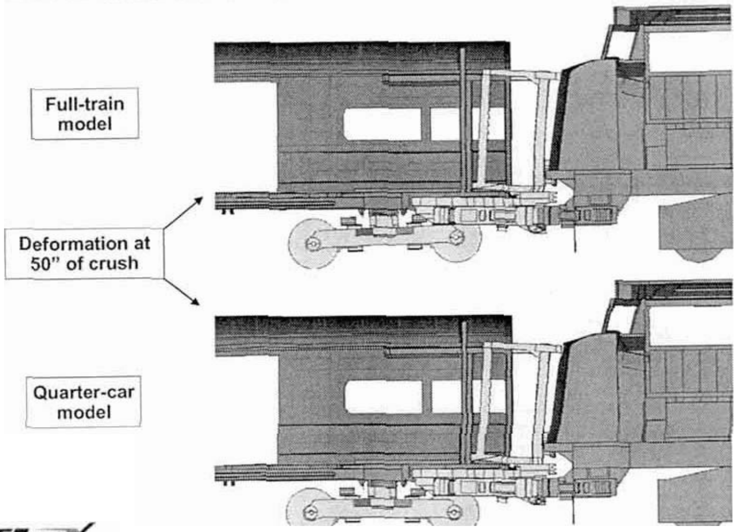


**The** Finite Element Mesh

10

Train Crush Analysis **Model Results**

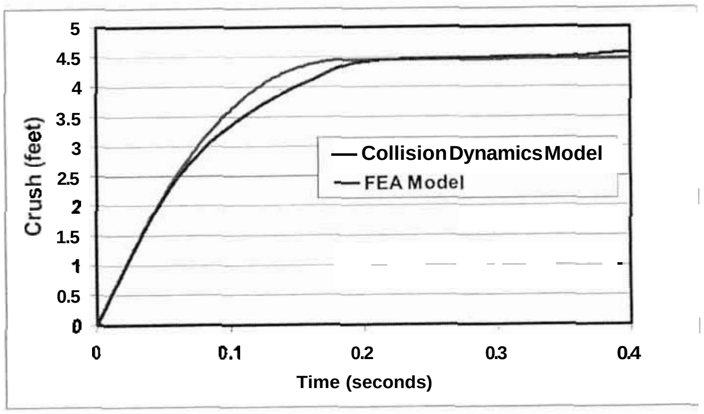
**A comparison with results from the quarter-symmetry model at 50 inches of crush shows that the deformation modes are consistent.**






Train Crush Analysis **Model Results**

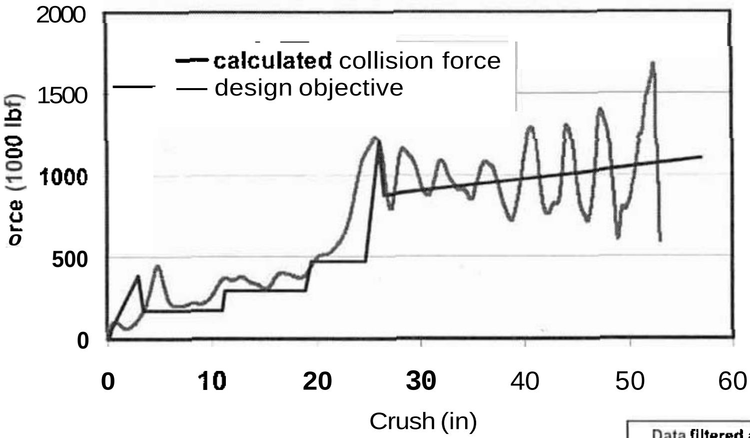
**Predictions of crush between the cab car and the standing locomotive are consistent with 1-D collision dynamics models and indicate that a total of about 53 inches of crush will occur.**



## Train Crush Analysis

Model Results

The collision force-crush curve, calculated directly from CEM train motions, is consistent with the design objective.



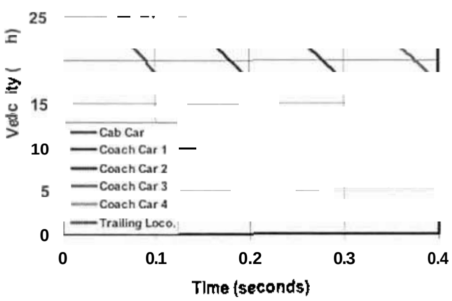

Data filtered at CFC 180

13

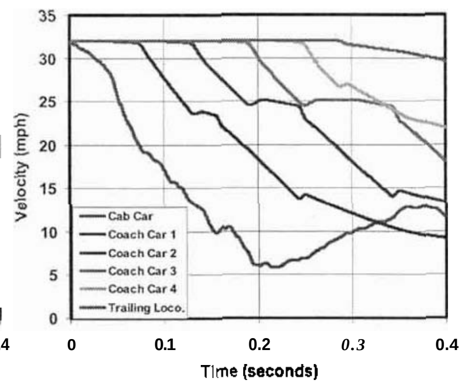
## Train Crush Analysis

Model Results

Predictions of passenger train car velocities are consistent with those made by 1-D collision dynamics models.




1-D Collision Dynamics Model




FEA Model

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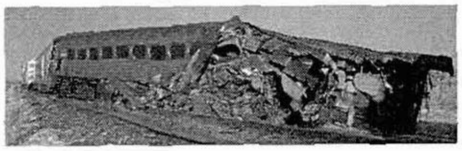
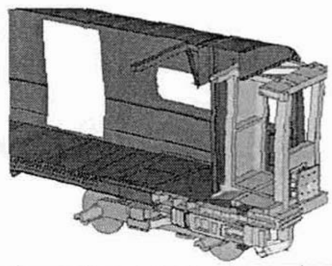
## Summary:

- Model results show that the CEM cab car will interact with the locomotive as designed.
- Ideal and non-ideal initial impact conditions have been evaluated
- The design requirements have been met:
  - Energy absorption
  - Force-crush characteristics
  - Modes of deformation.



Post-Test Deformation of Conventional Cab Car



**Predicted Post-Test Deformation of CEM Cab Car**

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