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LS-DYNA® MODELING ENHANCEMENT SUPPORT

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16. Abstract

The Pooled Fund Program member states provided funding for LS-DYNA modeling enhancements in Years 17 thru 22 (2006-2011), with a project period of 2006-2016. This report documents many of the modeling issues addressed throughout the project period. The funding has been effectively utilized to advance the current state-of-the-art for computer simulation and has provided the following benefits for the entire industry: (1) improved roadside safety hardware, (2) reduced development time and cost, (3) improved understanding of the behavior of roadside safety features, especially for impacts outside of normal crash test conditions, (4) improved LS-DYNA modeling techniques and procedures, and (5) improved confidence in modeling.

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The authors would also like to acknowledge Livermore Software Technology Corporation (LSTC), developers of LS-DYNA, for their on-going support since 1993. The National Crash Analysis Center (NCAC) developed and provided various car and truck models used by MwRSF. The majority of the simulation work performed during this project was completed utilizing the Holland Computing Center of the University of Nebraska-Lincoln.

Acknowledgement is also given to the following UNL graduate students who have contributed to the LS-DYNA knowledge base due to their creative usage of the code in many different scenarios.

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1 INTRODUCTION

1.1 Problem Statement

LS-DYNA® finite element analysis is now a well-established numerical modeling tool used for development and evaluation of roadside safety features. Although LS-DYNA has been used often and successfully by roadside safety researchers and engineers, there still remain several limitations for its use that are solely based on the inability to focus on basic modeling.

Original funding for developing basic LS-DYNA modeling techniques was provided by FHWA throughout the Centers of Excellence. After that funding had been eliminated, the Pooled Fund Program member states began providing a limited amount of annual funding to continue such efforts. That funding was provided in Years 17 thru 22 (2006-2011). Due to project priorities, MwRSF researchers were unable to devote enough man-power to expend all of those resources in a timely fashion, and thus, the annual funding was temporarily halted. At this time, the referenced funds are nearing depletion.

1.2 Objective

The objective of this research effort was to advance roadside safety simulation techniques and procedures which would ultimately be used to improve safety hardware design. Funding was used to address specific modeling needs shared by many safety programs.

1.3 Scope

This report documents many of the things accomplished with LS-DYNA during the project period, including (1) MwRSF projects that used LS-DYNA since 2004, (2) vehicle modeling, (3) MGS modeling, (4) soil modeling, and (5) friction modeling. It is to give the reader an indication of the many advances and usages MwRSF has made over the past 10 years in nonlinear finite element simulation.

For two primary reasons, it is not possible to distinguish which items discussed in this report were accomplished specifically with this project funding. First, solving LS-DYNA problems and improving LS-DYNA techniques are often done in lock-step with one or more other MwRSF projects. And, second, a majority of the funding allocated was during summer periods to cover a portion of Dr. Reid's summer salary; his salary during the Fall, Winter and Spring are covered by the Mechanical & Materials Engineering Department. Because Dr. Reid worked with LS-DYNA throughout the year, every year, as well as working on other pooled fund specific projects, distinguishing exactly what was done during what portion of the year is not possible, and thus it is not possible to distinguish exactly what was achieved by this project. However, it is safe to say that a significant portion of the LS-DYNA work described in this report would not have been possible without the LS-DYNA supplement project provided by the pooled fund.

Special Note from author J.D. Reid:

This report is different than most all other MwRSF reports. Each chapter is basically stand alone, with many chapters being presented in a different format and style than the reader is used to. It is not important that everyone understand everything within each chapter. Computer simulation is part science and part art; that idea flows into how this report was organized and written. The overall story being told is how MwRSF has made effective use (or not) of LS-DYNA simulation over the past 10 years.

2 LS-DYNA USAGE SINCE 2004

Although project funding did not start until 2006, it is appropriate to start with LS-DYNA usage since 2004 because in that year the following paper was published documenting significant LS-DYNA work at MwRSF prior to then:

> J.D. Reid, "LS-DYNA Simulation Influence on Roadside Hardware," *Transportation Research Record 1890*, TRB, National Research Council, Washington, D.C., November 2004, pp. 34-41.

Table 1 lists the projects completed by MwRSF since 2004 that have used LS-DYNA in some capacity. Similarly, Table 2 lists the Theses and Dissertations of the MwRSF graduate students who have used LS-DYNA in some capacity in their work. Often, there is a direct correlation between a Master's Thesis and an MwRSF project. But many MwRSF projects do not have corresponding Master's Thesis.

Table 1. Projects that used LS-DYNA

Report Title	Report Number	Report Date	Description of DYNA Usage	Usage	Importance to Project	Improvements Made
Development of the *Midwest Guardrail System* (MGS) for Standard and Reduced Post Spacing and in Combination with Curbs	TRP-03-139-04	Sept. 1, 2004	Study guardrail design parameters, dynamic bogie testing on steel posts placed at various embedment depths	Moderate	High	
Critical Flare Rates for W-Beam Guardrail - Determining Maximum Capacity Using Computer Simulation	TRP-03-157-04	Jan. 24, 2005	Simulation evaluation w/ test, simulation of 13:1 and 10:1 Flared impact	Moderate	Low	
Development of Tie-Down and Transition Systems for Temporary Concrete Barrier on Asphalt Road Surfaces	TRP-03-180-06	Feb. 23, 2007	Determination of CIP for full scale crash test	Moderate	High	
Analyzing Guardrail System Crash Behavior in Cyprus	TRP-03-182-06	Dec. 1, 2006	Low budget investigation of guardrail systems in Cyprus	Low	Critical	Allows tight-budget countries opportunity to gain knowledge on roadside safety
Phase III Development of a Short-Radius Guardrail for Intersecting Roadways	TRP-03-183-07	Dec. 6, 2007	Evaluation of effectiveness of a redesigned anchorage	Moderate	Medium	
Approach Slope for Midwest Guardrail System	TRP-03-188-08	Dec. 4, 2008	Determination of critical slope and associated offset for MGS	Moderate	High	
Performance Evaluation of Safety Grates For Cross-Drainage Culverts	TRP-03-196-08	Oct. 23, 2008	Identification of criticial impact conditions for culvert grates, determination of appropriate size	Moderate	High	
Performance Limits for 152-mm (6-in.) High Curbs Placed in Advance of the MGS Using MASH-08 Vehicles Part I: Vehicle-Curb Testing and LS-DYNA Analysis	TRP-03-205-09	May 6, 2009	Evaluation of pickup model, verification of critical locations from trajectory analysis	Moderate	High	
Development of a TCB to Permanent Concrete Median Barrier Approach Transition	TRP-03-208-10	July 15, 2010	Determine CIP for second full-scale crash test on TCB transition	Low	Medium	
Termination and Anchorage of Temporary Concrete Barriers	TRP-03-209-09	Oct. 29, 2009	Investigate behavior of terminating TCB under various end segment constraints	Low	Medium	
Phase I Development of a Non-Proprietary, Four-Cable, High Tension Median Barrier	TRP-03-213-11	Dec. 28, 2011	Determine critical ditch width, cable barrier placement within depressed median, and top cable height	Moderate	High	

Table 1 (Continued). Projects that used LS-DYNA

Report Title	Report Number	Report Date	Description of DYNA Usage	Usage	Importance to Project	Improvements Made
Analysis, Design, and Dynamic Evaluation of a TL-2 Rough Stone Masonry Guardwall	TRP-03-217-09	May 6, 2009	Determine the minimum top mounting height to prevent vehicular instabilities and barrier override	Moderate	Medium	
Investigating the Use of a New Universal Breakaway Steel Post	TRP-03-218-09	Aug. 3, 2009	Modeling of the fracturing bolt post	Moderate	High	
Safety Investigation and Guidance for Work-Zone Devices in Freight Transportation Systems Subjected to Passenger Car and Truck Impacts with New Crash Standards	TRP-03-225-10 (MATC-UNL-100)	March 1, 2010	Evaluate the performance of one sign support system	Moderate	Medium	Little research on sign support performance was performed prior to this project
Development of a Low-Cost, Energy-Absorbing Bridge Rail	TRP-03-226-10	Aug. 11, 2010	Model side-mounted tubular post tear-out concept to better understand behavior of energy-absorbing post	Extensive	High	Model considered important to future development of energy absorbing hinge systems
Development of Advanced Finite Element Material Models for Cable Barrier Wire Rope	TRP-03-233-10 (MATC-UNL-220)	Aug. 2, 2010	Develop an improved material model of wire rope	Extensive	Critical	New wire rope model more accurately simulated wire rope tension and bogie vehicle motion than previous models
Performance Limitis for 6-in. (152-mm) High Curbs Placed in Advance of the MGS Using MASH Vehicles Part III: Full-Scale Crash Testing (TL-2)	TRP-03-237-10	Nov. 24, 2010	Determine the critical offset distance for TL-2 conditions, Impacting MGS at various offsets from the curb	Low	Medium	
Phase I Development of an Aesthetic, Precast Concrete Bridge Rail	TRP-03-239-12	Feb. 13, 2012	Determine the barrier height necessary to prevent rollover, peak impact loads	Moderate	High	
Zone of Intrusion Study	TRP-03-242-10	Oct. 15, 2010	Investigate ZOI	Moderate	Critical	
Cost-Effective Treatment of Existing Guardrail Systems	TRP-03-254-13	May 5, 2013	Determine the IS of the impact giving the containment limit for its respected guardrail height	Low	Low	
Design and Evaluation of the SAFER Barrier Installed on Portable Concrete Barrier	TRP-03-257-11	July 28, 2011	Model SAFER barrier installed on TCB	Moderate	High	
Feasibility Analysis and Concept Devlopment of a Crash Cushion Diaphragm Structure For High-Speed Race Tracks	TRP-03-261-11	March 20, 2012	Evaluate and refine Crash Cushion diagphragm components	Extensive	Critical	project resulted in prototype hardware for the diaphragm, guide rail, and angle brackets for use in a prototype race track crash cushion

Table 1 (Continued). Projects that used LS-DYNA

Report Title	Report Number	Report Date	Description of DYNA Usage	Usage	Importance to Project	Improvements Made
Test Matrices for Evaluating Cable Median Barriers Placed in V-Ditches	TRP-03-265-12	July 13, 2012	Study bumper trajectories and kinematics of a vehicle as it travels into and through a median ditch	Extensive	Critical	
Improved Models of Cable-to-Post Attachments for High-Tension Cable Barriers	TRP-03-267-12 (MATC)	May 25, 2012	Develop constitutive models of keyway bolts for use in simulations of full-scale tests	Extensive	Critical	
Development and Recommendations for a Non-Propretary, High-Tension, Cable End Terminal System	TRP-03-268-12	July 17, 2012	Modeling cable terminal anchor hardware and compared to bogie testing results.	Extensive	Critical	Redesigned model eliminated many of the crash performance issues with previous high-tension, cable anchor bracket assembly
Determination of the Maximum MGS Mounting Height – Phase II Detailed Analysis with LS-DYNA®	TRP-03-274-12	Dec. 5, 2012	Detailed analysis of an increased-height MGS	Extensive	Critical	
Minimum Effective Guardrail Length For the MGS	TRP-03-276-13	Aug. 12, 2013	Analyze MGS performance with lengths of 62 ft – 6 in. and 50 ft	Moderate	Medium	
Downstream Anchoring Requirements for the Midwest Guardrail System	TRP-03-279-13	Oct. 28, 2013	Model bogie tests and validated against test results	Extensive	Medium	
Development of a New Energy-Absorbing Roadside/Median Barrier System with Restorable Elastomer Cartridges	TRP-03-281-13	July 16, 2013	Determine optimal size and shape of the energy absorber	Extensive	Critical	Simulation effort revealed accurate elastomeric models without fully characterizing elasomeric behavior
Design of Cable-to-Post Attachments for Use in a Non-Proprietary, High-Tension, Cable Median Barrier	TRP-03-285-13	Aug. 29, 2013	Model vertical pull test on an ASTM A449 keyway bolt placed in a dual-width keyway	Low	Medium	
Design of an Improved Post for Use in a Non-Proprietary High-Tension Cable Median Barrier	TRP-03-286-15	May 7, 2015	Design and evaluate improved post sections for the non-proprietary high-tension cable median barrier system	Moderate	Critical	Lead to the development of MWP
Numerical Investigation on the Performance of Steel Guardrail Systems with Varied Mechanical Properties	TRP-03-290-13	July 25, 2013	Determine dynamic deflections, working widths, and safety performance of the MGS using various combinations of steel post strength, steel rail strength, and soil strength	Extensive	Critical	

Table 1 (Continued). Projects that used LS-DYNA

Report Title	Report Number	Report Date	Description of DYNA Usage	Usage	Importance to Project	Improvements Made
Zone of Intrusion for Permanent 9.1-Degree Single-Slope Concrete Barriers	TRP-03-292-13	March 14, 2014	Determine the ZOI of the barrier at different speeds	Extensive	Critical	Simulation of dummies in roadside safety applictaions. Creates insight on what improvements need to be made to Concrete Barriers
Devlopment of a Retrofit, Low-Deflection, Temporary Concrete Barrier System	TRP-03-295-14	March 31, 2014	Development and analysis for limiting TCB deflections	Extensive	Critical	
Extending TL-2 Short-Radius Guardrail to Larger Radii	TRP-03-296-14	March 31, 2014	Yuma County system simulated with larger radii of 24, 48, and 72 ft	Extensive	Critical	
Development of a MASH TL-3 Transistion Between Guardrail and Portable Concrete Barriers	TRP-03-300-14	June 26, 2014	Develop a stiffness transition between PCBs and W-beam guardrail to improve safety	Extensive	Critical	previously-developed PCB transitions have only involved attachment to permanent, safety-shape concrete roadside barriers and permanent concrete median barriers
Increase Span Length for the MGS Long-Span Guardrail System	TRP-03-310-14	Dec. 17, 2014	Detailed analysis of the MGS long-span guardrail system	Extensive	Critical	
Predicting the Dynamic Fracture of Steel via a Non-Local Strain-Energy Density Failure Criterion	TRP-03-311-14 (NTC)	June 23, 2014	Model non-local fracture of steel	Moderate	Critical	
Conceptual Development of an Impact-Attenuation System for Intersecting Roadways	TRP-03-312-15	Sept. 30, 2015	Model prototype net attenuator system to investigate performance for treatment of bridge rails adjacent to intersecting roadways	Moderate	Medium	model could be useful for future investigations into the viability of the net attenuator concept
MGS Dynamic Deflections and Working Widths at Lower Speeds	TRP-03-314-15	Sept. 29, 2015	Models MGS installed on level terrain and in combination with curbs to investigate dynamic deflections and working widths at lower speeds and at alternative impact locations	Extensive	Critical	
Design and Evaluation of an Energy-Absorbing, Reusable Roadside/Median Barrier	TRP-03-317-15	July 29, 2015	Evaluate several concrete beam splices	Extensive	Critical	

Table 2. Theses and Dissertations that used LS-DYNA

Title - Thesis (M.S.)/Dissertation (PhD)	M.S./PhD	Author	Date	MwRSF Report	Description of DYNA Usage	Usage Amount	Importance to Project	Improvements Made
Front Suspension and Tire Modeling – for Use in Culvert Grate Impact Simulation	M.S.	D.A. Boesch	April 2004	N/A	Front suspension and tire modeling	Extensive	Critical	Very little improvement had been made to front suspension and tire modeling model since its development in 1996
Identification of a Critical Flare Rate for W-Beam Guardrail in High-Speed Facilities Using Computer Simulation	M.S.	B.D. Kuipers	Dec. 2004	TRP-03-157-04	Post-In-Soil modeling, Identification of critical flare rate for w-beam guardrail in high-speed facilities	Extensive	Medium	
Crash Cushion Diaphragm Modeling and Correlation with Bogie Test	M.S.	N. Sharma	Dec. 2007	N/A	Crash Cushion Diaphragm Modeling and Correlation with Bogie Test	Extensive	Critical	
Critical Offset of the Midwest Guardrail System Behind A Curb	M.S.	L. Zhu	June 2008	TRP-03-205-09	Pickup model evaluation, replicate curb impact, verify critical locations	Extensive	Medium	
Investigating the Use of a New Universal Steel Breakaway Post	M.S.	S.W. Arens	May 2009	TRP-03-218-09	Analyze the fracturing-bolt steel post	Moderate	High	
Development of Guidelines for Deformable and Rigid Switch in LS-DYNA Simulation	PhD	L. Zhu	Aug. 2009	N/A	Development of guidelines for deformable and rigid switch	Extensive	Critical	Few research results available at the time for implementing D-R switches
Analysis of Existing Work-Zone Devices with MASH Safety Performance Criteria	M.S.	J.D. Schmidt	Dec. 2009	TRP-03-225-10 (MATC-UNL-100)	Evaluate the performance of one sign support system	Moderate	Medium	Little research on sign support performance prior to this project
Development of a Low-Cost, Energy-Absorbing Bridge Rail	M.S.	J.C. Thiele	Dec. 2009	TRP-03-226-10	Model side-mounted tubular post tear-out concept to study behavior	Extensive	High	Model considered important to future development of energy absorbing hinge systems
A Concise Model of 3X7 Wire Rope Used in Cable Guardrail Systems	M.S.	C.S. Stolle	May 2010	TRP-03-233-10 (MATC-UNL-220)	Create a more accurate model of 19-mm diameter 3x7 wire rope	Extensive	Critical	New wire rope model more accurately simulated wire rope tension and bogie vehicle motion than previous models
Feasibility Analysis and Concept Development of a Crash Cushion Diaphragm Structure for High-Speed Race Tracks	M.S.	C.L. Meyer	Dec. 2011	TRP-03-261-11	Evaluate modifications of two concepts for diaphragm to guide rail connection	Extensive	Critical	Project resulted in prototype hardware for the diaphragm, guide rail, and angle brackets for use in a prototype race track crash cushion
Development and Recommendations for a Non-Proprietary, High-Tension, Cable End Terminal System	M.S.	R.J. Terpsma	April 2012	TRP-03-268-12	Model cable terminal anchor and compared to bogie testing results	Extensive	Critical	Redesigned model eliminated many of the crash performance issues with previous high-tension, cable anchor bracket assembly

Table 2 (Continued). Theses and Dissertations that used LS-DYNA

Title - Thesis (M.S.)/Dissertation (PhD)	M.S./PhD	Author	Date	MwRSF Report	Description of DYNA Usage	Usage Amount	Importance to Project	Improvements Made
Identification of a Maximum Guardrail Height for the Midwest Guardrail System Using Computer Simulation	M.S.	R.D. Julin	June 2012	TRP-03-274-12	Determine critical rail height on various approach slopes	Extensive	Critical	
Development of a New Energy-Absorbing Roadside/Median Barrier System with Restorable Elastomer Cartridges	PhD	J.D. Schmidt	Nov. 2012	TRP-03-281-13	Determine optimal size and shape of energy absorber	Extensive	Critical	Simulation effort revealed accurate elastomeric models without fully characterizing elasomeric behavior
Predicting Vehicle Dynamics for Roadside Safety Using Multibody Systems Simulations	M.S.	B. Schlueter	Nov. 2012	N/A	Model systems of vehicle; suspension, steering, drivetrain. Validation of model with tests.	Low	High	Foundation for future multibody systems simulations to solve vehicle dynamics problems in roadside safety
Cost-Effective Treatment of Existing Guardrail Systems	M.S.	M.J. Wibelhaus	Nov. 2012	TRP-03-254-13	Model pickup impact at various rail heights	Low	Low	
Cable Median Barrier Failure Analysis and Remediation	PhD	C.S. Stolle	Dec. 2012	N/A	Model of CMB to identify causes of penetrations; Compared results to 3 crashes w/ photgraphic evidence	Moderate	High	
Design of Cable-to-Post Attachments for Use in a Non-Proprietary, High-Tension, Cable Median Barrier	M.S.	R.J. Bateman	May 2013	TRP-03-285-13	Model vertical pull test on an ASTM A449 keyway bolt placed in a dual-width keyway	Low	Medium	
Zone of Intrusion For Permanent 9.1° Single-Slope Concrete Barriers	M.S.	C. Stolle	June 2013	TRP-03-292-13	Modeling of 9.1° Single-Slope concrete Barriers to study ZOI	Extensive	Critical	Simulation of dummies in roadside safety applications. Creates insight on improving Concrete Barriers
Predicting the Dynamic Fracture of Steel via a Non-Local Strain-Energy Density Failure Criterion	PhD	K.D. Schrum	Dec. 2013	TRP-03-311-14 (NTC)	Model non-local fracture	Moderate	Critical	
Development of a MASH TL-3 Transition Between Guardrail and Portable Concrete Barriers	M.S.	D.A. Gutierrez	May 2014	TRP-03-300-14	Analyze, refine, and evaluate PCB transistions	Extensive	Critical	Previously-developed PCB transitions have only involved attachment to permanent, safety-shape concrete roadside barriers and permanent concrete median barriers
Increased Span Length For the MGS Long-Span Guardrail System	M.S.	N.A. Weiland	July 2014	TRP-03-310-14	Simulate 25-ft Long-Span system then compared to full-scale crash tests. Simulation of CRT Post impact	Extensive	Critical	Simulations of the long-span system indicated that improvements to the end-anchorage models should be pursued

3 PROJECT EXAMPLES SINCE 2004

Since LS-DYNA is a graphical tool, this section contains simulation results of 12 selected projects from Tables 1 and 2, and where appropriate, comparison to physical testing. For each project and for easy reference, the report number is listed at the top of each page and the report title is used for the corresponding figure caption. Additionally, the list of those 12 selected projects is as follows:

1. Investigating the Use of a New Universal Breakaway Steel Post – TRP-03-218-09
2. Development of a Low-Cost, Energy-Absorbing Bridge Rail – TRP-03-226-10
3. Development of Advanced Finite Element Material Models for Cable Barrier Wire Rope – TRP-03-233-10
4. Feasibility Analysis and Concept Development of a Crash Cushion Diaphragm Structure for High-Speed Race Tracks – TRP-03-261-11
5. Test Matrices for Evaluating Cable Median Barriers Placed in V-Ditches – TRP-03-265-12
6. Improved Models of Cable-to-Post Attachments Cable Barriers for High-Tension – TRP-03-267-12
7. Development and Recommendations for a Non-Proprietary, High-Tension, Cable End Terminal System – TRP-03-268-12
8. Determination of the Maximum MGS Mounting Height – Phase II Detailed Analysis with LS-DYNA – TRP-03-274-12
9. Zone of Intrusion for Permanent 9.1-Degree Single-Slope Concrete Barriers – TRP-03-292-13
10. Development of a Retrofit, Low-Deflection, Temporary Concrete Barrier System – TRP-03-295-14
11. Increase Span Length for the MGS Long-Span Guardrail System – TRP-03-310-14
12. Front Suspension and Tire Modeling for Use in Culvert Grate Impact Simulation – D.A. Boesch Thesis

From MwRSF Research Report No. TRP-03-218-09

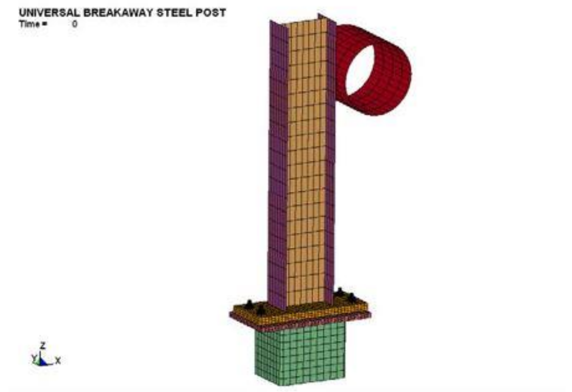


Figure 137. Rigid Cylinder Impact

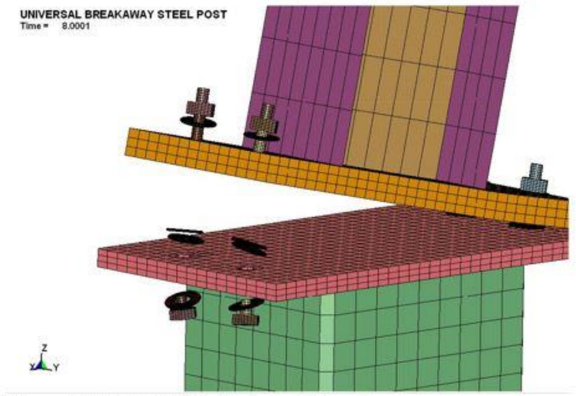


Figure 139. Rigid Cylinder Impact Results

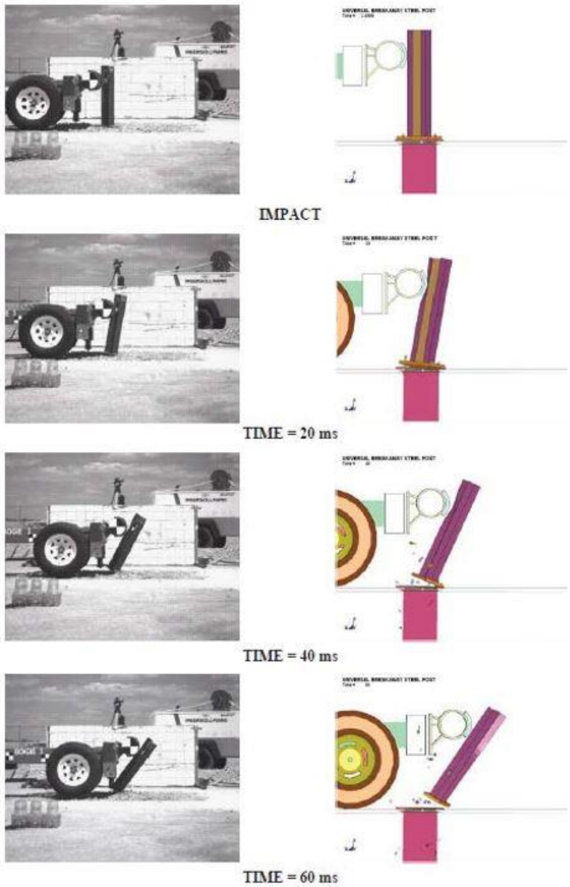


Figure 149. Time Sequential Photographs – Diagonal Axis Impact

Figure 1. Investigating the Use of a New Universal Breakaway Steel Post

From MwRSF Research Report No. TRP-03-226-10

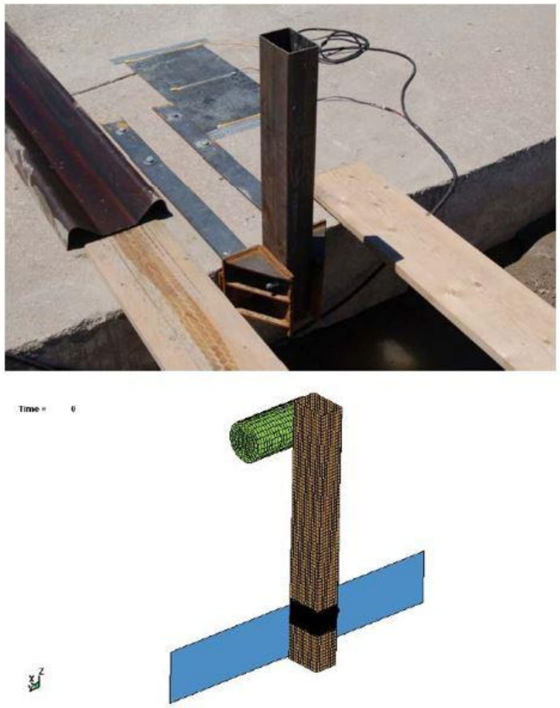


Figure 58. Physical and Simulated Models, Test No. MGSBRB-5

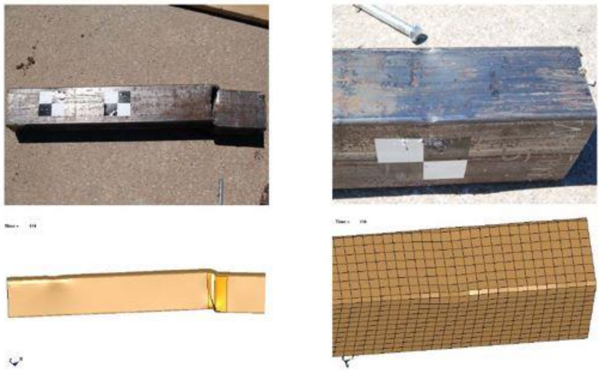


Figure 64. Simulation and Physical Test Results, Test No. MGSBRB-5

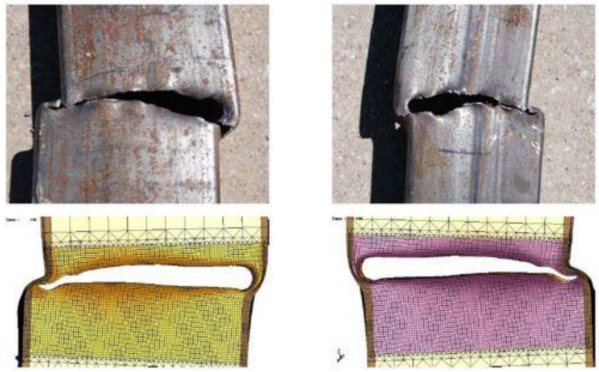


Figure 65. Simulation and Physical Test Results, Test No. MGSBRB-5

Figure 2. Development of a Low-Cost, Energy-Absorbing Bridge Rail

From MwRSF Research Report No. TRP-03-233-10

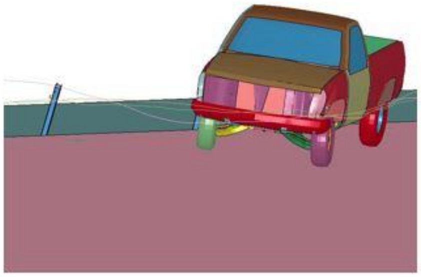
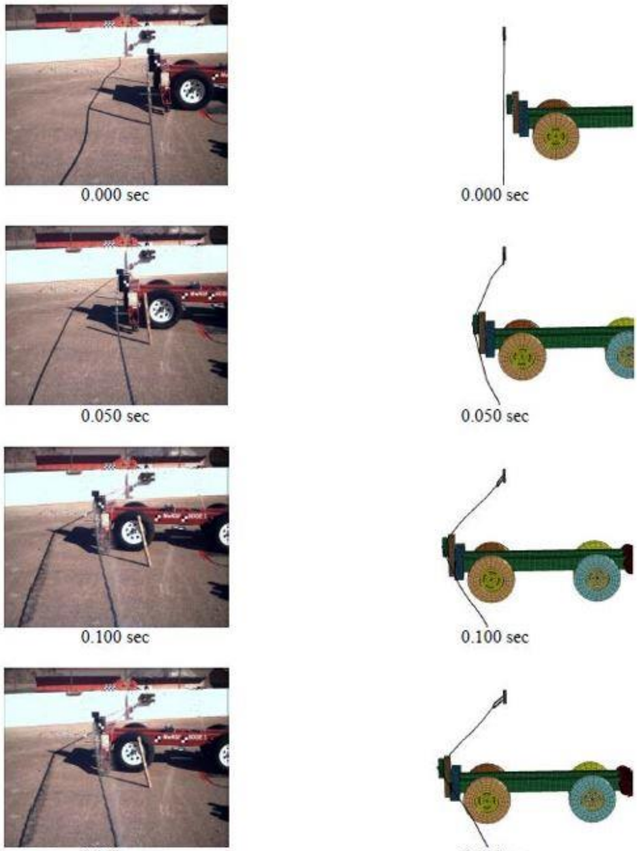


Figure 213 (cont). Sequential Photographs, Test and Simulation, Test No. CS-1_Simulation

Figure 213 (cont). Sequential Photographs, Test and Simulation, Test No. CS-1_Test



0.000 sec 0.000 sec
0.050 sec 0.050 sec
0.100 sec 0.100 sec
0.150 sec 0.110 sec

Figure 183. Sequential Photographs, Test and Simulation, Test No. DBC 4

Figure 3. Development of Advanced Finite Element Material Models for Cable Barrier Wire Rope

From MwRSF Research Report No. TRP-03-261-11

Figure 164. 7 Degrees – MSTCC-3 Deformation Angle

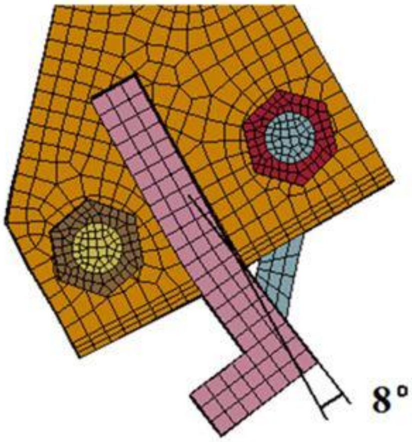


Figure 167. 8 Degrees – Deformation Angle of Design 19

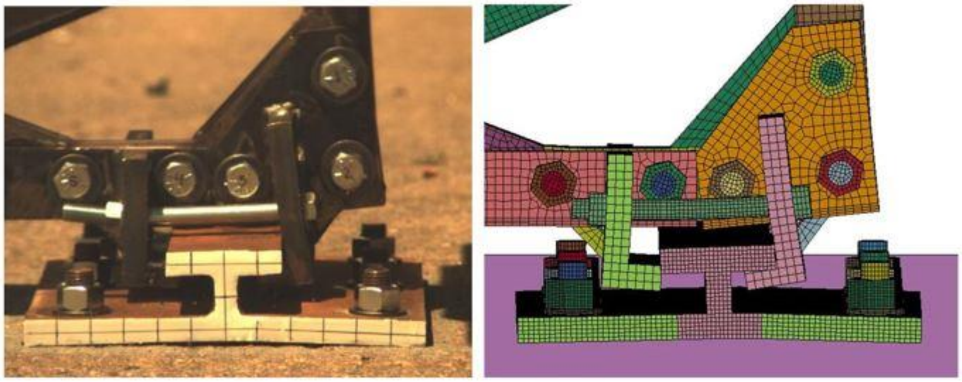
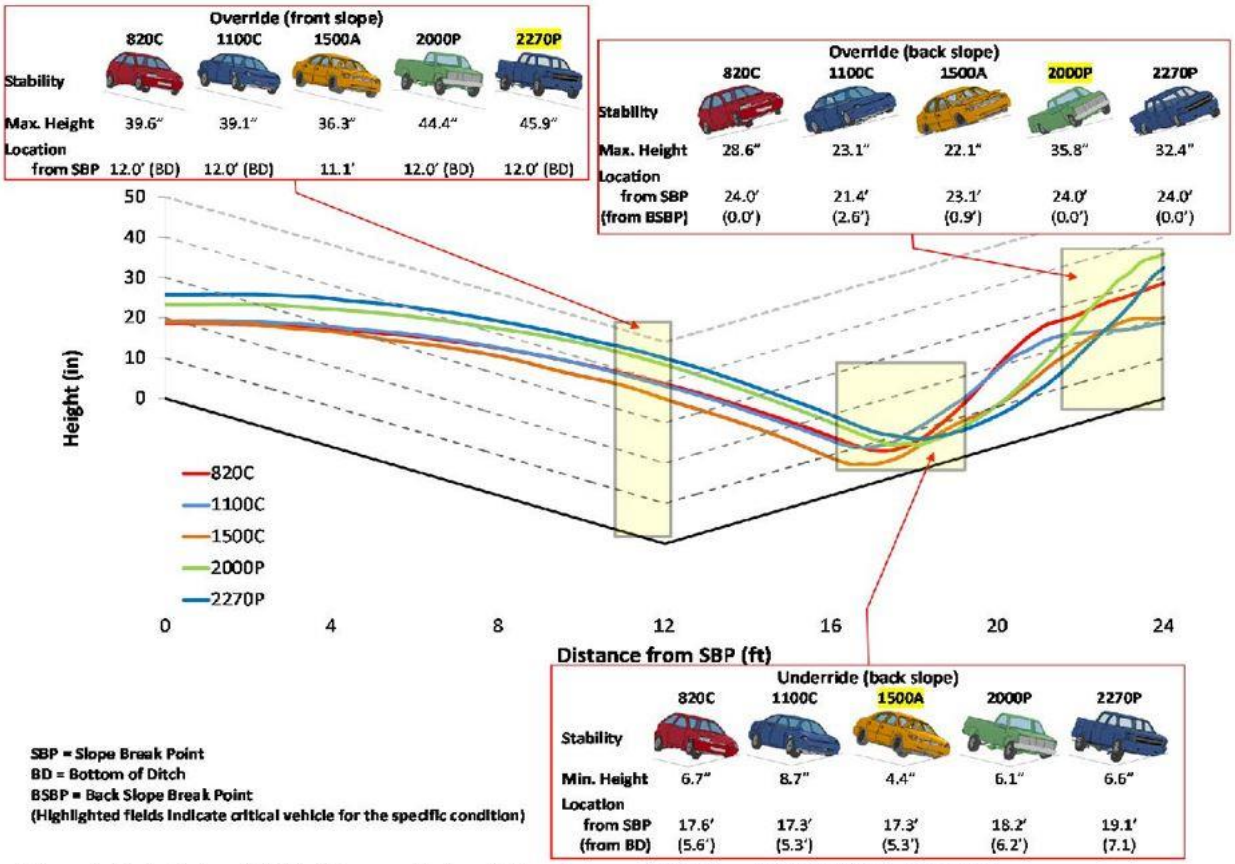


Figure 192. Impact-Side Guide Rail and Bracket at t= 9 msec

Figure 4. Feasibility Analysis and Concept Development of a Crash Cushion Diaphragm Structure for High-Speed Race Tracks

From MwRSF Research Report No. TRP-03-265-12



Override (front slope)

	820C	1100C	1500A	2000P	2270P
Stability					
Max. Height	39.6"	39.1"	36.3"	44.4"	45.9"
Location from SBP	12.0' (BD)	12.0' (BD)	11.1'	12.0' (BD)	12.0' (BD)

Override (back slope)

	820C	1100C	1500A	2000P	2270P
Stability					
Max. Height	28.6"	23.1"	22.1"	35.8"	32.4"
Location from SBP (from BSBP)	24.0' (0.0')	21.4' (2.6')	23.1' (0.9')	24.0' (0.0')	24.0' (0.0')

Underride (back slope)

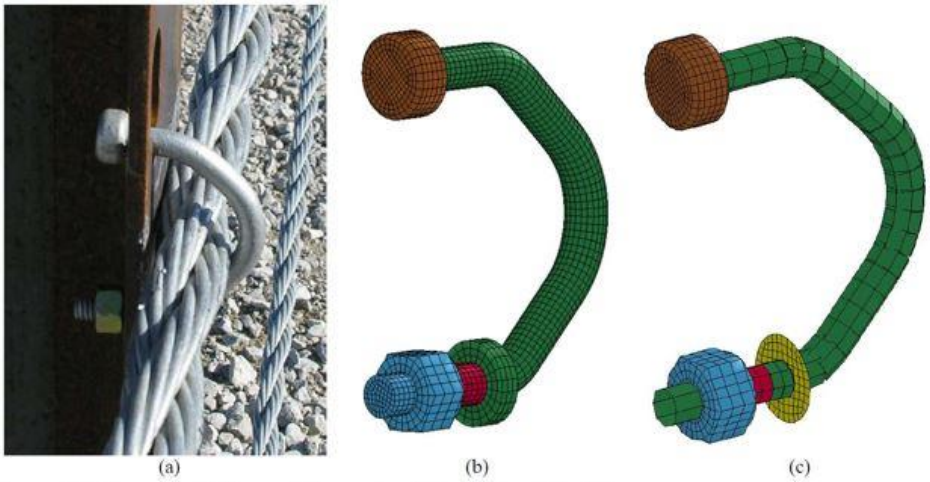
	820C	1100C	1500A	2000P	2270P
Stability					
Min. Height	6.7"	8.7"	4.4"	6.1"	6.6"
Location from SBP (from BD)	17.6' (5.6')	17.3' (5.3')	17.3' (5.3')	18.2' (6.2')	19.1' (7.1)

SBP = Slope Break Point
BD = Bottom of Ditch
BSBP = Back Slope Break Point
(Highlighted fields indicate critical vehicle for the specific condition)

Figure 2. Trajectories of Critical Bumper Nodes of Five Passenger Vehicles – 4H1V V-Ditch, 24 ft Wide

Figure 5. Test Matrices for Evaluating Cable Median Barriers Placed in V-Ditches

From MwRSF Research Report No. TRP-03-267-12



(a) (b) (c)

Figure 10. Keyway Bolts and Computer Simulation Models

Figure 30. Comparison of Component Test with Solid Element and Beam Element Models

Figure 6. Improved Models of Cable-to-Post Attachments Cable Barriers for High-Tension

From MwRSF Research Report No. TRP-03-268-12

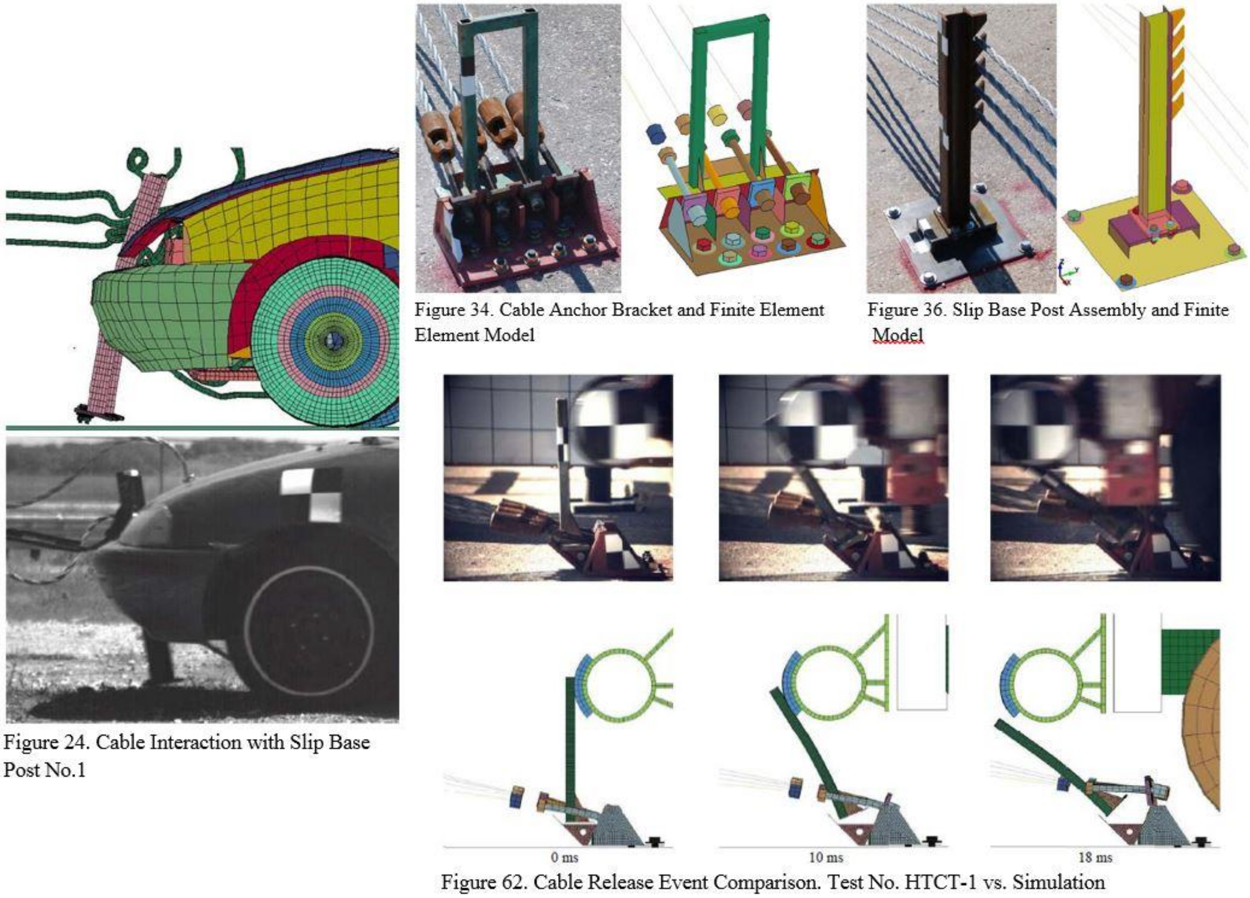


Figure 24. Cable Interaction with Slip Base Post No.1

Figure 34. Cable Anchor Bracket and Finite Element Element Model

Figure 36. Slip Base Post Assembly and Finite Model

Figure 62. Cable Release Event Comparison. Test No. HTCT-1 vs. Simulation

Figure 7. Development and Recommendations for a Non-Proprietary, High-Tension, Cable End Terminal System

From MwRSF Research Report No. TRP-03-274-12

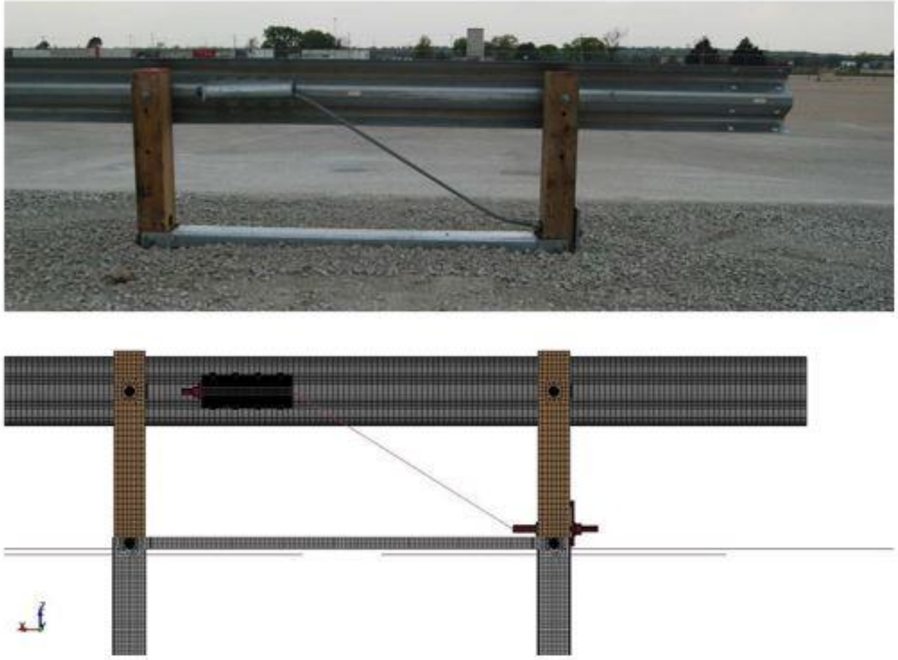


Figure 18. (a) Actual End Anchorage and (b) Finite Element Model

Figure 19. (a) Actual Overall System and (b) Simulation Model

Figure 8. Determination of the Maximum MGS Mounting Height – Phase II Detailed Analysis with LS-DYNA

From MwRSF Research Report No. TRP-03-292-13

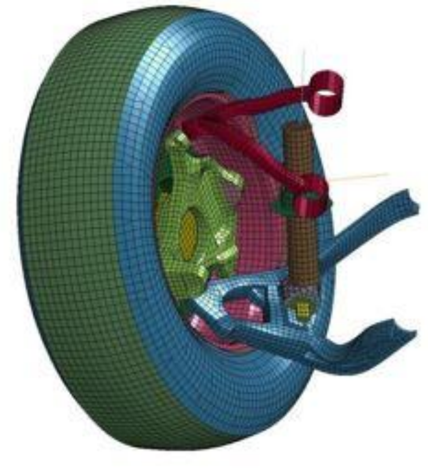


Figure 66. Suspension Damage for the Model with Full Suspension Failure

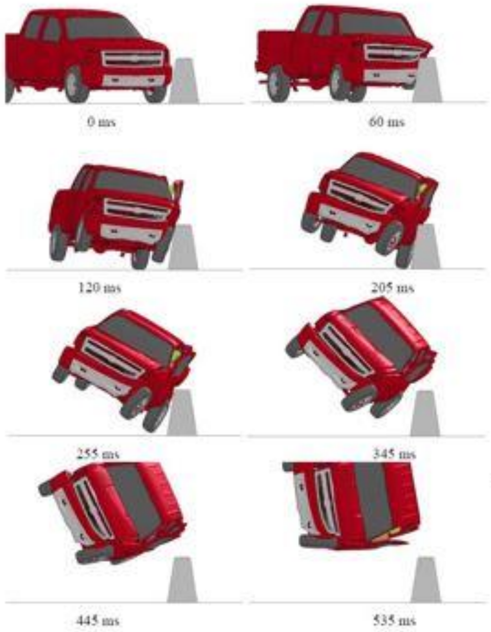


Figure 80. Dummy, Seat, Seatbelt, and Vehicle Simulation

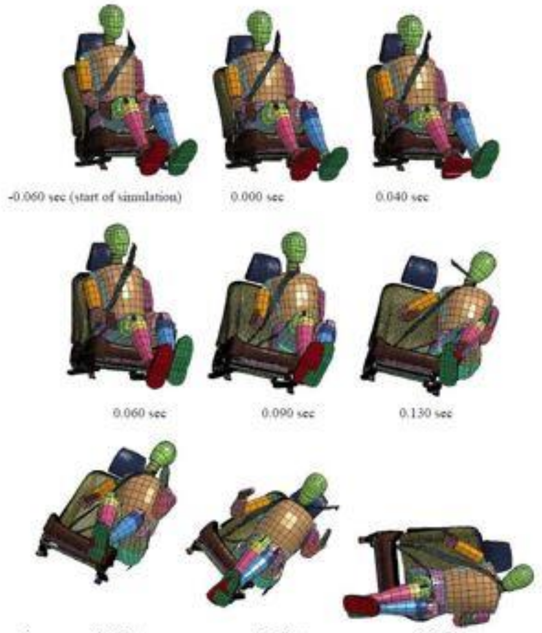


Figure 81. Dummy Reaction in the Vehicle

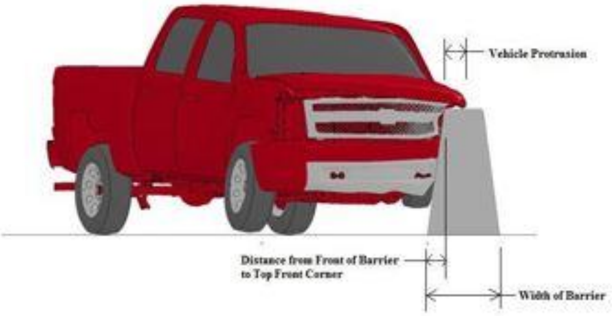


Figure 67. Working Width Measurements

Figure 9. Zone of Intrusion for Permanent 9.1-Degree Single-Slope Concrete Barriers

From MwRSF Research Report No. TRP-03-295-14

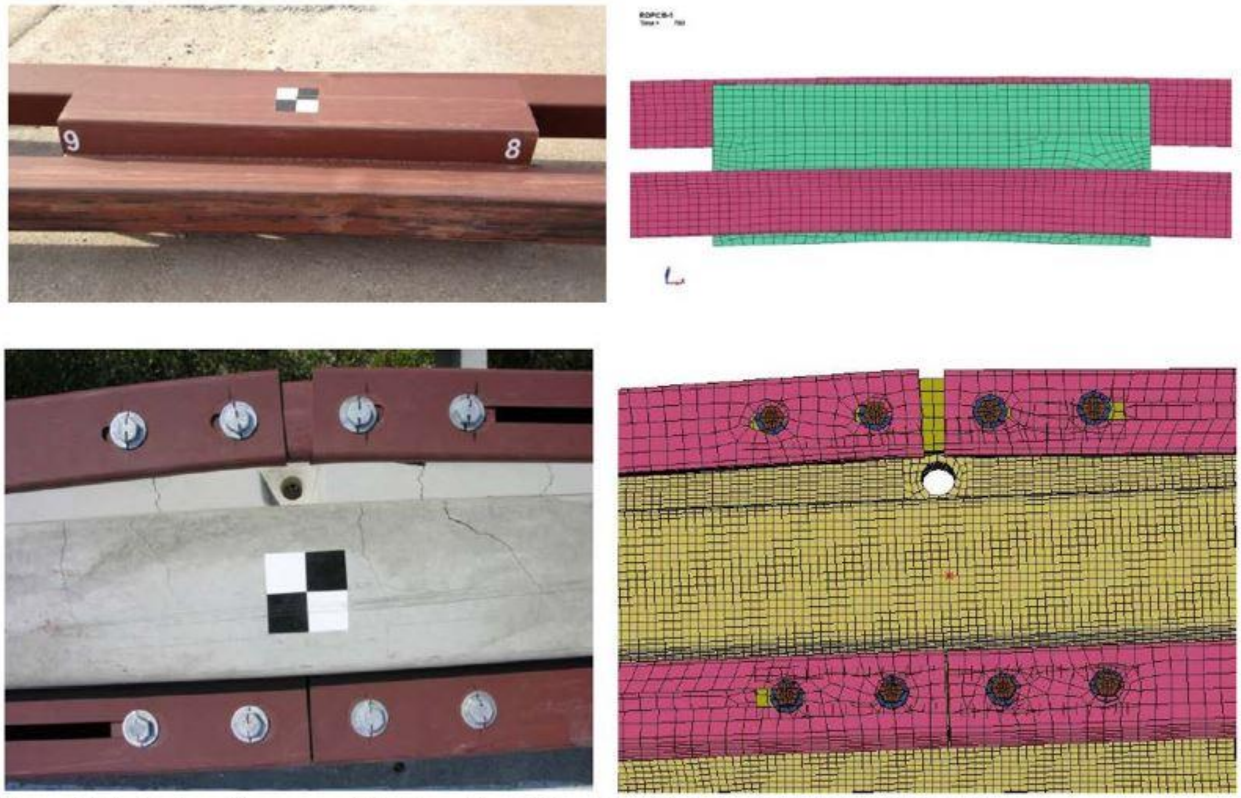


Figure 111. System Damage and Deformation, Stimulaion Model and Test No. RDTCB-1

Figure 140. Barrier Segment Connection Designs, Test No. RDTCB-2

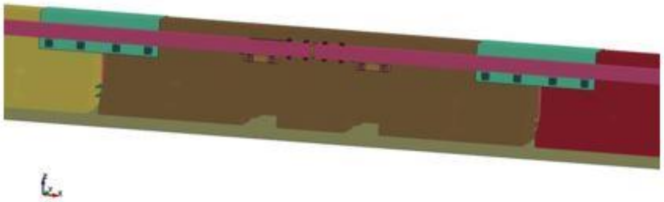


Figure 155. Simulation Model of System, Test No. RDTCB-2

Figure 10. Development of a Retrofit, Low-Deflection, Temporary Concrete Barrier System

From MwRSF Research Report No. TRP-03-310-14

Figure 1. Midwest Guardrail System 25-ft Long-Span Design

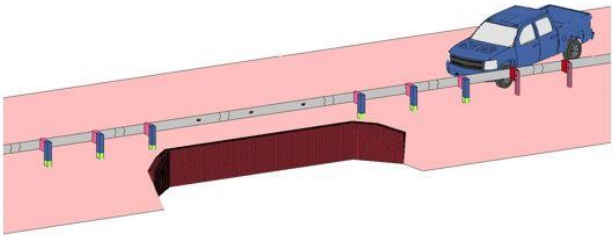


Figure 16. Double Wingwall Culvert, Test no. LSC-2

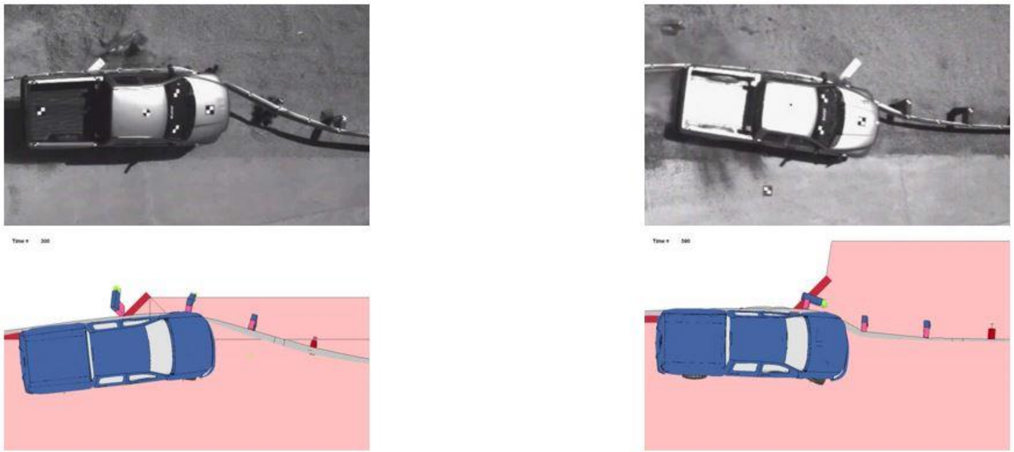


Figure 31. LS-DYNA Baseline Models Pocketing Angle Comparisons_LSC-1

Figure 11. Increase Span Length for the MGS Long-Span Guardrail System

From D.A. Boesch Master's Thesis

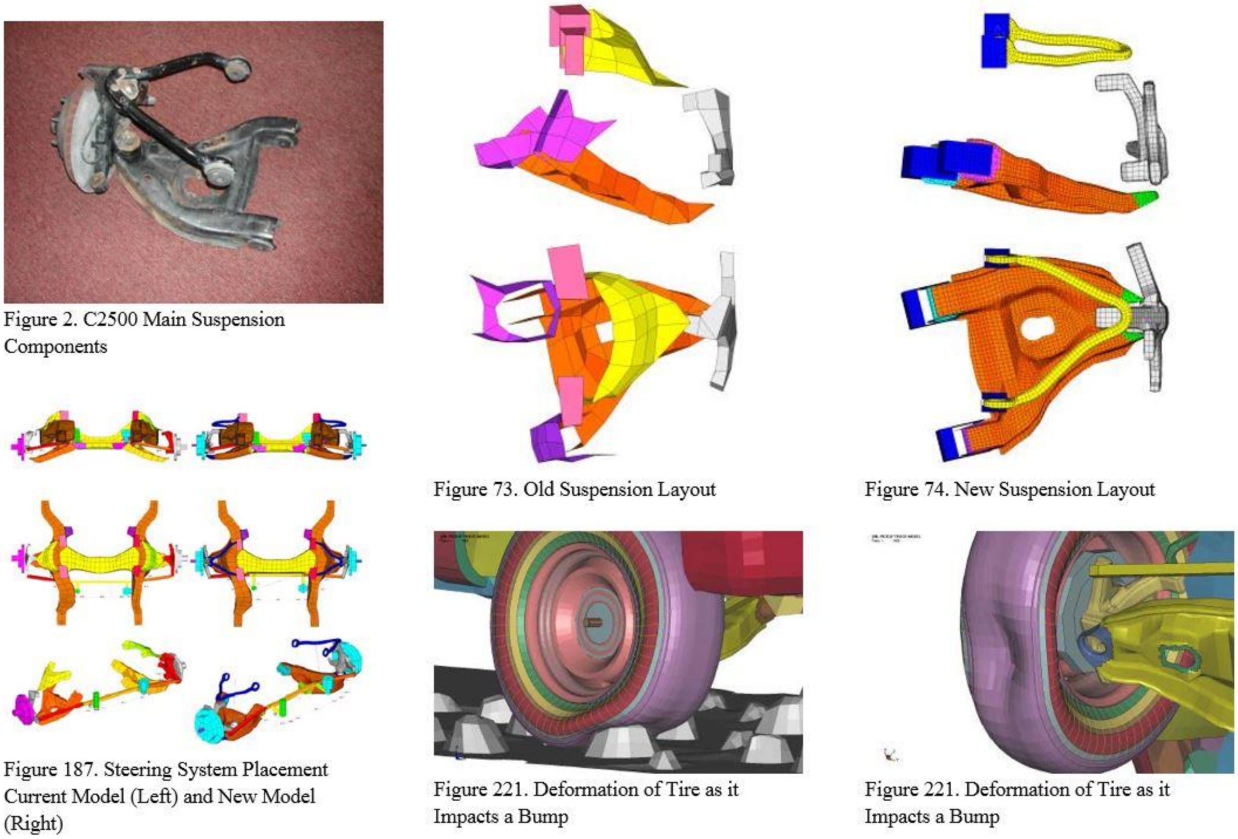


Figure 2. C2500 Main Suspension Components

Figure 73. Old Suspension Layout

Figure 74. New Suspension Layout

Figure 187. Steering System Placement Current Model (Left) and New Model (Right)

Figure 221. Deformation of Tire as it Impacts a Bump

Figure 221. Deformation of Tire as it Impacts a Bump

Figure 12. Front Suspension and Tire Modeling for Use in Culvert Grate Impact Simulation

4 VEHICLE MODELING

4.1 Implementing a Model for usage by MwRSF

When a vehicle model is obtained for usage by MwRSF, it goes through a rigorous inspection and organization process before it is used on a project. This process usually involves communicating with the source to discuss the model and to modify the model to be more responsive and stable in MwRSF applications. The integration steps are broken down into four major categories, called Models (capital M). Each Model category usually has multiple sub-models of the vehicle within that category.

Model 1 – original model
Model 2 – split model into multiple include files
Model 3 – change units
Model 4 – position and make ready for roadside hardware imp

During the vehicle model integration process many simple model checks are made by simulating controlled cases; including (1) run the model as is [it is not uncommon for the original model obtained to have troubles successfully completing on our computers using our version of LS-DYNA], (2) simulate the NCAP test [35 mph frontal impact in a fixed, rigid wall], (3) insure there is a ground below the tires and gravity is defined in the model, and then run a gravity check [simulate the model for 2000 ms while the vehicle does nothing but settles down on the ground], (4) run the model for an extended period of time while it simply rolls straight ahead at 100 km/h, and (5) while rolling at 30 mph apply a controlled force to the front steering knuckle in order to evaluate the steering capabilities, including removing the force and checking that the vehicle returns to a straight path. Each of these simulation cases may or may not be run for each Model category. It all depends on the vehicle on hand, the target project for the vehicle, and the amount of time available for thoroughness.

1. Model 1 – original model

   The original model is investigated to get acquainted with it and to see what details it has or does not have. Slightly modified versions of the original model would include modifying control parameters (*CONTROL_xxx dyna commands) as well as some parameters within specific keywords, and setting values to MwRSF recommended values. Sometimes when a vehicle model goes unstable during a simulation, the original model needs to be re-investigated to see if the trouble is related to the base model or with the modified version(s) that are developed and improved (hopefully) over time.

2. Model 2 – split model into multiple include files

   The actual LS-DYNA model is often referred to as the dyna deck. When a vehicle model is obtained, it is usually in one large undocumented dyna deck file. Model 2 breaks the dyna deck into multiple files, called include files, in order to isolate the major functions within the dyna deck. For example, Version 3 of the reduced Silverado model is divided into the following files:

silverado-v3r.k
silverado-v3r-accelerometers-dummies-misc.k
silverado-v3r-connections.k
silverado-v3r-contacts.k
silverado-v3r-control.k
silverado-v3r-elements.k
silverado-v3r-gravity-and-ground.k
silverado-v3r-init-stress-beam.k
silverado-v3r-init-vel.k
silverado-v3r-nodes.k
silverado-v3r-parts.k
silverado-v3r-wheels-tires.k

File silverado-control.k controls the model; it sets global control parameters, request specific outputs, and includes silverado-v3.k. If this vehicle is used to simulate an impact event, say the MGS, then the control file will also include the mgs model along with any special handling required to control the simulation. For example, renumbering the nodes and elements of the vehicle may be required to prevent the vehicle and mgs from having the same numbering schemes, which is not allowed. Another common example is to use the control file to reposition the vehicle for different impact conditions.

The included file silverado-v3.k is actually the master file for the entire silverado model. It is pretty much stand-alone and can be used without the silverado-control.k file for various reasons (for example, like being included directly by another model). File silverado-v3.k main purpose is to include all of the other files listed above. Sometimes it is used to override parameters or outputs set in the control file.

During this Model 2 development phase a lot is learned about the model and how it is put together. The various dyna decks are also documented for better reference. When a model needs to be modified, it is often much easier and quicker to work with the include files. Models 3 and 4, described next, will continue to use include files. Sometimes during those phases, some of the include files from Model 2 are broken-up into even more detailed include files.

3. Model 3 – change units

LS-DYNA has no units, it is up to the analyst to use consistent units. Both NCAC and GMU use units of ton, mm, s, N, MPa, N-mm; while MwRSF uses units of kg, mm, ms, kN, GPa, kN-mm for LS-DYNA models. Thus, a conversion of units is required. There are multiple ways to do this conversion. Unfortunately, it has been found that various versions of LS-DYNA have limitations on their automatic unit conversion transformation capabilities. This requires special handling and review to ensure all units are converted properly. Typically, the author converts one file at a time (the include files from Model 2). Depending on the include file breakdown, several of those files do not need conversion.

Changing units will change the results from the simulation. This is a complex issue and not easily explained, and complete details are beyond the scope of this document. As an example, the Dodge Neon is simulated impacting a fixed wall head-on at 35 mph; this is referred to as the NCAP test. The simulation is done twice, first with the original units of mm, s and tons, and second after the units have been changed to mm, ms and kg.

The deformations after the impacts are shown in Figure 13. The difference in the crush is practically unobservable. However, the accelerations of the C.G. and the forces on the barrier due to the impacting Neon are different, as shown in Figures 14 and 15. Examining the velocity curves, as shown in Figure 16, the differences in the accelerations are inconsequential in regard to their effect on the velocity. It is common in LS-DYNA simulation studies to say that results are the same, but different.

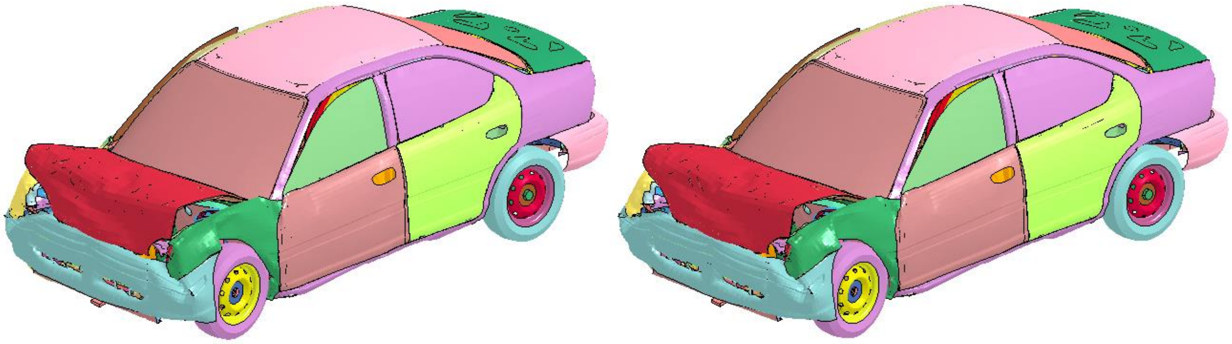


Figure 13. NCAP Simulation: mm, s and tons units versus mm, ms and kg units

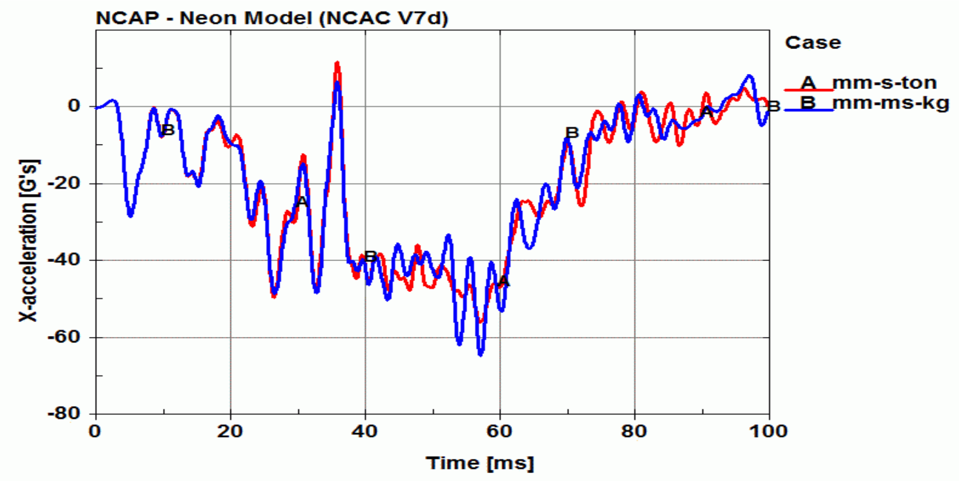


Figure 14. Neon NCAP – Accelerations

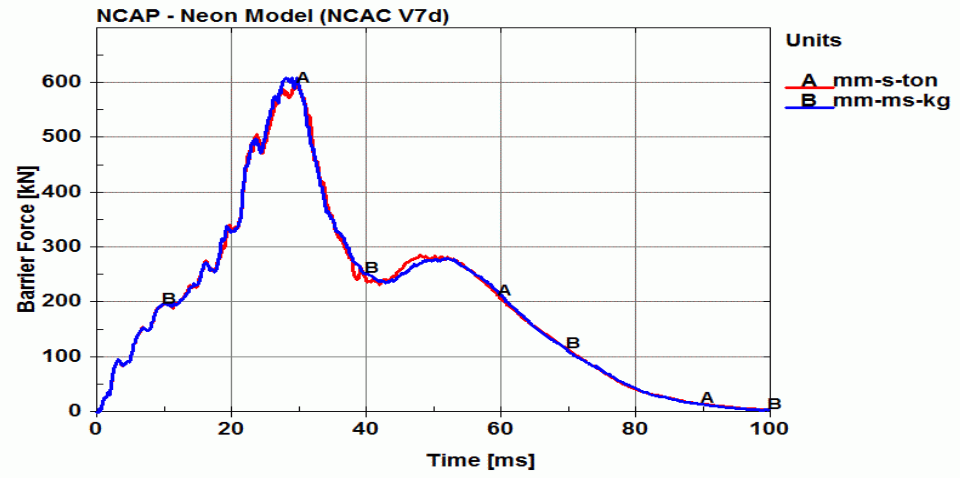


Figure 15. Neon NCAP – Barrier Forces

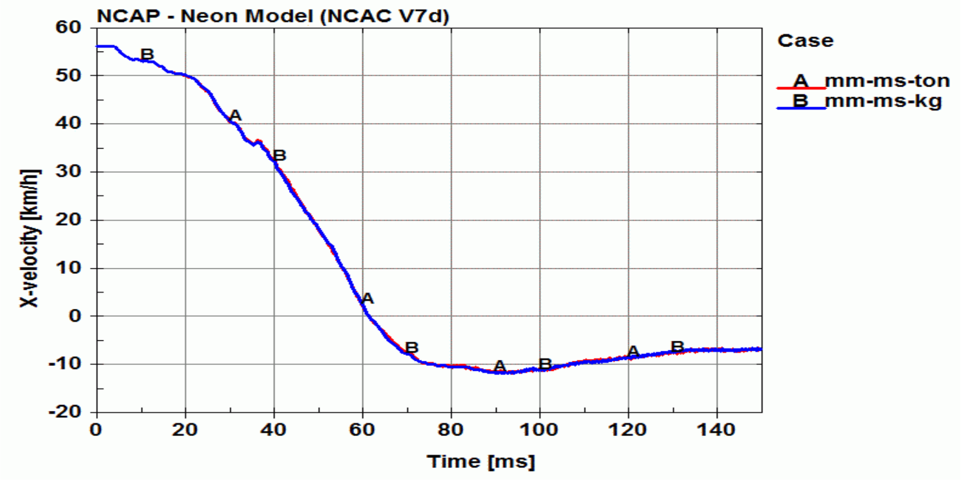


Figure 16. Neon NCAP – Velocities

4. Model 4 – position and make ready for roadside hardware impact

At this point in the implementation process, the vehicle model is ready for usage, but it still requires some manipulation and variations. Three factors are discussed here: (1) orientation and position, (2) tires and wheels, and (3) vehicle mesh. In practice, there are special cases that arise based on specific project requirements and vehicles being used for that project. Detailing the special cases is beyond the scope of this report.

(1) Orientation and Position: Since most impact conditions are at 100 km/h and 25-degrees, a baseline vehicle will be set-up at these conditions at a standard location in space. That way, those developing roadside hardware know where to place their model. Changing the initial velocity of the vehicle is rather simple so variations on that are placed within the control file, all but the active speed are commented out. If a simple translation of the vehicle is needed prior to simulation that can be easily accomplished in the control file. If a different initial orientation (i.e., rotation) is required, that is often better done separately, creating a

different version of the model. Typically, there might be three orientations, heading in the x-direction, at a 25-degree angle for the standard impact, and at 155-degree angle for the reverse direction impact condition.

(2) Tires and Wheels: Initial tires from NCAC are almost always extremely stiff, far beyond anything seen in physical testing. However, these tires are very stable under many impact conditions. UNL has developed a variation on that model which significantly softens the tires. The switch is done by swapping out the dyna keyword commands associated with the tire pressurization airbags with a significantly different method. In practice, once set-up, to change tire models it is simply a matter of changing the tire include file name in the vehicle model. The softer tire, while more accurate, is prone to be more unstable than the stiff tire. Why? Because the softer the tire, the more it can deform, which can lead to reaching its limit of deformation and cause numerical instability. In real life, a tire could de-bead or rupture in such situations. The tire models do not have those capabilities.

A third tire model, referred to as the UNL detailed tire model, was developed by Dustin Boesch for his Master’s Thesis for the c2500 pick-up truck model. This tire model takes into account the actual complexities of a real tire. It’s deformation behavior matches physical testing very well. It also does not have the capability to de-bead or rupture, so is even more prone to instabilities at high deformations. This tire model is specific to wheel and tire type of the actual vehicle being modeled and thus, must be developed for each desired tire/wheel combination. A very time consuming task (often months). Swapping between the simpler tire models and this detailed tire model requires several modifications to the include files that make up the vehicle model. This model is required for accurate riding over curbs, or rocks, or any debris that results in significant tire compression.

(3) Vehicle Mesh: It is not uncommon for portions of a vehicle model to need re-meshing. This is usually due to unforeseen large deformations or snagging of a relatively coarse mesh compared to its deformation pattern. The re-meshing is done on a case-by-case basis and may or may not make its way back to updating the baseline vehicle model. A localized re-meshing, used to solve a particular numerical problem to help a particular project, may or may not be a good idea for the overall effectiveness of a vehicle model. Meshing is still part art, and often requires re-working surrounding components as well as the connections made to the portion being re-meshed.

In summary, trying to organize and keep clean all the various versions of a vehicle model can be cumbersome, to say the least. It a project needs, say a 2270p pick-up truck model, it’s not so trivial – which orientation, which tires and wheels, does it need a specialized meshed version, etc. – all need to be determined and made available in a timely manner.

4.2 Chevy 2500 Pickup – 2000 kg (2000p)

By the time this project started, the c2500 pick-up model was well established within MwRSF. Various models including coarse mesh model and detailed mesh model were in use, with the many variations of tires, orientation, and so forth. As the NCHRP 350 official vehicle, the c2500 was used on a majority of the simulation projects for many years, and is still in use today. With MASH, this c2500 is no longer the official pick-up truck used in most projects, so it more or less is treated as a bogie vehicle for its relative simplicity, robustness and computational efficiency. This model requires some maintenance on a case-by-case basis, but does not utilize project funding to do so.

4.3 Chevy Geo Metro – 820 kg (820c)

The original Geo Metro model, representing the NCHRP 350 small car vehicle, was released by NCAC in January 1999. Many versions and variations were developed by several groups between 1999 and 2011. The family tree structure of the variations is quite diverse. MwRSF investigated many of the Geo models it had direct access to. In 2007, Marco Anghileri, from Politecnico di Milano, Italy, provided MwRSF with its modified version. This model is referred to as iGeo (the i standing for Italy). MwRSF implemented the iGeo following the procedure described earlier. The iGeo became MwRSF’s go-to small car model; including a surrogate 1100 kg model by adding mass at strategic locations. This model requires some maintenance on a case-by-case basis, but does not utilize project funding to do so.

4.4 Dodge Neon – 1317 kg (1500 kg and 1100 kg)

Version 5 of the Dodge Neon was obtained from NCAC in November 2004. That version was used for experimental purposes. Version 7 was obtained in January 2006 and prepared for MwRSF usage. Primarily, mass was added to it to make it a 1500 kg vehicle in order to simulate a mid-size vehicle. One such application was for a project with Cyprus, investigating their guardrail systems. Version 7d was obtained in June 2009 and prepared for MwRSF usage. Mass was modified to make this version a surrogate 1100 kg vehicle, the new MASH small car vehicle. It has been used on several MwRSF projects. The Neon has proven to be a little unstable at times but has not been required in projects often enough to make a concentrated effort beyond the basic implementation process in order to significantly improve its shortcomings. MwRSF does not crash test with Dodge Neon’s.

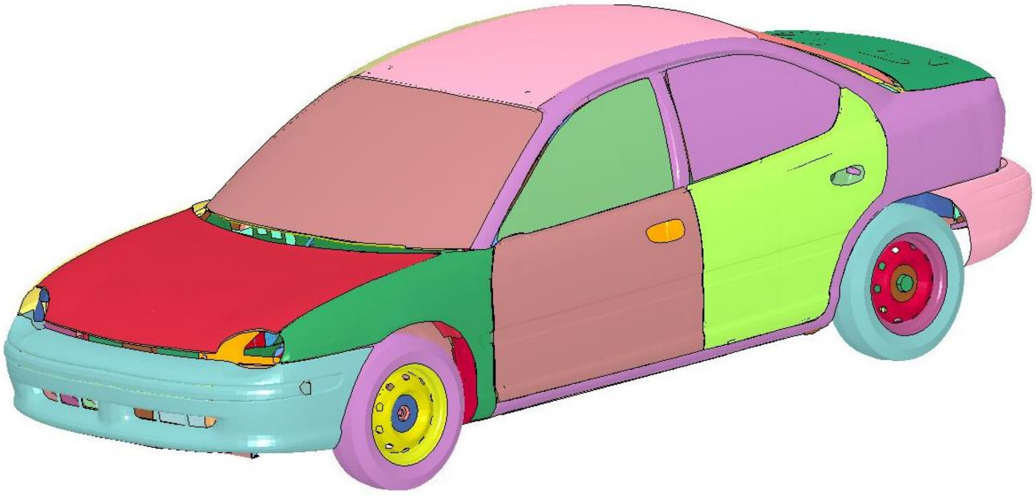


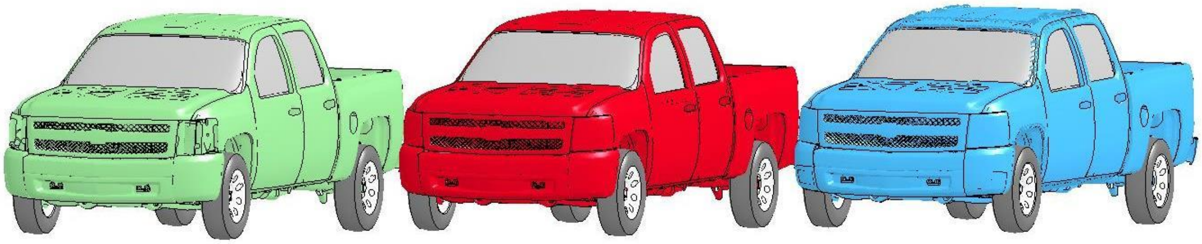
Figure 17. Dodge Neon Model

4.5 Chevy Silverado Pickup – 2270 kg (2270p)

Version 1 of the Silverado model was obtained from NCAC in October 2008. It was prepared for MwRSF usage with two variations; one with the original NCAC tires and one with the reduced MwRSF tires. Version 1 was used for simulating impact with the MGS and with the MGS-on-Curb. This model was short lived.

Version 2 of the Silverado was obtained from NCAC in February 2009 and prepared for MwRSF usage. This version had significant updates and was deemed a better model than Version 1. This model was the workhorse 2270p model for several years and is still in use. It is considered a little less accurate than Version 3, but much more stable. One significant difference between Version 2 and Version 3 models is that Version 2 does not have steering capabilities. This model was used to successfully calibrate the MGS model with the NCHRP Verification and Validation procedures. Version 2 has many variations dealing with connection and mesh problems as they showed up on individual projects.

Version 3 and Version 3-reduced of the Silverado were obtained from NCAC in March 2012 and prepared for MwRSF usage. These versions had significant updates and were deemed better models than Version 2. Version 3-reduced is a much smaller model than the other versions, and thus is relatively CPU inexpensive. Version 3-reduced is currently by far the most common model used for MwRSF projects. Both versions have many variations. For example, Version 3-reduced (silverado-v3r) has a variation that includes the detailed tire models developed by MwRSF.

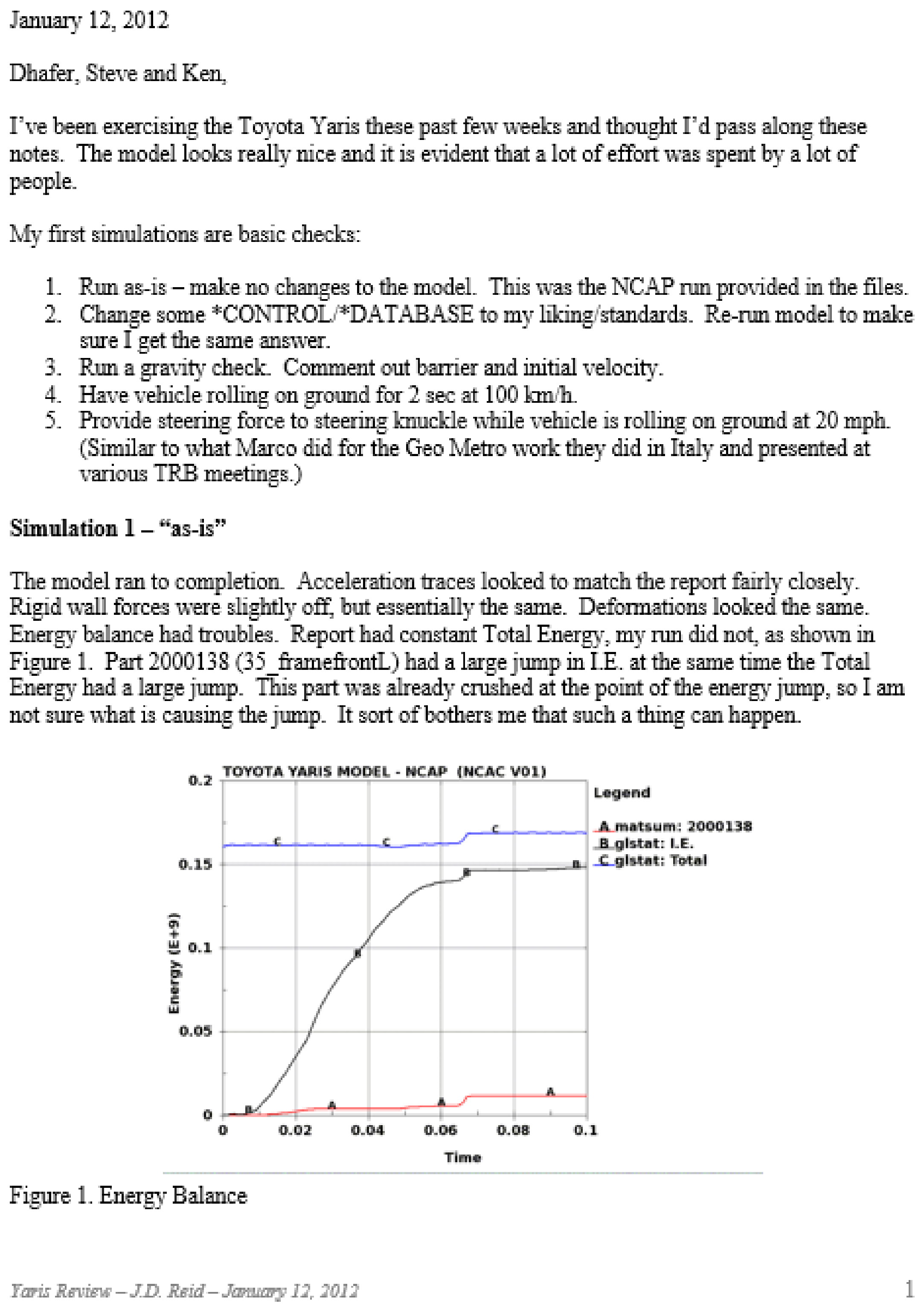


Version 2 Version 3 Version 3-reduced

Figure 18. Three Versions of the Silverado Model

4.6 Toyota Yaris – 1100 kg (1100c)

Version v1m of the Yaris was obtained from NCAC in December 2011. After an initial investigation of the model, a brief review was sent to NCAC discussing observations. In order to provide a better understanding for the vehicle model integration process discussed previously, a copy of that review follows.



January 12, 2012

Dhafer, Steve and Ken,

I've been exercising the Toyota Yaris these past few weeks and thought I'd pass along these notes. The model looks really nice and it is evident that a lot of effort was spent by a lot of people.

My first simulations are basic checks:

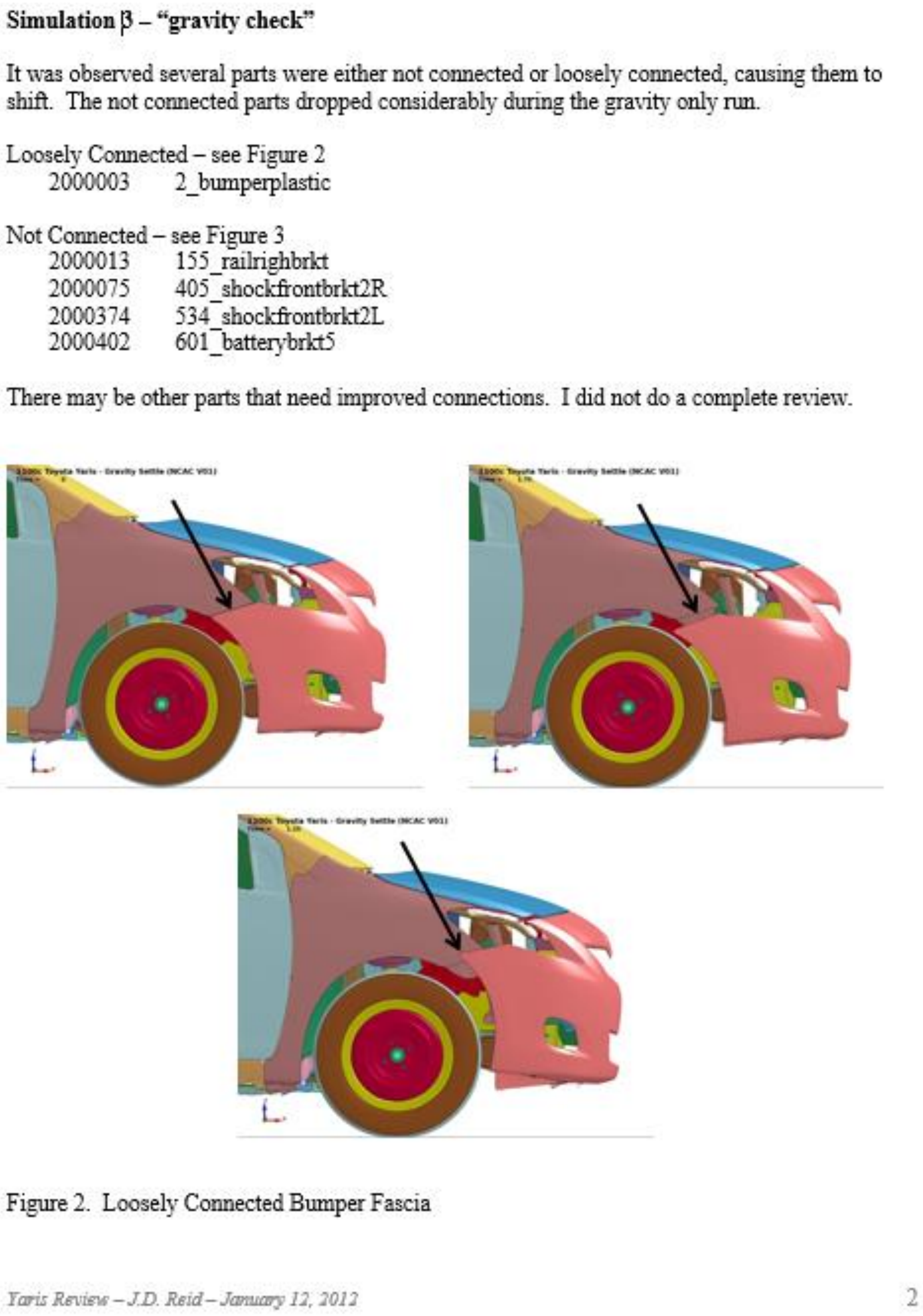
1. Run as-is – make no changes to the model. This was the NCAP run provided in the files.
2. Change some *CONTROL/*DATABASE to my liking/standards. Re-run model to make sure I get the same answer.
3. Run a gravity check. Comment out barrier and initial velocity.
4. Have vehicle rolling on ground for 2 sec at 100 km/h.
5. Provide steering force to steering knuckle while vehicle is rolling on ground at 20 mph. (Similar to what Marco did for the Geo Metro work they did in Italy and presented at various TRB meetings.)

Simulation 1 – "as-is"

The model ran to completion. Acceleration traces looked to match the report fairly closely. Rigid wall forces were slightly off, but essentially the same. Deformations looked the same. Energy balance had troubles. Report had constant Total Energy, my run did not, as shown in Figure 1. Part 2000138 (35_framefrontL) had a large jump in I.E. at the same time the Total Energy had a large jump. This part was already crushed at the point of the energy jump, so I am not sure what is causing the jump. It sort of bothers me that such a thing can happen.

Figure 1. Energy Balance

Yaris Review to NCAC – Page 1



Simulation β – "gravity check"

It was observed several parts were either not connected or loosely connected, causing them to shift. The not connected parts dropped considerably during the gravity only run.

Loosely Connected – see Figure 2

2000003	2_bumperplastic

Not Connected – see Figure 3

2000013	155_railrighbrkt
2000075	405_shockfrontbrkt2R
2000374	534_shockfrontbrkt2L
2000402	601_batterybrkt5

There may be other parts that need improved connections. I did not do a complete review.

Figure 2. Loosely Connected Bumper Fascia

Yaris Review – J.D. Reid – January 12, 2012 2

Yaris Review to NCAC – Page 2

Figure 3. Parts Not Connected – Sequence Showing Parts Dropping from Vehicle

The model does not settle on the ground very well. I would expect 1 or 2 significant bounces only (as occurs on other models) but the ground forces, as shown in Figure 4, clearly show the vehicle does not settle very well. This may significantly affect steering/corning behavior. This may be caused by several items associated with the tires/suspension components.

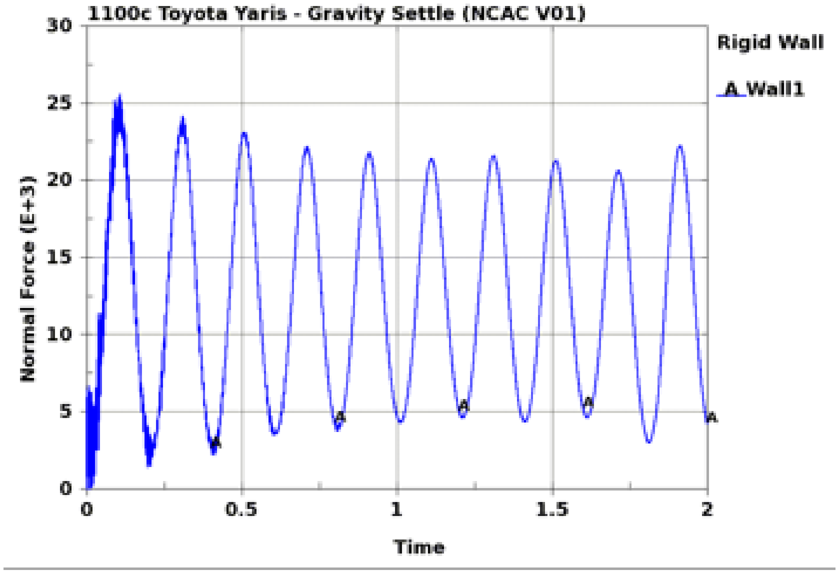


Figure 4. Ground Forces for Gravity Check – Vehicle Does Not Settle

Yaris Review to NCAC – Page 3

Simulation 5 – "steering"

Steering, although possible, seemed to have problems. After several variations I ended creating a model that (1) basically held the main vehicle in place by using a lot of randomly placed Boundary SPC's; but none on the front tire/suspension/steering parts, and (2) applied loading to the steering knuckle at the location where the steering arm is attached to it. This scenario isolates just the steering mechanics.

The steering gear should be stationary (i.e. attached to the vehicle structure), but it moves a lot during the steering maneuver. This is part 2000516 – 640_steeringmechmain. This can be seen in the attached movie: movie_000-steering-top.wmv. Only the tire/suspension/steering is shown in the movie, the rest of the parts are turned off.

I also think the strut does not behave properly. See movie_001-steering-angle.wmv but also Figure 5. I don't know for sure what is wrong, but it appears the top mount is more of a revolute joint rather than a spherical type joint; as such the shaft on the strut bends unrealistically. Strut motion is difficult, for sure, but it should stay in-line during steering.

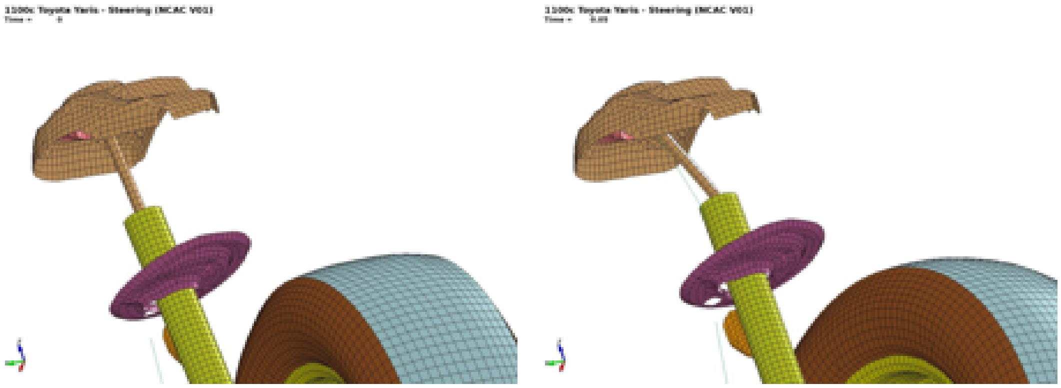


Figure 5. Unrealistic strut deformation

Yaris Review to NCAC – Page 4

Finally the loading to cause steering appears to be extremely high. I started out with 1,000 N just as in the Geo Metro steering example but got almost no motion at all. I eventually switch to a controlled wall motion and ended with the forces shown in Figure 6. This technique provides the actual forces required to cause steering. Not the value at lower angles is around 15,000 N and then ramps up considerably as the angle increases. I don't believe a steering force of 15,000 N is realistic.

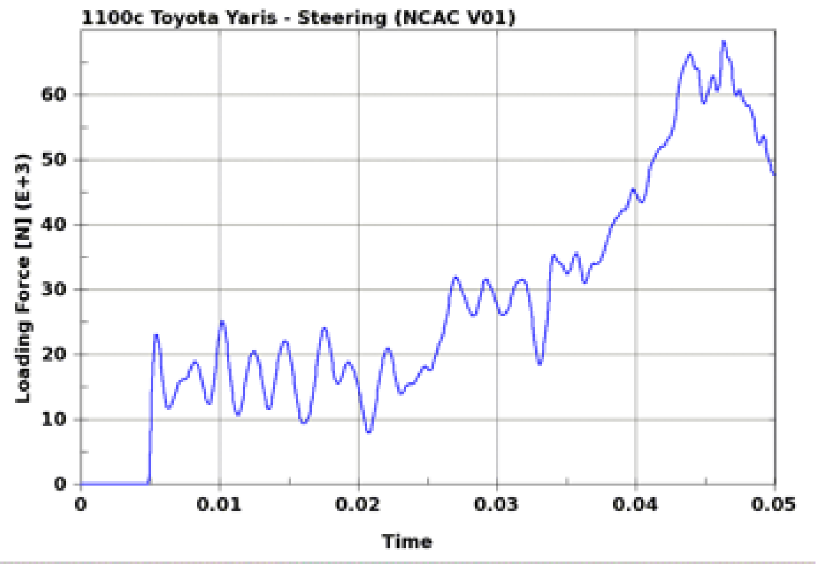


Figure 6. Force Required to Cause Steering

Yaris Review to NCAC – Page 5

Version v2g of the Yaris was obtained from NCAC on March 29, 2012 and prepared for MwRSF usage. This version addressed, among other things, the issues raised in the January 12 review. However, the model size grew from 770 parts with 975,000 elements up to 920 parts with 1,515,000 elements. Seriously taxing our ability to understand all the details within the model and our computer resources to handle such a large model. Note that in addition to the vehicle model, one must also have a roadside hardware model to go along with it; further increasing the overall size of the project model.

4.6.1 Difficulties in Simulating the Yaris

Many difficulties arose when trying to get the Yaris to work well with the MGS model. A partial listing of some of the difficulties follows, this work was done in 2012. These items are not in any particular order since they weren't solved in a linear fashion. The comments are a direct copy from the dyna decks, and thus left in somewhat poor English grammar.

```
*****  tires

Different results were obtained when using the NCAC tire model
and the UNL tire model.

The UNL tire model is more physically correct way to model the tire.

The UNL tire model would sometimes go unstable due to excessive crush.
By changing the sidewall E to 0.3 (from 0.03) the model became much
more stable.  Of course, the tire stiffness goes up - it was already
more stiff than physical testing results we have of other tires.

*****  bumper (fascia - plastic)

Front bumper gave lots of troubles. It is attached to the structure
using spotwelds (sw) in some locations, and NRB's in others. The sw
did NOT have failure defined.  Thus, the bumper elements at the sw
would sometimes stretch a great deal, and causing the model to bomb.
So, failure was added to the sw.  Seemed to work but then, in some
cases, the bumper would again go unstable, but at the NRB connections.

Failure criteria was then added to the entire bumper, similar to
Mario's work with the iGeo and MGS.

Now the bumper basically falls apart during impact.

*****  multiple contacts vs single contact approach

Initially I tried the approach of (1) auto_ss for the yaris,
(2) contacts for the MGS, and (3) auto_s2s between yaris & MGS.
Lots of penetrations, sometimes eventually causing abort.
Several patches to this approach were attempted.

Then, I tried adding as much as possible of the mgs parts to the
yaris auto_ss and getting rid of as many contacts as possible
because of this approach.  This worked really, really well
```

(in general)

***** soft = 0, 1 does not work for the Yaris model

***** edge penetrations

In some simulations a part of the yaris would slice into the edge of a flange. Even though soft=2 was being used, that edge-to-edge penetration was not picked up and the simulations eventually went unstable. Attempts to add extra edge penetration contacts were unsuccessful. I don't believe I ever really fixed this problem; just other changes made it go away for the specific simulation cases I ran.

***** scale factor (sfs)

Sometimes the simulation would blow up using the default sfs = 1.
Sometimes with it set to sfs=0.5 it would work.
 - example of not working: force too low and door snagged on rail
Sometimes with it set to sfs=0.75 it would work.
 - example of not working: force too high,
      causing rail bolt hole area to blow-up
I could not find a value that would always work in the various cases I was trying. This remains a case dependent parameter.

Interesting note. Ray Julin showed some very significant differences in results when varying sfs in his Thesis (e.g., Figure 26). That was for iGeo-MGS simulations.

***** reverse direction

Once the std direction of yaris-mgs simulation was working,
I switched direction of the Yaris to match full-scale testing.
Contact troubles again arose. Primarily the sfs variation quandry.

***** rail height

Simulating various rail height MGS models, resulted in different troubles - each to be addressed individually.

4.6.2 Yaris Model 2015 Update

Versions C_v1l and D_v2j of the Yaris were obtained from GMU on August 2015. Version C_v1l is the coarse mesh version of the model, and D_v2j is the detailed version. D_v2j is the descendant of the v2g model of 2012. Upon initial review of D_v2j it was determined that the steering capability was deactivated. Initial investigation into making the steering functional, revealed that that process may require quite a bit of effort. Thus, D_v2j was set aside for the time being.

Because of its reduced size (378,672 elements) a considerable amount of computer power could be saved if the reduced (coarse mesh) model was used. Thus, C_v1l was prepared for MwRSF usage. After completing the integration process, the Yaris C_v1l was simulated impacting the MGS at 100 km/h and 25 degrees. The impact corner of the Yaris underwent severe damage and the model went unstable. The last state before going unstable is shown in Figure 19. The deformation in the simulation did not compare well to physical testing of this same system. For now, this model has also been set aside.

The 2012 version v2g remains MwRSF's main 1100c vehicle model. MwRSF has three versions of this model (1) original NCAC simple stiff tire model, (2) MwRSF simplified softer tire model, and (3) MwRSF detailed tire model. Switching between the simplified tire models is rather simple. Constructing the detailed tire model for the Yaris tire size took several months of effort.

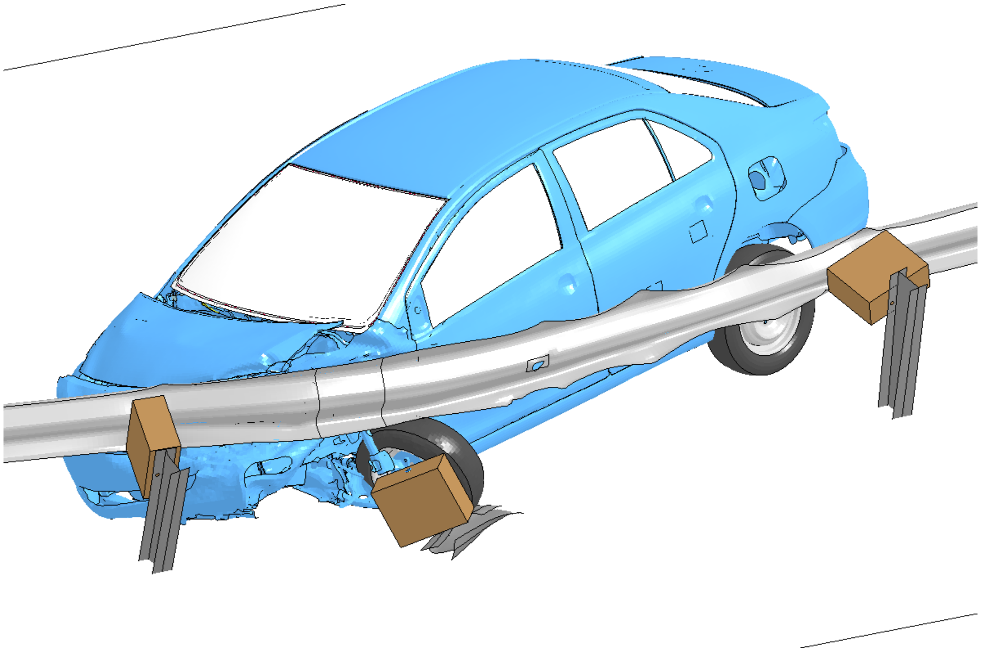


Figure 19. 2015 Yaris reduced model

4.7 Ford F800 Single Unit Truck – 8000 kg and 10000 kg

The history of the single unit truck (SUT), a model of the Ford F800, is not entirely clear. In the early 2000's NCAC released a few versions for the simulation community. At some point, Battelle received funding from FHWA to make an improved version while at the same time documenting the model details in an easy to use web site, still accessible in Aug. 2016:

http://thyme.ornl.gov/FHWA/F800WebPage/description/

MwRSF was active in investigating and using the various SUT models between 2005 and 2008, primarily focusing on Battelle's versions (see Figure 20). The SUT models were used for some concrete barrier projects and for investigating proposed updates to the vehicle for MASH.

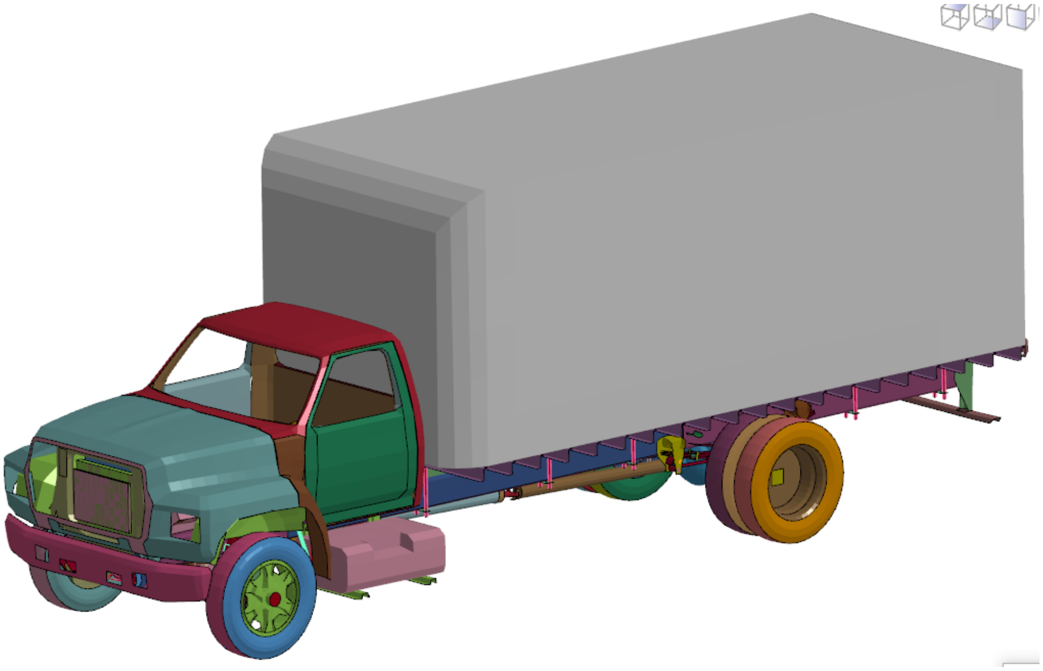


Figure 20. SUT Version 5 Model from Battelle

4.8 MwRSF Bogies

MwRSF has a suite of vehicles used for bogie testing, to simulate such testing MwRSF also maintains a suite of bogie models; these are shown in Figures 21 and 22. Portions of these bogie models were developed with project funding. Currently, these models are up-to-date and do not require any significant modifications. The usage of the models consists of (1) orientating the vehicle in the desired direction, (2) updating the mass to what is used in the actual bogie test, (3) changing the impactor head (if required), and (4) changing the height of the impactor.

Figure 21. MwRSF Bogies

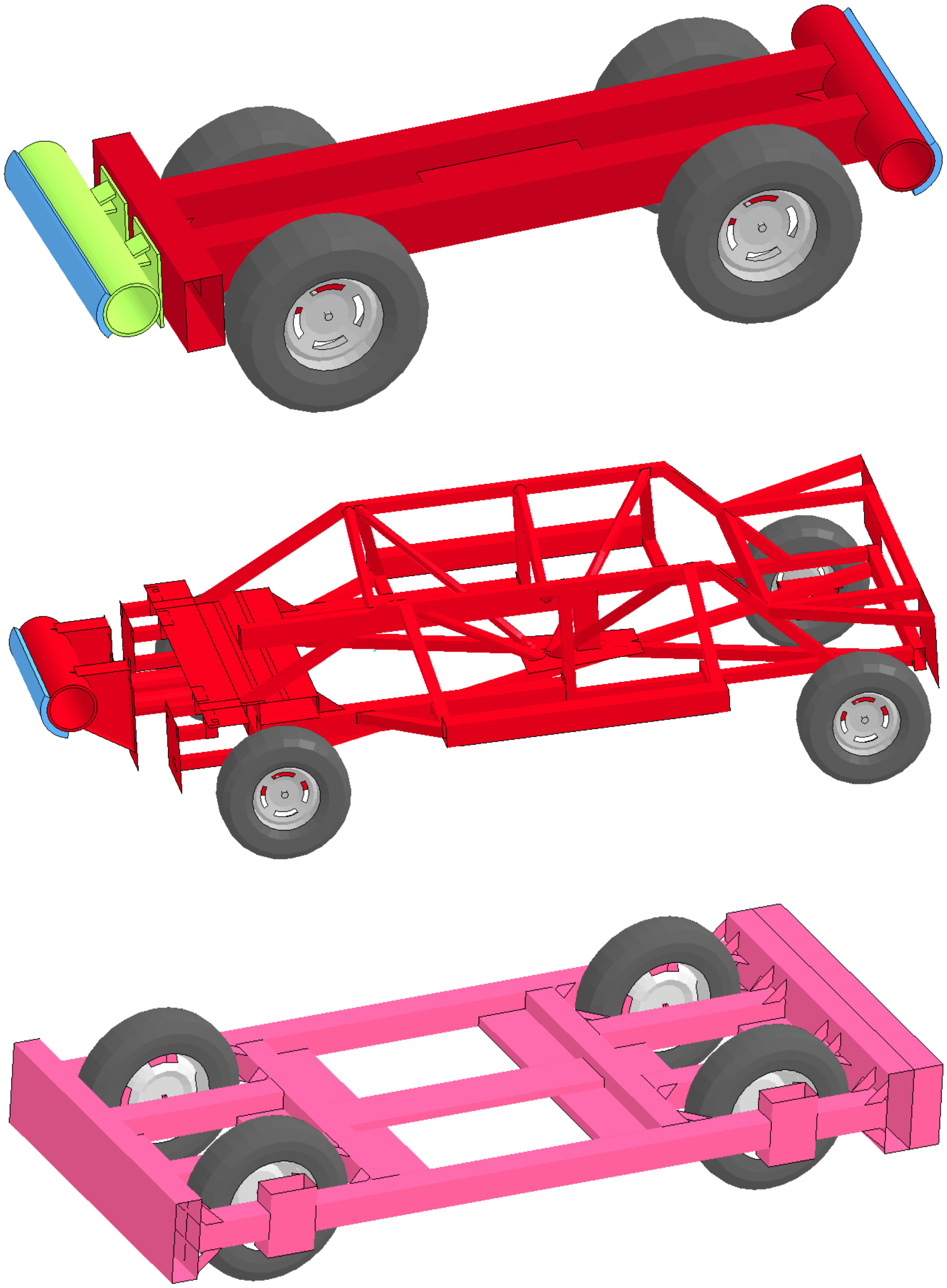


Figure 22. MwRSF Bogie Models

Sometimes a very simplified vehicle model can be used to investigate the basic behavior of a roadside design. For example, a solid element bogie model with foam material model can be made to crush with reasonable force loads compared to a vehicle (see Figure 23). The front end of a vehicle is usually made to crush and absorb the energy of an impact, while the back end is more structurally rigid, protecting the occupant from deforming parts. That phenomenon is captured in the simple model with two different nonlinear crushing material properties.

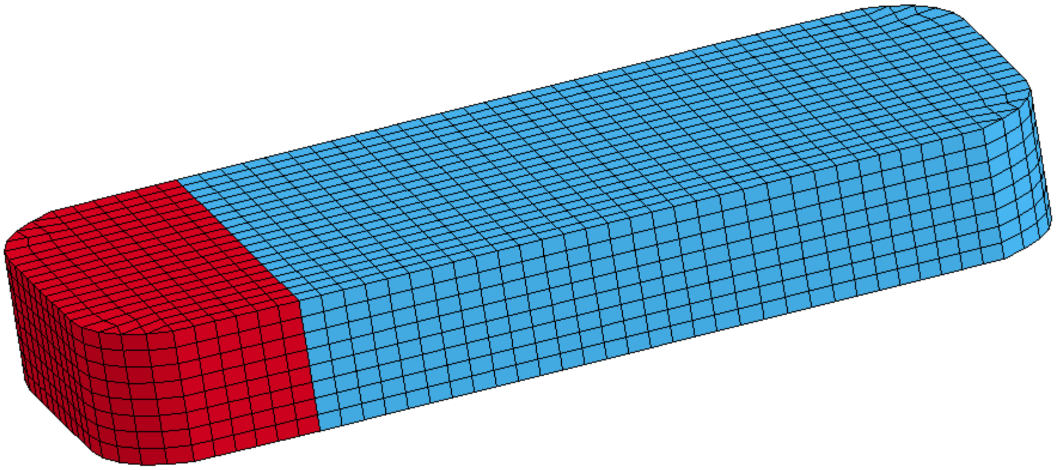


Figure 23. Solid Element Foam Bogie

4.9 Component and Subsystem Models

In order to investigate and improve various portions of a model, it is common to create component and subsystem models to aid in that process. As a single example, when the Silverado suspension system needed to be investigated to determine and improve its various characteristics, the subsystem model depicted in Figure 24 was developed. With this isolated subsystem the springs, shocks, deformability, joint stiffnesses, steering, and fracturing of connections could all be examined much easier and in greater detail than just using the entire vehicle model.

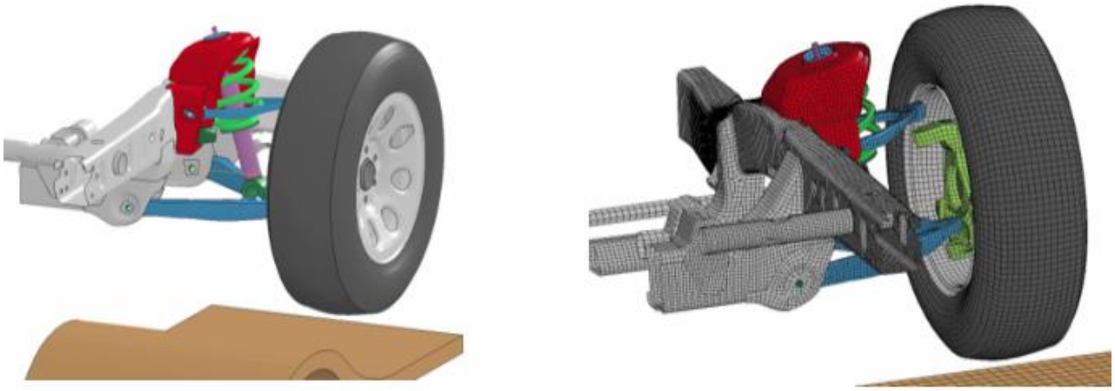


Figure 24. Silverado Front Suspension Subsystem

5 MGS MODELING

Since 2006 the Midwest Guardrail System (MGS) has been the foundation for many subsequent projects, including the MGS with approach slopes, curbs, maximum height, minimum effective length, downstream anchorage requirements, transition to concrete barriers, and long-span. Overtime, improvement or refinement to the MGS LS-DYNA model has been required in order to continually improve MwRSF design and analysis capabilities. One such example is the modeling of the anchorage, as shown in Figure 25. Some of the projects using the MGS would use the simple anchor model when the anchorage was determined to be relatively non-influential during an impact event, saving significant cpu time. Other projects would use the most detailed version available because the anchorage behavior plays a significant role in the overall system behavior.

Other aspects of the MGS model also have multiple versions and techniques deployed, including the post-in-soil models, the rail-to-post connections, and the splices. All of these have required multiple investigations to improve their usefulness. As an example, a post-in-soil modeling effort is described in Section 6.

Many of the modeling details of the MGS are not as detailed or as accurate as ultimately desired for predicting system behavior. Although great strides have been made, much more remains in this area.

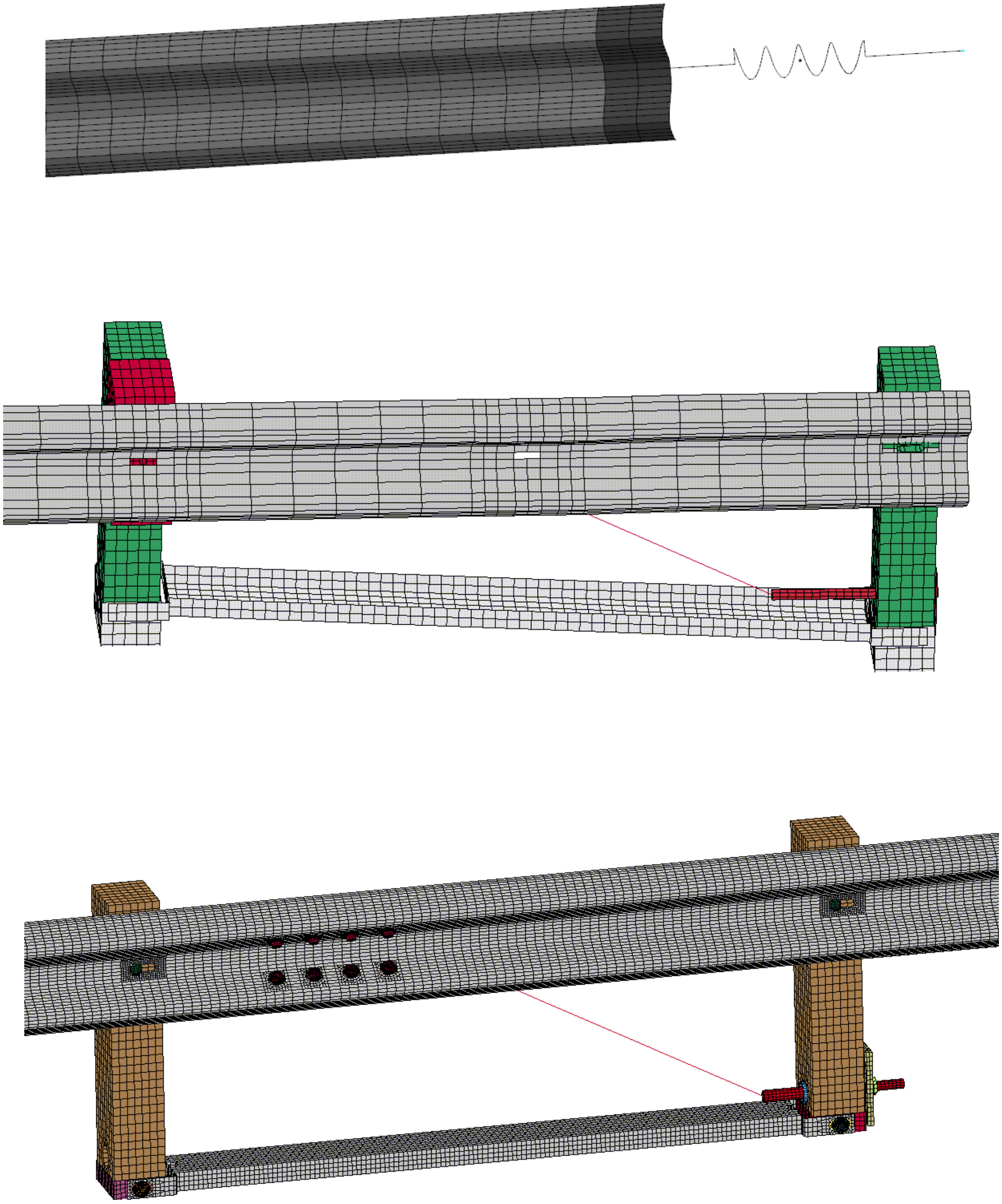


Figure 25. Various Modeling Approaches for MGS End Anchor - 2011

6 SOIL MODELING

For the most part, W-beam and thrie-beam guardrail systems are installed in soil foundations. The interaction of the guardrail posts and soil is a critical factor in how a guardrail system behaves under impact conditions. In order to simulate that behavior with LS-DYNA, the post-in-soil behavior must be modeled. Over the past 23 years there have been many techniques developed to model the soil. Throughout 2014 and the first half of 2015, an attempt was made to gather the most promising soil modeling techniques and document those in a PowerPoint presentation, and generate actual LS-DYNA models that used those techniques. This work was to be shared by all those interested.

As a result of that work, during the Finite Element Modeling & Crash Simulation Forum held during the 2015 TRB AFB(20) Summer Meeting in Chicago, IL, J.D. Reid led a two-hour discussion on soil modeling. The following pages contain a copy of the PowerPoint slides used to lead that discussion. The dyna decks (i.e., LS-DYNA models) used to generate much of the presentation are available.

The presentation outline was as follows:

- Phase I – Modeling Posts in Soil: Best Practices
- Phase II – Soil Modeling
  - Part 1 – single element study
  - Part 2 – three standardized bogie cases
  - Part 3 – application: MGS upstream anchor

Soil Modeling Phase I

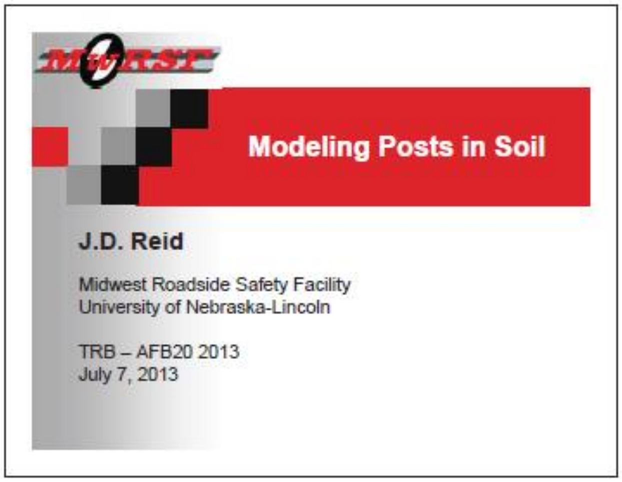
J.D. Reid

Midwest Roadside Safety Facility
University of Nebraska-Lincoln

Finite Element Modeling & Crash Simulation Forum
Chicago, IL
July 16, 2015

Introduction

- Phase I: Short Term
  - ⇨ **A Library of LS-Dyna Techniques**
- Phase II: Intermediate Term
  - ⇨ **Modeling Posts in Soil**
- Long Term
  - ⇨ **Soil Material Characterization**

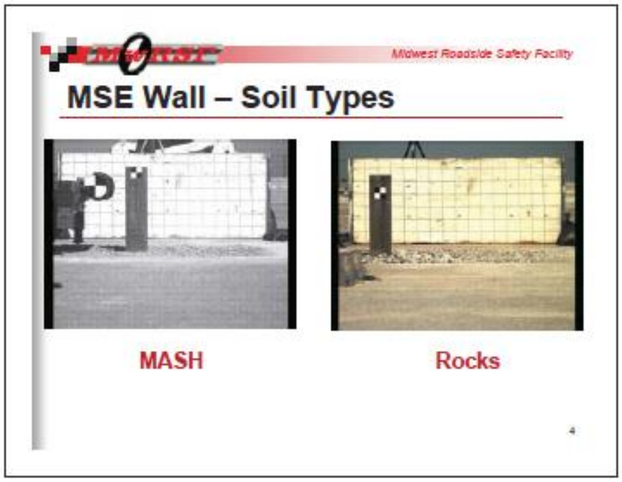


Modeling Posts in Soil

J.D. Reid

Midwest Roadside Safety Facility
University of Nebraska-Lincoln

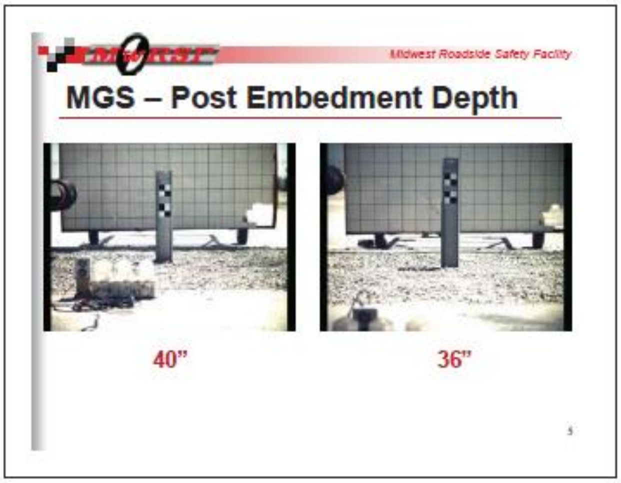
TRB – AFB20 2013
July 7, 2013



MSE Wall – Soil Types

MASH

Rocks



MGS – Post Embedment Depth

40”

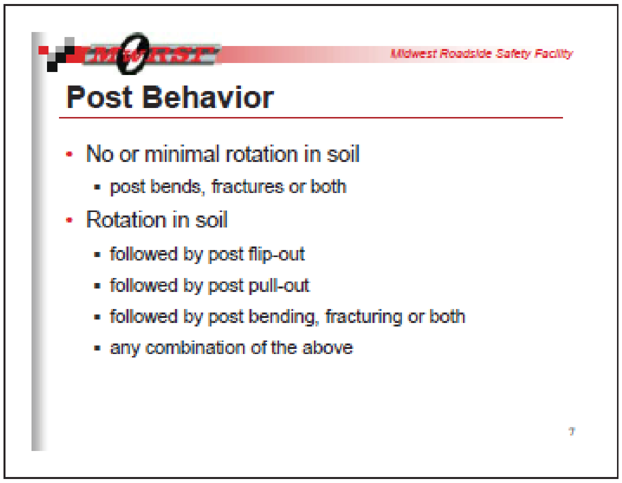
36”

MGS – Post Embedment Depth

40”

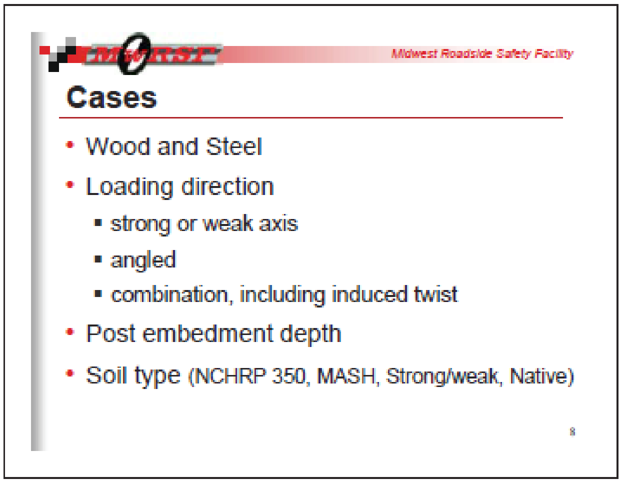
36”

Figure 26. Soil Modeling: Phase I, slides 1 – 6



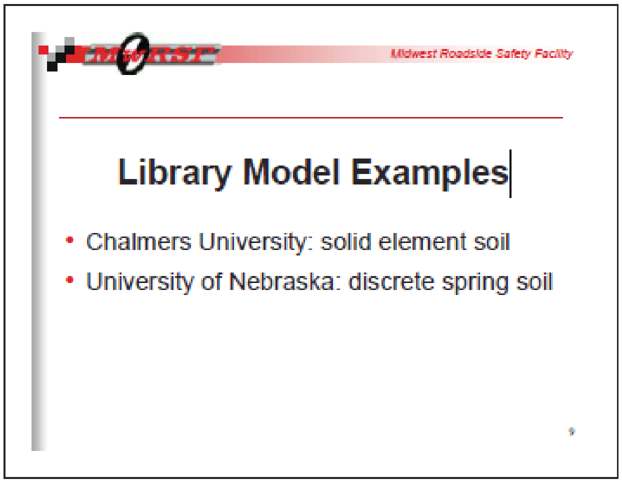
Post Behavior

- No or minimal rotation in soil
  - post bends, fractures or both
- Rotation in soil
  - followed by post flip-out
  - followed by post pull-out
  - followed by post bending, fracturing or both
  - any combination of the above



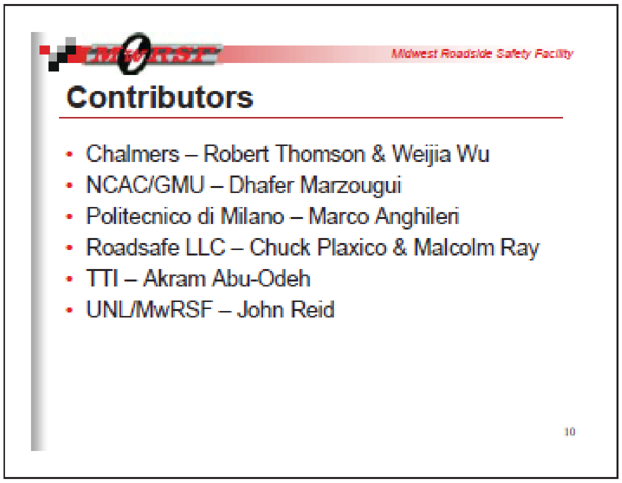
Cases

- Wood and Steel
- Loading direction
  - strong or weak axis
  - angled
  - combination, including induced twist
- Post embedment depth
- Soil type (NCHRP 350, MASH, Strong/weak, Native)



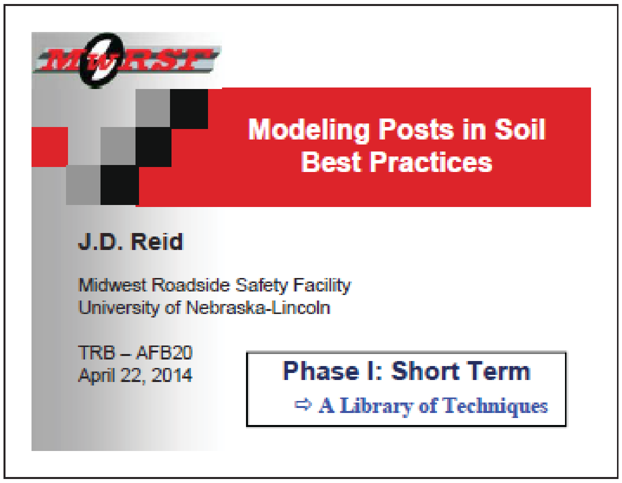
Library Model Examples

- Chalmers University: solid element soil
- University of Nebraska: discrete spring soil



Contributors

- Chalmers – Robert Thomson & Weijia Wu
- NCAC/GMU – Dhafer Marzougui
- Politecnico di Milano – Marco Anghileri
- Roadsafe LLC – Chuck Plaxico & Malcolm Ray
- TTI – Akram Abu-Odeh
- UNL/MwRSF – John Reid



Modeling Posts in Soil Best Practices

J.D. Reid

Midwest Roadside Safety Facility
University of Nebraska-Lincoln

TRB – AFB20
April 22, 2014

Phase I: Short Term
⇨ **A Library of Techniques**

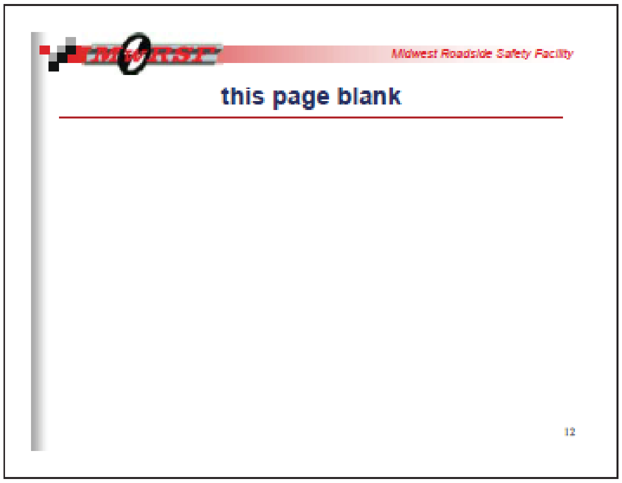


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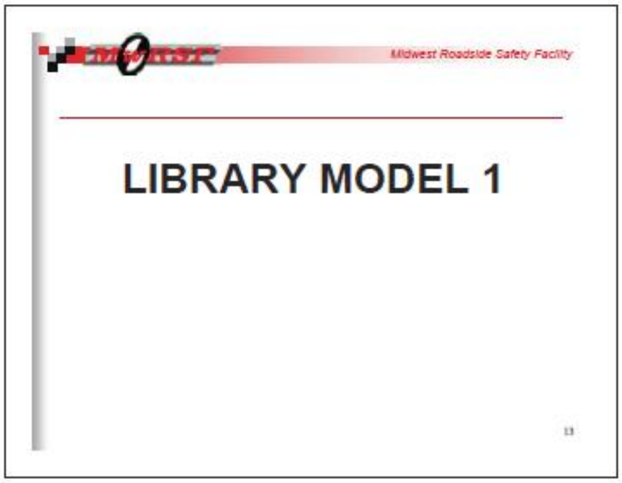
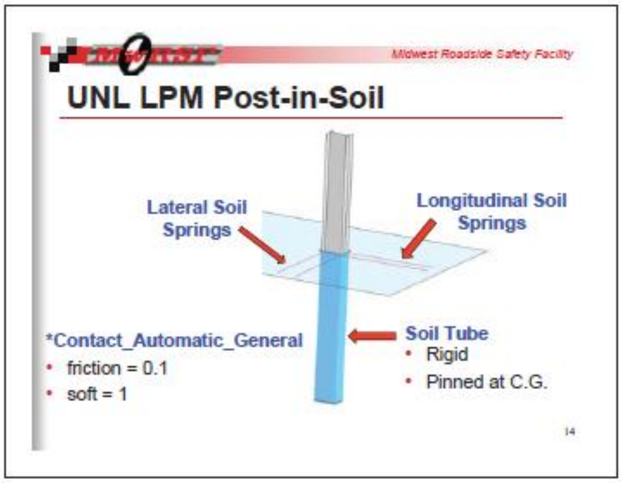
Figure 27. Soil Modeling: Phase I, slides 7 – 12



LIBRARY MODEL 1



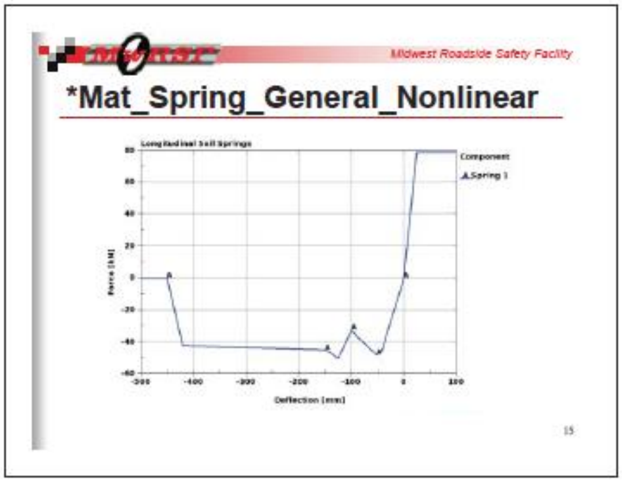
UNL LPM Post-in-Soil

Lateral Soil Springs

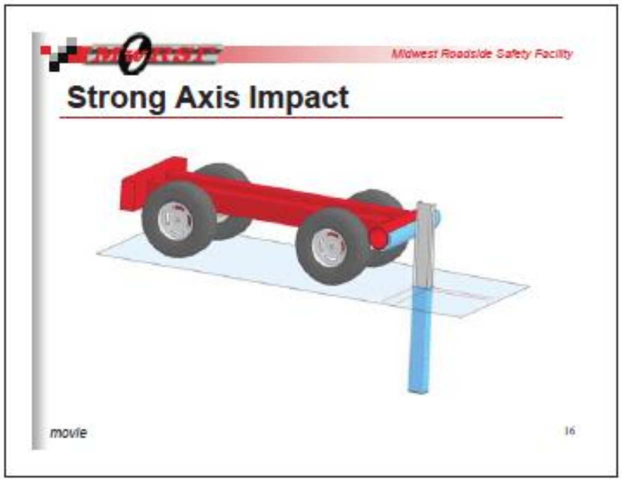
Longitudinal Soil Springs

*Contact_Automatic_General
- friction = 0.1
- soft = 1

Soil Tube
- Rigid
- Pinned at C.G.

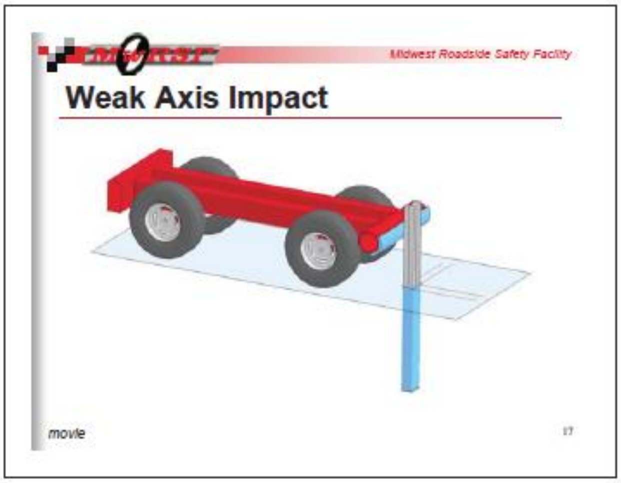


***Mat_Spring_General_Nonlinear**



Strong Axis Impact

movie



Weak Axis Impact

movie

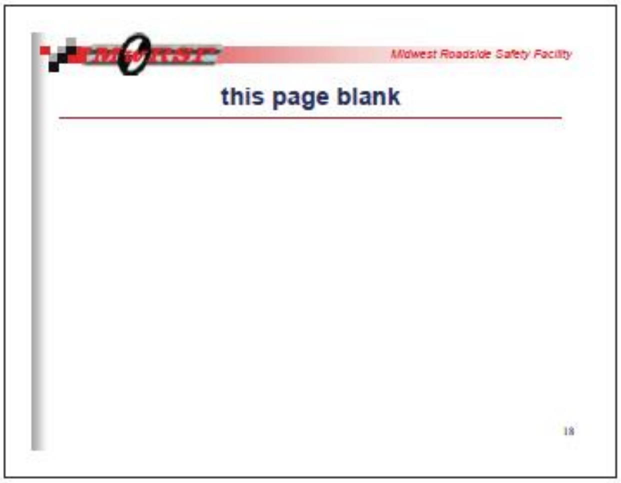


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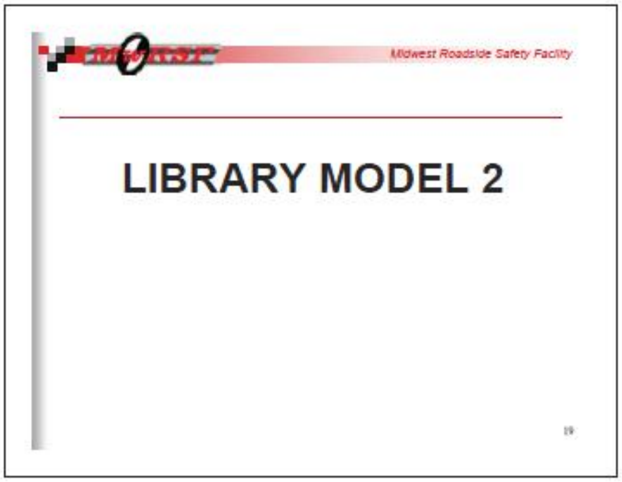
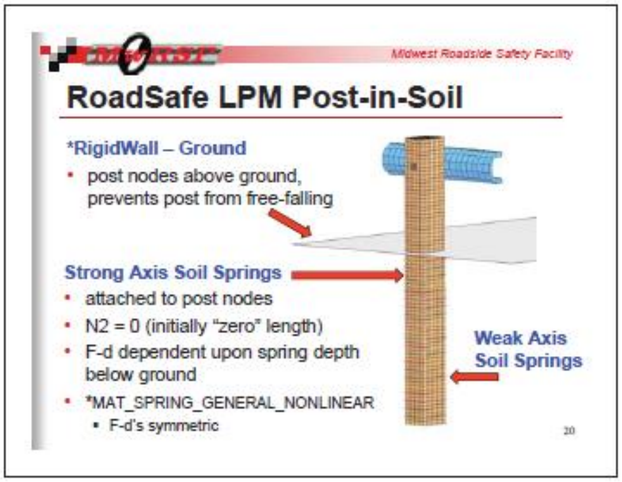
Figure 28. Soil Modeling: Phase I, slides 13 – 18



LIBRARY MODEL 2

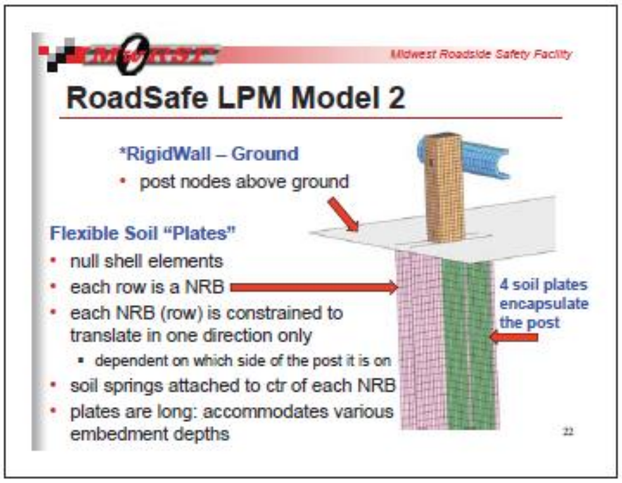


RoadSafe LPM Post-in-Soil

***RigidWall – Ground**
- post nodes above ground, prevents post from free-falling

Strong Axis Soil Springs
- attached to post nodes
- N2 = 0 (initially "zero" length)
- F-d dependent upon spring depth below ground
- *MAT_SPRING_GENERAL_NONLINEAR
  - F-d's symmetric

Weak Axis Soil Springs



RoadSafe LPM Model 2

***RigidWall – Ground**
- post nodes above ground

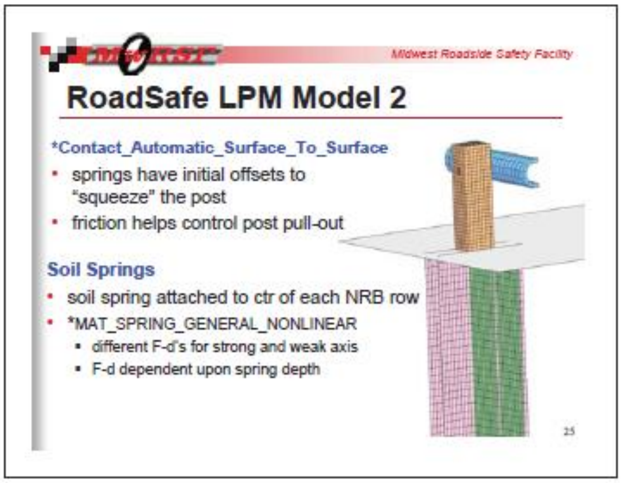
Flexible Soil "Plates"
- null shell elements
- each row is a NRB
- each NRB (row) is constrained to translate in one direction only
  - dependent on which side of the post it is on
- soil springs attached to ctr of each NRB
- plates are long: accommodates various embedment depths

4 soil plates encapsulate the post

RoadSafe LPM Model 2

RoadSafe LPM Model 2

movie

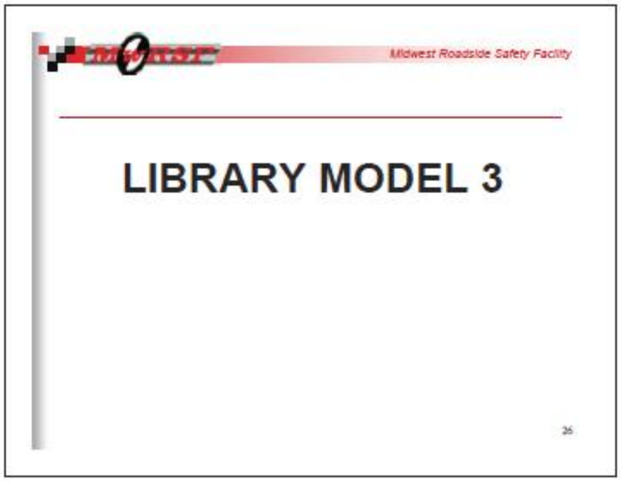


RoadSafe LPM Model 2

***Contact_Automatic_Surface_To_Surface**
- springs have initial offsets to "squeeze" the post
- friction helps control post pull-out

Soil Springs
- soil spring attached to ctr of each NRB row
- *MAT_SPRING_GENERAL_NONLINEAR
  - different F-d's for strong and weak axis
  - F-d dependent upon spring depth

Figure 29. Soil Modeling: Phase I, slides 19 – 25



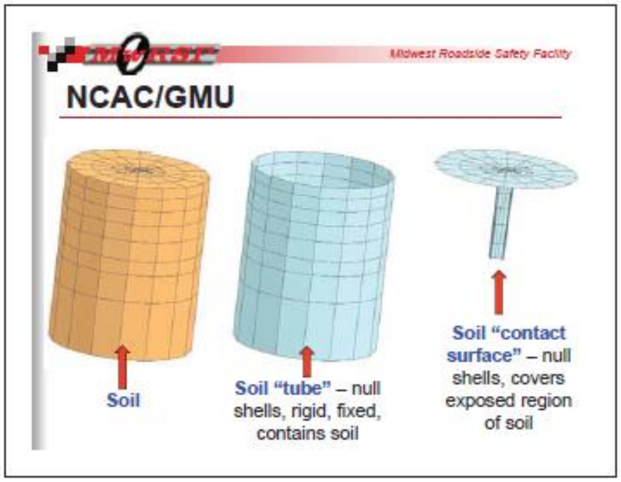
Midwest Roadside Safety Facility

LIBRARY MODEL 3

Midwest Roadside Safety Facility

NCAC/GMU

movies



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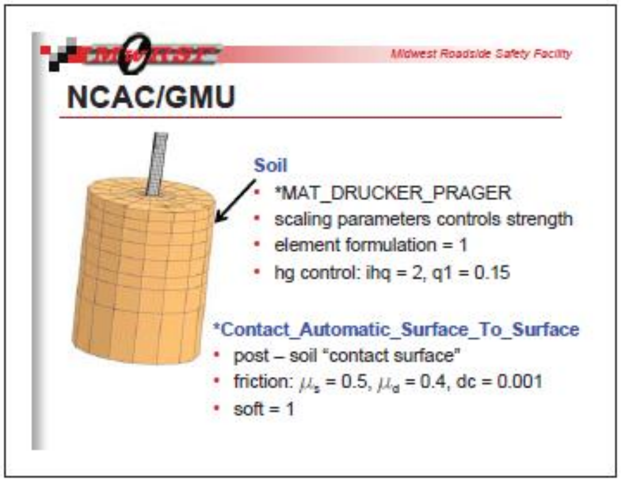
NCAC/GMU

Soil

Soil "tube" – null shells, rigid, fixed, contains soil

Soil "contact surface" – null shells, covers exposed region of soil

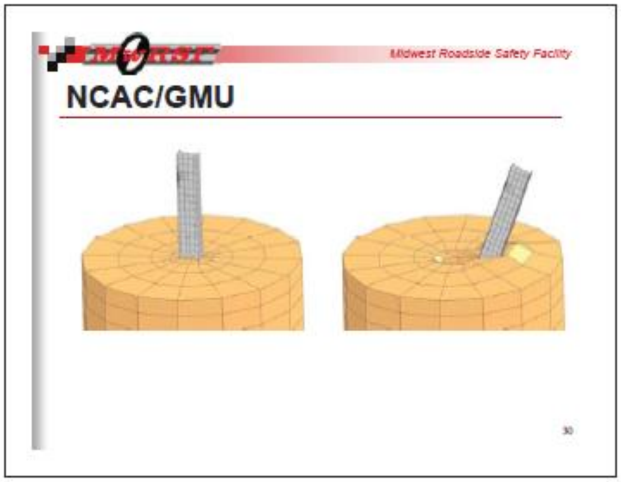


Midwest Roadside Safety Facility

NCAC/GMU

Soil
- *MAT_DRUCKER_PRAGER
- scaling parameters controls strength
- element formulation = 1
- hg control: ihq = 2, q1 = 0.15

***Contact_Automatic_Surface_To_Surface**
- post – soil "contact surface"
- friction: $\mu_s = 0.5$, $\mu_d = 0.4$, dc = 0.001
- soft = 1



Midwest Roadside Safety Facility

NCAC/GMU

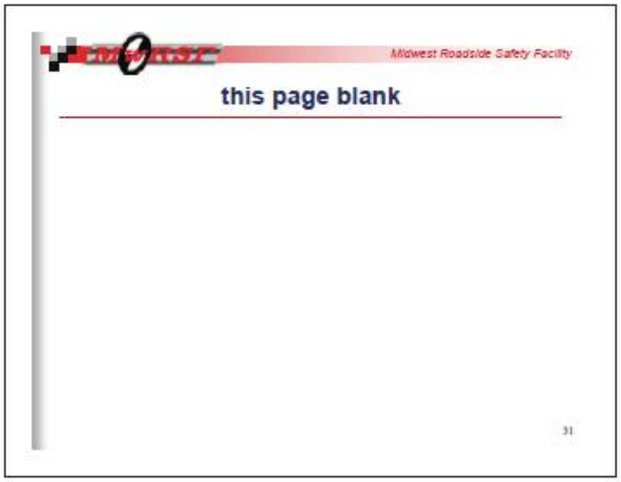


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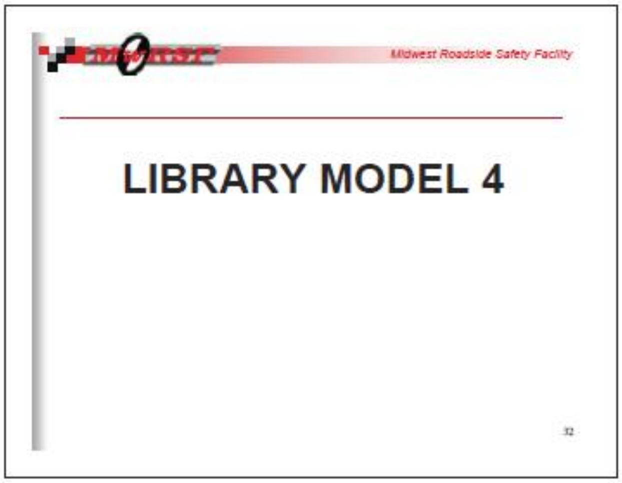
Figure 30. Soil Modeling: Phase I, slides 26 – 31



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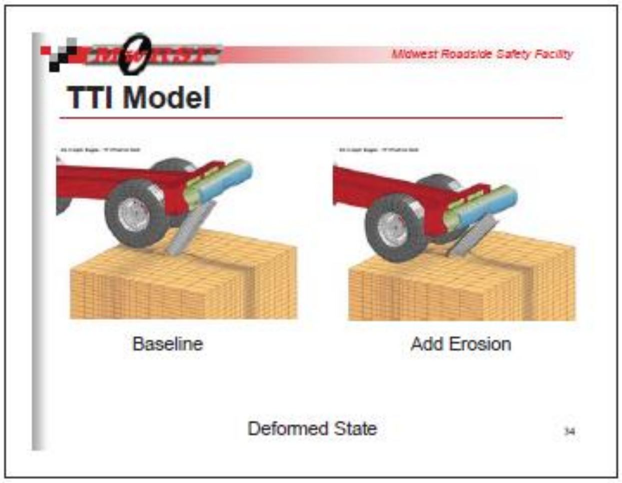
LIBRARY MODEL 4



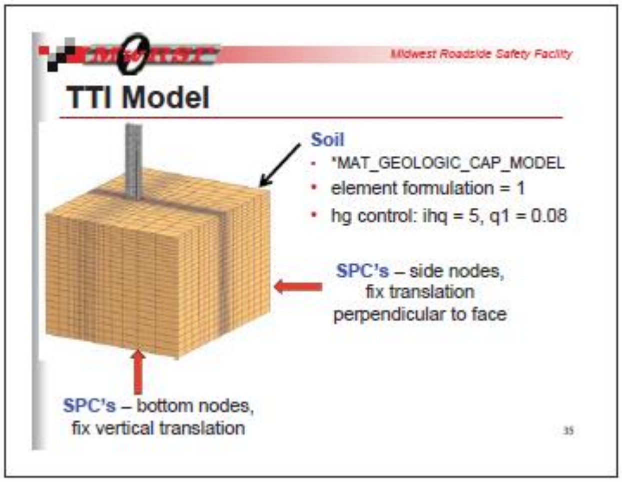
Midwest Roadside Safety Facility

TTI Model

Baseline

Add Erosion

Deformed State



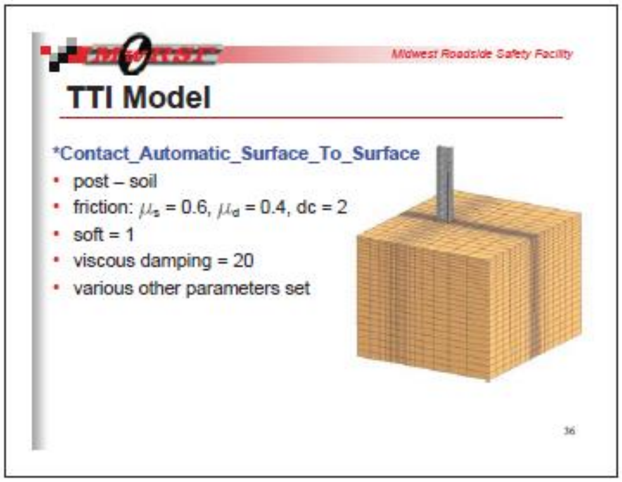
Midwest Roadside Safety Facility

TTI Model

Soil
- *MAT_GEOLOGIC_CAP_MODEL
- element formulation = 1
- hg control: ihq = 5, q1 = 0.08

SPC's – side nodes, fix translation perpendicular to face

SPC's – bottom nodes, fix vertical translation



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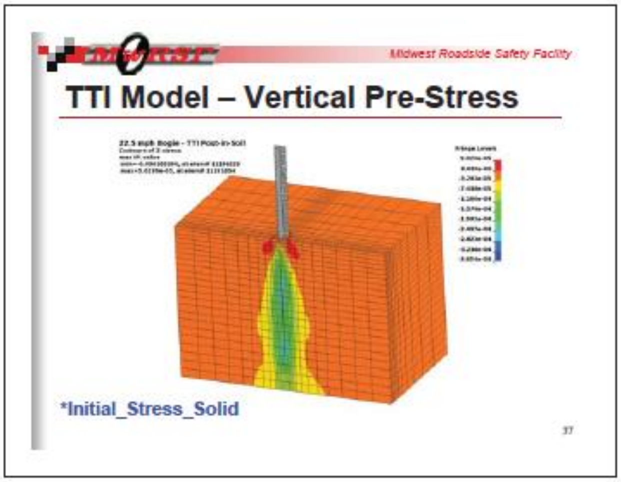
TTI Model

*Contact_Automatic_Surface_To_Surface
- post – soil
- friction: $\mu_s = 0.6$, $\mu_d = 0.4$, dc = 2
- soft = 1
- viscous damping = 20
- various other parameters set



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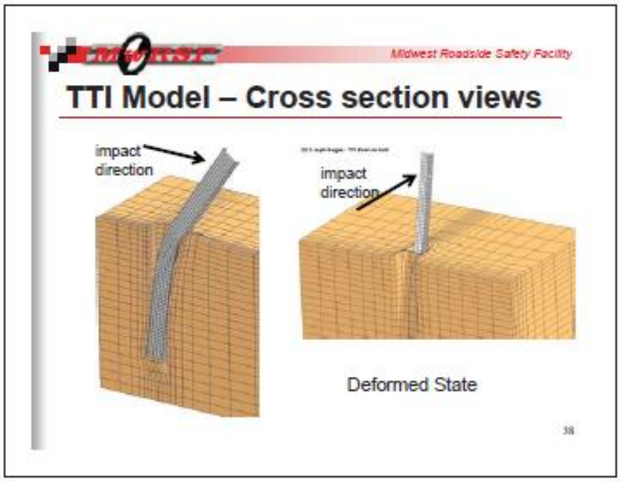
TTI Model – Vertical Pre-Stress

*Initial_Stress_Solid



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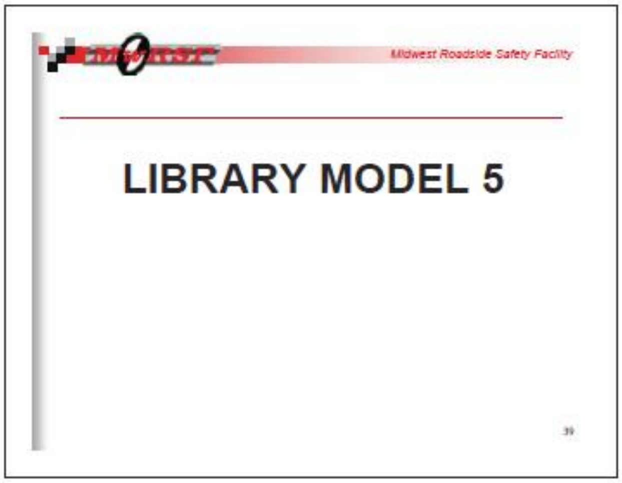
TTI Model – Cross section views

Deformed State

Figure 31. Soil Modeling: Phase I, slides 32 – 38



LIBRARY MODEL 5

Politecnico di Milano (Italy)

Soil

- *MAT_SOIL_AND_FOAM
- Element formulation = 1
- HG control: default
- Lower soil pressure defined 10x higher than upper soil

SPC's – outer nodes, fix translation

SPC's – bottom nodes, fix translation

Politecnico di Milano (Italy)

Contacts

*CONSTRAINED_LAGRANGE_IN_SOLID

- Slave: post Master: soil
- ctype = 2: constrained acceleration and velocity
- direct = 1: normal, compression and tension

*CONTACT_AUTOMATIC_SINGLE_SURFACE

- post flange and web

*CONTACT_TIED_NODES_TO_SURFACE_OFFSET

- Slave: post web edges
- Master: flange

Politecnico di Milano (Italy)

movie

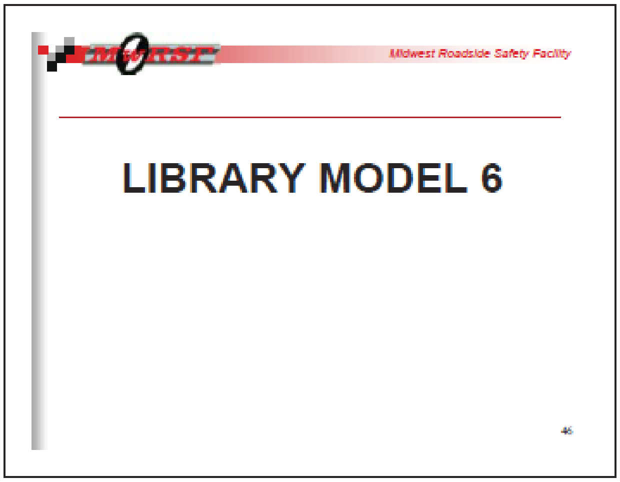
Politecnico di Milano (Italy)

Deformed State

Politecnico di Milano (Italy)

Cross Section View

Figure 32. Soil Modeling: Phase I, slides 39 – 45



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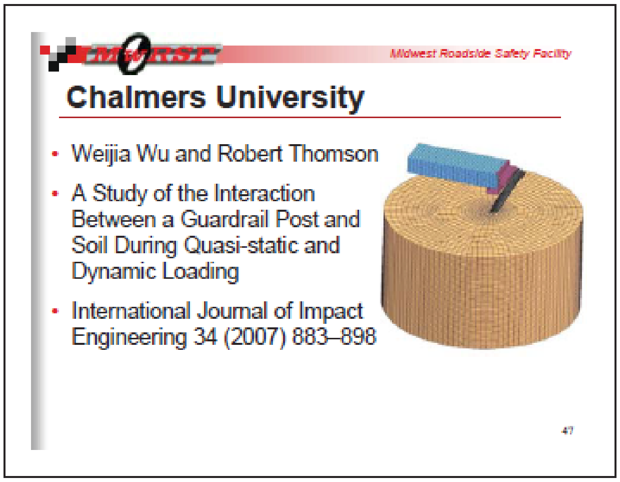
LIBRARY MODEL 6



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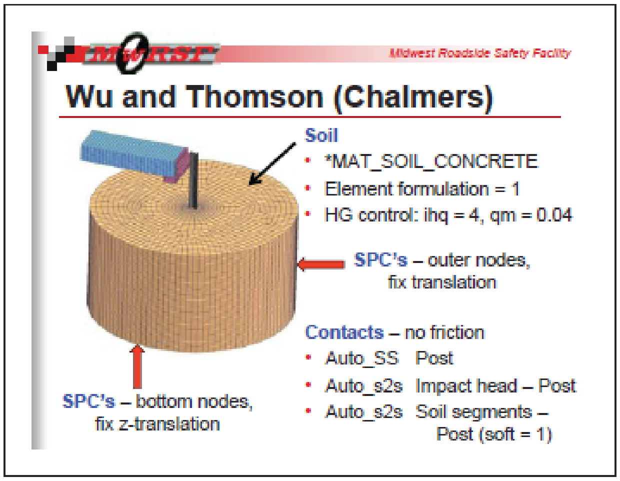
Chalmers University

- Weijia Wu and Robert Thomson
- A Study of the Interaction Between a Guardrail Post and Soil During Quasi-static and Dynamic Loading
- International Journal of Impact Engineering 34 (2007) 883–898



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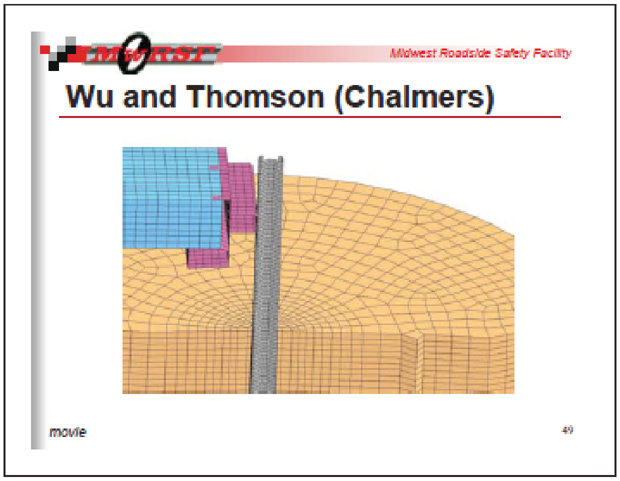
Wu and Thomson (Chalmers)

Soil
- *MAT_SOIL_CONCRETE
- Element formulation = 1
- HG control: ihq = 4, qm = 0.04

SPC's – outer nodes, fix translation

Contacts – no friction
- Auto_SS Post
- Auto_s2s Impact head – Post
- Auto_s2s Soil segments – Post (soft = 1)

SPC's – bottom nodes, fix z-translation



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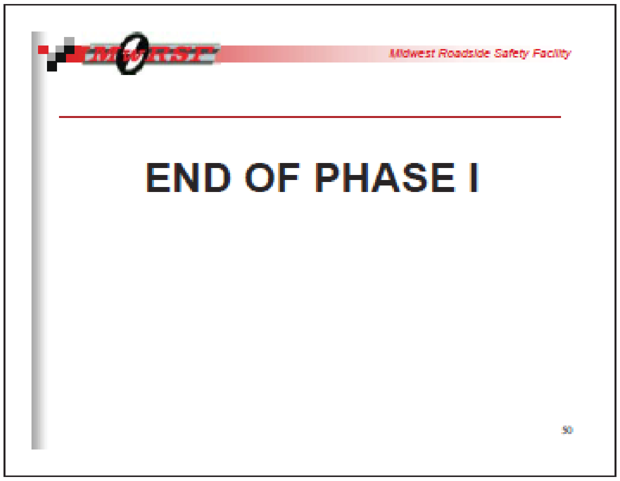
Wu and Thomson (Chalmers)

movie



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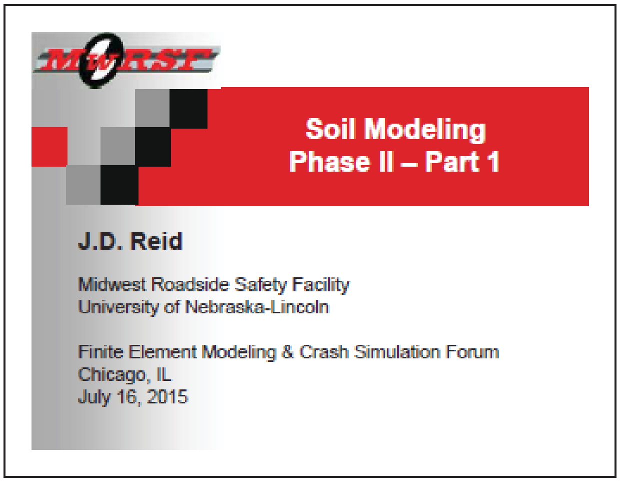
END OF PHASE I

Figure 33. Soil Modeling: Phase I, slides 46 – 50

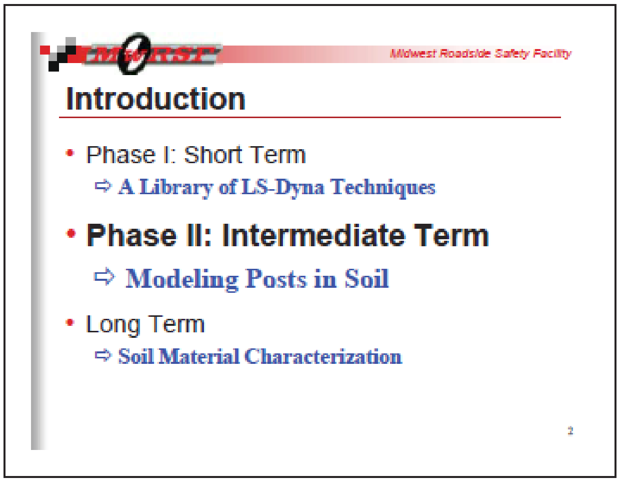


Soil Modeling
Phase II – Part 1

J.D. Reid

Midwest Roadside Safety Facility
University of Nebraska-Lincoln

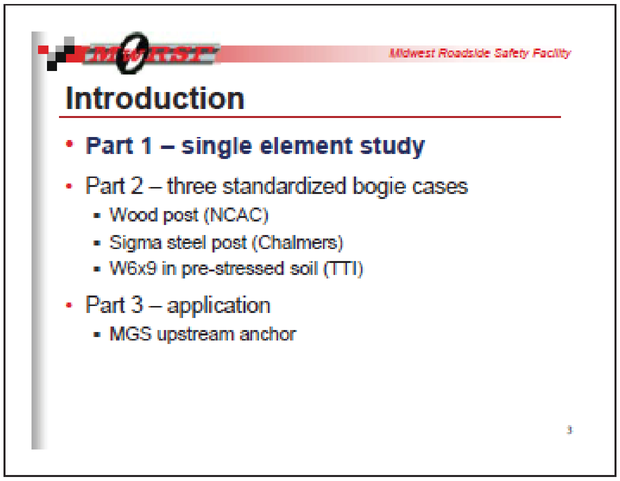
Finite Element Modeling & Crash Simulation Forum
Chicago, IL
July 16, 2015



Midwest Roadside Safety Facility

Introduction

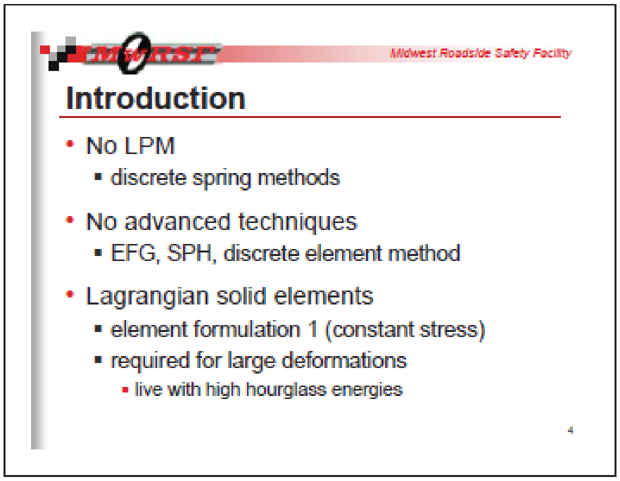
- Phase I: Short Term
  - ⇨ **A Library of LS-Dyna Techniques**
- **Phase II: Intermediate Term**
  - ⇨ **Modeling Posts in Soil**
- Long Term
  - ⇨ **Soil Material Characterization**



Midwest Roadside Safety Facility

Introduction

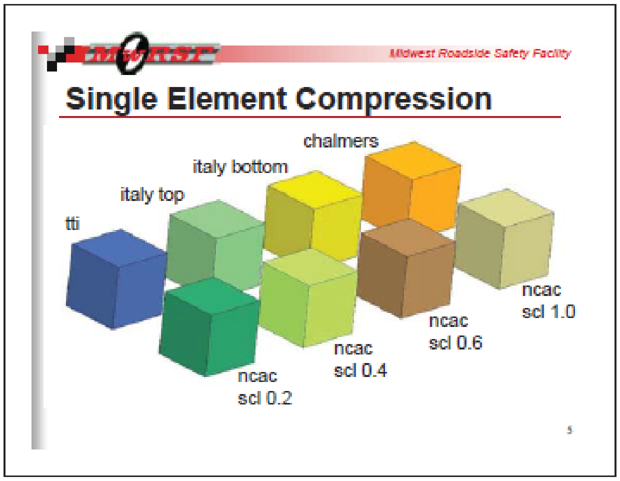
- **Part 1 – single element study**
- Part 2 – three standardized bogie cases
  - Wood post (NCAC)
  - Sigma steel post (Chalmers)
  - W6x9 in pre-stressed soil (TTI)
- Part 3 – application
  - MGS upstream anchor



Midwest Roadside Safety Facility

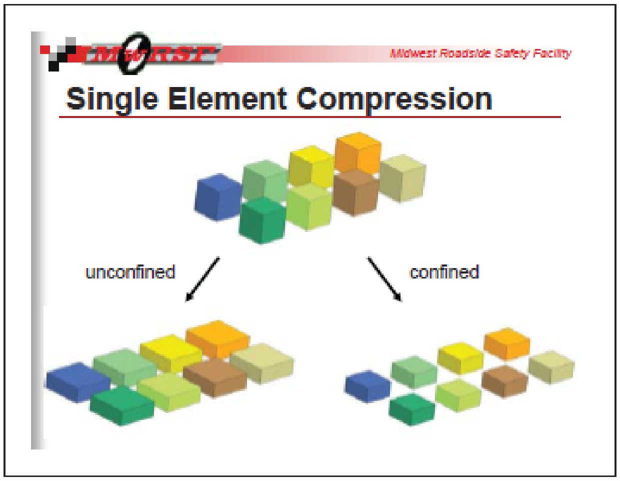
Introduction

- No LPM
  - discrete spring methods
- No advanced techniques
  - EFG, SPH, discrete element method
- Lagrangian solid elements
  - element formulation 1 (constant stress)
  - required for large deformations
    - live with high hourglass energies



Midwest Roadside Safety Facility

Single Element Compression



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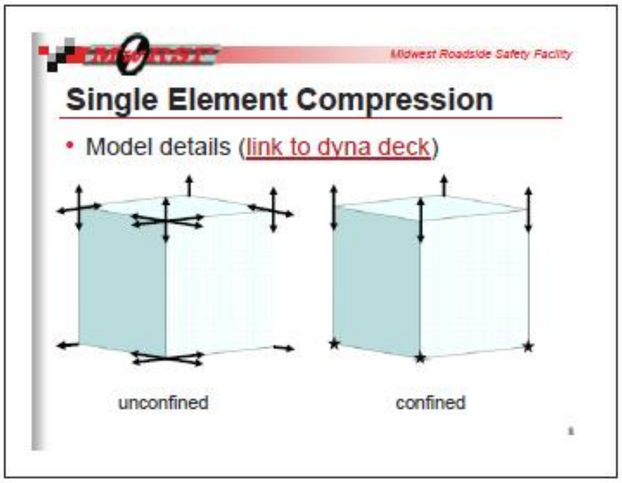
Single Element Compression

Figure 34. Soil Modeling: Phase II, Part 1, slides 1 – 6



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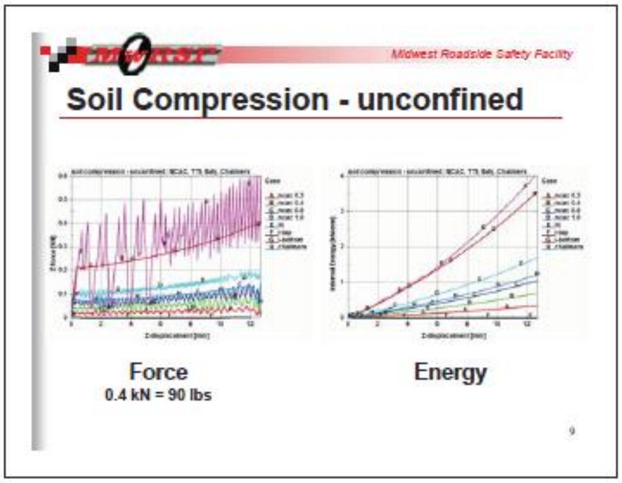
Single Element Compression

- Model details (link to dyna deck)



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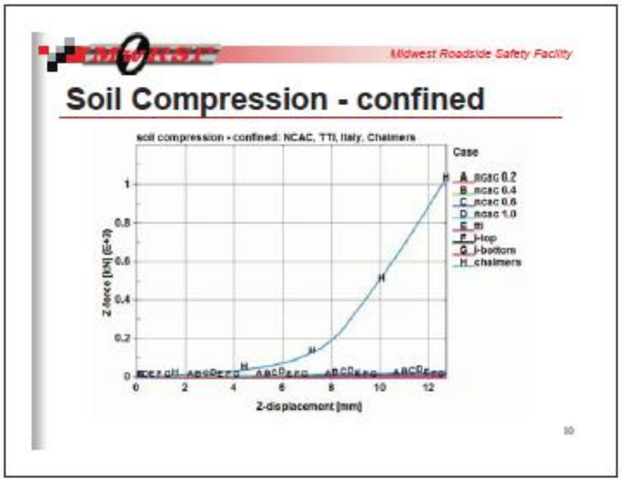
Soil Compression - unconfined

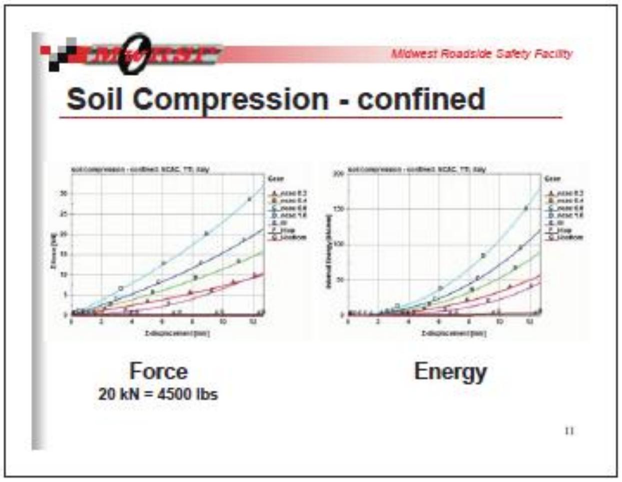
Force
0.4 kN = 90 lbs

Energy



Midwest Roadside Safety Facility

Soil Compression - confined



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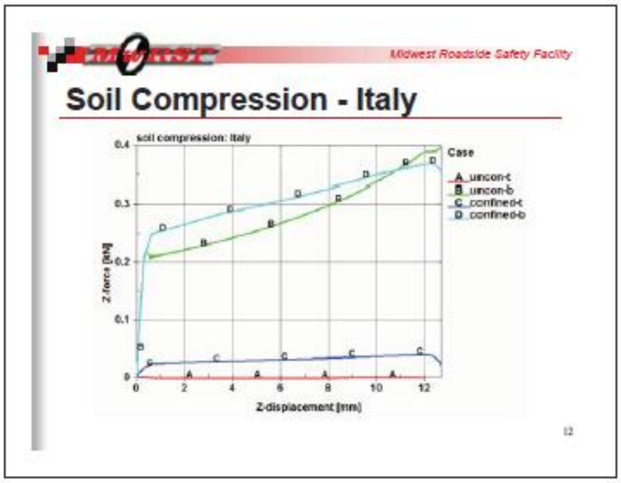
Soil Compression - confined

Force
20 kN = 4500 lbs

Energy



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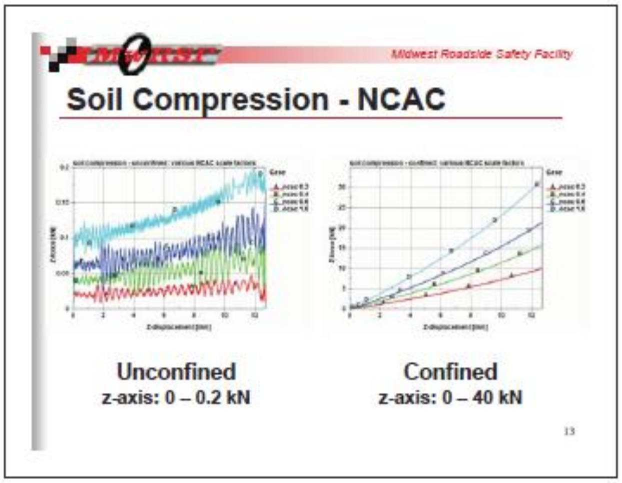
Soil Compression - Italy



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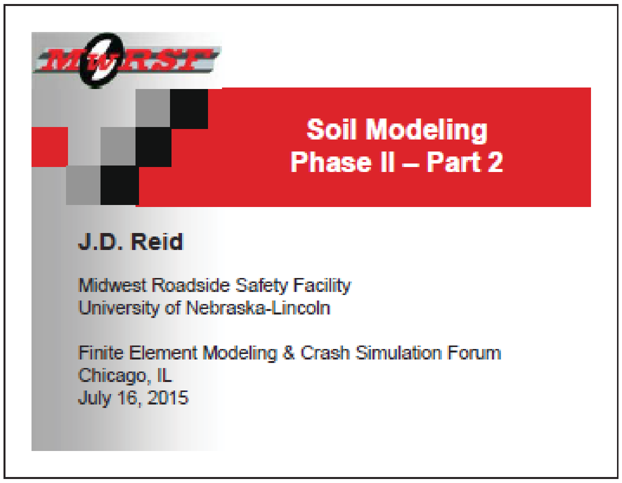
Soil Compression - NCAC

Unconfined
z-axis: 0 – 0.2 kN

Confined
z-axis: 0 – 40 kN

Figure 35. Soil Modeling: Phase II, Part 1, slides 8 –13



Soil Modeling
Phase II – Part 2

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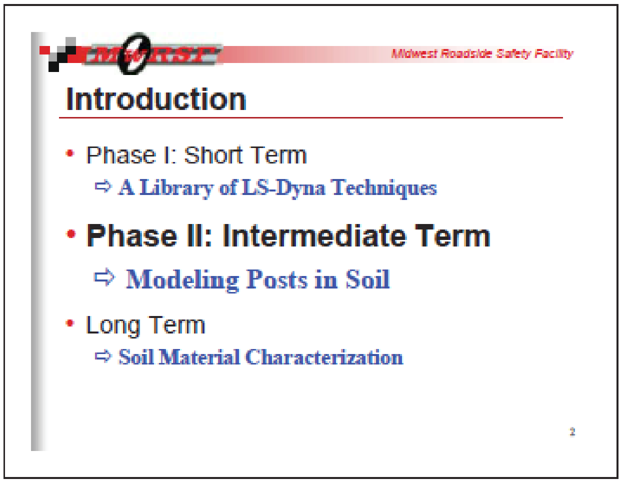
Chicago, IL
July 16, 2015



Introduction

- Phase I: Short Term
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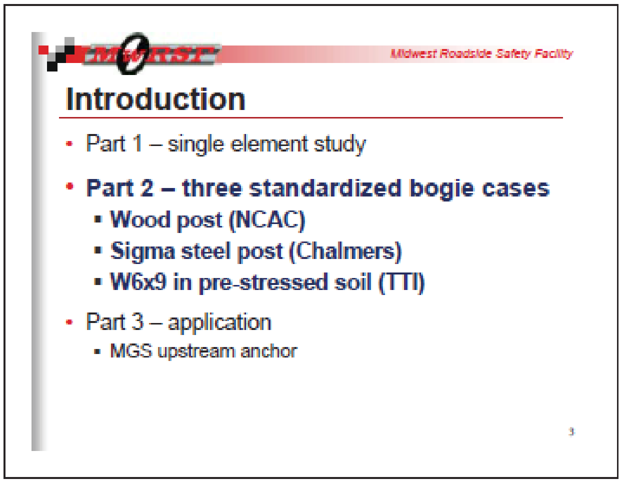
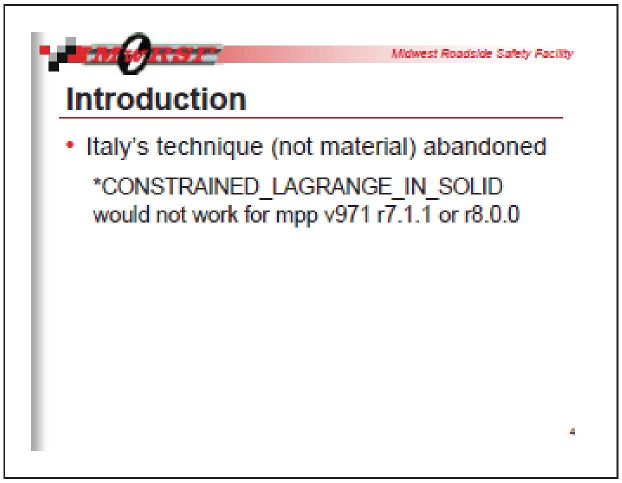
- **Phase II: Intermediate Term**
  - ⇨ **Modeling Posts in Soil**
- Long Term
  - ⇨ Soil Material Characterization



Introduction

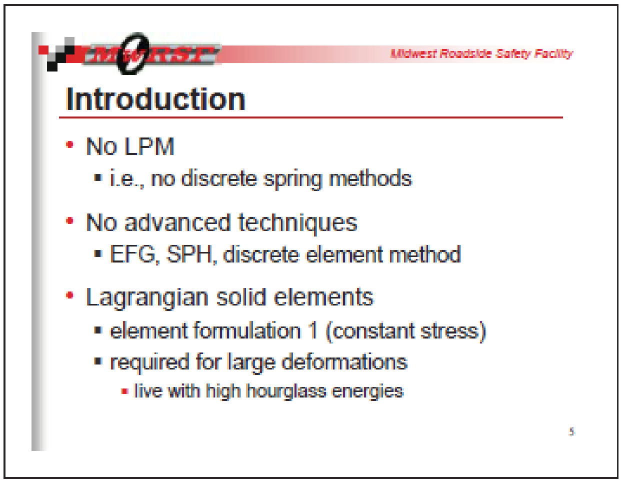
- Part 1 – single element study
- **Part 2 – three standardized bogie cases**
  - **Wood post (NCAC)**
  - **Sigma steel post (Chalmers)**
  - **W6x9 in pre-stressed soil (TTI)**
- Part 3 – application
  - MGS upstream anchor



Introduction

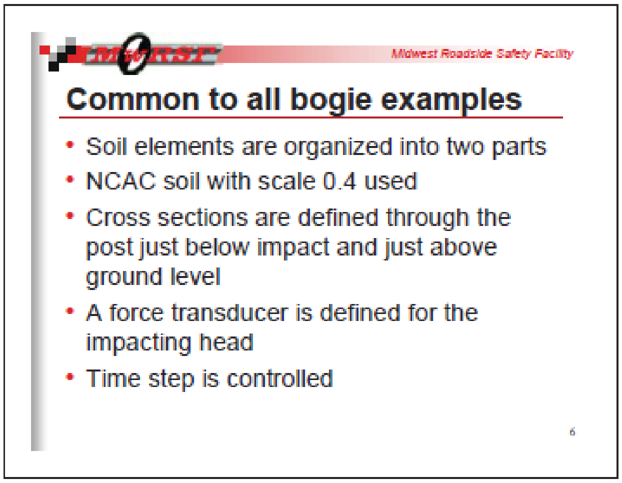
- Italy's technique (not material) abandoned

  *CONSTRAINED_LAGRANGE_IN_SOLID
  would not work for mpp v971 r7.1.1 or r8.0.0



Introduction

- No LPM
  - i.e., no discrete spring methods
- No advanced techniques
  - EFG, SPH, discrete element method
- Lagrangian solid elements
  - element formulation 1 (constant stress)
  - required for large deformations
    - live with high hourglass energies



Common to all bogie examples

- Soil elements are organized into two parts
- NCAC soil with scale 0.4 used
- Cross sections are defined through the post just below impact and just above ground level
- A force transducer is defined for the impacting head
- Time step is controlled

Figure 36. Soil Modeling: Phase II, Part 2, slides 1 – 6

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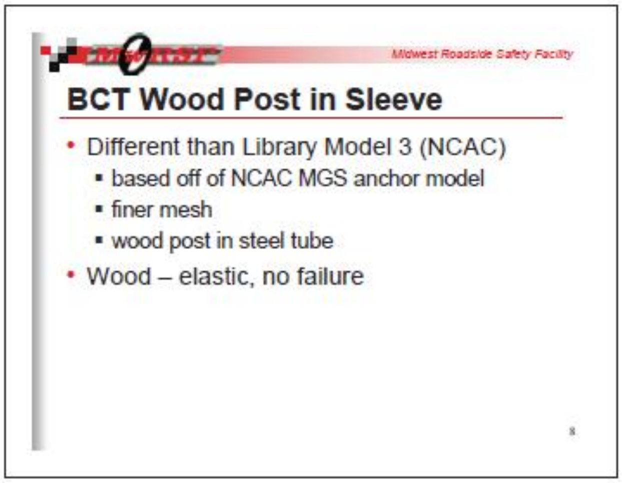
BCT Wood Post in Sleeve



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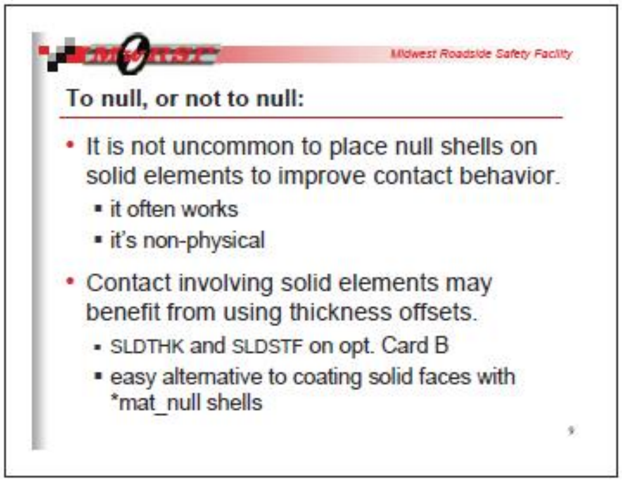
BCT Wood Post in Sleeve

- Different than Library Model 3 (NCAC)
  - based off of NCAC MGS anchor model
  - finer mesh
  - wood post in steel tube
- Wood – elastic, no failure



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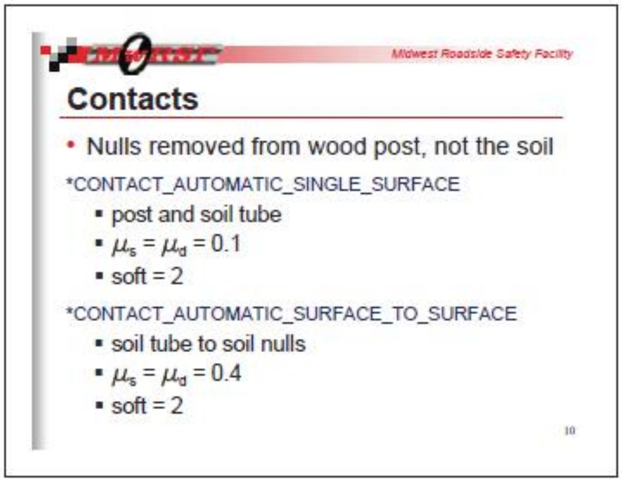
To null, or not to null:

- It is not uncommon to place null shells on solid elements to improve contact behavior.
  - it often works
  - it's non-physical
- Contact involving solid elements may benefit from using thickness offsets.
  - SLDTHK and SLDSTF on opt. Card B
  - easy alternative to coating solid faces with *mat_null shells



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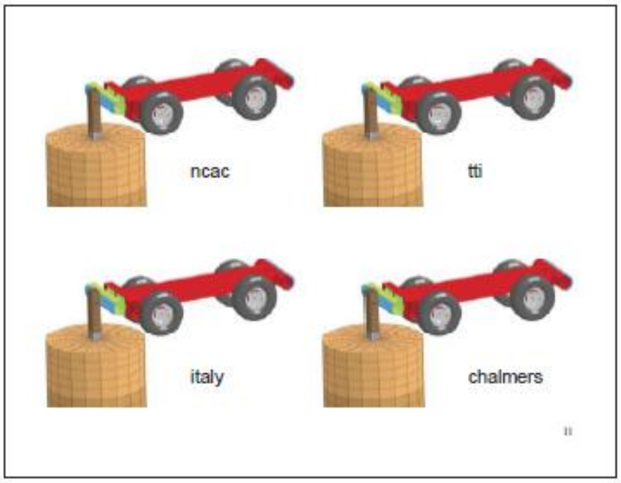
Contacts

- Nulls removed from wood post, not the soil

*CONTACT_AUTOMATIC_SINGLE_SURFACE
  - post and soil tube
  - $\mu_s = \mu_d = 0.1$
  - soft = 2

*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE
  - soil tube to soil nulls
  - $\mu_s = \mu_d = 0.4$
  - soft = 2



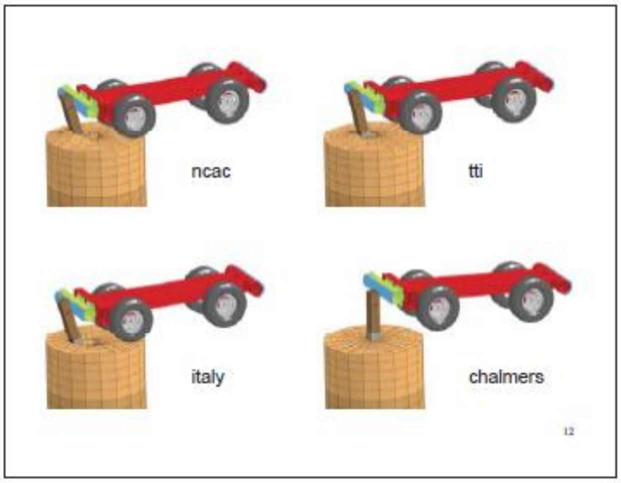
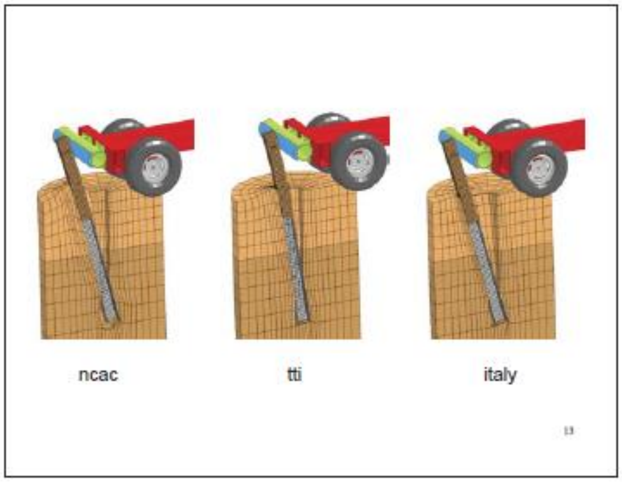
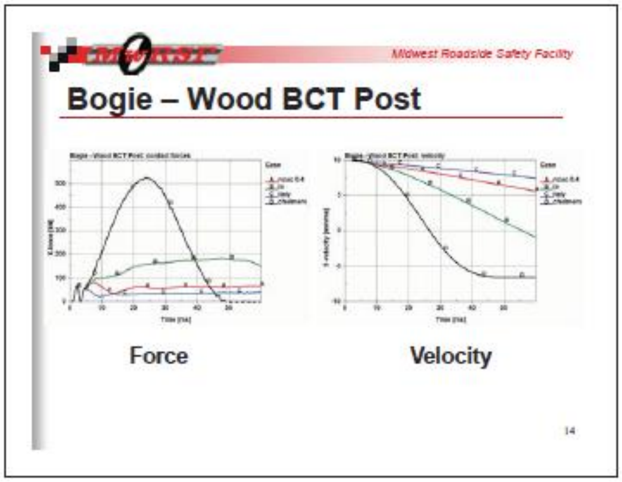


Figure 37. Soil Modeling: Phase II, Part 2, slides 7 – 12



ncac tti italy



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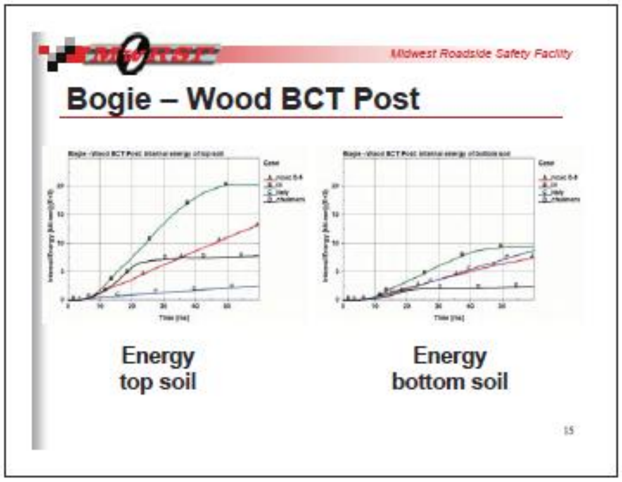
Bogie – Wood BCT Post

Force Velocity



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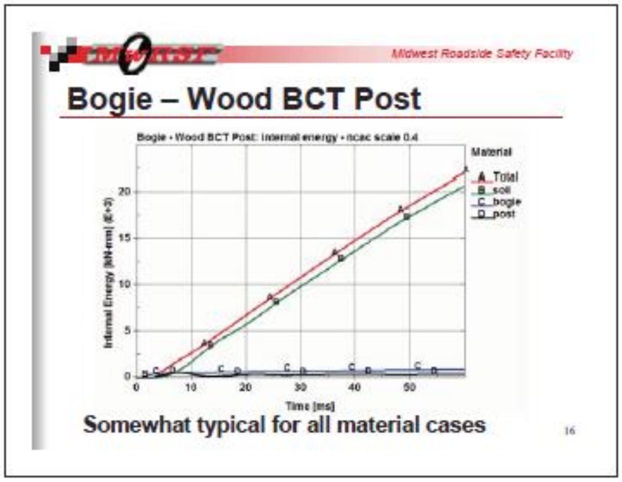
Bogie – Wood BCT Post

Energy top soil

Energy bottom soil



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Bogie – Wood BCT Post

Somewhat typical for all material cases

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Impactor – Sigma Steel Post

Impactor: 730 kg = 1600 lbs
Speed: 5 mm/ms = 11 mph

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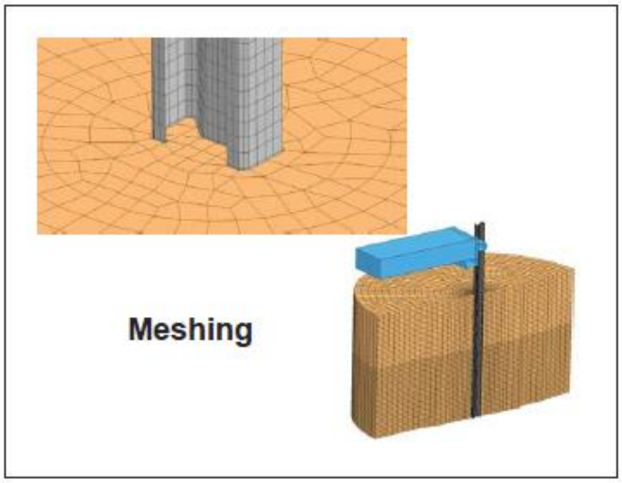
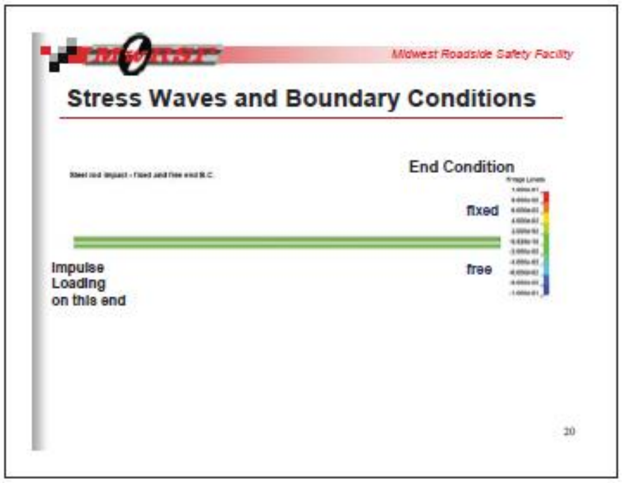
Impactor – Sigma Steel Post

*CONTACT_AUTOMATIC_SINGLE_SURFACE
- soft = 2, all parts
- $\mu_s = \mu_d = 0.08$

Figure 38. Soil Modeling: Phase II, Part 2, slides 13 – 18



Meshing



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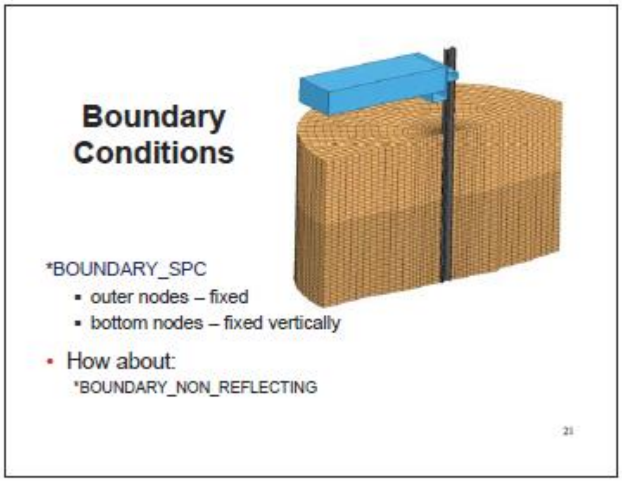
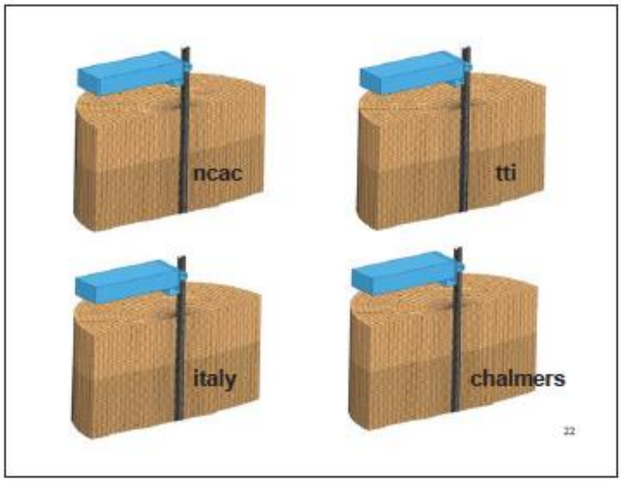
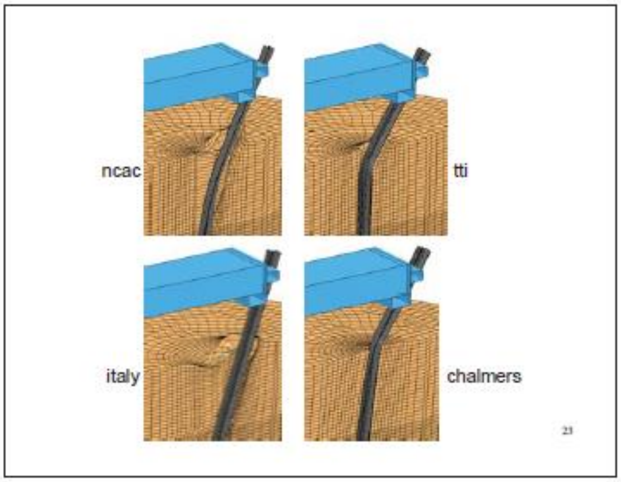
Stress Waves and Boundary Conditions

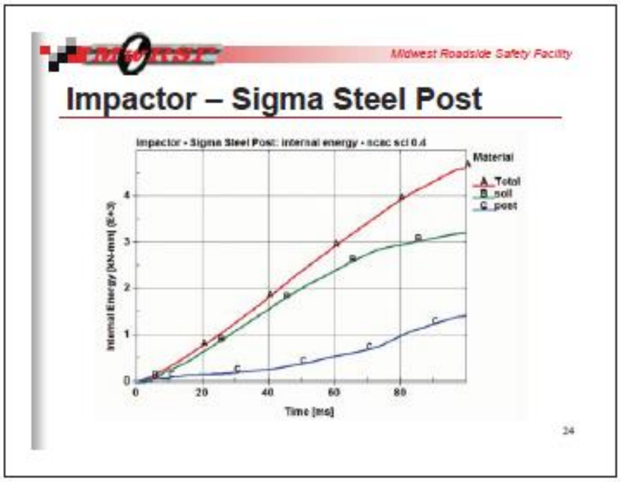


Boundary Conditions

*BOUNDARY_SPC
  - outer nodes – fixed
  - bottom nodes – fixed vertically
- How about:
  *BOUNDARY_NON_REFLECTING







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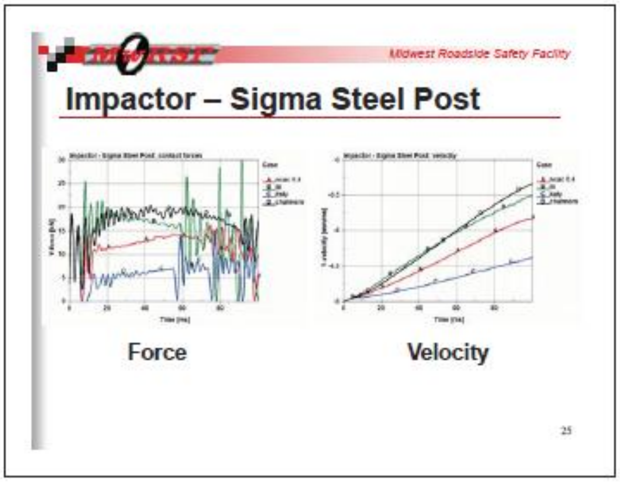
Impactor – Sigma Steel Post

Figure 39. Soil Modeling: Phase II, Part 2, slides 19 – 24



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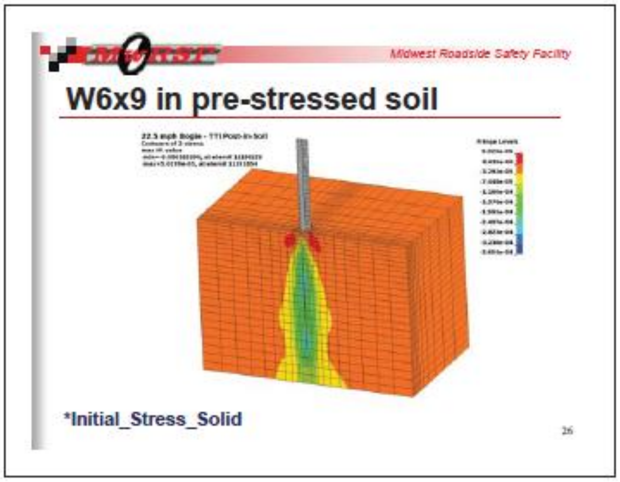
Impactor – Sigma Steel Post

Force

Velocity



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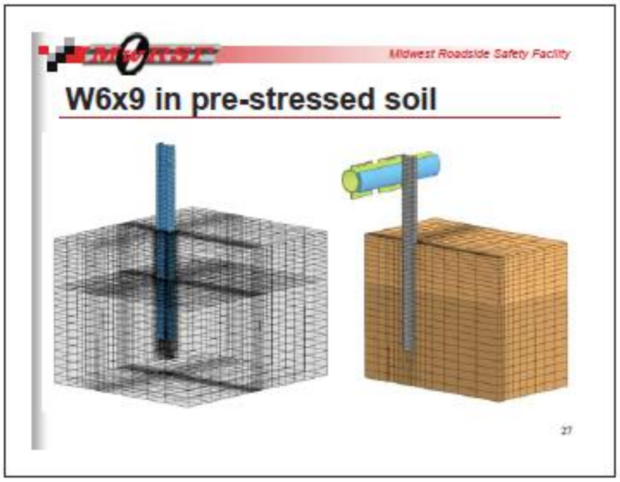
W6x9 in pre-stressed soil

*Initial_Stress_Solid



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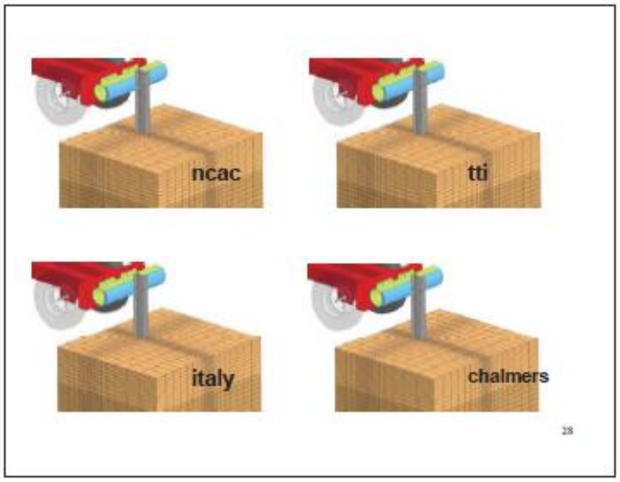
W6x9 in pre-stressed soil



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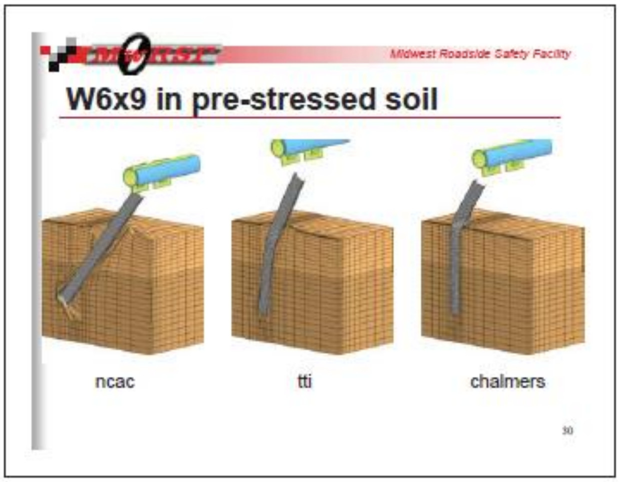
W6x9 in pre-stressed soil – Italy

*MAT_SOIL_AND_FOAM



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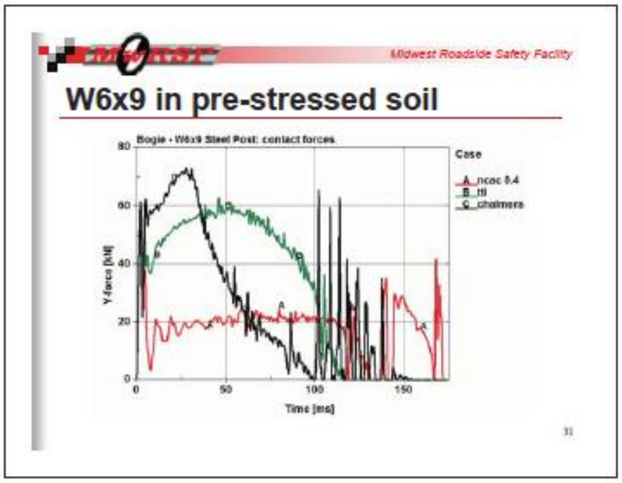
W6x9 in pre-stressed soil

Figure 40. Soil Modeling: Phase II, Part 2, slides 25 – 30



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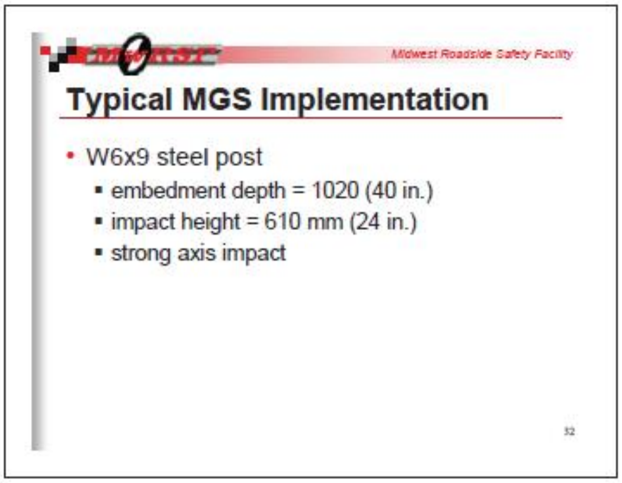
W6x9 in pre-stressed soil



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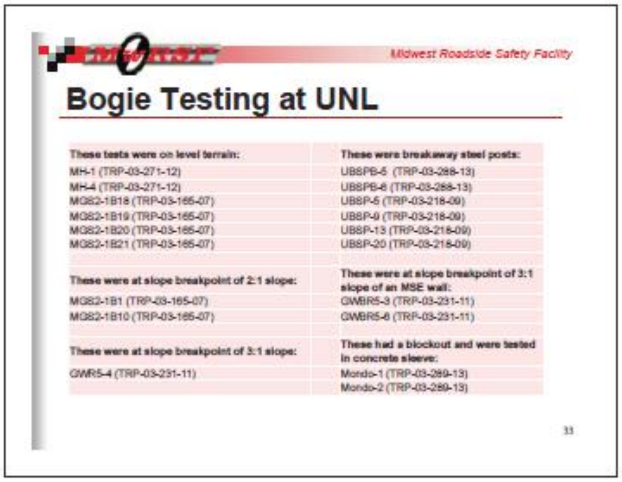
Typical MGS Implementation

- W6x9 steel post
  - embedment depth = 1020 (40 in.)
  - impact height = 610 mm (24 in.)
  - strong axis impact



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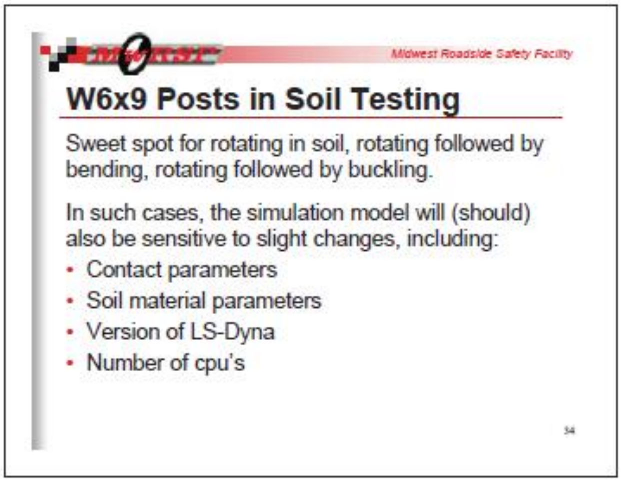
Bogie Testing at UNL

These tests were on level terrain:	**These were breakaway steel posts:**
MH-1 (TRP-03-271-12)	UBSPB-5 (TRP-03-288-13)
MH-4 (TRP-03-271-12)	UBSPB-6 (TRP-03-288-13)
MGS2-1B18 (TRP-03-165-07)	UBSP-5 (TRP-03-218-09)
MGS2-1B19 (TRP-03-165-07)	UBSP-9 (TRP-03-218-09)
MGS2-1B20 (TRP-03-165-07)	UBSP-13 (TRP-03-218-09)
MGS2-1B21 (TRP-03-165-07)	UBSP-20 (TRP-03-218-09)
These were at slope breakpoint of 2:1 slope:	**These were at slope breakpoint of 3:1 slope of an MSE wall:**
MGS2-1B1 (TRP-03-165-07)	GWBR5-3 (TRP-03-231-11)
MGS2-1B10 (TRP-03-165-07)	GWBR5-6 (TRP-03-231-11)
These were at slope breakpoint of 3:1 slope:	**These had a blockout and were tested in concrete sleeve:**
GWR5-4 (TRP-03-231-11)	Mondo-1 (TRP-03-289-13)
	Mondo-2 (TRP-03-289-13)



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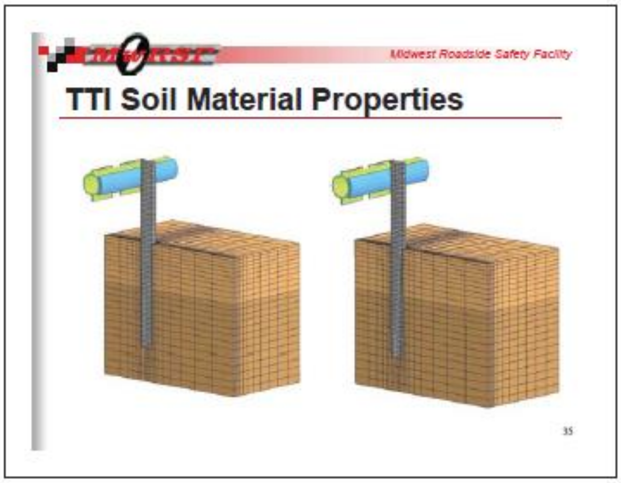
W6x9 Posts in Soil Testing

Sweet spot for rotating in soil, rotating followed by bending, rotating followed by buckling.

In such cases, the simulation model will (should) also be sensitive to slight changes, including:

- Contact parameters
- Soil material parameters
- Version of LS-Dyna
- Number of cpu's



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TTI Soil Material Properties

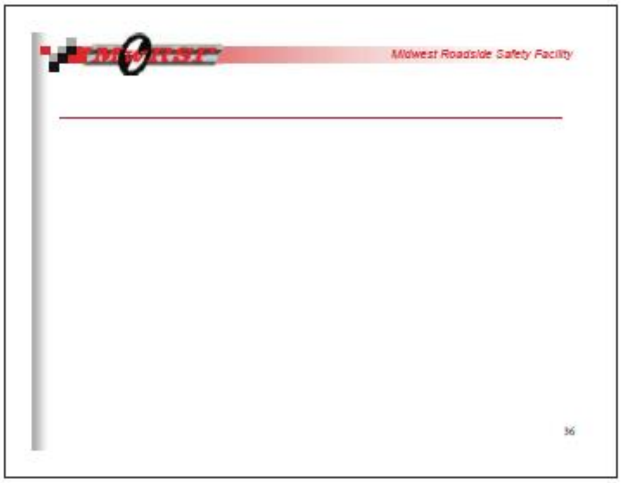

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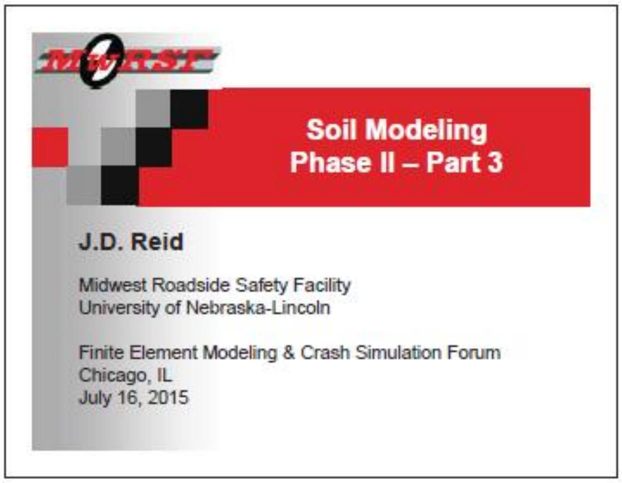
Figure 41. Soil Modeling: Phase II, Part 2, slides 31 – 36



Soil Modeling
Phase II – Part 3

J.D. Reid

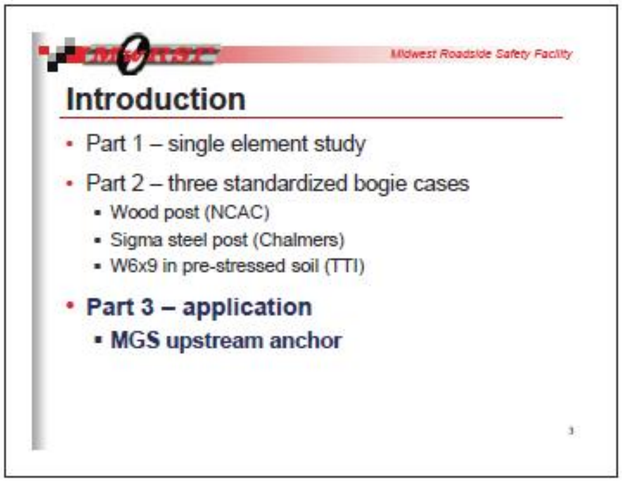
Midwest Roadside Safety Facility
University of Nebraska-Lincoln

Finite Element Modeling & Crash Simulation Forum
Chicago, IL
July 16, 2015

Midwest Roadside Safety Facility

Introduction

- Phase I: Short Term
  - ⇨ A Library of LS-Dyna Techniques
- **Phase II: Intermediate Term**
  - ⇨ **Modeling Posts in Soil**
- Long Term
  - ⇨ Soil Material Characterization



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Introduction

- Part 1 – single element study
- Part 2 – three standardized bogie cases
  - Wood post (NCAC)
  - Sigma steel post (Chalmers)
  - W6x9 in pre-stressed soil (TTI)
- **Part 3 – application**
  - **MGS upstream anchor**

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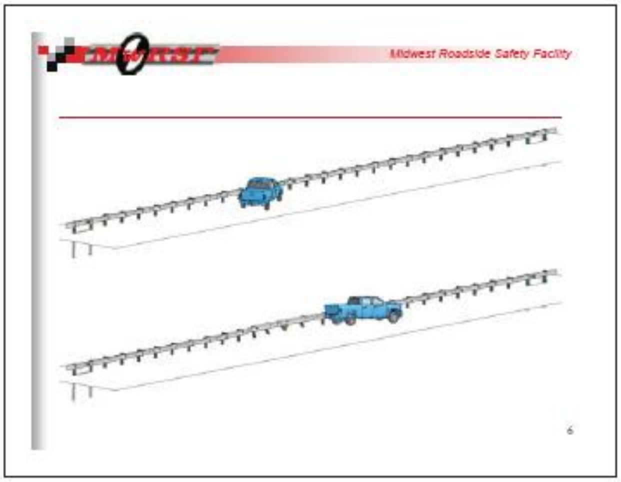
MGS – Midwest Guardrail System



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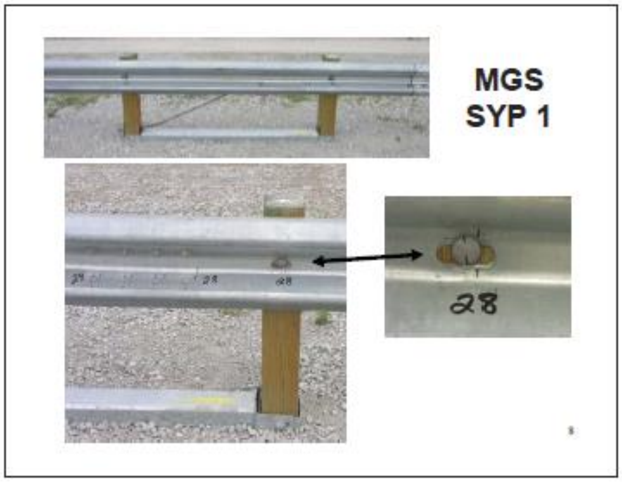
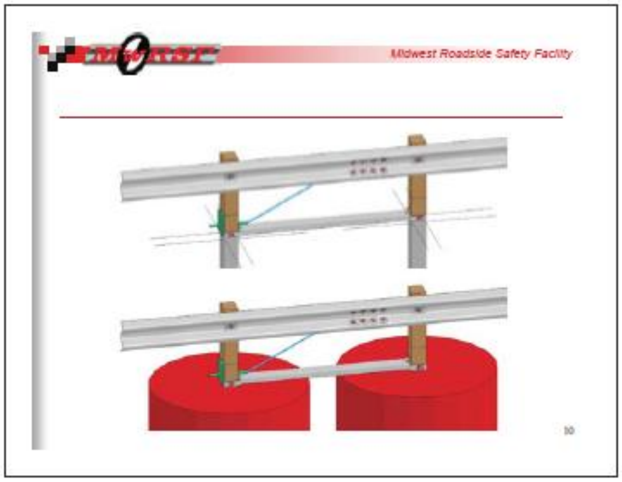
MGS Upstream Anchor

Figure 42. Soil Modeling: Phase II, Part 3, slides 1 – 7



MGS SYP 1



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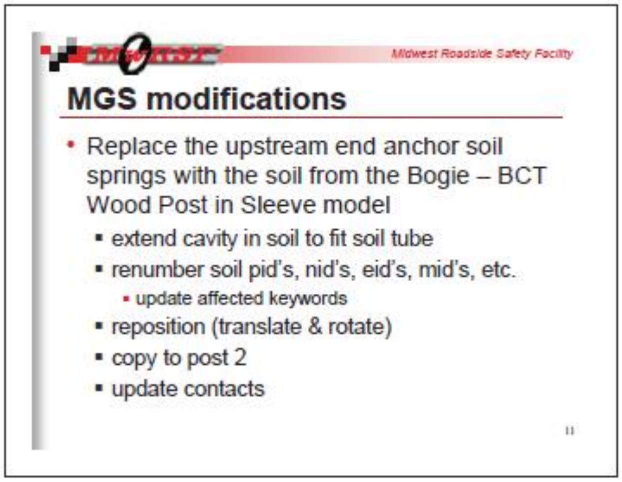

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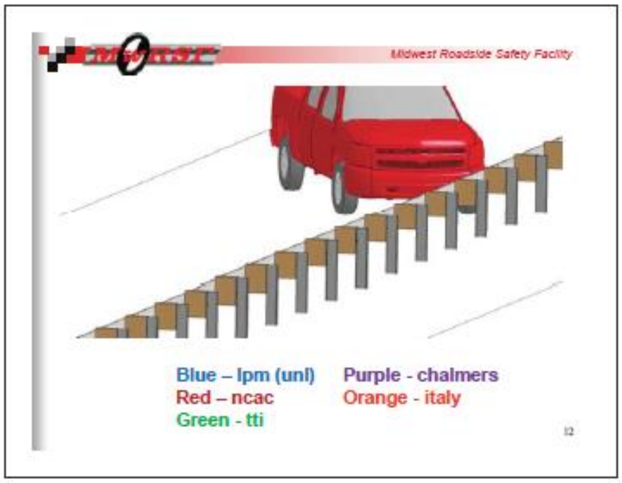
MGS modifications

- Replace the upstream end anchor soil springs with the soil from the Bogie – BCT Wood Post in Sleeve model
  - extend cavity in soil to fit soil tube
  - renumber soil pid's, nid's, eid's, mid's, etc.
    - update affected keywords
  - reposition (translate & rotate)
  - copy to post 2
  - update contacts



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Blue – lpm (unl)
Red – ncac
Green - tti
Purple - chalmers
Orange - italy

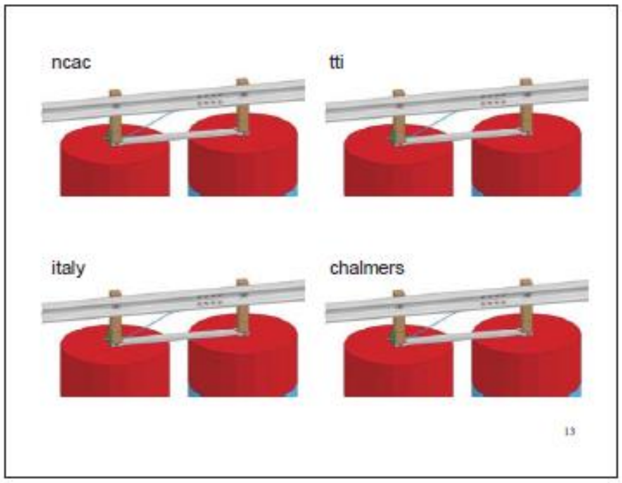

Figure 43. Soil Modeling: Phase II, Part 3, slides 8 – 13

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All Cases – including LPM

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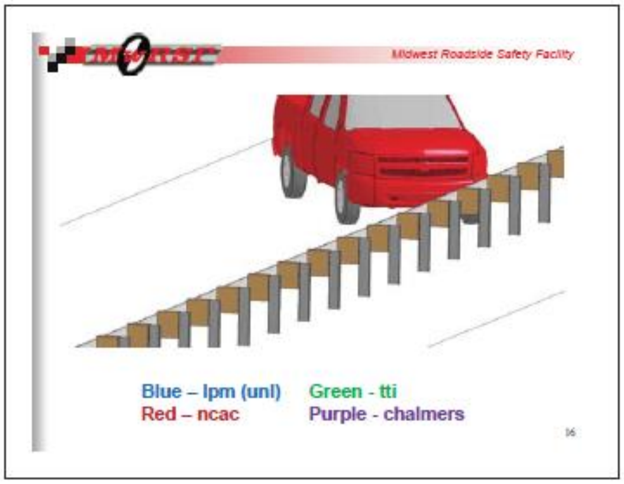
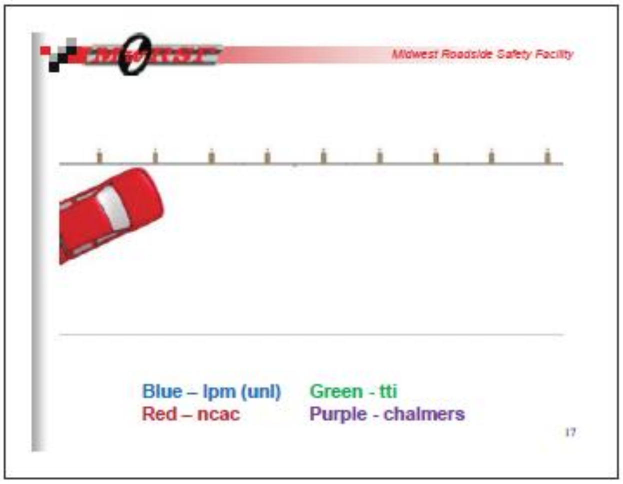
All Cases – including LPM



Midwest Roadside Safety Facility

Blue – lpm (unl)
Green - tti
Red – ncac
Purple - chalmers



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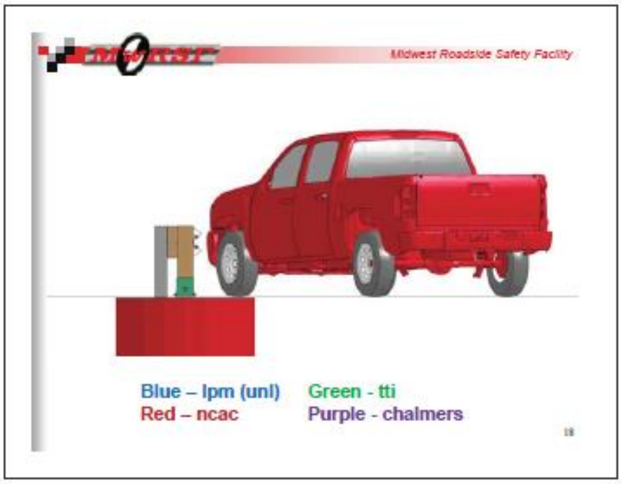
Blue – lpm (unl)
Green - tti
Red – ncac
Purple - chalmers



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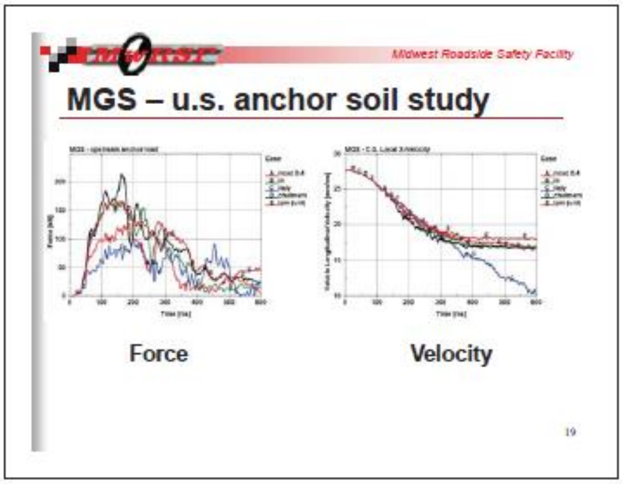
Blue – lpm (unl)
Green - tti
Red – ncac
Purple - chalmers



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MGS – u.s. anchor soil study

Force

Velocity

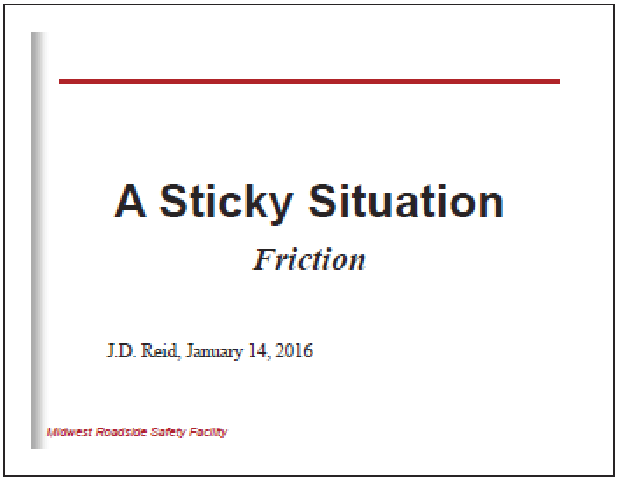
Figure 44. Soil Modeling: Phase II, Part 3, slides 14 – 19

7 FRICTION MODELING

Modeling friction realistically has proven to be a very difficult phenomenon to capture; whether it’s for a vehicle bumper rubbing against a w-beam rail, a bolt sliding along a slot, a tire riding up a concrete barrier, or some other common interaction between two parts during an impact event.

During the Highway & Vehicle Safety Finite Element Modeling & Crash Simulation Forum held during the 2016 TRB Annual Meeting in Washington, D.C., J.D. Reid led a two-hour discussion on friction modeling. The following pages contain a copy of the PowerPoint slides used to lead that discussion. Information for the discussion came from many years of investigating various frictional effects.

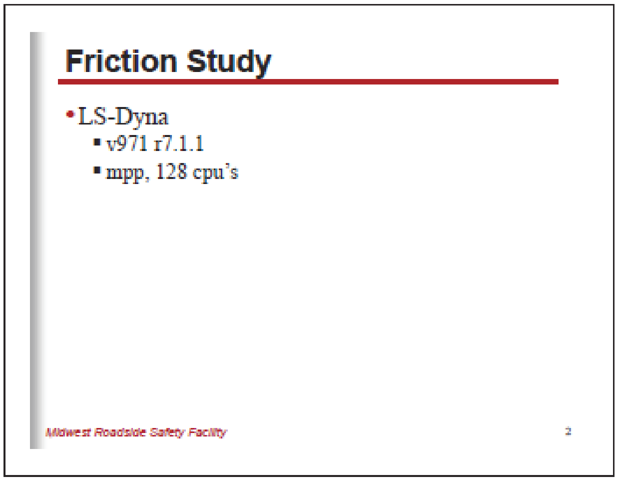
As a result of these studies, it is highly recommended that simulation studies of roadside hardware include some sort of bracketing technique to determine the range of behavior one might expect from varying friction over a wide range of values.



A Sticky Situation

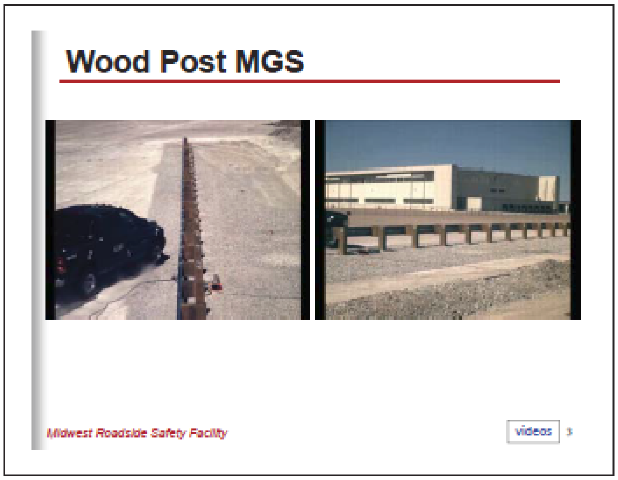
Friction

J.D. Reid, January 14, 2016

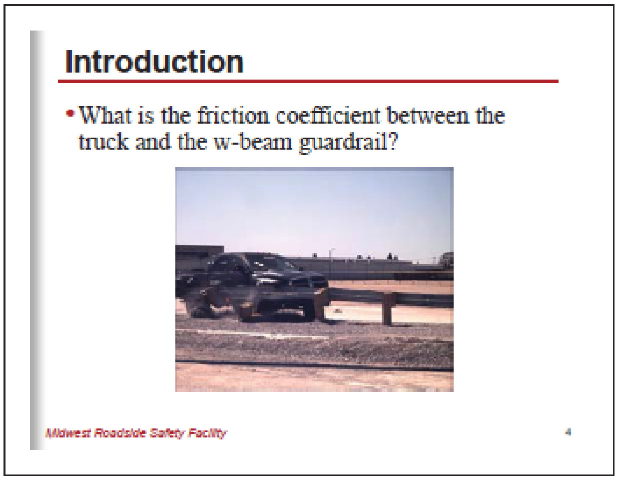


Friction Study

- LS-Dyna
  - v971 r7.1.1
  - mpp, 128 cpu's

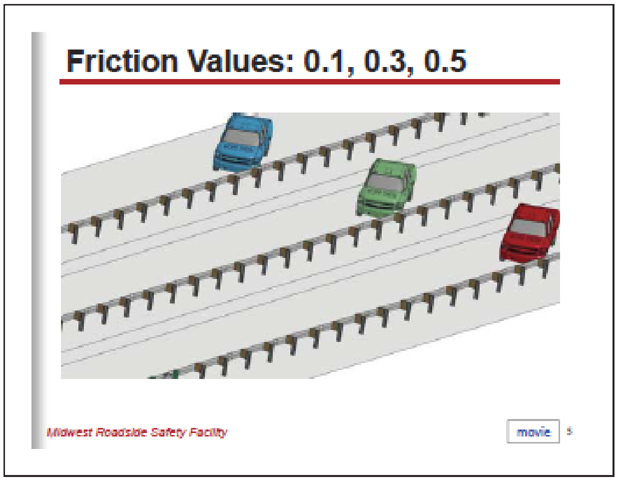


Wood Post MGS



Introduction

- What is the friction coefficient between the truck and the w-beam guardrail?



Friction Values: 0.1, 0.3, 0.5

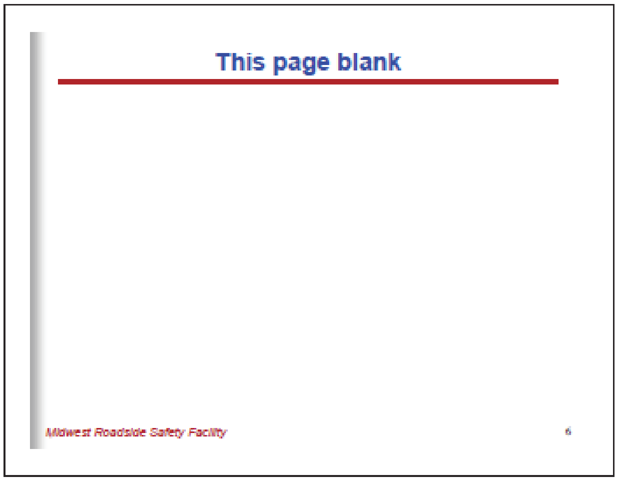


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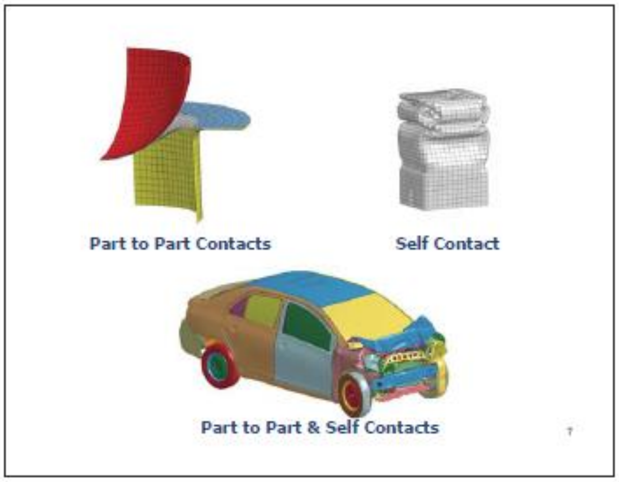
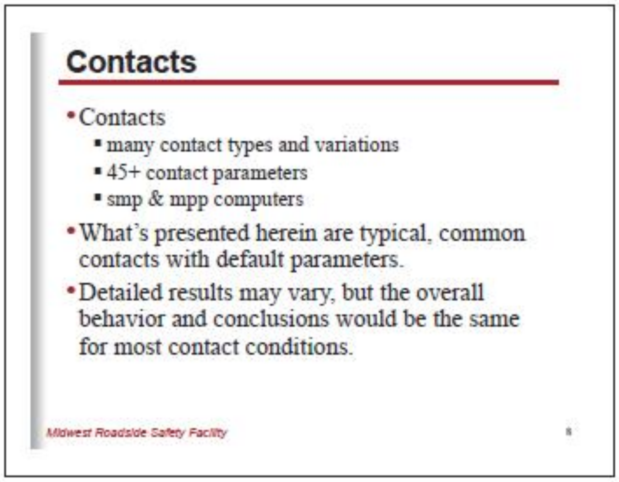
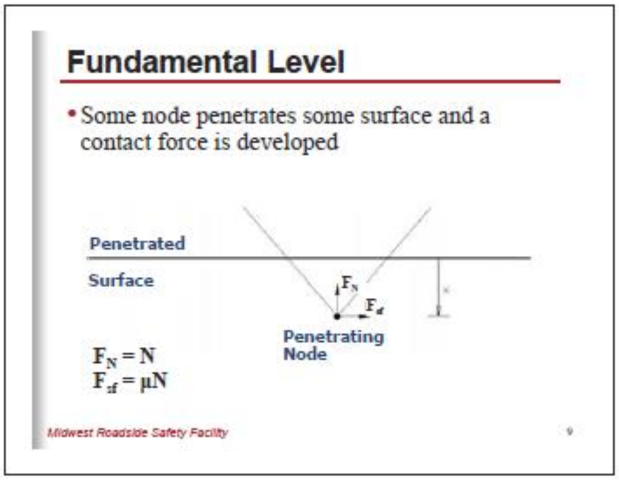
Figure 45. Friction Modeling: slides 1 – 6





Contacts

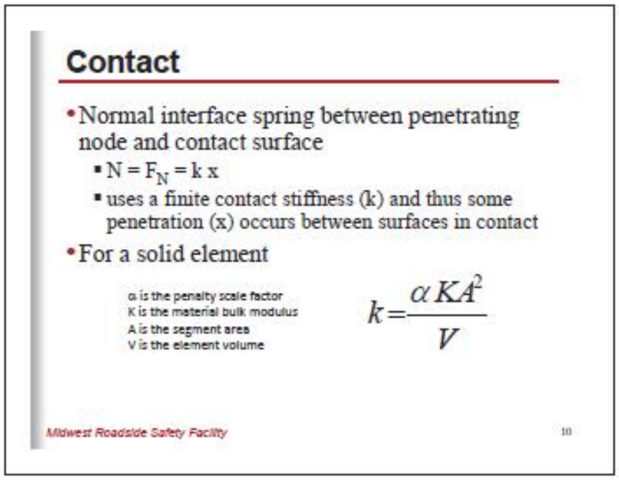
- Contacts
  - many contact types and variations
  - 45+ contact parameters
  - smp & mpp computers
- What's presented herein are typical, common contacts with default parameters.
- Detailed results may vary, but the overall behavior and conclusions would be the same for most contact conditions.



Fundamental Level

- Some node penetrates some surface and a contact force is developed

$F_N = N$
$F_{sf} = \mu N$

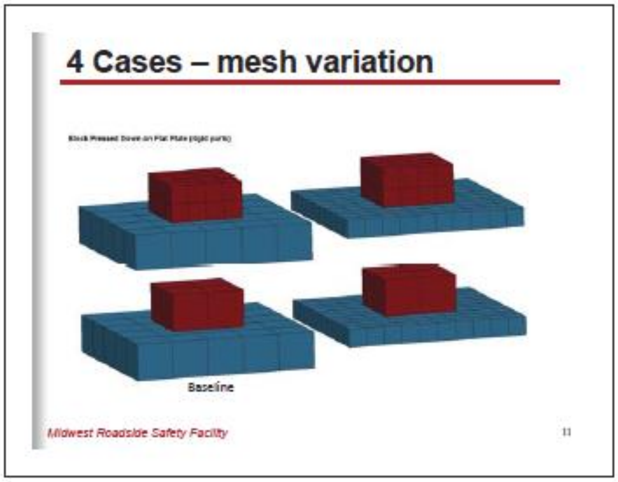


Contact

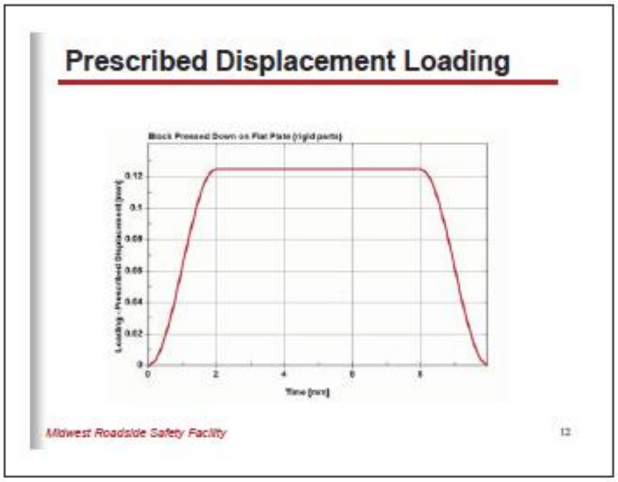
- Normal interface spring between penetrating node and contact surface
  - $N = F_N = k\,x$
  - uses a finite contact stiffness (k) and thus some penetration (x) occurs between surfaces in contact
- For a solid element

α is the penalty scale factor
K is the material bulk modulus
A is the segment area
V is the element volume

$$k = \frac{\alpha K A^2}{V}$$

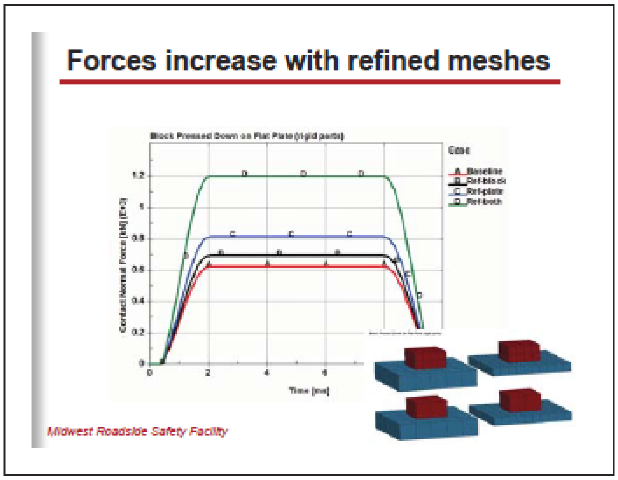


4 Cases – mesh variation



Prescribed Displacement Loading

Figure 46. Friction Modeling: slides 7 – 12



Forces increase with refined meshes

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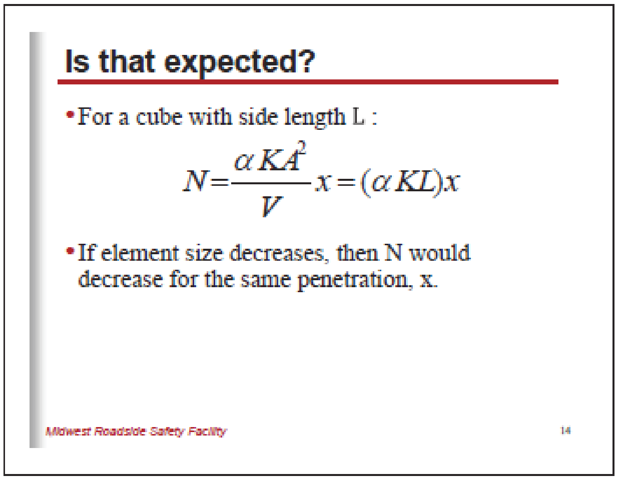

Is that expected?

- For a cube with side length L :

$$N = \frac{\alpha K A^2}{V} x = (\alpha K L) x$$

- If element size decreases, then N would decrease for the same penetration, x.

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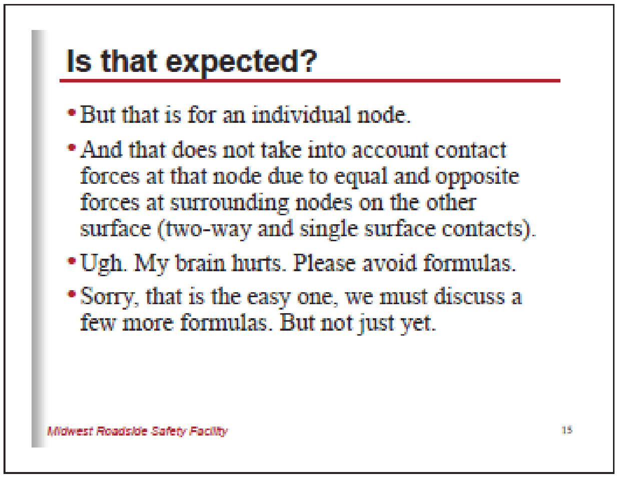

Is that expected?

- But that is for an individual node.
- And that does not take into account contact forces at that node due to equal and opposite forces at surrounding nodes on the other surface (two-way and single surface contacts).
- Ugh. My brain hurts. Please avoid formulas.
- Sorry, that is the easy one, we must discuss a few more formulas. But not just yet.

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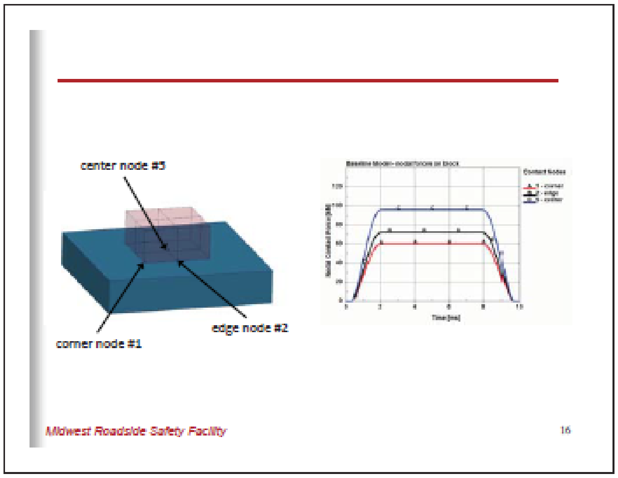
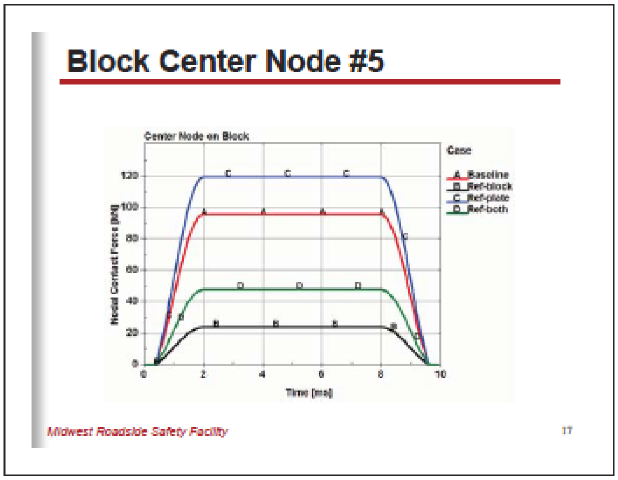


Midwest Roadside Safety Facility 16



Block Center Node #5

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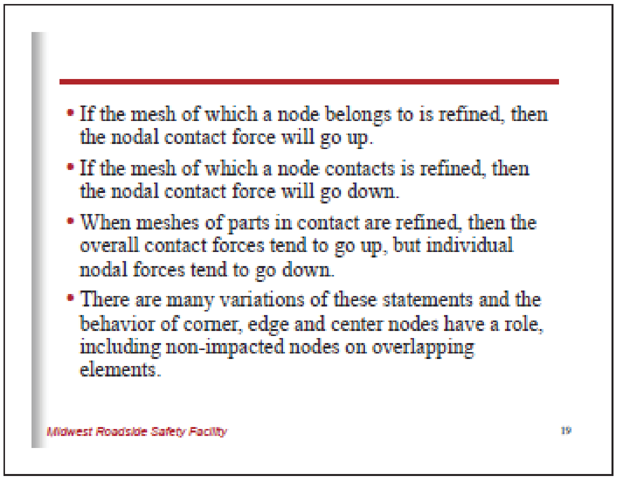
Figure 47. Friction Modeling: slides 13 – 18



- If the mesh of which a node belongs to is refined, then the nodal contact force will go up.
- If the mesh of which a node contacts is refined, then the nodal contact force will go down.
- When meshes of parts in contact are refined, then the overall contact forces tend to go up, but individual nodal forces tend to go down.
- There are many variations of these statements and the behavior of corner, edge and center nodes have a role, including non-impacted nodes on overlapping elements.

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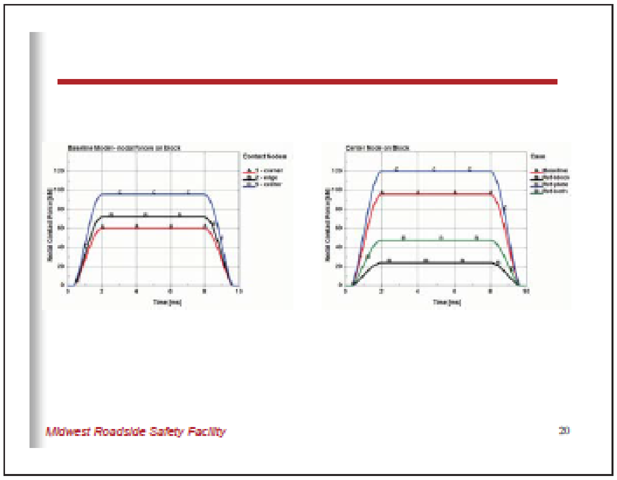
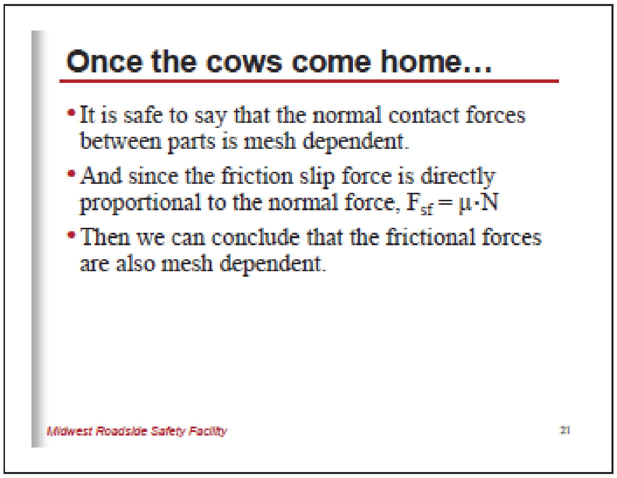


Midwest Roadside Safety Facility 20



Once the cows come home…

- It is safe to say that the normal contact forces between parts is mesh dependent.
- And since the friction slip force is directly proportional to the normal force, $F_{sf} = \mu \cdot N$
- Then we can conclude that the frictional forces are also mesh dependent.

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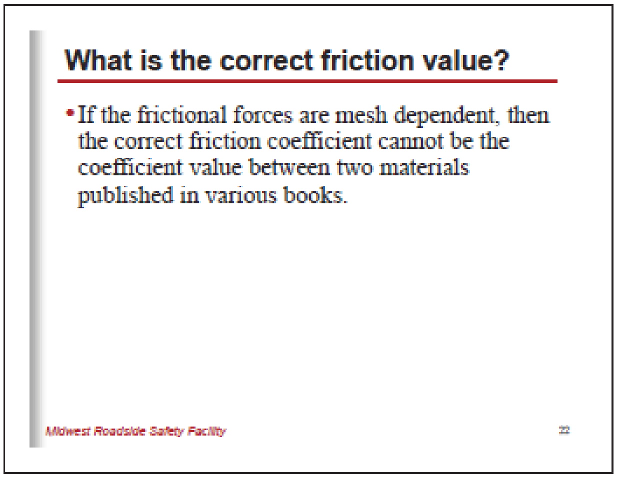

What is the correct friction value?

- If the frictional forces are mesh dependent, then the correct friction coefficient cannot be the coefficient value between two materials published in various books.

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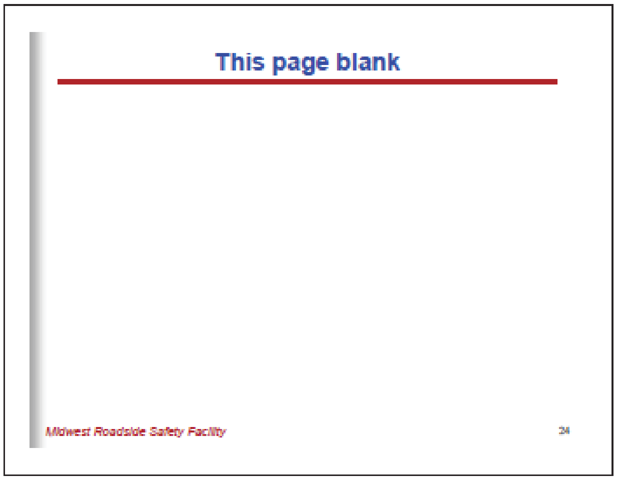

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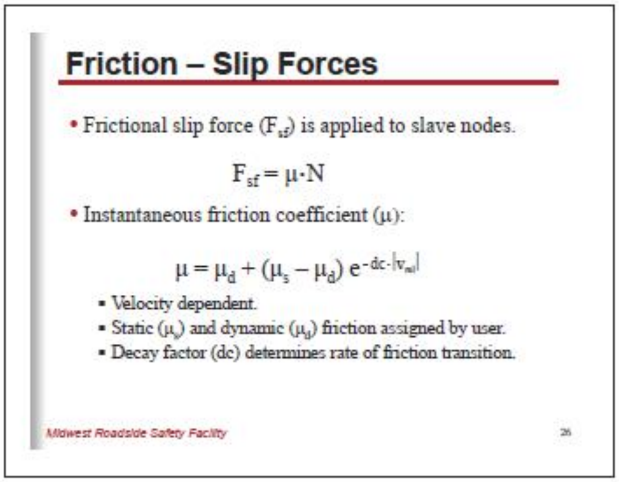
Figure 48. Friction Modeling: slides 19 – 24

Bolted Joints with Friction



Friction – Slip Forces

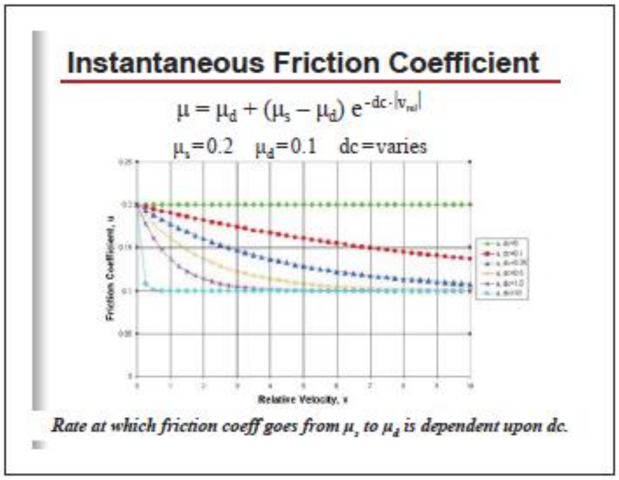
- Frictional slip force (F_{sf}) is applied to slave nodes.

$$F_{sf} = \mu \cdot N$$

- Instantaneous friction coefficient (μ):

$$\mu = \mu_d + (\mu_s - \mu_d)\, e^{-dc \cdot |v_{rel}|}$$

  - Velocity dependent.
  - Static (μ_s) and dynamic (μ_d) friction assigned by user.
  - Decay factor (dc) determines rate of friction transition.

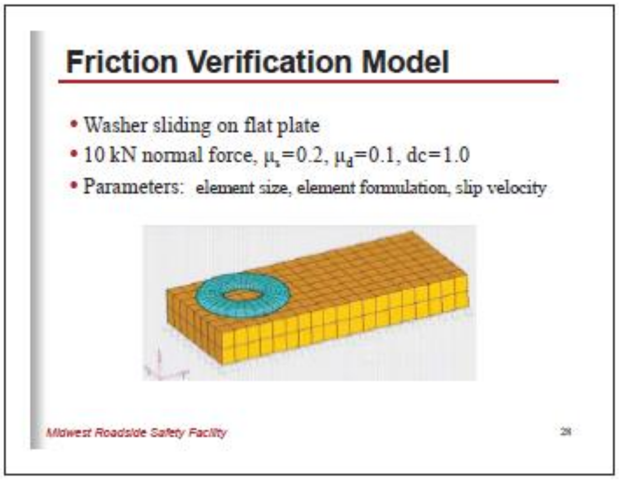


Instantaneous Friction Coefficient

$$\mu = \mu_d + (\mu_s - \mu_d)\, e^{-dc \cdot |v_{rel}|}$$

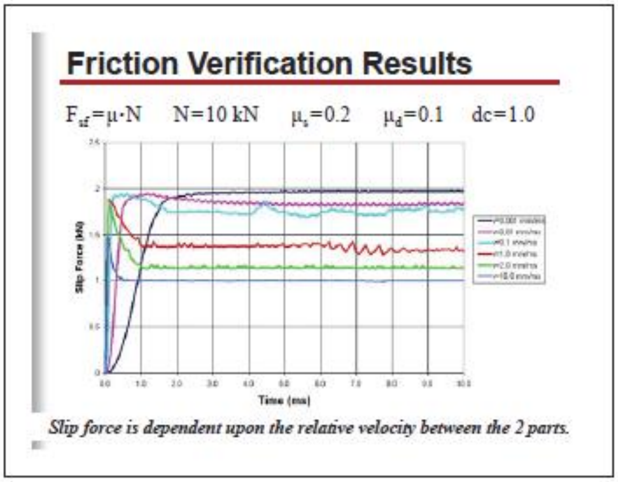
μ_s=0.2 μ_d=0.1 dc=varies

Rate at which friction coeff goes from μ_s to μ_d is dependent upon dc.



Friction Verification Model

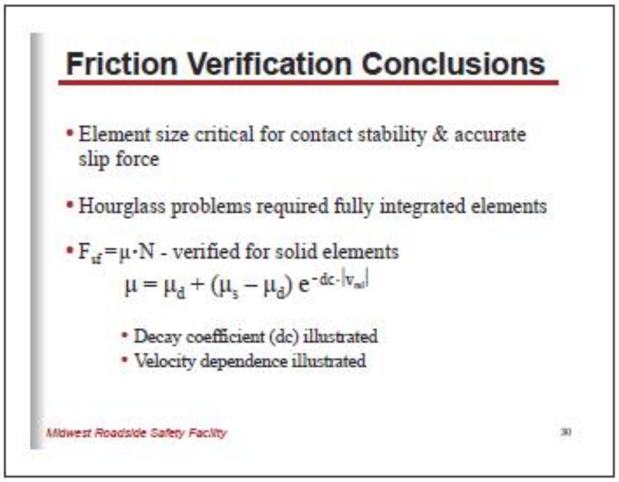
- Washer sliding on flat plate
- 10 kN normal force, μ_s=0.2, μ_d=0.1, dc=1.0
- Parameters: element size, element formulation, slip velocity



Friction Verification Results

$F_{sf}=\mu \cdot N$ N=10 kN μ_s=0.2 μ_d=0.1 dc=1.0

Slip force is dependent upon the relative velocity between the 2 parts.



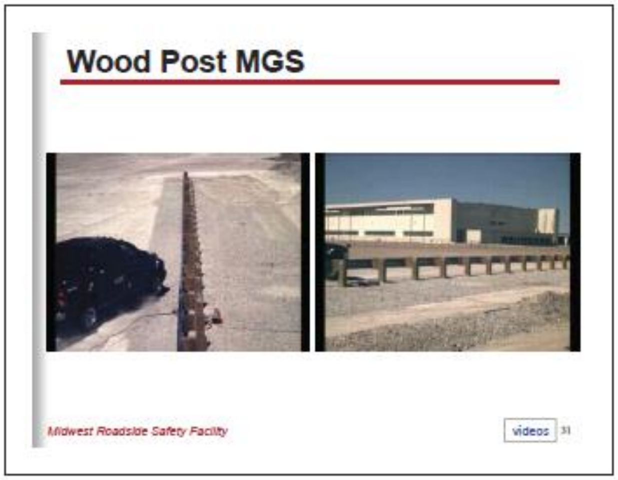
Friction Verification Conclusions

- Element size critical for contact stability & accurate slip force
- Hourglass problems required fully integrated elements
- $F_{sf}=\mu \cdot N$ - verified for solid elements

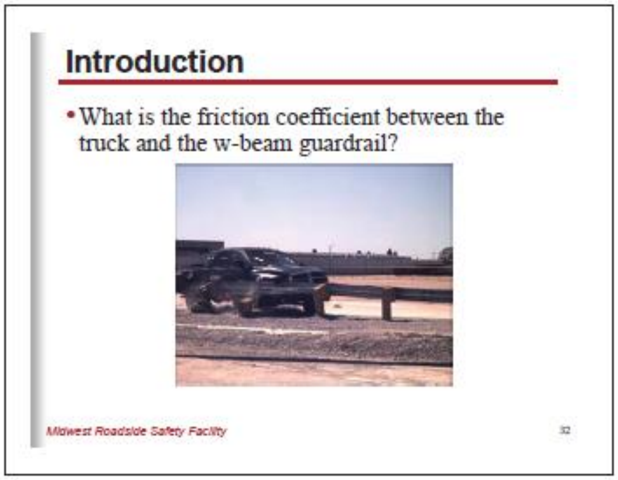
$$\mu = \mu_d + (\mu_s - \mu_d)\, e^{-dc \cdot |v_{rel}|}$$

  - Decay coefficient (dc) illustrated
  - Velocity dependence illustrated

Figure 49. Friction Modeling: slides 25 – 30

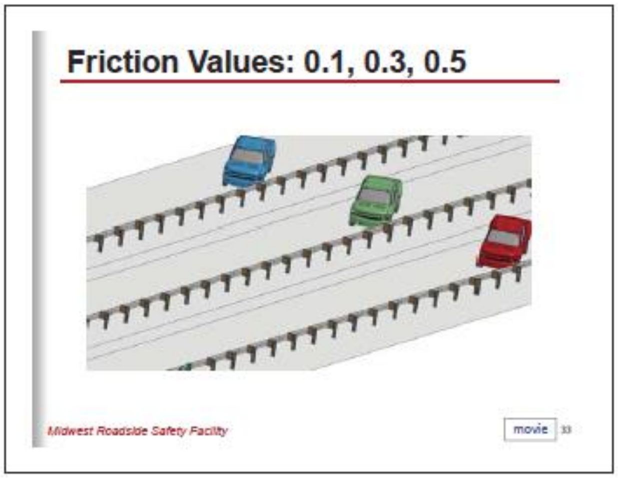


Wood Post MGS

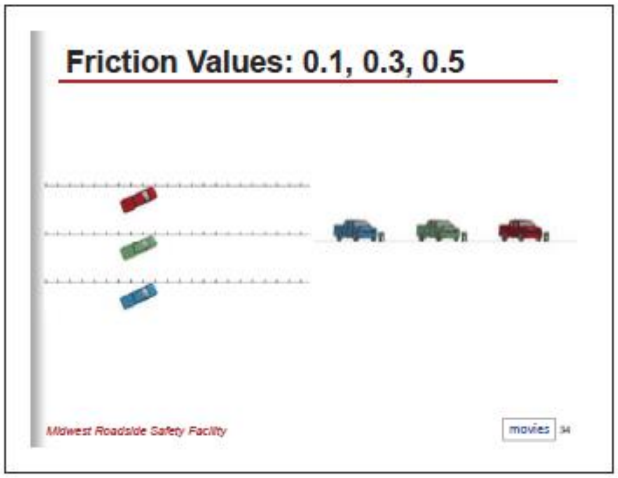


Introduction

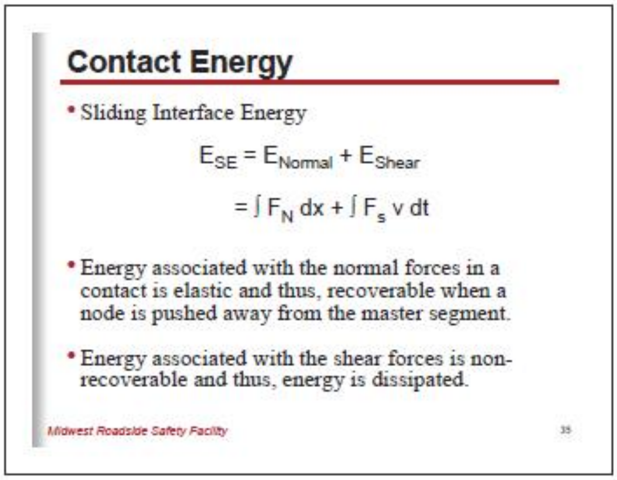
- What is the friction coefficient between the truck and the w-beam guardrail?



Friction Values: 0.1, 0.3, 0.5



Friction Values: 0.1, 0.3, 0.5



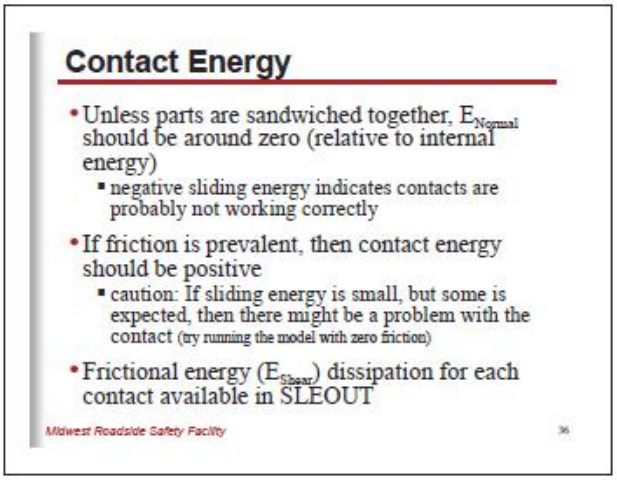
Contact Energy

- Sliding Interface Energy

$$E_{SE} = E_{Normal} + E_{Shear}$$

$$= \int F_N \, dx + \int F_s \, v \, dt$$

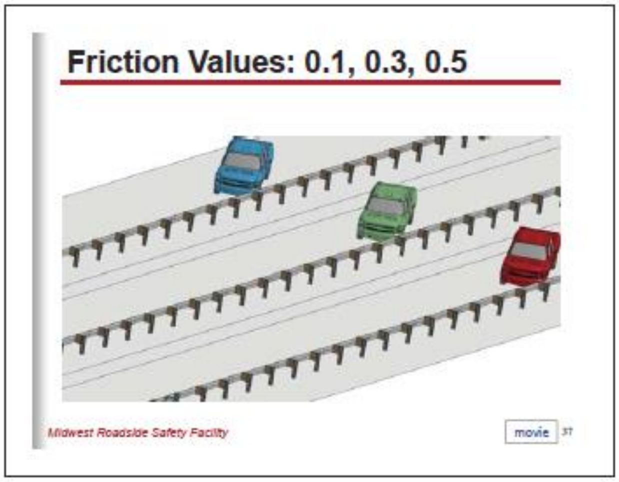
- Energy associated with the normal forces in a contact is elastic and thus, recoverable when a node is pushed away from the master segment.
- Energy associated with the shear forces is non-recoverable and thus, energy is dissipated.



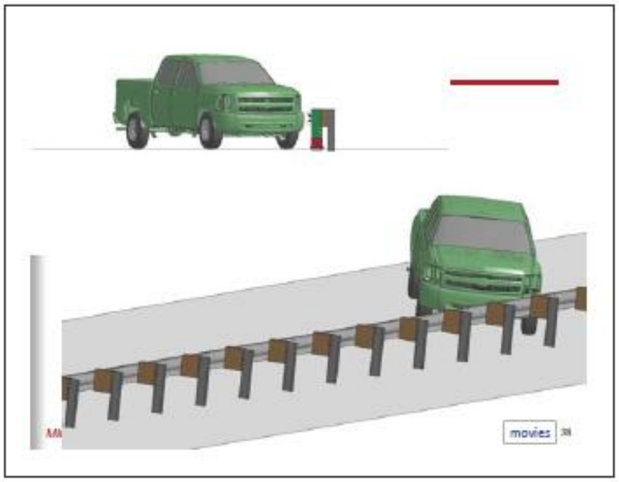
Contact Energy

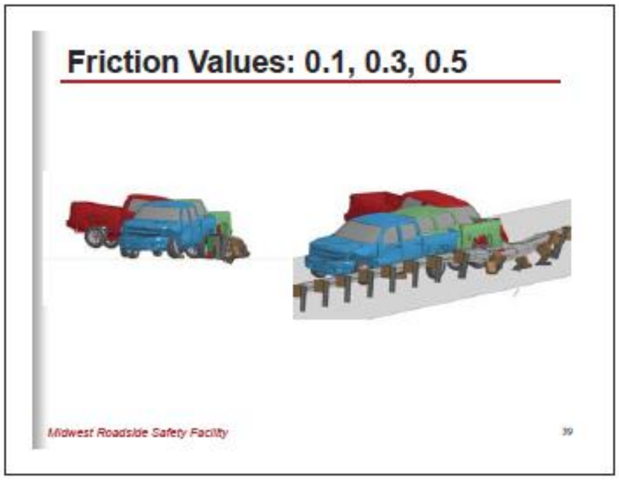
- Unless parts are sandwiched together, E_{Normal} should be around zero (relative to internal energy)
  - negative sliding energy indicates contacts are probably not working correctly
- If friction is prevalent, then contact energy should be positive
  - caution: If sliding energy is small, but some is expected, then there might be a problem with the contact (try running the model with zero friction)
- Frictional energy (E_{Shear}) dissipation for each contact available in SLEOUT

Figure 50. Friction Modeling: slides 31 – 36

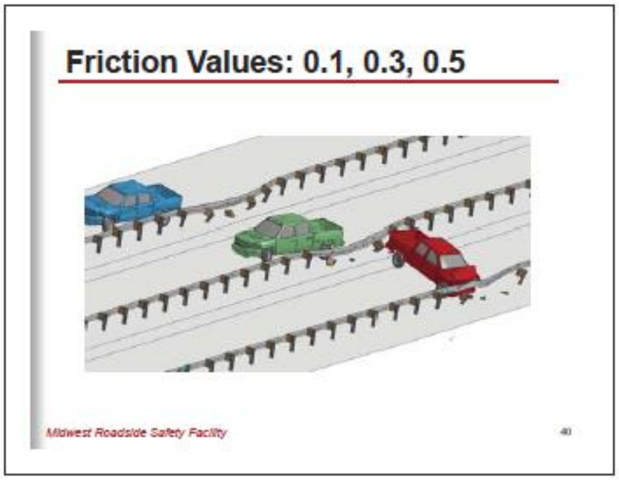


Friction Values: 0.1, 0.3, 0.5

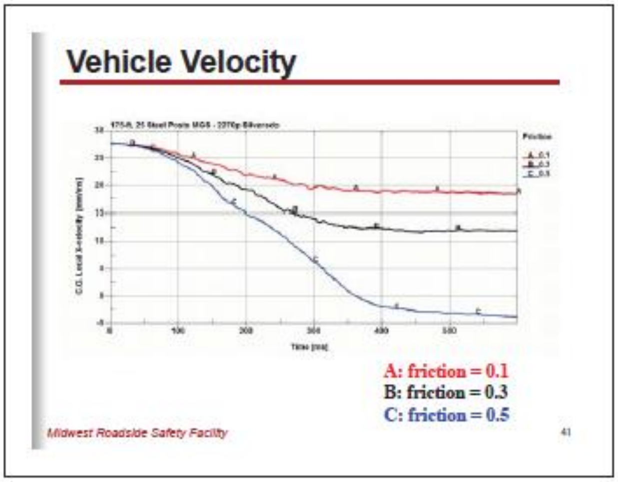




Friction Values: 0.1, 0.3, 0.5

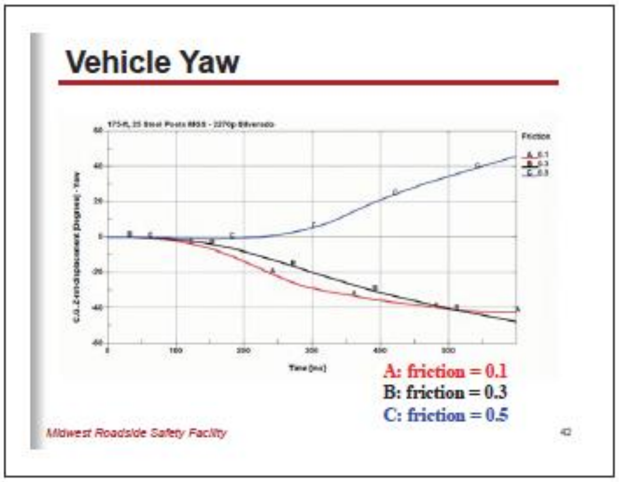


Friction Values: 0.1, 0.3, 0.5



Vehicle Velocity

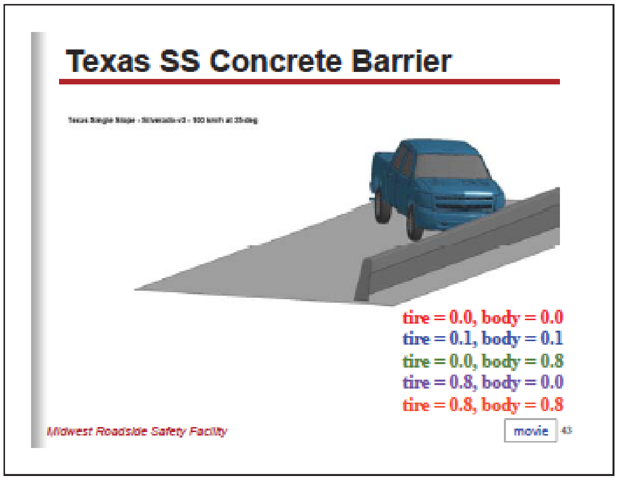
A: friction = 0.1
B: friction = 0.3
C: friction = 0.5



Vehicle Yaw

A: friction = 0.1
B: friction = 0.3
C: friction = 0.5

Figure 51. Friction Modeling: slides 37 – 42

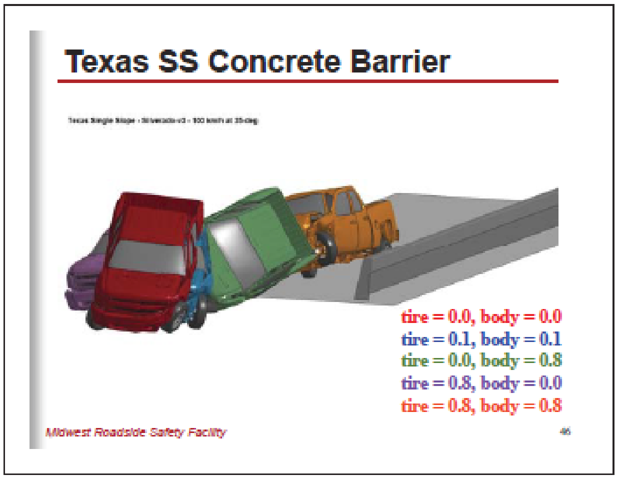


Texas SS Concrete Barrier

tire = 0.0, body = 0.0
tire = 0.1, body = 0.1
tire = 0.0, body = 0.8
tire = 0.8, body = 0.0
tire = 0.8, body = 0.8

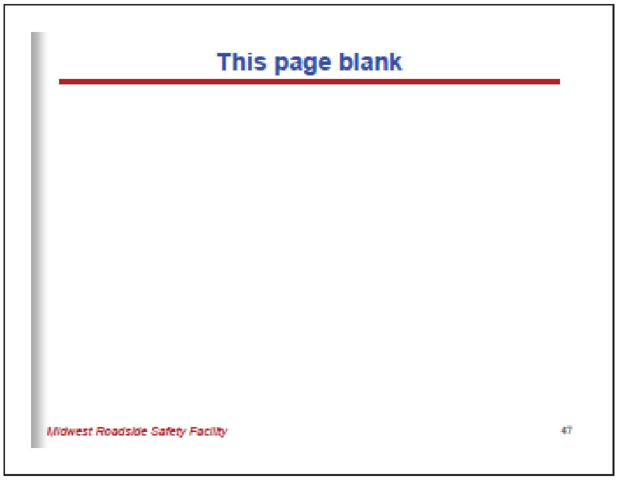
Texas SS Concrete Barrier

Texas SS Concrete Barrier



Texas SS Concrete Barrier

tire = 0.0, body = 0.0
tire = 0.1, body = 0.1
tire = 0.0, body = 0.8
tire = 0.8, body = 0.0
tire = 0.8, body = 0.8



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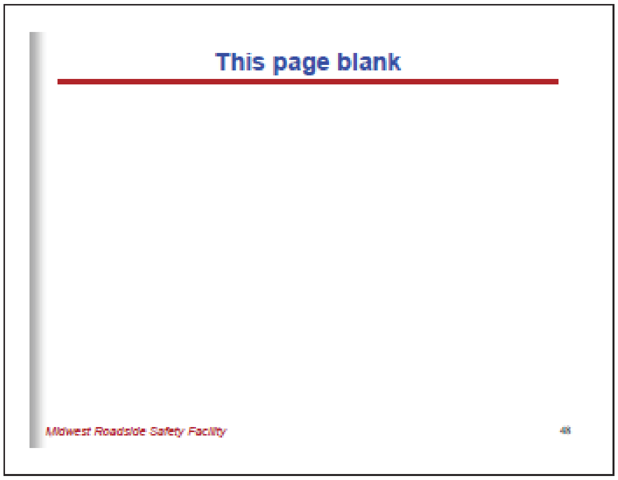

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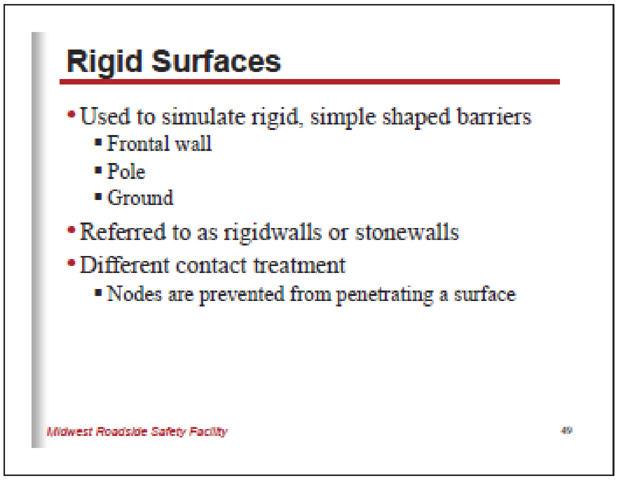
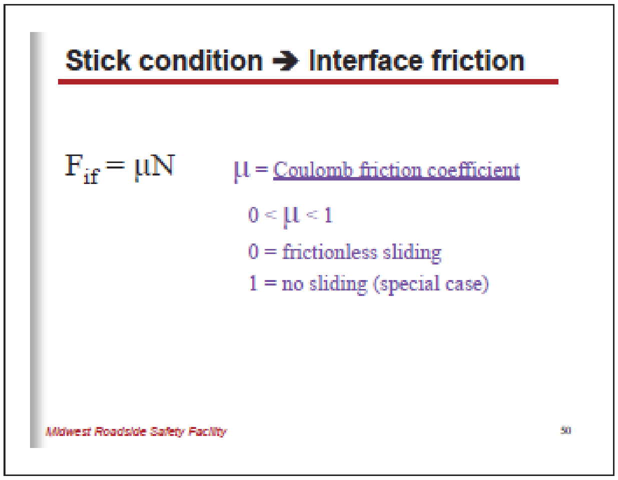
Figure 52. Friction Modeling: slides 43 – 48



Rigid Surfaces

- Used to simulate rigid, simple shaped barriers
  - Frontal wall
  - Pole
  - Ground
- Referred to as rigidwalls or stonewalls
- Different contact treatment
  - Nodes are prevented from penetrating a surface



Stick condition ➔ Interface friction

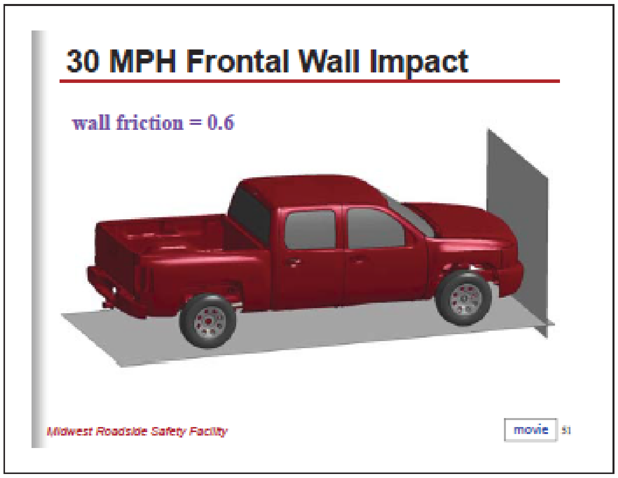
$F_{if} = \mu N$

μ = Coulomb friction coefficient

$0 < \mu < 1$

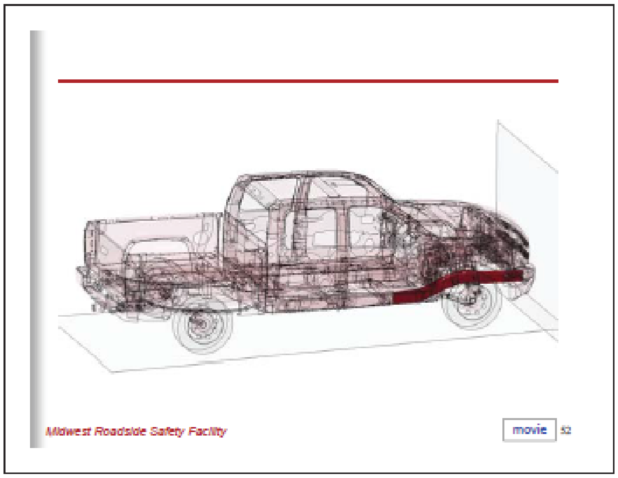
0 = frictionless sliding

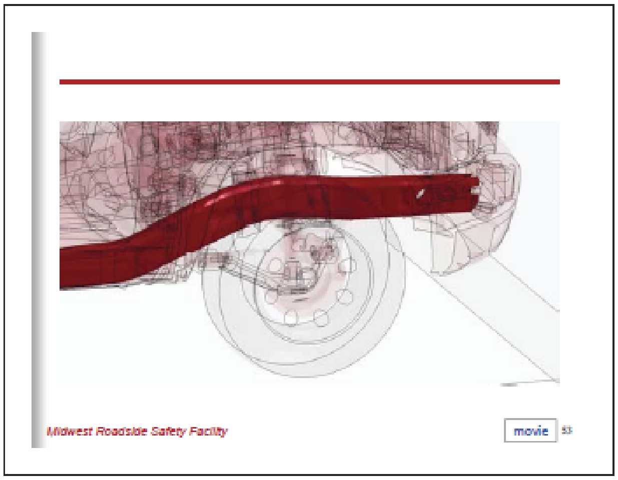
1 = no sliding (special case)



30 MPH Frontal Wall Impact

wall friction = 0.6





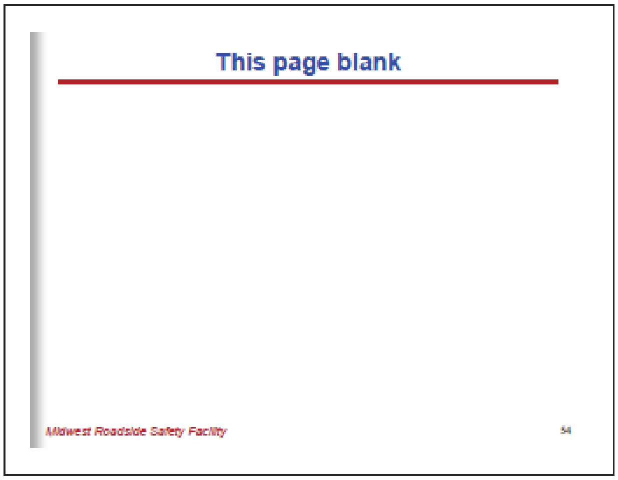


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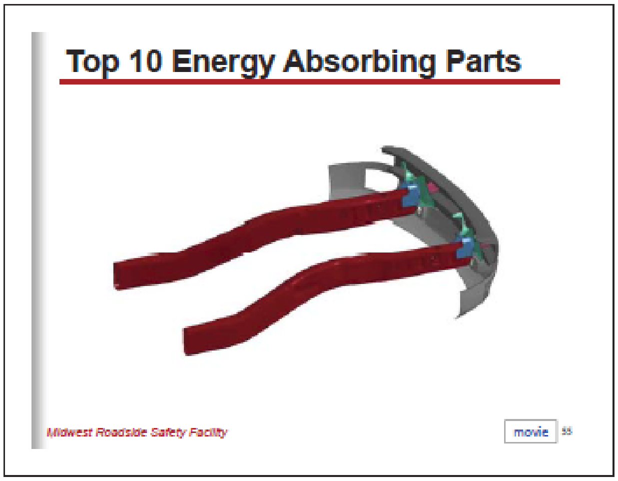
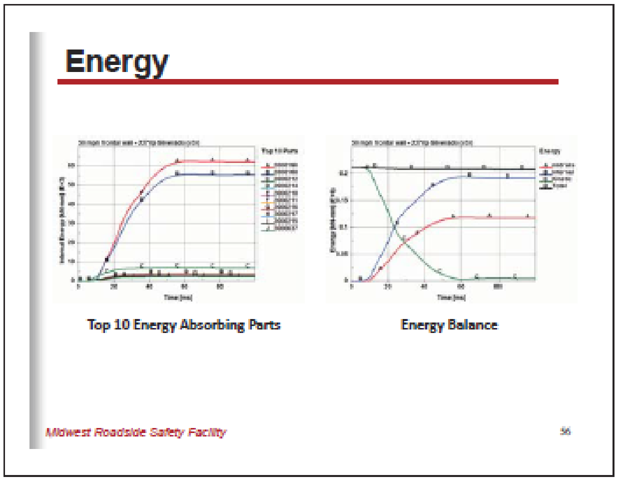
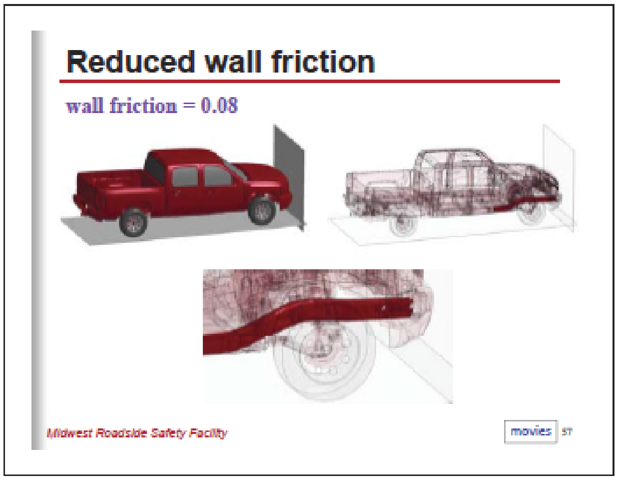
Figure 53. Friction Modeling: slides 49 – 54



Top 10 Energy Absorbing Parts

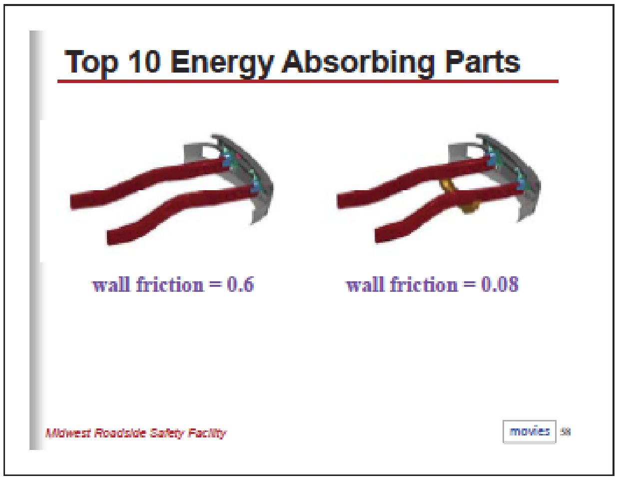


Energy



Reduced wall friction

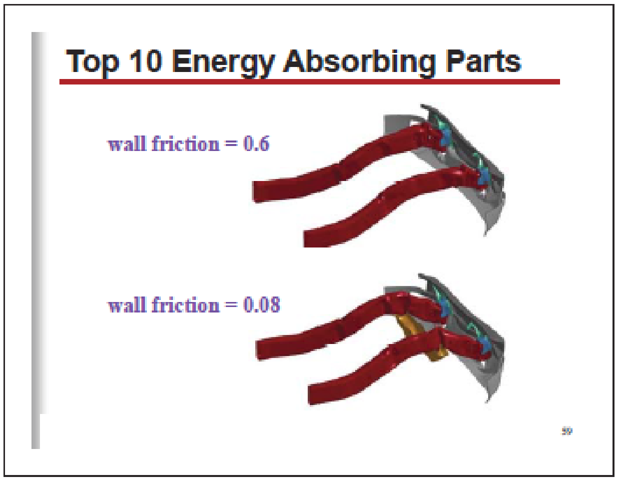
wall friction = 0.08



Top 10 Energy Absorbing Parts

wall friction = 0.6

wall friction = 0.08



Top 10 Energy Absorbing Parts

wall friction = 0.6

wall friction = 0.08

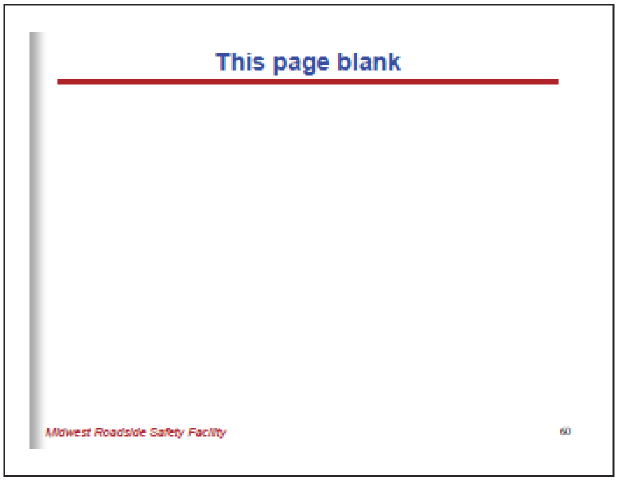


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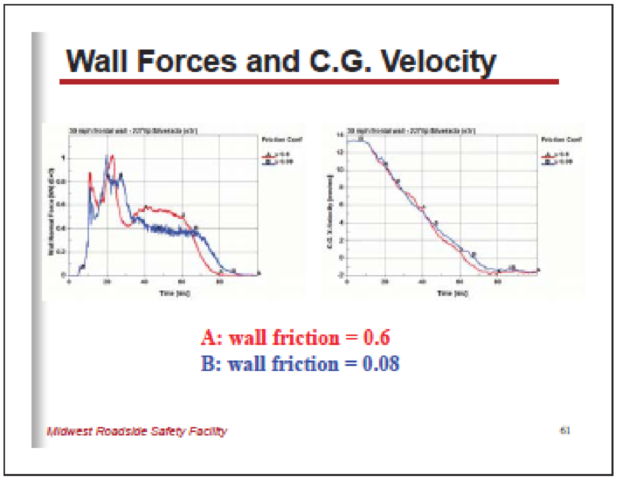
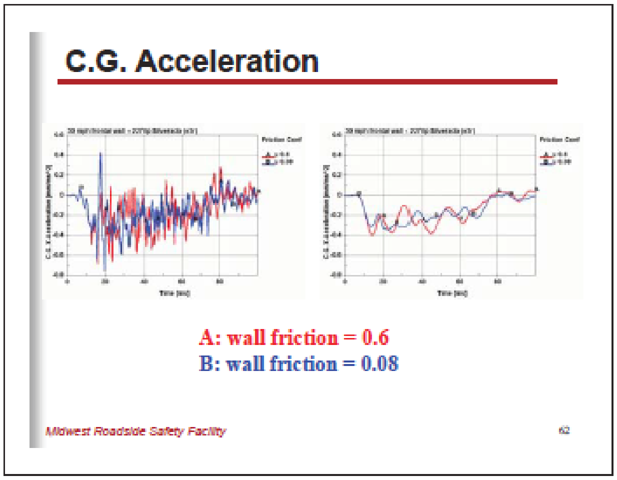
Figure 54. Friction Modeling: slides 55 – 60



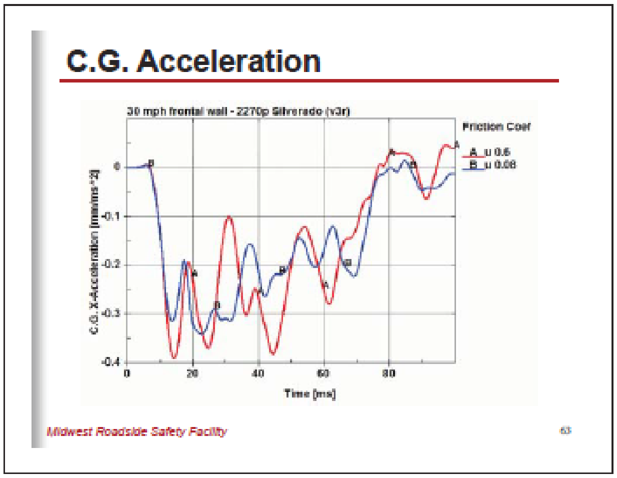
Wall Forces and C.G. Velocity

A: wall friction = 0.6
B: wall friction = 0.08

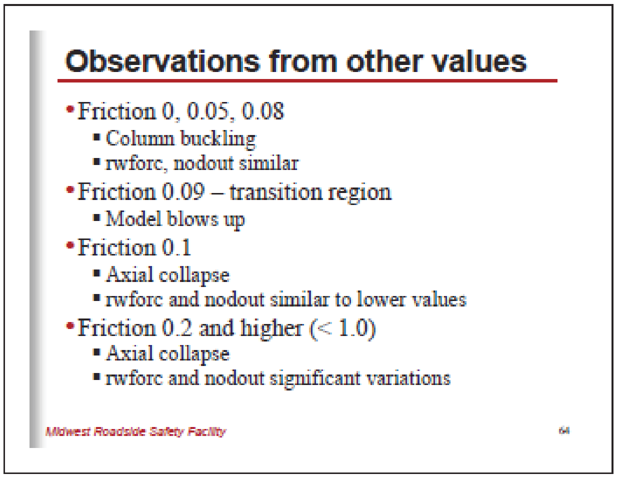


C.G. Acceleration

A: wall friction = 0.6
B: wall friction = 0.08

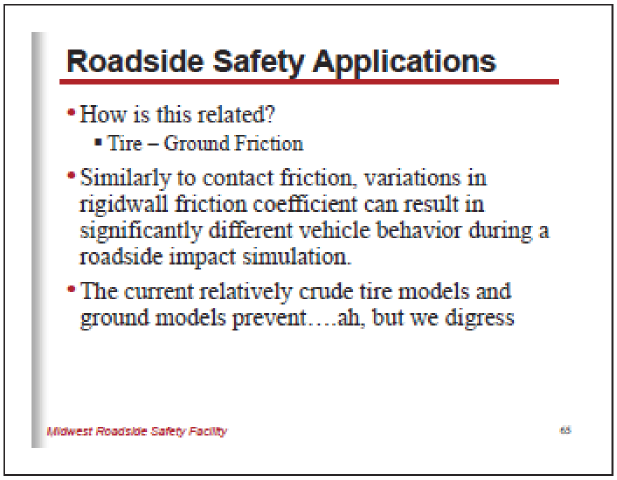


C.G. Acceleration



Observations from other values

- Friction 0, 0.05, 0.08
  - Column buckling
  - rwforc, nodout similar
- Friction 0.09 – transition region
  - Model blows up
- Friction 0.1
  - Axial collapse
  - rwforc and nodout similar to lower values
- Friction 0.2 and higher (< 1.0)
  - Axial collapse
  - rwforc and nodout significant variations



Roadside Safety Applications

- How is this related?
  - Tire – Ground Friction
- Similarly to contact friction, variations in rigidwall friction coefficient can result in significantly different vehicle behavior during a roadside impact simulation.
- The current relatively crude tire models and ground models prevent….ah, but we digress

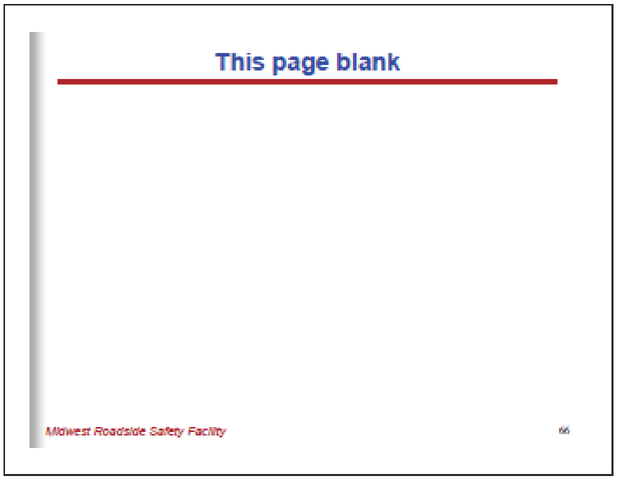


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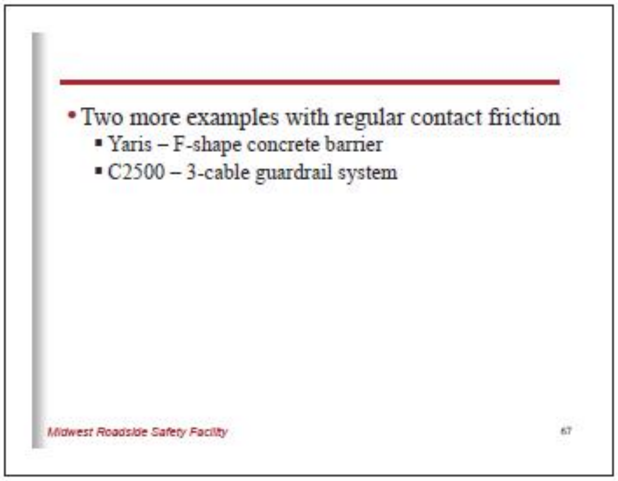
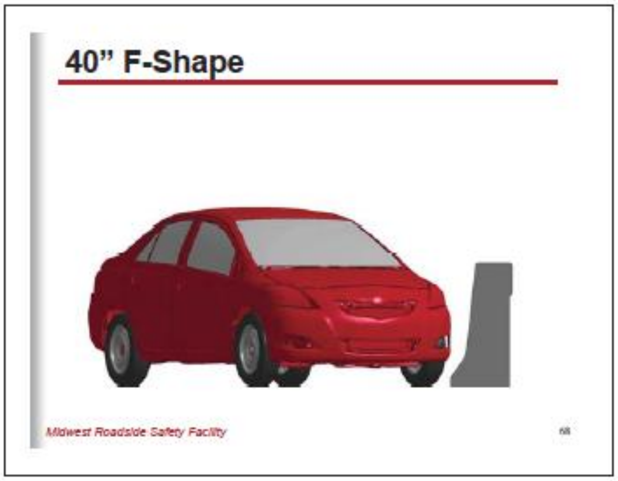
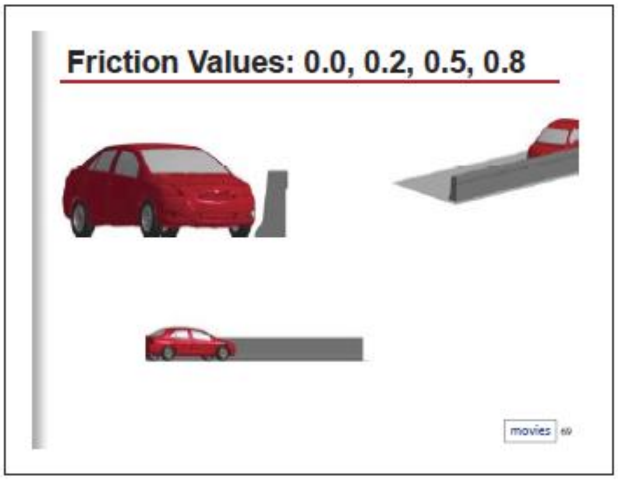
Figure 55. Friction Modeling: slides 61 – 66



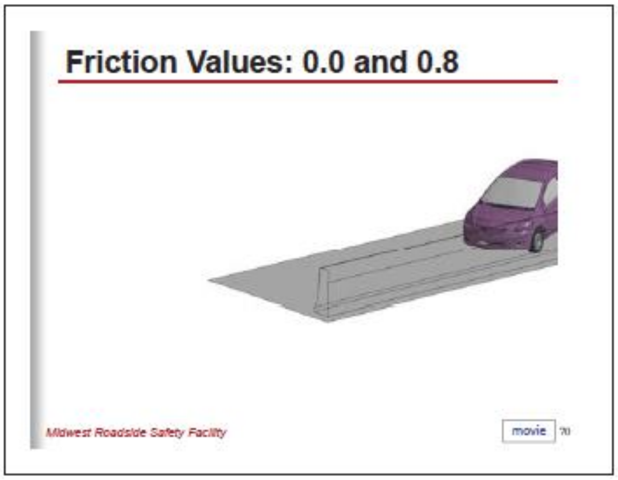
- Two more examples with regular contact friction
  - Yaris – F-shape concrete barrier
  - C2500 – 3-cable guardrail system



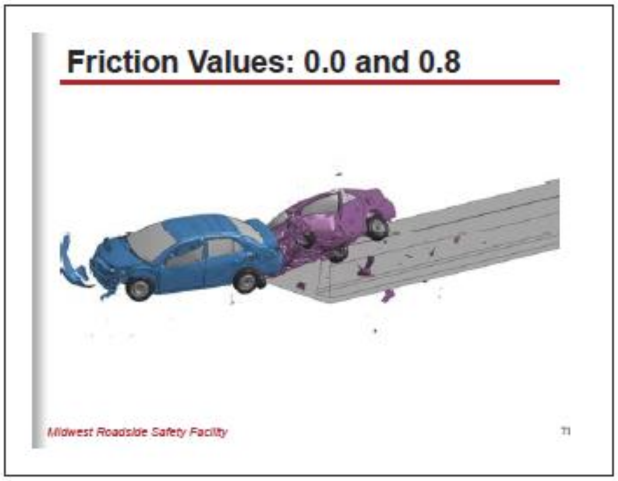
40" F-Shape



Friction Values: 0.0, 0.2, 0.5, 0.8



Friction Values: 0.0 and 0.8



Friction Values: 0.0 and 0.8

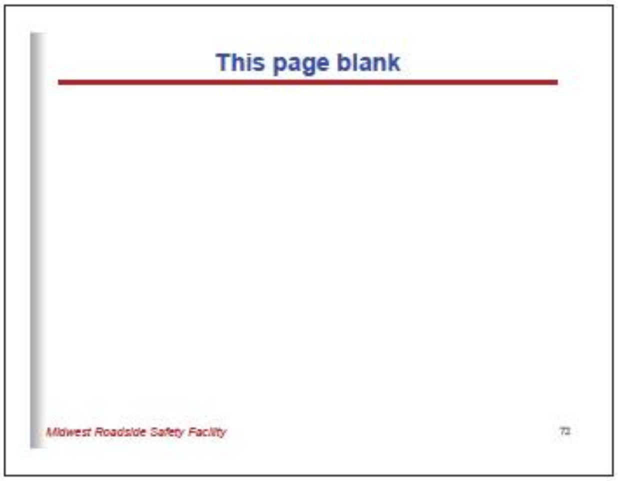


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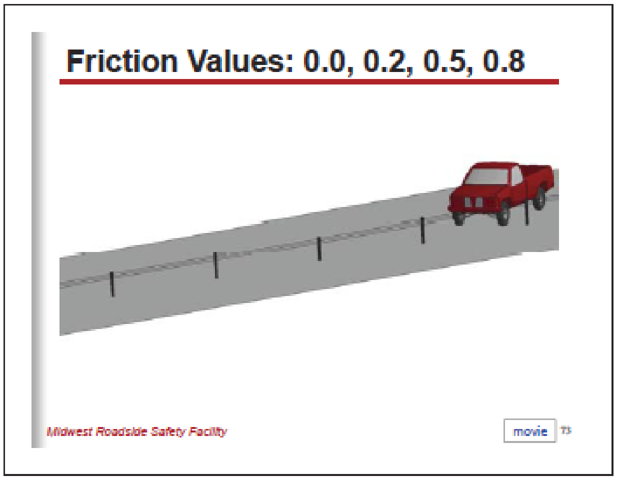
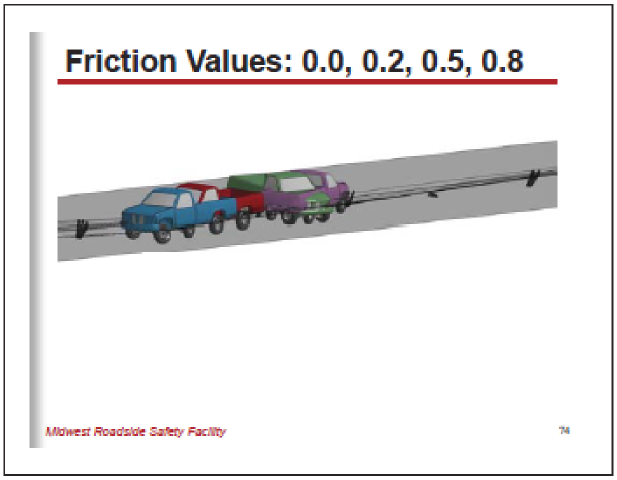
Figure 56. Friction Modeling: slides 67 – 72

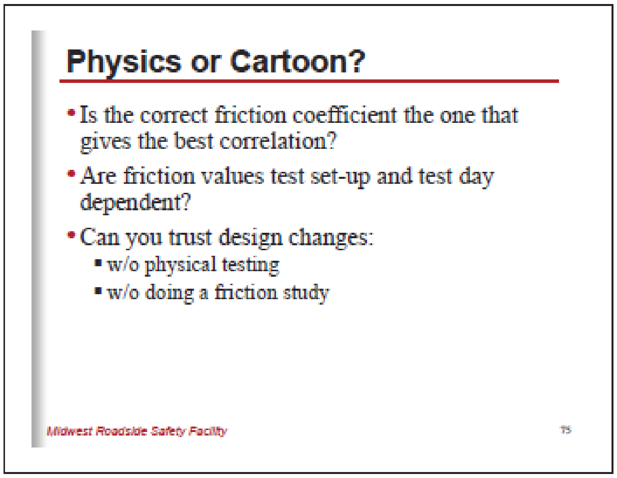


Friction Values: 0.0, 0.2, 0.5, 0.8

movie

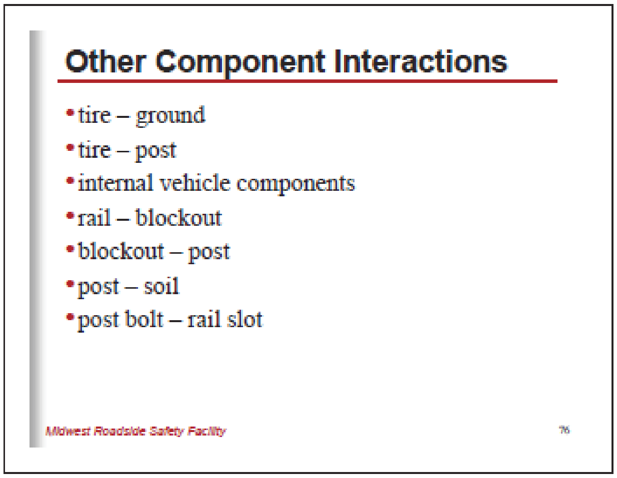


Friction Values: 0.0, 0.2, 0.5, 0.8



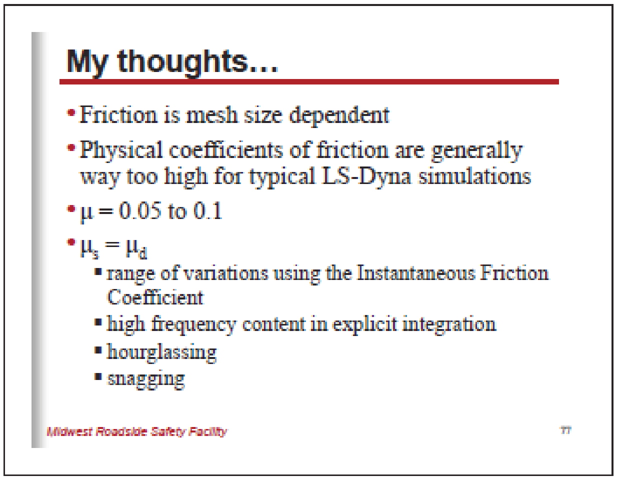
Physics or Cartoon?

- Is the correct friction coefficient the one that gives the best correlation?
- Are friction values test set-up and test day dependent?
- Can you trust design changes:
  - w/o physical testing
  - w/o doing a friction study



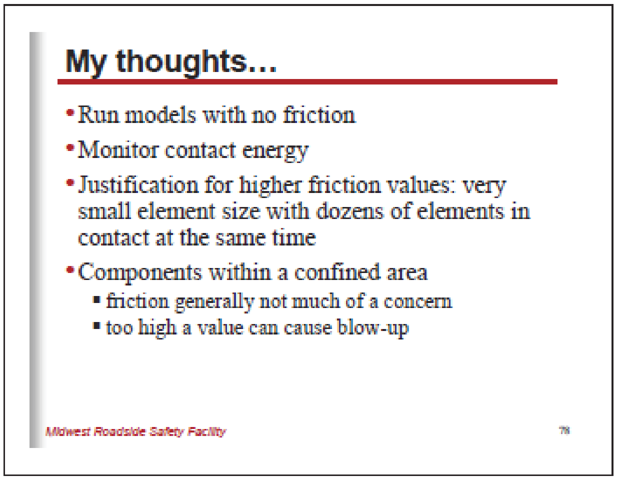
Other Component Interactions

- tire – ground
- tire – post
- internal vehicle components
- rail – blockout
- blockout – post
- post – soil
- post bolt – rail slot



My thoughts…

- Friction is mesh size dependent
- Physical coefficients of friction are generally way too high for typical LS-Dyna simulations
- $\mu = 0.05$ to 0.1
- $\mu_s = \mu_d$
  - range of variations using the Instantaneous Friction Coefficient
  - high frequency content in explicit integration
  - hourglassing
  - snagging



My thoughts…

- Run models with no friction
- Monitor contact energy
- Justification for higher friction values: very small element size with dozens of elements in contact at the same time
- Components within a confined area
  - friction generally not much of a concern
  - too high a value can cause blow-up

Figure 57. Friction Modeling: slides 73 – 78

8 MASS SCALING, CONTACTS, ELEMENT FORMULATIONS

8.1 Background

Finite element models contain basic things like nodes, elements, and material properties. But they also contain more abstract, mathematically based concepts like mass scaling, contacts and element formulations. These concepts involve dozens of various parameters that influence how a model behaves. For example, contacts are defined between parts that interact with each other. There are 64 types of contacts available within LS-DYNA. For a specific contact, there are over 45 parameters that can be set by the analyst. Fortunately, the default values are most often the most desirable. However, performing parameters studies to understand which parameters are critical or most useful to modify under various circumstances are often required. Developing base knowledge from such parameter studies was often the outcome from the work of this project.

8.2 ASME 2009 paper

Throughout the project period (2006-2016), many attempts were made to publish and present the techniques and procedures that were developed. One such publication and presentation was for the 2009 ASME International Mechanical Engineering Congress and Exposition (similar to the TRB annual meeting in Washington D.C. but for Mechanical Engineering). The paper reference being:

> J.D. Reid, "Investigating Mass Scaling in Vehicle Crashworthiness," *Track 19-4: Crashworthiness in Transportation Systems*, Proceedings of IMECE09, ASME, Paper IMECE2009-12410, Orlando, FL, November 2009.

To give the reader a flavor of the ASME paper, as well as a flavor of the types of things investigated with project funding, a copy of the abstract is as follows:

> Mass scaling is a technique used in explicit nonlinear finite element analysis that adds mass to relatively small elements in order to increase the time step, and thus, decrease the overall cpu requirements of a simulation. With multi-million element vehicle crash models becoming common, the likelihood of several very small, time step controlling elements is high. Mass scaling can provide great benefits in these cases. However, there is very little information on the actual usage and possible effects of mass scaling for vehicle crashworthiness in the literature. Inherit to explicit FEA is the well-known high frequency content in accelerations. Thus, even very small addition of mass will result in different acceleration traces. Because of that, various techniques are needed to determine if the mass scaled results are the same, or at least similar enough, as the non-mass scaled results. Two applications are investigated; a crush tube and an NCAP test of a Chevy Silverado. The latter model size approaches one million elements.

9 SUMMARY AND CONCLUSIONS

The Pooled Fund Program member states provided funding for LS-DYNA modeling enhancements in Years 17 thru 22 (2006-2011), with a project period of 2006-2016. That funding has been effectively utilized to advance the current state-of-the-art for computer simulation and has provided the following benefits for the entire industry:

1. Improved roadside safety hardware.
2. Reduced development time and cost.
3. Improved understanding of the behavior of roadside safety features, especially for impacts outside of normal crash test conditions.
4. Improved LS-DYNA modeling techniques and procedures.
5. Improved confidence in modeling.

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