Application of Finite Element Analysis (FEA) in Roadside Hardware Safety

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FEA in Roadside Hardware Safety

- Over the years, significant improvements in transportation safety have been achieved thanks to the use of Finite Element Analysis (FEA)
- Different transportation safety fields have benefited from this technology (automotive, aviation, ship design, etc.)
- Specifically FEA has been used over the past twenty years as a design tool to evaluate and improve roadside hardware
- More recently, implementation of FEA analysis is used in lieu of full-scale crash testing for eligibility (certification) for incremental design improvements

Advantages of FEA

- Use of FEA has been proven in numerous studies to be significantly more effective and efficient that testing alone
- Fewer full-scale crash tests would be needed by reducing the number of failed tests
- A more optimized design would be reached since significantly more simulations can be carried out at a significantly reduces cost
- Computer simulations also give more data than what can be extracted from the full-scale crash tests.
  - The results from the simulations include displacements, velocities, and accelerations of every point on the vehicle and the roadside system
  - The energies absorbed by each component of the vehicle and each component of the roadside system are also computed and stored in the simulation results.
- This information could be used to identify critical weaknesses in the design and give better understanding of the roadside system performance

FEA Approach as a Design Tool

- **Make use of numerical tools to develop better understanding of barrier features and parameters affecting its safety performance**
- **Model Development**
  - Develop computer models and modeling methodologies
  - Calibrate component and material models
  - Validate full model (full-scale crash tests)
- **Run iterative computer simulations to optimize/improve barrier performance**
- **Validate computer results using crash tests**
- **Run further simulations to study special cases**

FEA for Roadside Hardware Eligibility

- **V&V procedures for eligibility submission are based on Report W179 developed under an NCHRP study (NCHRP Project 22-24)**
- **Currently FEA eligibility submission are accepted for incremental (minor) hardware improvements**
- **FEA procedure would consists of following steps:**
  - Create and calibrate roadside hardware model (components test)
  - Validate model using full-scale crash test on baseline device
  - Incorporate design modification in barrier model
  - Compare simulation results of modified design to baseline design
  - Document all model calibrations (for both vehicle and roadside device), model validations, barrier design update and comparisons between baseline and updated model (comparisons should follow Report W179 guidelines)

Roadside Testing Background

- **Report 350/MASH describe testing procedures and evaluation criteria for roadside hardware**
- **Based on Worst Practical Conditions**
- **Test matrices for different roadside devices**
  - Longitudinal Barriers
  - Terminals and Crash Cushions
  - Support Structures, Work-Zone Traffic Control Devices, and Breakaway Utility Poles
  - Truck-Mounted and Trailer-Mounted Attenuators (TMAs)

MASH Test Levels

- **Six Test Levels**
  - Levels 1-3 based on speed
    - TL1 –50 km/h (31 mph)
    - TL2 –70 km/h (43 mph)
    - TL3 –100 km/h (62 mph)
  - Levels 4-6 add large trucks
    - Single unit truck
    - Tractor Trailer
    - Tractor tanker

TABLE 1-1. Test Levels

Test Level	Test Vehicle Designation* and Type	Test Conditions	
		Speed mph (km/h)	Angle (degrees)
1	1100C (Passenger Car) 2270P (Pickup Truck)	31 (50.0) 31 (50.0)	25 25
2	1100C (Passenger Car) 2270P (Pickup Truck)	44 (70.0) 44 (70.0)	25 25
3	1100C (Passenger Car) 2270P (Pickup Truck)	62 (100.0) 62 (100.0)	25 25
4	1100C (Passenger Car) 2270P (Pickup Truck) 10000S (Single-Unit Truck)	62 (100.0) 62 (100.0) 56 (90.0)	25 25 15
5	1100C (Passenger Car) 2270P (Pickup Truck) 36000V (Tractor-Van Trailer)	62 (100.0) 62 (100.0) 50 (80.0)	25 25 15
6	1100C (Passenger Car) 2270P (Pickup Truck) 36000T (Tractor-Tank Trailer)	62 (100.0) 62 (100.0) 50 (80.0)	25 25 15

Ref: Manual for Assessing Safety Hardware

Test Matrix

TABLE 2-2. Recommended Test Matrices for Longitudinal Barriers

Test Level	Barrier Section[c]	Test No.	Vehic.	Impact Speed,[a] mph (km/h)	Impact Angle,[a] θ, deg.	Impact Point	Acceptable IS Range,[a] kip-ft (kJ)	Evaluation Criteria[b]
1	Length-of-need	1-10 1-11	1100C 2270P	31 (50.0) 31 (50.0)	25 25	(c) (c)	≥13 (17.4) ≥27 (36.0)	A,D,F,H,I A,D,F,H,I
	Transition	1-20[d] 1-21	1100C 2270P	31 (50.0) 31 (50.0)	25 25	(c) (c)	≥13 (17.4) ≥27 (36.0)	A,D,F,H,I A,D,F,H,I
2	Length-of-need	2-10 2-11	1100C 2270P	44 (70.0) 44 (70.0)	25 25	(c) (c)	≥25 (34.2) ≥52 (70.5)	A,D,F,H,I A,D,F,H,I
	Transition	2-20[d] 2-21	1100C 2270P	44 (70.0) 44 (70.0)	25 25	(c) (c)	≥25 (34.2) ≥52 (70.5)	A,D,F,H,I A,D,F,H,I
3	Length-of-need	3-10 3-11	1100C 2270P	62 (100.0) 62 (100.0)	25 25	(c) (c)	≥51 (69.7) ≥106 (144)	A,D,F,H,I A,D,F,H,I
	Transition	3-20[d] 3-21	1100C 2270P	62 (100.0) 62 (100.0)	25 25	(c) (c)	≥51 (69.7) ≥106 (144)	A,D,F,H,I A,D,F,H,I
4	Length-of-need	4-10 4-11 4-12	1100C 2270P 10000S	62 (100.0) 62 (100.0) 56 (90.0)	25 25 15	(c) (c) (c)	≥51 (69.7) ≥106 (144) ≥142 (193)	A,D,F,H,I A,D,F,H,I A,D,G
	Transition	4-20[d] 4-21 4-22	1100C 2270P 10000S	62 (100.0) 62 (100.0) 56 (90.0)	25 25 15	(c) (c) (c)	≥51 (69.7) ≥106 (144) ≥142 (193)	A,D,F,H,I A,D,F,H,I A,D,G
	Length-of-need	5-10	1100C	62 (100.0)	25	(c)	≥51 (69.7)	A,D,F,H,I
		5-22	36000V	50 (80.0)	15	(c)	≥404 (548)	A,D,G
6	Length-of-need	6-10 6-11 6-12	1100C 2270P 36000T	62 (100.0) 62 (100.0) 50 (80.0)	25 25 15	(c) (c) (c)	≥51 (69.7) ≥106 (144) ≥404 (548)	A,D,F,H,I A,D,F,H,I A,D,G
	Transition	6-20[d] 6-21 6-22	1100C 2270P 36000T	62 (100.0) 62 (100.0) 50 (80.0)	25 25 15	(c) (c) (c)	≥51 (69.7) ≥106 (144) ≥404 (548)	A,D,F,H,I A,D,F,H,I A,D,G

3	Length-of-need	3-10 3-11	1100C 2270P	62 (100.0) 62 (100.0)	25 25	(c) (c)	≥51 (69.7) ≥106 (144)	A,D,F,H,I A,D,F,H,I

Vehicle

Speed

Angle

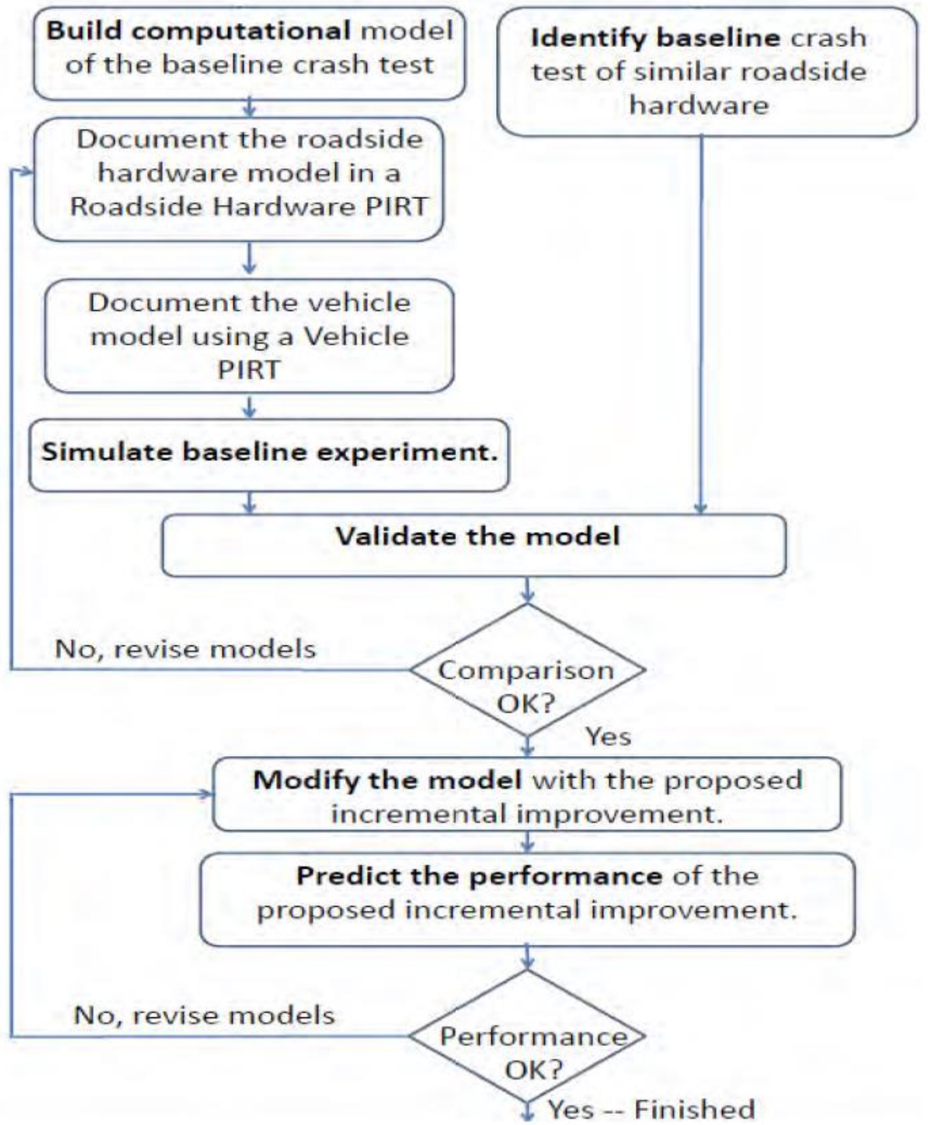
Evaluation criteria

Ref: Manual for Assessing Safety Hardware

Evaluation Criteria

- **Roadside barriers are evaluated based on three types of criteria**
  - ⇨ Structural adequacy of the tested device
  - ⇨ Occupant risk
  - ⇨ Vehicle trajectory

Report W179 V&V Procedure



Ref: NCHRP Report W179

Vehicle and Barrier Model Calibrations

- **Calibrations consist of using experimental data (from coupon and component tests) and known analytical solutions to obtain/define unknown parameters in the model**
- **The parameters include material properties, contact frictions, connection failure, etc.**
- **Calibration tests are often setup such that one (or few) of the unknown parameters influence the outcome of the test**
- **Calibrations are performed on both the vehicle and barrier models and aimed at addressing all key parameters affecting the outcome of the simulation**

Sample Barrier Component Calibration

Table 20. Phenomena Importance Ranking Table (PIRT) for the G4(1S).

	Validated Phenomenon	Validated? Verified? Calibrated?
1.	Three-Point Bend Test of W150x13.5 Post About Weak Axis	Validated
2.	Load-to-rupture of splice connection under quasi-static axial loading	Qualitative Validation
3.	Pull-through of post-bolt-head connection to w-beam using axial load machine	Qualitative Validation
4.	Full-scale bogie impact tests of the W150x13.5post embedded in 1,980 kg/m^3 soil	Qualitative Validation
5.	Full-scale bogie impact tests of the W150x13.5post embedded in 2,110 kg/m^3 soil	Qualitative Validation
6.	Full-scale bogie impact tests of the W150x13.5post embedded in 2,240 kg/m^3 soil	Validated

PHENOMENA # *1:* **Plastic deformation of guardrail posts due to bending about weak axis**

Sprauge-Geers Metrics List all the data channels to be compared below. Using RSVVP calculate the M and P metrics comparing the experiment and the simulation. Values less than or equal to 20 are acceptable.	M	P	Pass?
• *Force-Displacement*	3.6	1.1	Yes

ANOVA Metrics List all the data channels to compare in the rows below. Use RSVVP to calculate the ANOVA metrics and enter the values below. The following criteria must be met: • The mean residual error must be less than or equal to five percent of the peak acceleration ($\bar{e} \le 0.05 \cdot a_{Peak}$) • The standard deviation of the residuals must be less than or equal to 25 percent of the peak acceleration ($\sigma \le 0.25 \cdot a_{Peak}$)	Mean Residual	Standard Deviation of Residuals	Pass?
• *Force-Displacement*	0.03	0.03	Yes

PHENOMENA

Three-Point Bend Test of W150x13.5 Post About Weak Axis

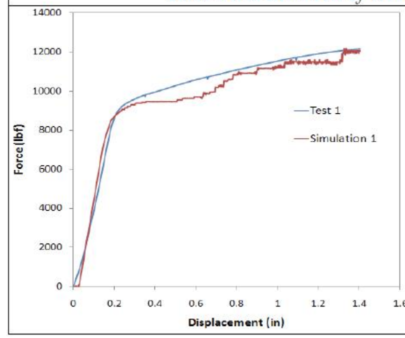


Figure 52. Example of a validation sheet from a roadside hardware PIRT.

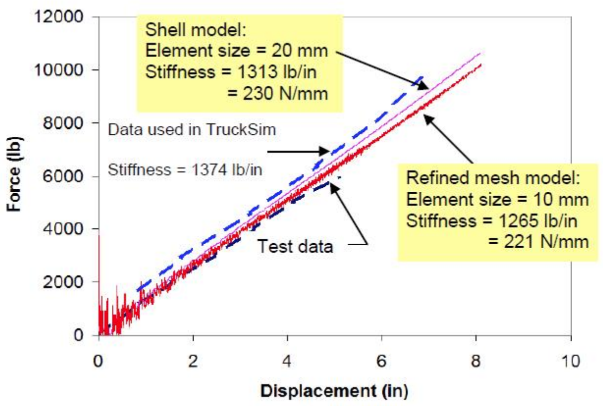
Ref: NCHRP Report W179

Sample Vehicle Model Calibration

Table 21. Partial PIRT for the NCAC C2500R pickup truck. *(83)*

Phenomena	Summary	Valid?
Front suspension coil springs	Properties calibrated with physical test data	Calibration
Front suspension dampers	Properties verified with physical test data obtained from external source and calibrated with laboratory tests conducted at WPI	Calibration
Suspension stops on front A-arms	Response verified through visual observation of computer model results	Verification
Stabilizer bar	Response verified through visual observation of computer model results	Verification
Rear leaf spring suspension	Spring properties for vertical stiffness calibrated with physical test data. Lateral and torsional stiffness properties obtained analytically.	Calibration
Steering system properties	Properties calibrated with physical tests	Calibration
Steer stops on steering system	Response verified through visual observation of computer model results	Verification
Inertial Properties	Properties calibrated through data obtained from NHTSA and TTI	Calibration
Vertical front suspension response	Roll-off drop tests	Validation*
Vertical rear suspension response	Roll-off drop tests	Validation*
Front and rear suspension response	90-degree curb traversal tests – 6-inch AASHTO type B curb	Validation*
Front and rear suspension response and steer response	25-degree curb traversal tests – 6-inch AASHTO type B curb	Validation*

* *Qualitative assessment only*



Ref: NCHRP Report W179

Full-scale Verification & Validations

- **Model verification and validation consists of three parts:**
  - **Analysis Solution Verification**
    - Checks that simulation is stable and results are conforming to the conservation laws (i.e. the numerical solution obeyed basic laws of physics)
  - **Time History Evaluation**
    - Quantitative comparisons of time histories between test and simulation
    - Six time history curves are often compared (3 accelerations & 3 angular rates at vehicle cg)
    - A program, Roadside Safety Verification and Validation Program (RSVVP), was created to compare the curves using different statistical variation metrics (Sprague-Geers MPC and ANOVA)
    - Simulation time histories are compared to original measured data
    - Acceptance (pass/fail) criteria are determined based on variation between repeated tests
  - **Phenomena Importance Ranking Tables (PIRTs)**
    - Comparison of the phenomena observed in the crash test and simulation
    - Comparisons are based on the evaluation criteria of the barrier (e.g. ORA, Roll angle, etc.)
    - All evaluation criteria are compared
    - PIRTs are device dependent

Analysis Solution Verification

Table C1-1. Analysis Solution Verification Table.

Verification Evaluation Criteria	Change (%)	Pass?
Total energy of the analysis solution (i.e., kinetic, potential, contact, etc.) must not vary more than 10 percent from the beginning of the run to the end of the run.	1.3	YES
Hourglass Energy of the analysis solution at the end of the run is less than *five percent* of the total *initial energy* at the *beginning* of the run.	0	YES
Hourglass Energy of the analysis solution at the end of the run is less than *ten percent* of the total *internal energy* at the *end* of the run.	0	YES
The part/material with the highest amount of hourglass energy at the end of the run is less than ten percent of the total internal energy of the part/material at the end of the run.	0	YES
Mass added to the total model is less than five percent of the total model mass at the beginning of the run.	0	YES
The part/material with the most mass added had less than 10 percent of its initial mass added.	0	Yes
The moving parts/materials in the model have less than five percent of mass added to the initial moving mass of the model.	0	Yes
There are no shooting nodes in the solution?	Yes	Yes
There are no solid elements with negative volumes?	Yes	Yes

The Analysis Solution (check one) ☒ passes ☐ does NOT pass all the criteria in Table C1-1 ☐ with ☒ without exceptions as noted.

Ref: NCHRP Report W179

Time History Evaluation

Table C1-2. Roadside Safety Validation Metrics Rating Table – Time History Comparisons

Evaluation Criteria

O ***Sprague-Geers Metrics***
List all the data channels being compared. Calculate the M and P metrics using RSVVP and enter the results. Values less than or equal to 40 are acceptable.

Time interval [0 sec; 0.7 sec]

	RSVVP Curve Preprocessing Options						M	P	Pass?
	Filter Option	Sync. Option	Shift		Drift				
			True Curve	Test Curve	True Curve	Test Curve			
X acceleration	CFC 180	Min. area of Residuals	Y	N	Y	N	21.5	33.3	Y
Y acceleration	CFC 180	Min. area of Residuals	Y	N	Y	N	43.9	35.7	N
Z acceleration	CFC 180	Min. area of Residuals	Y	N	Y	N	21.1	43.0	N
Roll rate	CFC 180	Min. area of Residuals	N	N	N	N	35.3	32.7	Y
Pitch rate	CFC 180	Min. area of Residuals	N	N	N	N	13.3	48.0	N
Yaw rate	CFC 180	Min. area of Residuals	N	N	N	N	11.7	8.7	Y

P ***ANOVA Metrics***
List all the data channels being compared. Calculate the ANOVA metrics using RSVVP and enter the results. Both of the following criteria must be met:

- The mean residual error must be less than five percent of the peak acceleration ($\bar{e} \leq 0.05 \cdot a_{Peak}$) and
- The standard deviation of the residuals must be less than 35 percent of the peak acceleration ($\sigma \leq 0.35 \cdot a_{Peak}$)

	Mean Residual	Standard Deviation of Residuals	Pass?
X acceleration/Peak	0.02	0.34	Y
Y acceleration/Peak	0.05	0.27	Y
Z acceleration/Peak	0.02	0.32	Y
Roll rate	0.02	0.27	Y
Pitch rate	0.05	0.36	N
Yaw rate	0.04	0.12	Y

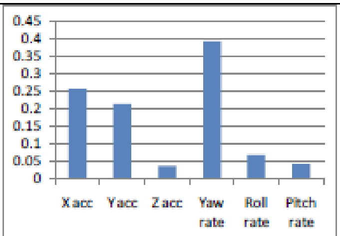
The Analysis Solution (check one) ☐ passes ☒ does NOT pass all the criteria in Table C1-2.

Ref: NCHRP Report W179

Time History Evaluation (Multi-Channel)

Table C1-3(a). Roadside Safety Validation Metrics Rating Table – Time History Comparisons

Evaluation Criteria (time interval [0 sec; 0.7 sec])		
Channels (Select which were used)		
☒ **X Acceleration**	☒ **Y Acceleration**	☒ **Z Acceleration**
☒ **Roll rate**	☒ **Pitch rate**	☒ **Yaw rate**
Multi-Channel Weights -Area (II) Method-	**X Channel – 0.255116** **Y Channel – 0.210572** **Z Channel – 0.034312** **Yaw Channel – 0.392648** **Roll Channel – 0.06581** **Pitch Channel – 0.041542**	



O	***Sprague-Geer Metrics*** Values less or equal to 40 are acceptable.	**M**	**P**	**Pass?**
		22.9	25	Y
P	***ANOVA Metrics*** Both of the following criteria must be met: • The mean residual error must be less than five percent of the peak acceleration ($\overline{e} \leq 0.05 \cdot a_{Peak}$) • The standard deviation of the residuals must be less than 35 percent of the peak acceleration ($\sigma \leq 0.35 \cdot a_{Peak}$)	**Mean Residual**	**Standard Deviation of Residuals**	Pass?
		0.03	0.24	Y

The Analysis Solution (check one) ☒ passes ☐ does NOT pass <u>all</u> the criteria in Table C1-3.

Ref: NCHRP Report W179

Phenomena Importance Ranking Tables

Table C1-4. Evaluation Criteria Test Applicability Table.

Evaluation Factors		Evaluation Criteria	Applicable Tests
Structural Adequacy	A	Test article should contain and redirect the vehicle; the vehicle should not penetrate, under-ride, or override the installation although controlled lateral deflection of the test article is acceptable.	10, 11, 12, 20, 21, 22, 35, 36, 37, 38
	B	The test article should readily activate in a predictable manner by breaking away, fracturing or yielding.	60, 61, 70, 71, 80, 81
	C	Acceptable test article performance may be by redirection, controlled penetration or controlled stopping of the vehicle.	30, 31,, 32, 33, 34, 39, 40, 41, 42, 43, 44, 50, 51, 52, 53
Occupant Risk	D	Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians or personnel in a work zone.	All
	E	Detached elements, fragments or other debris from the test article, or vehicular damage should not block the driver's vision or otherwise cause the driver to lose control of the vehicle. (Answer Yes or No)	70, 71
	F	The vehicle should remain upright during and after the collision although moderate roll, pitching and yawing are acceptable.	All except those listed in criterion G
	G	It is preferable, although not essential, that the vehicle remain upright during and after collision.	12, 22 (for test level 1 – 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44)
	H	Occupant impact velocities should satisfy the following: Occupant Impact Velocity Limits (m/s) Component / Preferred / Maximum Longitudinal and Lateral / 9 / 12	10, 20, 30,31, 32, 33, 34, 36, 40, 41, 42, 43, 50, 51, 52, 53, 80, 81
		Longitudinal / 3 / 5	60, 61, 70, 71
	I	Occupant ridedown accelerations should satisfy the following: Occupant Ridedown Acceleration Limits (g's) Component / Preferred / Maximum Longitudinal and Lateral / 15 / 20	10, 20, 30,31, 32, 33, 34, 36, 40, 41, 42, 43, 50, 51, 52, 53, 60, 61, 70, 71, 80, 81
Vehicle Trajectory	L	The occupant impact velocity in the longitudinal direction should not exceed 40 ft/sec and the occupant ride-down acceleration in the longitudinal direction should not exceed 20 G's.	11,21, 35, 37, 38, 39
	M	The exit angle from the test article preferable should be less than 60 percent of test impact angle, measured at the time of vehicle loss of contact with test device.	10, 11, 12, 20, 21, 22, 35, 36, 37, 38, 39
	N	Vehicle trajectory behind the test article is acceptable.	30, 31, 32, 33, 34, 39, 42, 43, 44, 60, 61, 70, 71, 80, 81

Ref: NCHRP Report W179

Phenomena Importance Ranking Tables

Table 27. Structural adequacy phenomena for test case 1.

Evaluation Criteria				Known Result	Analysis Result	Difference Relative/ Absolute	Agree?
Structural Adequacy	A	A1	Test article should contain and redirect the vehicle; the vehicle should not penetrate, under-ride, or override the installation although controlled lateral deflection of the test article is acceptable. (Answer Yes or No)	Yes	Yes		YES
		A2	Maximum dynamic deflection: - Relative difference is less than 20 percent or - Absolute difference is less than 0.15 m	1.0 m	0.985m	1.5% 0.02 m	YES
		A3	Length of vehicle-barrier contact: - Relative difference is less than 20 percent or - Absolute difference is less than 2 m	0.691 s	0.690 s	0.1%	YES
		A4	The relative difference in the number of broken or significantly bent posts is less than 20 percent.	3	3	0	YES
		A5	Did the rail element rupture or tear (Answer Yes or No)	No	No		YES
		A6	Were there failures of connector elements (Answer Yes or No).	Yes	Yes		YES
		A7	Was there significant snagging between the vehicle wheels and barrier elements (Answer Yes or No).	Yes	Yes		YES
		A8	Was there significant snagging between vehicle body components and barrier elements (Answer Yes or No).	No	No		YES

Ref: NCHRP Report W179

Phenomena Importance Ranking Tables

Table 28. Occupant risk phenomena for test case 1.

			Evaluation Criteria	Known Result	Analysis Result	Difference Relative/ Absolute	Agree?
Occupant Risk	D		Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians or personnel in a work zone. (Answer Yes or No)	Pass	Pass		YES
	F	F1	The vehicle should remain upright during and after the collision although moderate roll, pitching and yawing are acceptable. (Answer Yes or No)	Pass	Pass		YES
		F2	Maximum roll of the vehicle: - Relative difference is less than 20 percent or - Absolute difference is less than 5 degrees.	-8.7	-10.1	16% 1.4 deg	YES
		F3	Maximum pitch of the vehicle is: - Relative difference is less than 20 percent or - Absolute difference is less than 5 degrees.	-3.3	-4.3	30% 1.0 deg	YES
		F4	Maximum yaw of the vehicle is: - Relative difference is less than 20 percent or - Absolute difference is less than 5 degrees.	41	42.8	4% 1.8 deg	YES
	L		The occupant impact velocity in the longitudinal direction should not exceed 12 m/sec and the occupant ridedown acceleration in the longitudinal direction should not exceed 20 G's.				
		L1	• Longitudinal OIV (m/s)	5.4	4.7	13% 0.7m/s	YES
		L2	• Lateral OIV (m/s)	4.4	5.0	13.6% 0.6 m/s	YES
		L3	• THIV (m/s)	6.3	6.4	1.6% 0.1 m/s	YES
		L4	Occupant accelerations: - Relative difference is less than 20 percent or - Absolute difference is less than 4 g's.				
		L5	• Longitudinal ORA	7.9	8.9	12.7% 1.0 G	YES
		L6	• Lateral ORA	8.4	10.0	19.0% 1.6 G	YES
		L7	• PHD	12.1	13.2	9.1% 1.2 G	YES
			• ASI	0.68	0.72	5.9% 0.04	YES

Ref: NCHRP Report W179

Phenomena Importance Ranking Tables

Table 29. Vehicle trajectory phenomena for test case 1.

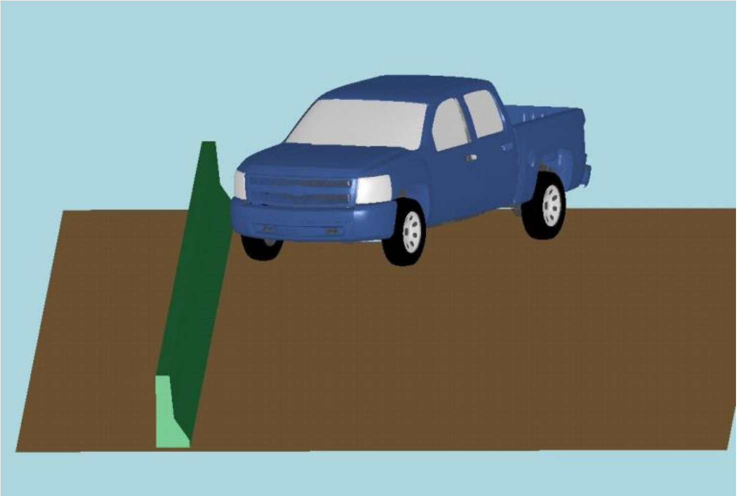
Evaluation Criteria				Known Result	Analysis Result	Difference Relative/ Absolute	Agree?
Vehicle Trajectory	M	M1	The exit angle from the test article preferable should be less than 60 percent of test impact angle, measured at the time of vehicle loss of contact with test device.	15.5° 61%	17.3° 68%		YES
		M2	Exit angle at loss of contact: - Relative difference is less than 20 percent or - Absolute difference is less than 5 degrees.	15.5°	17.3°	11.6% 1.8 deg	YES
		M3	Exit velocity at loss of contact: - Relative difference is less than 20 percent or - Absolute difference is less than 5 degrees.	55 km/h	62 km/h	12.7% 7.0 km/hr	YES
		M4	One or more vehicle tires failed or de-beaded during the collision event (Answer Yes or No).	Yes	N.A.		

Ref: NCHRP Report W179

Sample V&V Case:
Silverado / New Jersey
Concrete Median Barrier

Silverado / NJ CMB

- **TTI test 476460-1-4**
- **Impact Condition**
  - 62.6 mi/hr
  - 25.2 deg



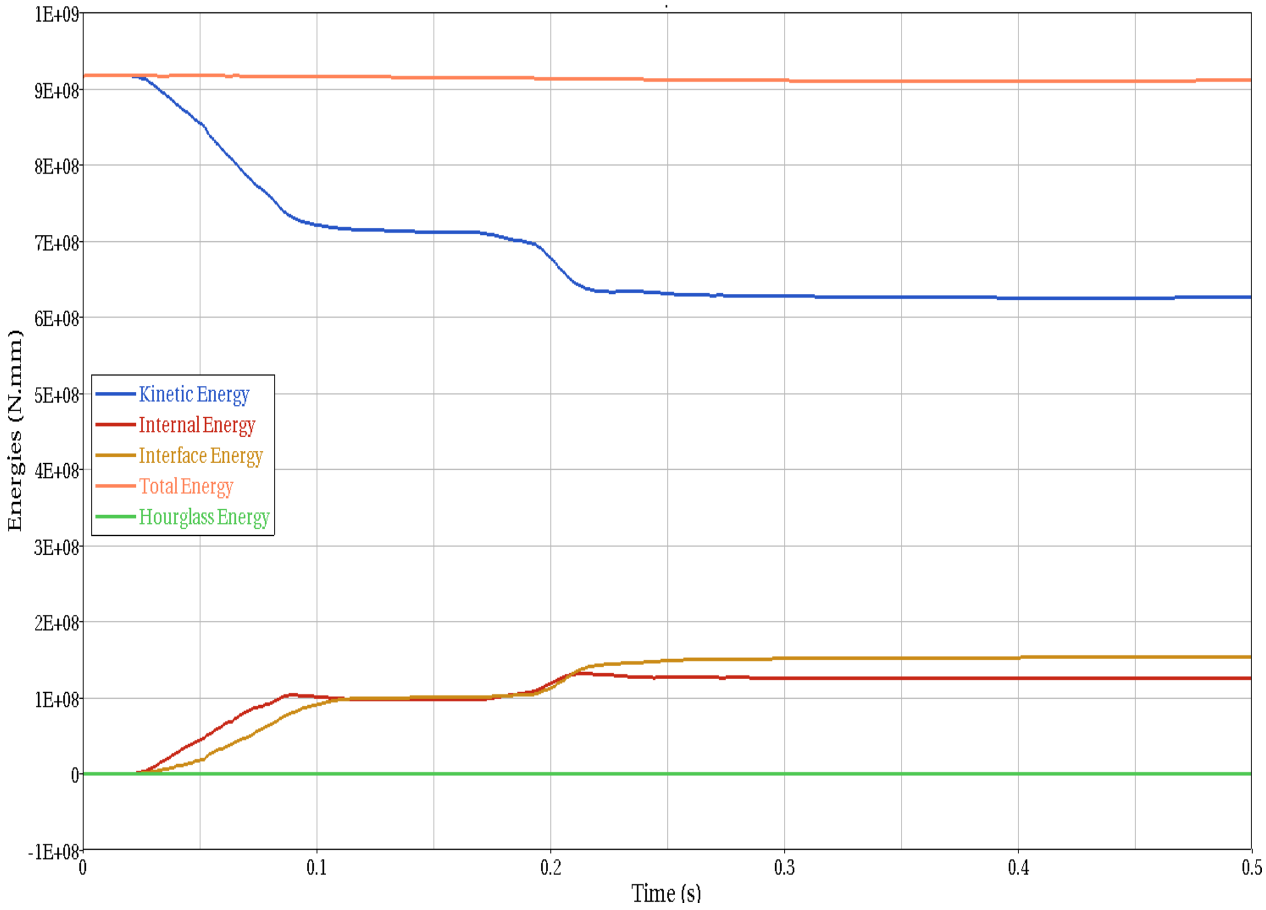
Silverado / NJ CMB

2270P – NJ CMB – 100 km/hr – 25 deg

Silverado / NJ CMB

2270P – NJ CMB – 100 km/hr – 25 deg

Silverado / NJ CMB



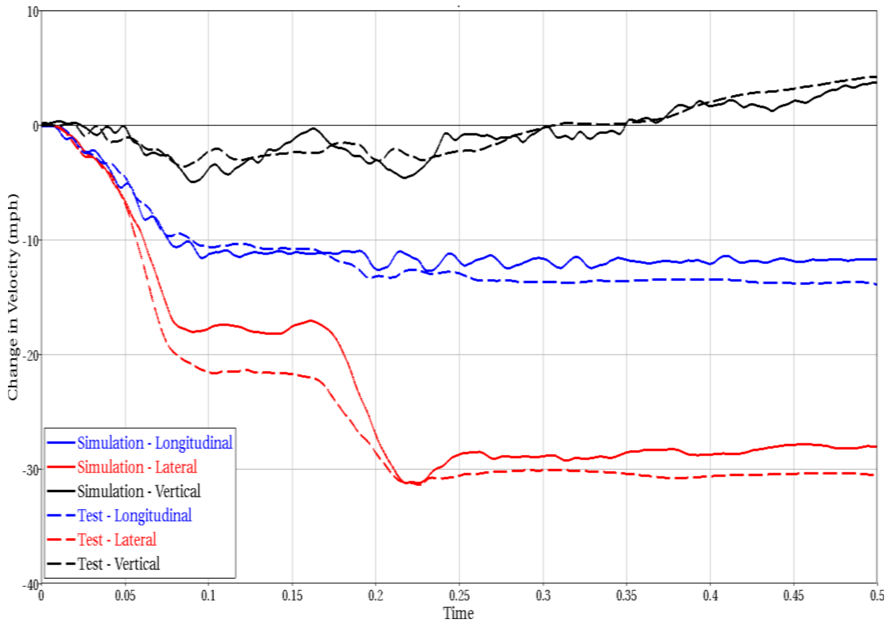
Energy Balance Plot

Silverado / NJ CMB

Analysis Solution Verification Summary

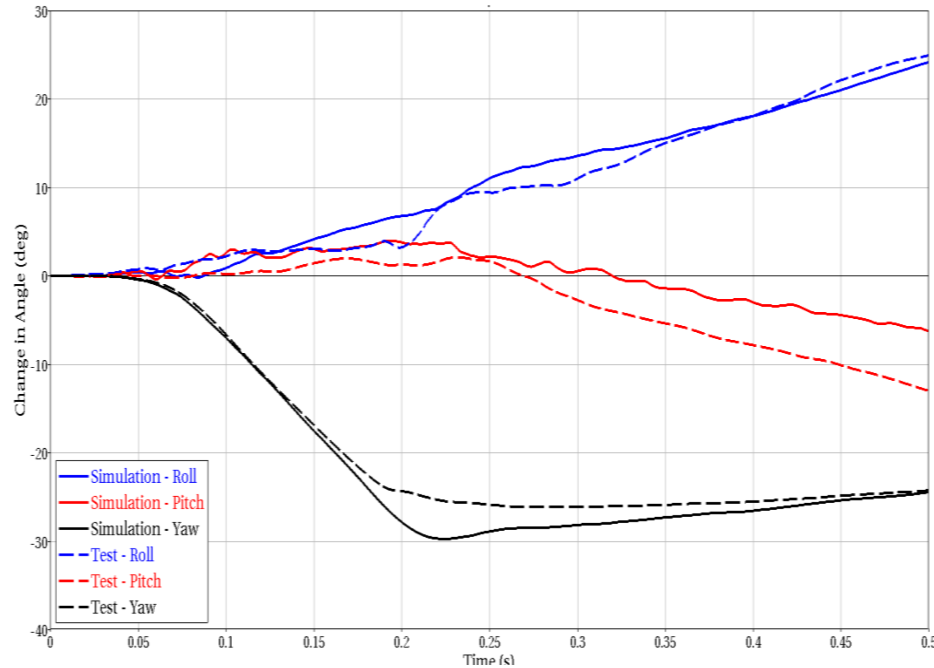
Verification Evaluation Criteria	Change (%)	Pass?
Total energy of the analysis solution (i.e., kinetic, potential, contact, etc.) must not vary more than 10 percent from the beginning of the run to the end of the run.	<1%	YES
Hourglass Energy of the analysis solution at the end of the run is less than 5 % of the total initial energy at the beginning of the run	<1%	YES
The part/material with the highest amount of hourglass energy at any time during the run is less than 5 % of the total initial energy at the beginning of the run.	<1%	YES
Mass added to the total model is less than 5 % the total model mass at the start of the run.	<1%	YES
The part/material with the most mass added had less than 10 % of its initial mass added.	<1%	YES
The moving parts/materials in the model have less than 5 % of mass added to the initial moving mass of the model.	<1%	YES
There are no shooting nodes in the solution?	NA	YES
There are no solid elements with negative volumes?	NA	YES

Silverado / NJ CMB



Change in Velocity Comparisons

Change in Angle Comparisons



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Single Channels RSVVP Comparisons

Single Channel Time History Comparison Results		Time interval [0 sec - 0.5 sec]		
O	***Sprauge-Geer Metrics***	**M**	**P**	**Pass?**
	X acceleration	52.9	35.6	NO
	Y acceleration	3.2	16.2	YES
	Z acceleration	71.7	45.3	NO
	Yaw rate	13.4	9.5	YES
	Roll rate	16.8	24.4	YES
	Pitch rate	35.4	39.9	YES
P	***ANOVA Metrics***	**Mean**	**SD**	**Pass?**
	X acceleration/Peak	1.32	29.37	YES
	Y acceleration/Peak	0.84	12.15	YES
	Z acceleration/Peak	0.66	44.94	NO
	Yaw rate	0.2	14.87	YES
	Roll rate	0.21	17.28	YES
	Pitch rate	10.86	53.95	NO
Multi-Channel Weighting Factors		**Time interval [0 sec; 0.5 sec]**		
Multi-Channel Weighting Method	**X Channel**	0.142263141		
Peaks Area I	**Y Channel**	0.312496147		
Area II Inertial	**Z Channel**	0.045240712		
	Yaw Channel	0.19476326		
	Roll Channel	0.200826808		
	Pitch Channel	0.104409933		
Sprauge-Geer Metrics		**M**	**P**	**Pass?**
	All Channels (weighted)	21.4	23.1	YES
ANOVA Metrics		**Mean**	**SD**	**Pass?**
	All Channels (weighted)	1.5	22	YES

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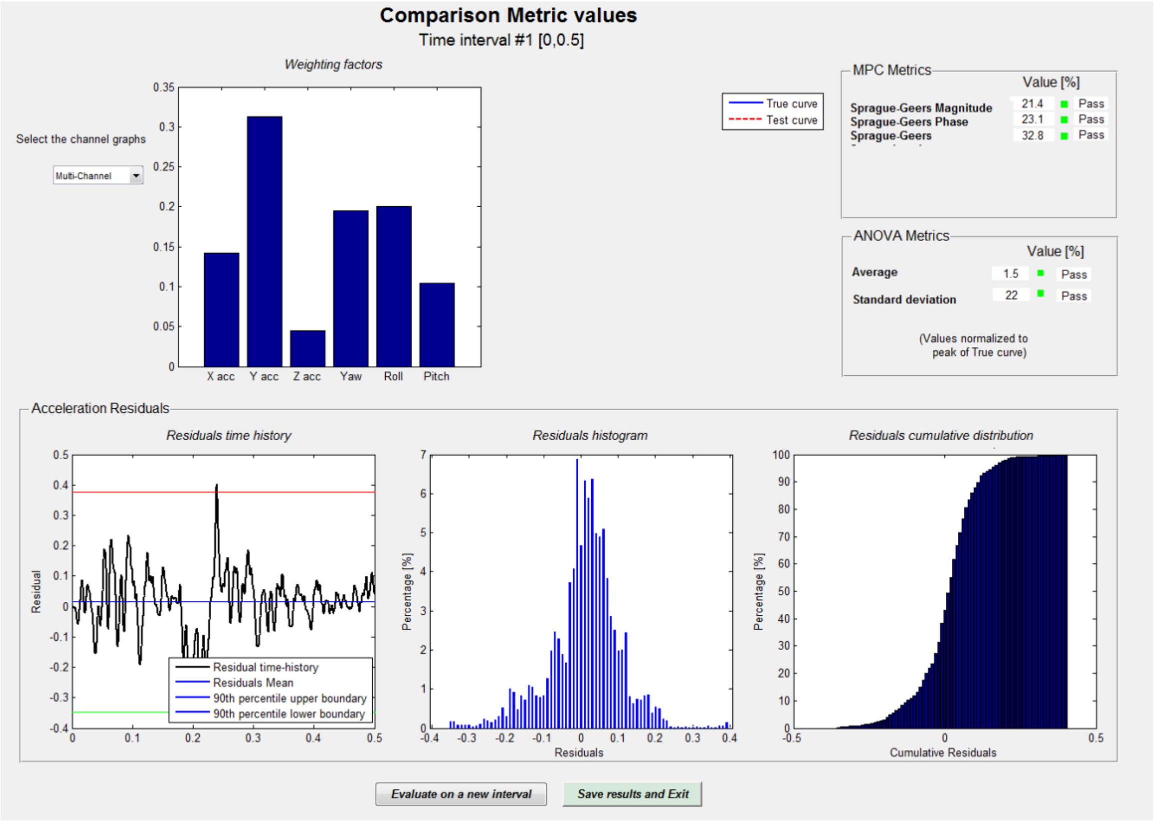

NCHRP 22-24 Comparison Metrics

All Channels Comparisons (Weighted)

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			Evaluation Criteria	Known Result	Analysis Result	Relative Diff. (%)	Agree?
Structural Adequacy	A	A1	Test article should contain and redirect the vehicle; the vehicle should not penetrate, under-ride, or override the installation although controlled lateral deflection of the test article is acceptable.	Yes	Yes		YES
		A2	The relative difference in the maximum dynamic deflection is less than 20 percent.	0.0 m	0.0 m	0%	YES
		A3	The relative difference in the time of vehicle-barrier contact is less than 20 percent.	0.238 s	0.214 s	10%	YES
		A4	The relative difference in the number of broken or significantly bent posts is less than 20 percent.	Yes	Yes		YES
		A5	Barrier did not fail (Answer Yes or No).	Yes	Yes		YES
		A6	There were no failures of connector elements (Answer Yes or No).	Yes	Yes		YES
		A7	There was no significant snagging between the vehicle wheels and barrier elements (Answer Yes or No).	Yes	Yes		YES
		A8	There was no significant snagging between vehicle body components and barrier elements (Answer Yes or No).	Yes	Yes		YES
Occupant Risk	D		Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians or personnel in a work zone (Answer Yes or No).	Yes	Yes		YES
	F	F1	The vehicle should remain upright during and after the collision. The maximum pitch & roll angles are not to exceed 75 degrees.	Yes	Yes		YES
		F2	Maximum vehicle roll – relative difference is less than 20% or absolute difference is less than 5 degrees.	25 (.5s)	24 (.5s)	4% 1 deg	YES
		F3	Maximum vehicle pitch – relative difference is less than 20% or absolute difference is less than 5 deg.	12 (.5s)	7 (.5s)	41% 5 deg	YES
		F4	Maximum vehicle yaw – relative difference is less than 20% or absolute difference is less than 5 deg.	30 (.5s)	26 (.5s)	13% 4 deg	YES
	H	H1	Longitudinal & lateral occupant impact velocities (OIV) should fall below the preferred value of 30 ft/s (9.1 m/s), or at least below the maximum allowed value of 40 ft/s (12.2 m/s)	Yes	Yes		YES
		H2	Longitudinal OIV (m/s) - Relative difference is less than 20%t or absolute difference is less than 2 m/s	4.3	4.7	9% 0.4 m/s	YES
		H3	Lateral OIV (m/s - Relative difference is less than 20% or absolute difference is less than 2 m/s	9.2	7.9	14% 1.3 m/s	YES
	I	I1	Longitudinal & lateral occupant ridedown accelerations (ORA) should fall below the preferred value of 15.0 g, or at least below the maximum allowed value of 20.49 g.	Yes	Yes		YES
		I2	Longitudinal ORA (g) - Relative difference is less than 20% or absolute difference is less than 4 g's	5.6	7.6	35% 2 g	YES
		I3	Lateral ORA (g) - Relative difference is less than 20% or absolute difference is less than 4 g's	9.6	12.9	34% 3 g	YES
Vehicle Trajectory			The vehicle rebounded within the exit box. (Answer Yes or No)	Yes	Yes		YES

Roadside Safety Phenomena Importance Ranking Table

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Composite Verification and Validation Summary

List the Report MASH08 Test Number		
Table C – Analysis Solution Verification S	Did all solution verification criteria in table pass?	YES
Table D - RSVVP Results	Do all the time history evaluation scores from the single channel factors result in a satisfactory comparison (i.e., the comparison passes the criterion)?	NO
	If all the values for Single Channel comparison did not pass, did the weighted procedure result in an acceptable	YES
Table E - Roadside Safety Phenomena Importance Ranking Table	Did all the critical criteria in the PIRT Table pass? Note: Tire deflation was observed in the test but not in the simulation. This due to the fact that tire deflation in not incorporated in the model. This is considered not to have a critical effect on the outcome of the test	YES
Overall	Are the results of Steps I through III all affirmative (i.e., YES)? If all three steps result in a "YES" answer, the comparison can be considered validated or verified. If one of the steps results in a negative response, the result cannot be considered validated or verified.	YES

Thank You!