

CAE Methodology for Evaluation of Fleet Crash Protection of New Vehicle Designs* - EFP

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**Systems modeling approach for evaluating self and partner, of new vehicle designs, sponsored by NHTSA, that Informed Midterm Evaluation for Light-Duty CAFE, MY 2022-2025*

References

- **Samaha, R. Radwan., Prasad P., Marzougui, D., Cui, C., Digges, K (GWU), Summers, S., Zhao, L., (NHTSA), Barsan-Anelli, A., (IISI) (2014), “Methodology for Evaluating Fleet Protection of New Vehicle Designs: Application to Lightweight Vehicle Designs”. DOT HS 812 051A.**
 - Samaha, R. Radwan, Prasad, P., Nix, L. (2013), “Opportunities of Injury Reduction in US Frontal Crashes: An Overview by Structural Engagement, Vehicle Class and Occupant Age,” Stapp Car Crash Journal, Vol. 57, Paper No. 13S-38 (award winner)
 - Samaha, R. Radwan, Prasad, P., Marzougui, D., C. C., Kan, C. D., & Eskandarian, A. (2013), “An integrated Modeling Method to Evaluate Fleet Safety Performance of New Vehicle Designs,” ASME 2013 International Mechanical Engineering Congress and Exposition, Paper No. 66285
 - Samaha, R. Radwan, Prasad, P., Kamakakkannan, S., Comisene, V., Nix, L., & Digges, K. (2013), “Occupant Modeling for Injury Risk Computation in Vehicle Fleet Frontal Crash Simulations,” ASME 2013, Paper No. 6627
- **Radwan, R. (2015), “Real World Derived Simulation Methodology for the Evaluation of Fleet Crash Protection of New Vehicle Designs,” The George Washington University, ProQuest Dissertations Publishing, Pub. No. 3686081**

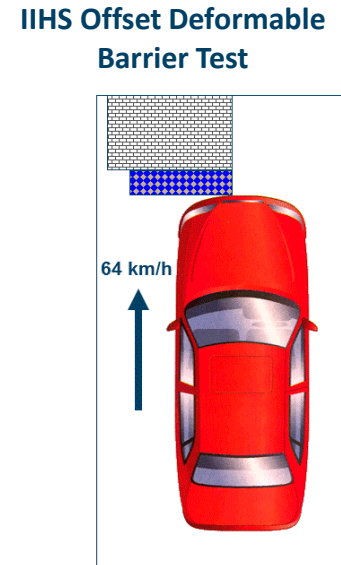
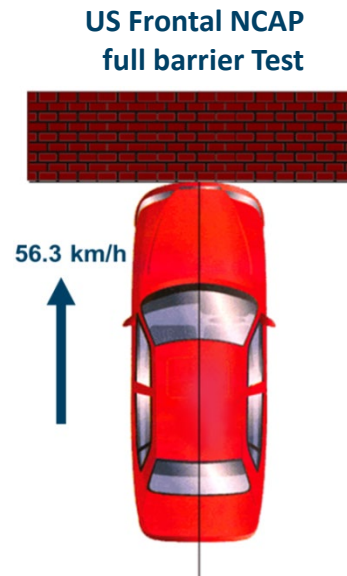
Background- Changing US Fleet

- New designs: power trains & light-weight materials
 - Limited historical crash data cannot be used to extrapolate into the future because they may not apply to future designs with new materials and architectures

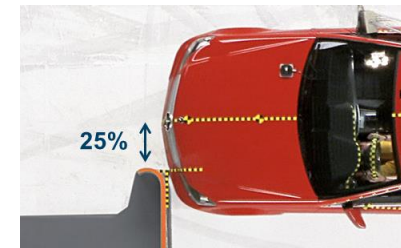
State-of-Art in Safety Evaluation of New Vehicle Designs



- Non-linear Finite Element (FE) modeling is currently used extensively in vehicle development process
- FE Models of a vehicle are now developed in pre-prototype stage and are exercised in regulations and consumer information safety testing
- **Test protocols:**
 - **Single vehicle to fixed object**
 - **Single speed**
 - **Typically, single size dummy driver**
- In the real world, crashes occur at various impact velocities, configurations, and impact partners and involve occupants of various sizes and ages.



IIHS Small Overlap Offset Barrier Test





EFP- Fleet Societal Risk for a Target vehicle

→ Fleet societal injury risk for a target vehicle is defined as the total injury risk of occupants in the target vehicle and crash partner vehicles,

in a matrix of simulated crashes
representative of real-world impact speeds,
crash configurations and impact partners

Fleet Societal Injury Risk

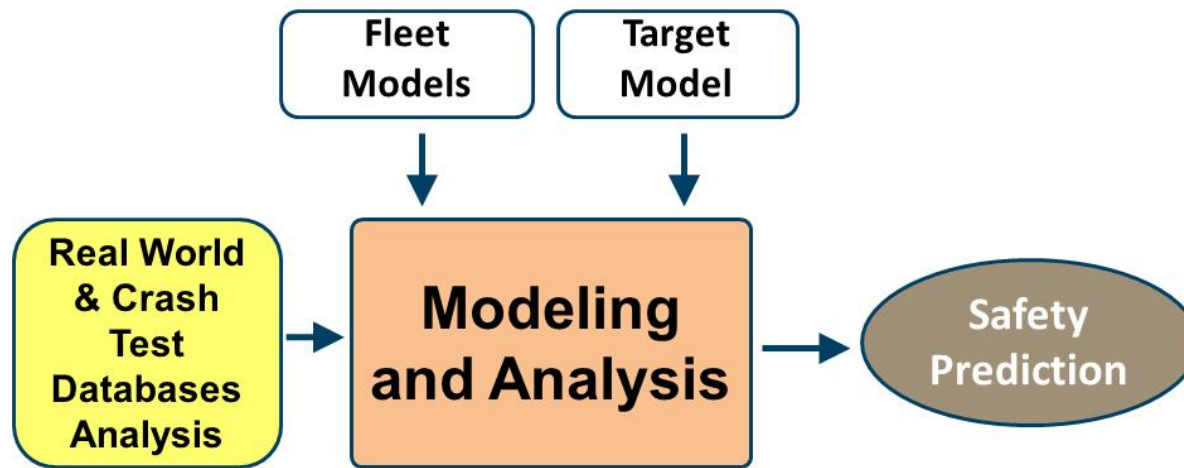
$$SIR(v) = \sum_{i=1}^{Nmode} \sum_{j=1}^{Jevent} \sum_{k=1}^{Kocclloc} \sum_{l=1}^{Loccsize} \sum_{m=1}^{Mconfig} \sum_{n=0}^{Npartner} \sum_{o=1}^{T/P} \sum_{p=1}^{Pspeed} w_{ijklmnop}(v) * CIR_{ijklmnop}(v)$$

Self and partner injury risk

- Societal Injury Risk (SIR) for a target vehicle v is defined as the sum of individual crash injury risks weighted by real world frequency of occurrence $w_{ijklmnop}(v)$ of a crash incident
- $CIR_{ijklmnop}(v)$ represents a Combined Serious Injury Risk for the head, neck, chest, and lower extremities body regions in a **single crash incident**
 - P impact speeds
 - O target/partner vehicle
 - N crash partners
 - M crash configurations
 - L occupant sizes
 - K occupant seating locations
 - J crash events (single vehicle, two/multiple vehicle)
 - I crash modes



EFP: A VIRTUAL MODEL SIMULATING REAL WORLD CRASH ENVIRONMENT

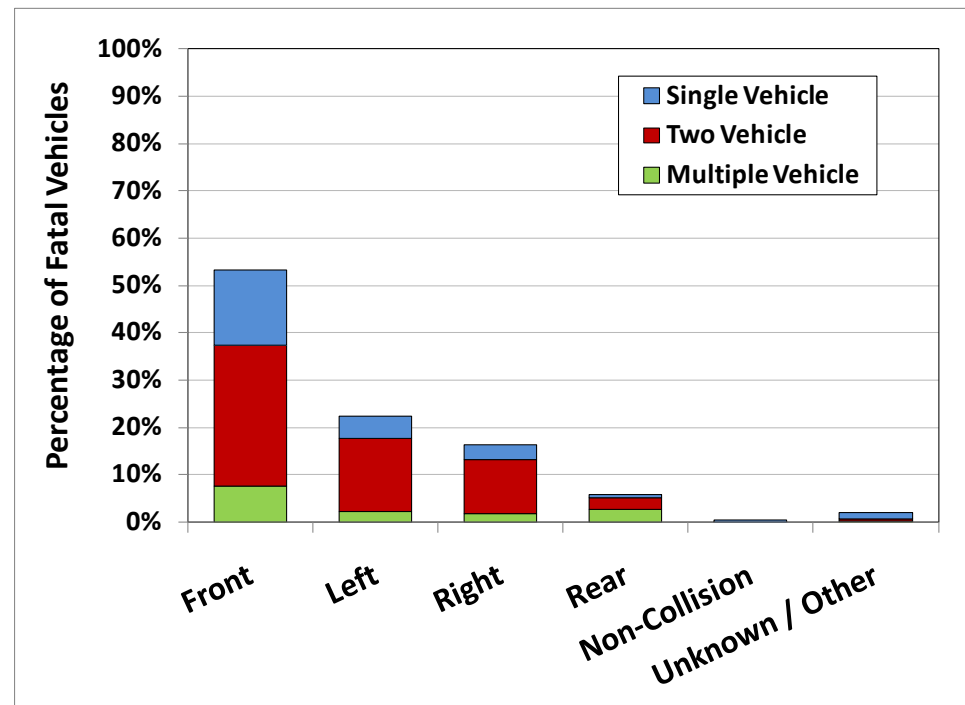


- Finite element structural models represent the fleet and target crash vehicles
- Crash configurations, to be simulated, are based on real world crash distributions and exposure from the National Automotive Sampling System Crashworthiness Data System (NASS CDS)
- Crash test data, representative of the crash configurations of interest, should be available to validate and verify the vehicle and occupant models

EFP Initially Implemented for Frontal Crashes

- Frontal crashes account for the highest numbers of fatalities
- Frontal crashes are most readily addressed with the available vehicle and occupant simulation models and injury metrics

MY 1998+ Crashed Vehicles with Fatalities

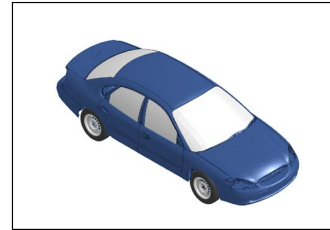


Fleet Vehicles Finite Element Models

- FE models validated to match vehicle accelerations (e.g. compartment crash pulse and engine), barrier load force, and overall energy balance in a full barrier NCAP frontal.

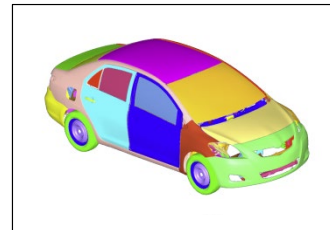
→ Vehicle FE models had minimal detail for relevant vehicle interiors (seat, door panels, dash) needed to conduct occupant simulations

Mid-size passenger car



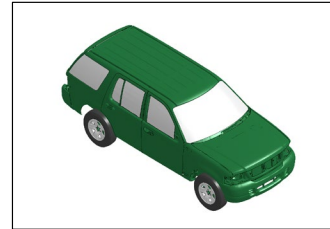
Ford Taurus
(2000-2007)

Small passenger car



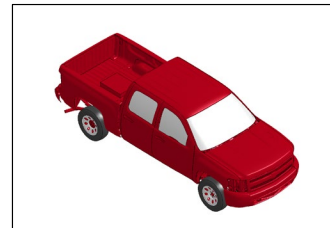
Toyota Yaris
(2005→current)

Sport Utility vehicle



Ford Explorer
(2002-2005)

Pickup truck

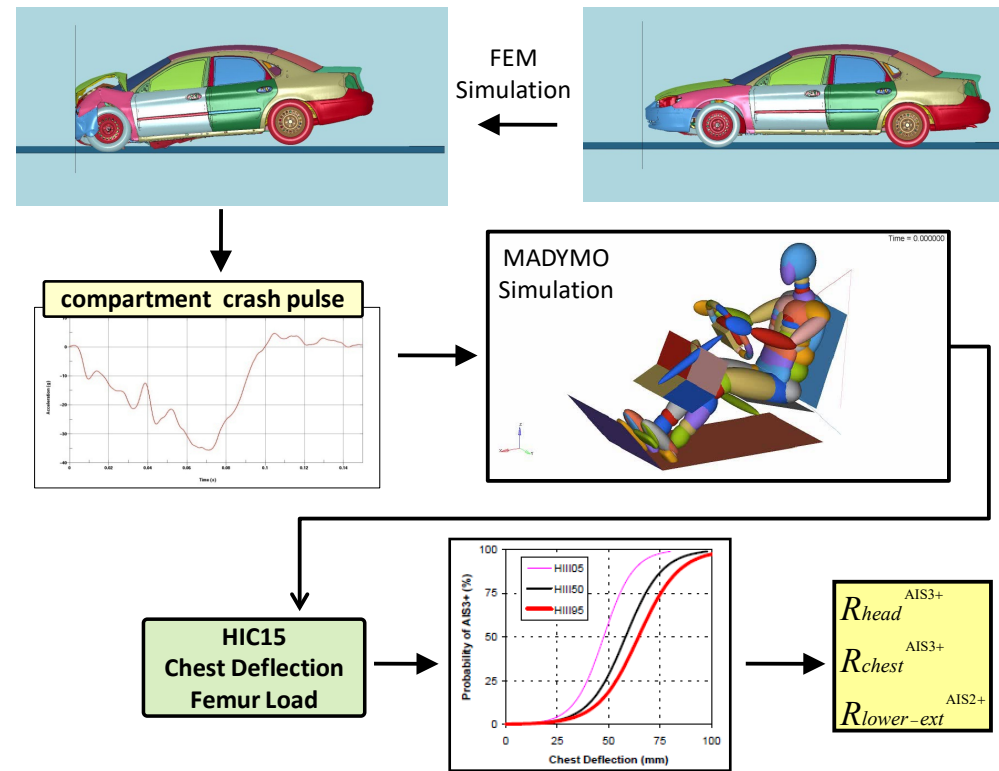


Chevrolet Silverado
(MY 2007→current)

Occupant Modeling

Given the lack of sufficient FE interior and restraint models for current implementation of EFP

→ Occupant modeling was decoupled from vehicle structural modeling and performed using MADYMO rigid body simulations.

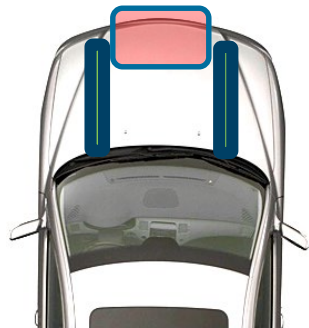


Simulated Frontal Crash Configurations

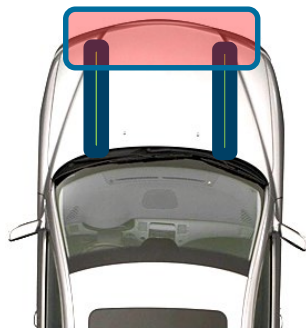
NASS CDS Frontal Crashes Classification

(Based on Structural Engagement)

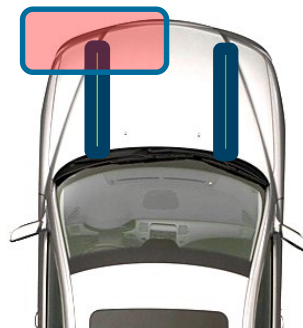
Between Rails



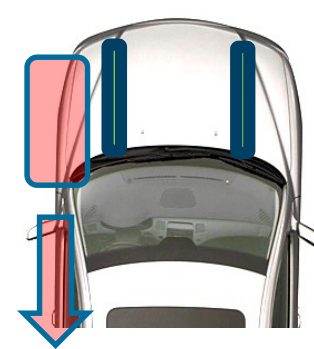
Full Engagement



Offset



Small Overlap Side



Corner

+

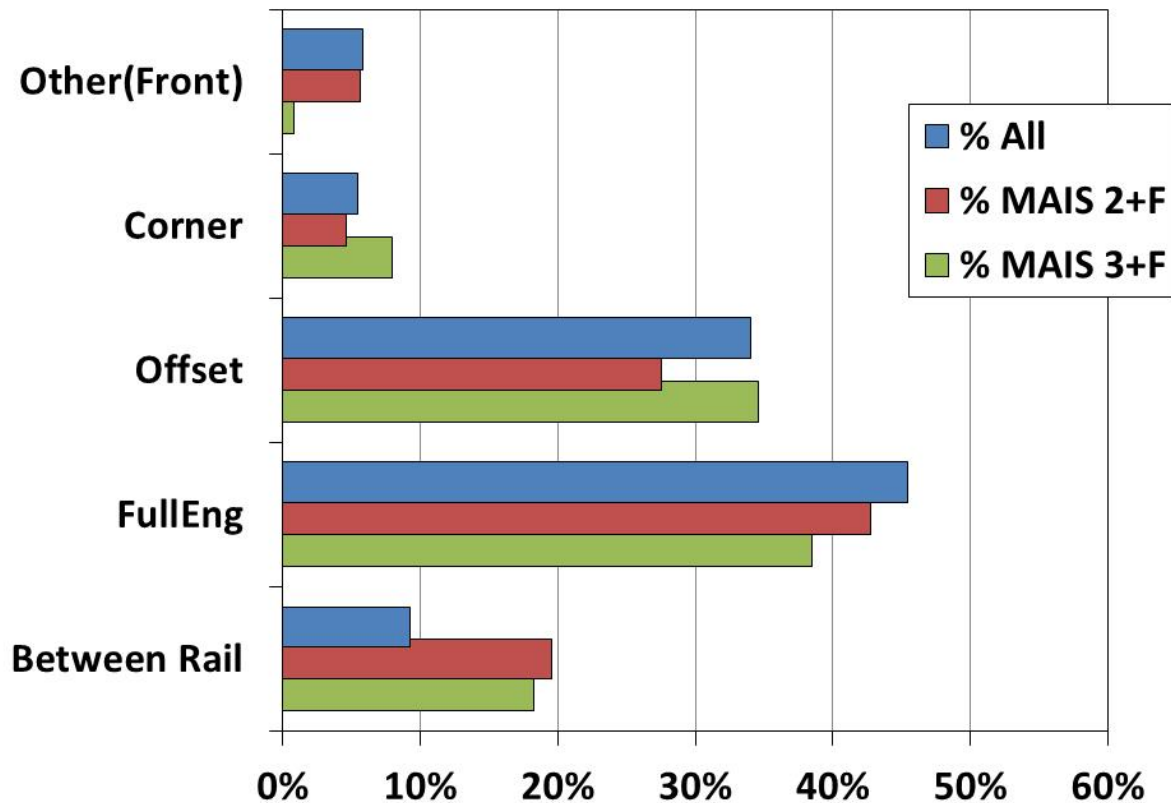
Small Overlap Front



Other group : Vehicles with underride or frontal damage & 9, 10, 2, or 3 DOF

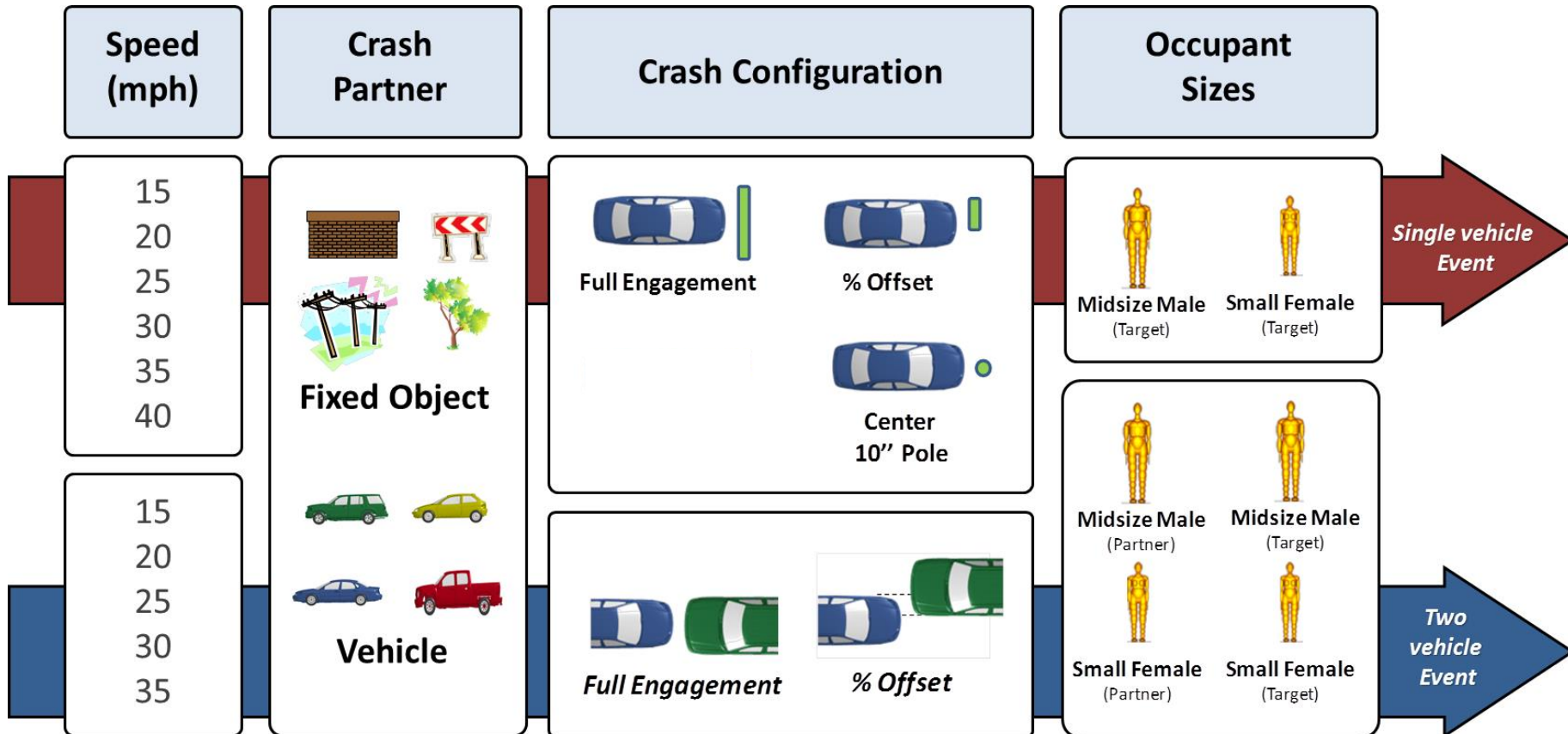
Crash Involvement and Injury Distribution by Crash Mode

MY 2000-2011 frontal airbag vehicles, belted driver, **16 ≤ AGE ≤ 50**



Weighted Data 16 ≤ Age ≤ 50 MY 2000+	All Crashes	MAIS 3+F	% All	% MAIS 3+F	Rate of MAIS 3+F
Between Rail	103,807	3,006	9.5%	18.2%	2.9%
FullEng	489,102	6,104	45.0%	36.9%	1.2%
Offset	371,155	5,782	34.1%	34.9%	1.6%
Corner	60,472	1,512	5.6%	9.1%	2.5%
Other(Front)	63,259	152	5.8%	0.9%	0.2%
Total	1,087,794	16,556	100%	100%	1.52%

Frontal Crash Configurations Simulated





Proof-of-Concept EFP

Application for Frontal Crashes

FE Model Design	Steel Properties			FE Model weight (kg/ <i>lbs</i>)
	Density (kg/m ³)	Elastic Modulus (GPa)	Yield Strength (Mpa)	
Baseline	7850	210	140-400	1515/ <i>3339</i>
Taurus_LW	5233	210	140-400	1138/ <i>2508</i>
Taurus_ST	7850	210	500	1515/ <i>3339</i>

- Implemented to evaluate if EFP could detect changes in occupant risk related to vehicle design modifications
- Taurus fleet partner FEM was used as a target baseline vehicle. Two simple design variants (not meant to be realistic) were used as “surrogate” new designs of the baseline: one 25% lighter & one stiffer
 - Taurus_LW: a simple light-weighting strategy, where density of all steel parts were reduced by 1/3, including a reduction of 100 kg from the engine (powertrain components)
 - Taurus_ST: all steel parts replaced with a dual phase Ultra High Strength Steel (DP500 UHSS), except the engine and transmission

Other Targets

Concept Lightweighted Vehicles for a midsize PC and CUV

- Midsize PC lightweight concept, designed by Electricore Inc. for NHTSA
 - Based off a 2011 Honda Accord achieving 23% mass reduction (Singh, et al. 2012).
 - The objective was to achieve the maximum amount of mass reduction appropriate for high volume production PC (200,000 vehicles per year) while maintaining the same vehicle functionalities, such as performance, safety, and crash rating with no more than a 10% cost increment compared to the baseline
- 1st midsize CUV lightweight concept, designed by FEV for EPA
 - Based off a 2010 Toyota Venza with a target mass reduction of 20% (FEV 2012).
- 2nd CUV lightweight concept, designed by Lotus Engineering for CARB
 - Based off a 2009 Toyota Venza with a target mass reduction greater than 30%. The goal was to identify mass saving opportunities while maintaining performance parity relative to the current vehicle (Lotus Engineering Inc. 2012).
- More recently, EDAG developed an FEM of a lightweighted Silverado. *While the model was not available for the study presented here, fleet simulations with a target LW Silverado are needed to understand the effect of light truck lightweighting on passenger car to light trucks crash safety.*



Fleet Simulation Matrices:

Single & Two Vehicle Frontal Crashes

Test Configuration		Vehicle Speed (mph)					
		15	20	25	30	35	40
Frontal	Frontal Impact Full Engagement (NCAP) 	X	X	X	X	X	
	Frontal Impact % Offset (IIHS) 		X	X	X	X	X
	Frontal Impact Center – 10" Pole 	X	X	X	X	X	

Single Vehicle Crash
Simulations: 15 LS-DYNA
and 30 MADYMO (50%tile
male & 5%tile female
drivers) Simulations per
Target Vehicle

Partner Vehicle	Target Vehicle	Vehicle Speed [Closing Speed]	Test Setup
Explorer 	⇒ 	15 mph [30]	 Full Engagement
Silverado 	⇒ 	20 mph [40]	
Yaris 	⇒ 	25 mph [50]	 50 % Offset
Taurus 	⇒ 	30 mph [60]	
		35 mph [70]	

Two Vehicle Crashes:
40 LS-DYNA and 160
MADYMO (50%tile
male & 5%tile female
drivers) Simulations
for Target & Partner

EFP Computed Societal* Risk for Baseline and Lightweight Concept Vehicle Designs

* sum of injury in the simulated single vehicle and in two vehicle crashes for self and partner driver, weighted by real world frequency an injury rate per 100 crash involved occupants

Test Configuration		Vehicle Speed (mph)					
		15	20	25	30	35	40
Frontal	Frontal Impact Full Engagement (NCAP)	X	X	X	X	X	
	Frontal Impact % Offset (IIHS)		X	X	X	X	X
	Frontal Impact Center - 10" Pole	X	X	X	X	X	

Partner Vehicle	Target Vehicle	Vehicle Speed [Closing Speed]	Test Setup
Explorer	⇒	15 mph [30]	 Full Engagement  50 % Offset
Silverado	⇒	20 mph [40]	
Yaris	⇒	25 mph [50]	
Taurus	⇒	30 mph [60]	
		35 mph [70]	

Target Vehicle	Taurus Baseline	Taurus LW	Taurus ST	Accord Baseline	Accord LW	Venza Baseline	Venza Low Option	Venza High Option
Weight (lbs)	3339	2508	3339	3681	2964	3980	3313	2537
reduction		831			716		668	1444
% mass reduction		25%	0%		19%		17%	36%
Societal Risk I	1.25%	1.41%	1.48%	1.56%	1.73%	1.36%	1.43%	1.57%
Risk Increase		12%	18%		11%		5%	15%

The serious injury (MAIS3+F) rate in air bag equipped vehicles of model year 1985 or later is 1.5 % in 1998 to 2010 NASS CDS data years

Case Study

Baseline vs. LW Fleet Safety Interactions via EFP

We have a baseline fleet and two concept lightweight fleet options:

- The **baseline fleet** is composed of two segments: PC (Accord Baseline) and CUV (Venza Baseline)
 - There are two **baseline targets**: Accord and Venza
- The first lightweight fleet (**LW1 fleet**) is composed of two segments: PC (Accord LW), LCUV1 (Venza Low Option (LO))
 - There are two **lightweight targets**: Accord LW and Venza LO
- The second lightweight fleet (**LW2 fleet**) is composed of two segments: PC (Accord LW), LCUV2 (Venza High Option (HO))
 - There are two **lightweight targets**: Accord LW and Venza HO

Fleet & Segment VTV Societal Risk in Frontal Crashes

Lightweight Fleets vs. Baseline Fleet

Target Vehicle	Accord	Venza	Fleet Mass Ratio	Total Fleet Risk
baseline weight (lbs)	3784	3982	1.05	
VTV Societal Risk Baseline Fleet	1.25%	1.29%		2.55%
lightweight concepts wt Venza LO (lbs)	3030	3314	1.09	
weight decrease from baseline	20%	17%		
VTV Societal Risk LW1 Fleet	1.46%	1.38%		2.84%
LW1 risk increase	17%	7%		11.7%
lightweight concepts wt Venza HO (lbs)	3030	2538	1.19	
weight decrease from baseline	20%	36%		
VTV Societal Risk LW2 Fleet	1.44%	1.41%		2.84%
LW2 risk increase	15%	9%		11.6%

Baseline Fleet: Accord & Venza Baselines

LW1 Fleet: Accord LW & Venza LO

LW2 Fleet: Accord LW & Venza HO

Societal Risk - Target + Partner Combined AIS3+ risk of Head, Neck, Chest & Femur

NOTE: Our results focus on VTV interactions. They do not include interactions with heavier than 10,000 GVWR truck.



Further work that would be helpful

- Perform fleet simulations for the lightweight Silverado concept vehicle as developed by EDAG for NHTSA
- Develop FE models of new and higher volume fleet vehicles
- Include the heavy truck (>10,000 lbs. GVWR) segment in the fleet
- Model other crash modes, specifically side impacts

THANK YOU





EFP Process and Components

1. Identify crash mode of interest: Frontal, Side, Rear, Rollover crashes
2. Establish crash configurations for identified crash mode and exposure based on structural engagement from real world distributions in the National Automotive Sampling System Crashworthiness Data System (NASS CDS)
3. Verify/Setup fleet partner FE vehicles models to represent existing vehicle fleet segments
4. Use vehicle structural modeling to:
 1. Simulate single- and two-vehicle crashes of target and fleet vehicles in representative crash configurations
 2. Predict crash pulse, dynamic crush, and intrusions in self and partner vehicles



EFP Process and Components (cont'd)

5. Verify/Setup occupant models for crash configuration of interest
6. Conduct occupant modeling, utilizing models of Anthropomorphic Test Devices (ATDs), more commonly known as dummies, of different sizes, to estimate occupant injury risk for each crash incident simulated
7. Predict probabilities of serious-to-fatal injuries in subject and partner vehicles for restrained occupants over modeled crash configurations and impact speeds



Current Limitations– Models

- Main limitation is the availability of newer fleet vehicle FE models. Current FEMs span model years 2001-2012, thus the results are more representative of transitional fleet safety effects.
- More detailed and improved characterization of the interior components and restraint systems will result in better model intrusions and occupant interactions.



Shover, et al (2009) "A Study of Motor Vehicle Side-Door Crashes: Characteristics of Small Overlap Side Crashes" ESV 09-0403-0543
Shover, et al (2009) "A Study of Motor Vehicle Side-Door Crashes: Characteristics of Small Overlap Side Crashes" ESV 09-0403-0543
Shover, et al (2009) "A Study of Motor Vehicle Side-Door Crashes: Characteristics of Small Overlap Side Crashes" ESV 09-0403-0543

Small Overlap Side



Cases with:

- Side damage and DOF 11, 12, or 1 o'clock
 - Center of direct damage forward of center of front wheel
- Determined to be a good approximation of cases with direct damage forward of the A-Pillar

Fleet Societal Injury Risk

$$SIR(v) = \sum_{i=1}^{Nmode} \sum_{j=1}^{Jevent} \sum_{k=1}^{Koccloc} \sum_{l=1}^{Loccsize} \sum_{m=1}^{Mconfig} \sum_{n=0}^{Npartner} \sum_{o=1}^{T/P} \sum_{p=1}^{Pspeed} w_{ijklmnop}(v) * CIR_{ijklmnop}(v)$$

- Societal Injury Risk (SIR) for a target vehicle v is defined as the sum of individual crash injury risks weighted by real world frequency of occurrence $w_{ijklmnop}(v)$ of a crash incident.
- $CIR_{ijklmnop}(v)$ represents a Combined Serious Injury Risk for the head, neck, chest, and lower extremities body regions in a single crash incident.



Combined Injury Risk for Frontal Impacts

5th and 50th %tile HIII Dummies

- Head: HIC15
- Neck: Tension
- Chest: Deflection
- Knee-Thigh-Hip: Femur loads

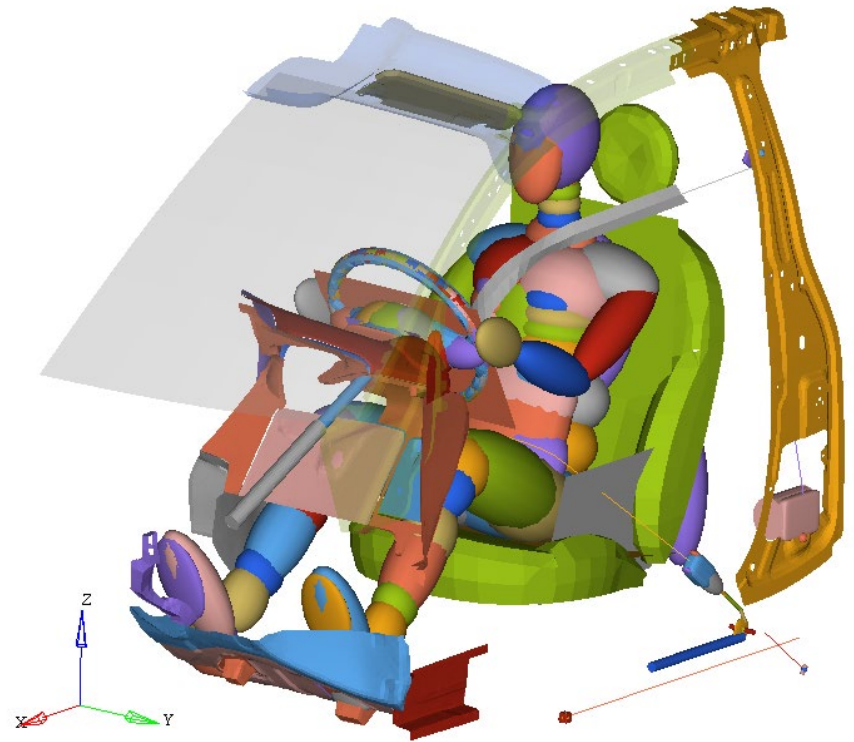
→ 2011 NCAP & FMVSS 208 biomechanical injury risk
functions

$$\begin{aligned} CIR_{occupsize} = & (1 - (1 - Prob_{head}(AIS3+)) \\ & * (1 - Prob_{chest}(AIS3+)) \\ & * (1 - Prob_{neck}(AIS3+)) \\ & * (1 - Prob_{femur}(AIS3+))) \end{aligned}$$

	H350/50th	NHTSA 25 mph 50th FE_pulse	NHTSA 30 mph 50th Test_Pulse 4690	NHTSA 30 mph 50th, FE_Pulse	NHTSA 35 mph, 50th Test_Pulse 3730	NHTSA 35 mph 50th Test_Pulse 3730	NHTSA 35 mph 50th FE_pulse
Response	Formula	Simulation FE Pulse Results	Simulation Test Pulse Results	Simulation FE Pulse Results	Crash Test Results (3730)	Simulation Test Pulse Results	Simulation FE Pulse Results
HIC15	$HIC = \left\{ \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t) dt \right]^{2.5} (t_2 - t_1) \right\}_{max}$	240	384	310	324	533	419
HIC36	$HIC = \left\{ \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t) dt \right]^{2.5} (t_2 - t_1) \right\}_{max}$	293	467	371	519	681	602
Neck Tension (T)	Upper Neck Fz Max	1553	1743	1873	2062	1781	1903
Chest deflection (mm)	Max Deflection	30	31	30.5	40	33.5	31.7
Chest acceleration (g)	Max Acceleration	43	42	47	47.5	45	47.5
Femur Load - Left (N)	Max Compression force Fz	4419	4649	5607	5809	4785	5453
Femur Load - Right (N)	Max Compression force Fz	5492	5579	6846	5338	5919	6769
HIC15 Risk (AIS3 %)	NORMDIST(LN(HIC15),7. 45231,0.73998,1)	0.39%	2.1%	1.0%	1.2%	5.6%	2.80%
Chest Deflection (AIS 3%)	1/(1+EXP(12.597- 0.05861*35-1.568*((chest def)^0.4612))))	4.61%	5%	5%	12%	7%	5.60%
Femur Load Max (AIS 3+%)	1/(1+EXP(4.9795-0.326* max Femur /1000)) - 1/(1+EXP(4.9795))	3.27%	3.38%	5.34%	3.69%	3.84%	5.20%
Neck Tension (AIS3%)	1/(1+EXP(10.9745-2.375* NeckTension//1000))	0.07%	0.1%	0.1%	0.2%	0.1%	0.16%
Combined Injury Risk	(1-(1-HR%)*(1-CD%)*(1- FL%)*(1-NT%))	0.08	0.10	0.11	0.17	0.15	0.13

Occupant Modeling Approach

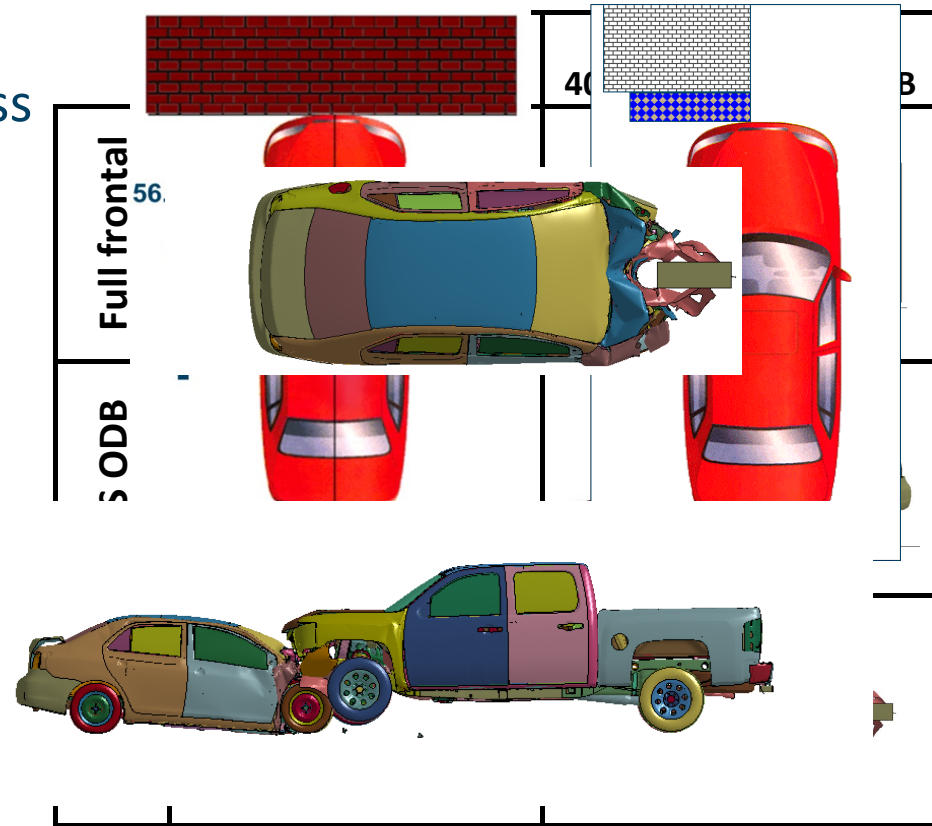
→ Available FE interior components were supplemented with scanned interior vehicle surfaces & MADYMO generic model environments.



Extended Model Validations & Verification and Robustness Checks

1. Develop and validate models
2. Perform verification and robustness simulations
 - Centerline pole
 - PC into Silverado

→ The models provided viable representations in these large deformation crash events.



Taurus Baseline Societal injury Computation

