Tension-Bending Risk Curves for the ATD Lower Lumbar Spine Subjected to Oblique Impact under FAA Emergency Landing Conditions

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FAA- PMHS test background

- [1]Oblique whole-body PMHS sled tests demonstrated distraction-bending injuries to L5/S1 level
- [1]Primary injury mechanism = multi-axis bending + tension

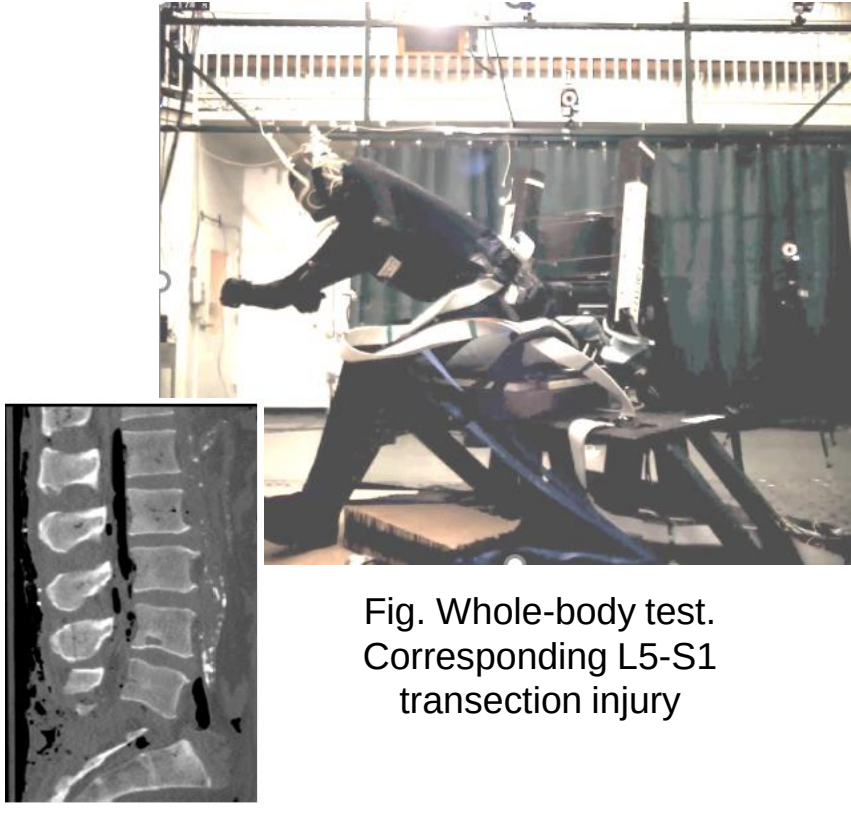


Fig. Whole-body test. Corresponding L5-S1 transection injury

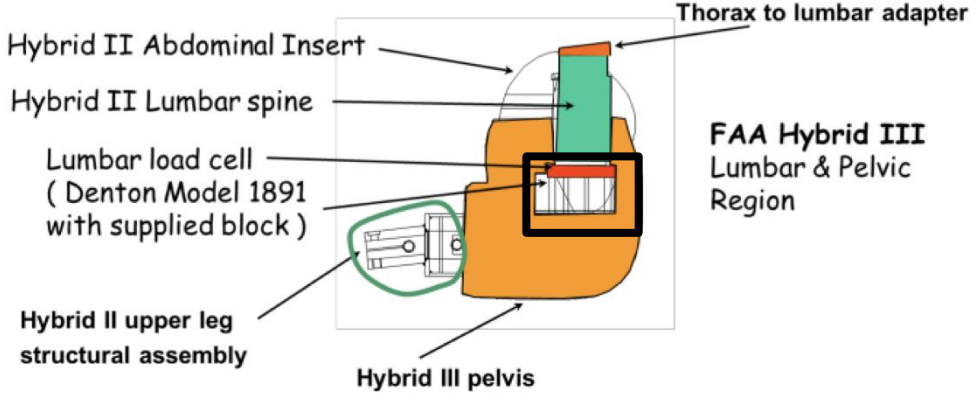
1. Humm et al. 2016. "Responses and injuries to PMHS in side-facing and oblique seats in horizontal longitudinal sled tests per FAA emergency landing conditions. Stapp Car Crash, 135-163.

FAA-H3 combined metric equation

- Lower lumbar spine injury metric (FAA- LL_{tb})
  - $\text{FAA-LL}_{tb} = \frac{Fz}{F_{int}} + \frac{My}{My_{int}} + \left|\frac{Mx}{Mx_{int}}\right|$
  - F_z = axial tensile load,
  - F_{int} = critical intercept value for tensile force,
  - My = flexion bending moment
  - My_{int} = critical value for flexion moment
  - Mx = lateral bending moment (absolute value)
  - Mx_{int} = critical value for lateral moment
  - “tb” = indices represent tension-bending

FAA-H3 spine assembly

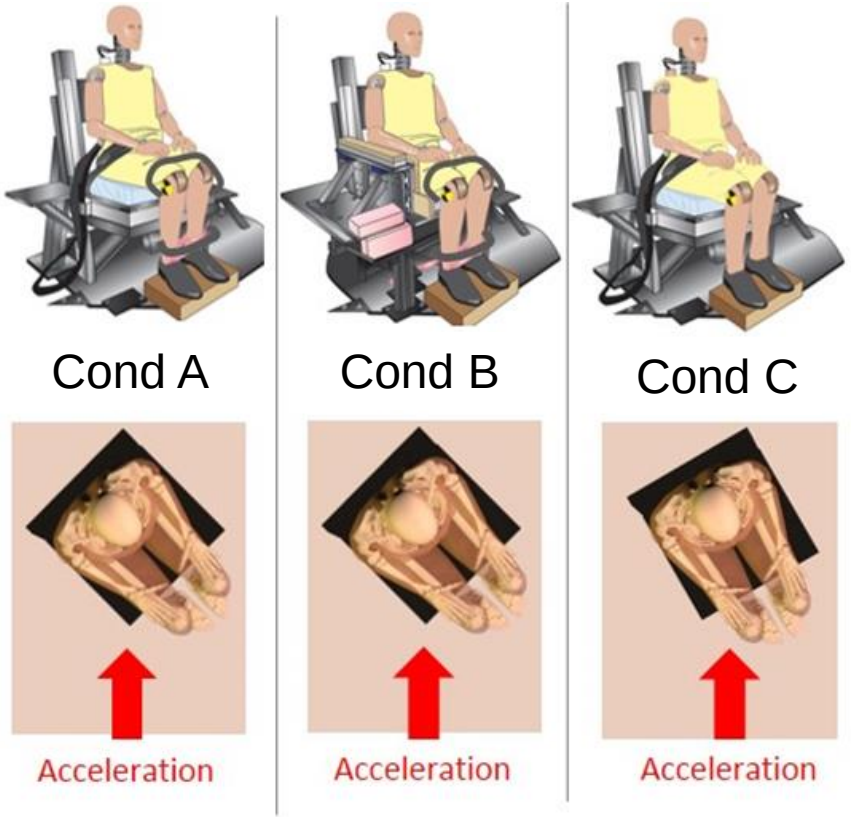
- FAA-H3-Metric was developed for lower lumbar spine load cell.
- Injury definition was based on FE and PMHS tests.
- Critical values were calculated based on risk curves.



FAA-H3 test condition summary

- FAA-H3 test conditions
  - A: no arm rest, 2 belts, 45 deg
  - B: arm rest, 1 belts, 45 deg
  - C: no arm rest, 2 belt, 30 deg

- 2 belt – standard lap belt plus lap belt used in side-facing seats



FAA-H3 test condition summary

- Pulse severity: 16 g (100%), 12 g (75%), 9.6 g (60%), 8 g (50%)
- The severities were referred as 1, 2, 3 and 4, respectively
- For example:
  - ATD test A.1 –no arm rest, 2 belts, 45 deg, with 16 g pulse severity

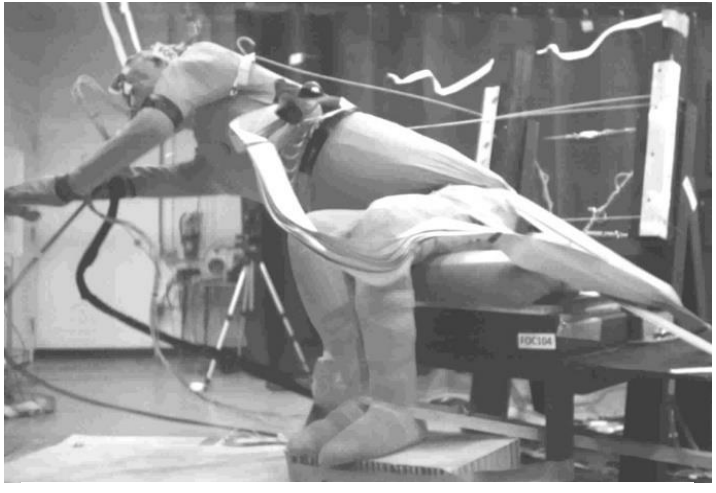
Injury definition for ATD-metric

- 2 sources for defining injuries in ATD
- Matched-pair PMHS results
  - Available for only N=5 test conditions
- [1]FEM based results
  - Available for all N=12 test conditions
  - To note, for modeling study, PMHS-age specific HBM was selected and simulated to obtain the injury status

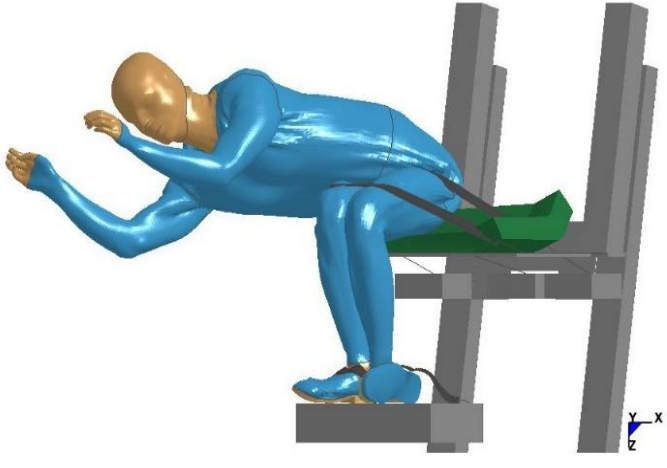
1. Somasundaram, K., et al. "Occupant Injury and Response on Oblique-Facing Aircraft Seats: A Computational Study." ASME. J Biomech Eng. 2023; 145(2): 021003. https://doi.org/10.1115/1.4055511

Kinematic – Condition A (16 g pulse)

FAA-H3



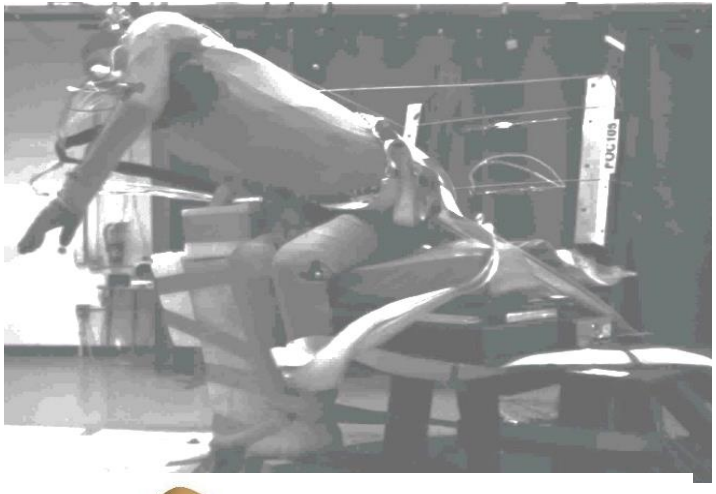
PMHS



GHBMC

Kinematic – Condition B (16 g pulse)

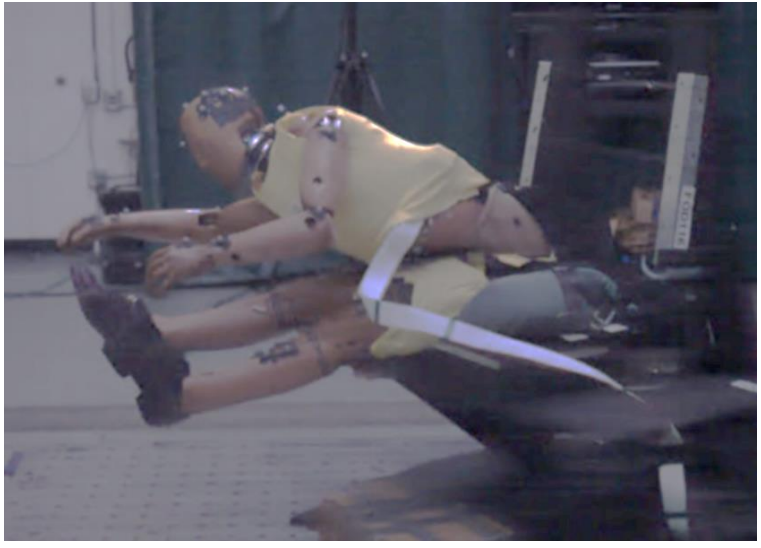
FAA-H3



PMHS

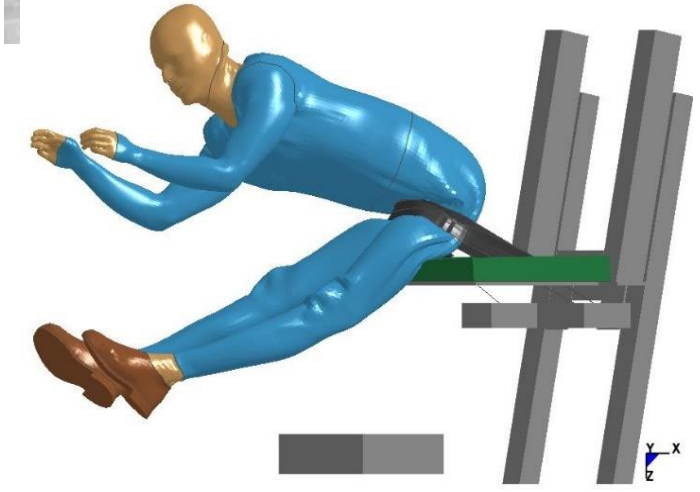
GHBMC

Kinematic – Condition C (16 g pulse)



FAA-H3

PMHS



GHBMC

FAA-H3 metric development

- For the condition with N>2, mean value was used
- Survival analysis was used to construct the risk curve for lower lumbar spine load cell

$$P(Injury) = 1 - \exp\left(-1 * (\alpha * FAA\_LLtb)^{k}\right)$$

Where, $\alpha = \exp(-1 * \lambda)$

- Metric = $\frac{Fz}{F_{int}} + \frac{My}{My_{int}} + \left|\frac{Mx}{Mx_{int}}\right|$

Test condition	Test ID	Pulse severity (g)	Seat angle	Pelvis restraint	Leg constraint	Arm rest	Matched pair tests for (Lspine/pelvis injury status)
A-1	Md00119	16	45°	2belt	Yes	NA	From PMHS (Yes)
A-1	Cd12024	16	45°	2belt	Yes	NA	
A-1	Cd12022	16	45°	2belt	Yes	NA	
A-1	Cd12023	16	45°	2belt	Yes	NA	
A-2	Md00120	12	45°	2belt	Yes	NA	from FEM (Yes)
A-2	Md00123	12	45°	2belt	Yes	NA	
A-3	Md00122	9.6	45°	2belt	Yes	NA	From PMHS (No)
A-3	Md00125	9.6	45°	2belt	Yes	NA	
A-4	Md00107	8	45°	2belt	Yes	NA	From FEM (No)
A-4	Md00121	8	45°	2belt	Yes	NA	
B-1	Cd12025	16	45°	1belt	Yes	Yes	From PMHS (No)
B-1	Cd12026	16	45°	1belt	Yes	Yes	
B-1	Md00128	16	45°	1belt	Yes	Yes	
B-1	Md00131	16	45°	1belt	Yes	Yes	
B-1	Cd12021	16	45°	1belt	Yes	Yes	
B-2	Md00129	12	45°	1belt	Yes	Yes	From FEM (No)
B-2	Md00124	12	45°	1belt	Yes	Yes	
B-3	Md00126	9.6	45°	1belt	Yes	Yes	From PMHS (No)
B-3	Md00127	9.6	45°	1belt	Yes	Yes	
B-4	Md00110	8	45°	1belt	Yes	Yes	From FEM (No)
B-4	Md00130	8	45°	1belt	Yes	Yes	
C-1	Md00116	16	30°	2belt	NA	NA	From PMHS (Yes)
C-2	Md00115	12	30°	2belt	NA	NA	From FEM (Yes)
C-3	Md00114	9.6	30°	2belt	NA	NA	From FEM (No)
C-4	Md00132	8	30°	2belt	NA	NA	From FEM (No)

Critical value for metric development

- The value measured at 80% probability of each bending or tension metric in isolation was considered as the intercept or critical value for the corresponding individual parameter.

Metric	L5 Fz (lbf)	L5 My (lb-ft)	L5 Mx (lb-ft)
Fz+Mx+My	2,833	226	255

Critical value estimation

- Normalized Confidence Interval Size (NCIS) defines the tightness of the interval of the developed risk

$$\text{NCIS} = \frac{\text{UL}-\text{LL}}{\text{M}}$$

- A quality index is defined for this purpose

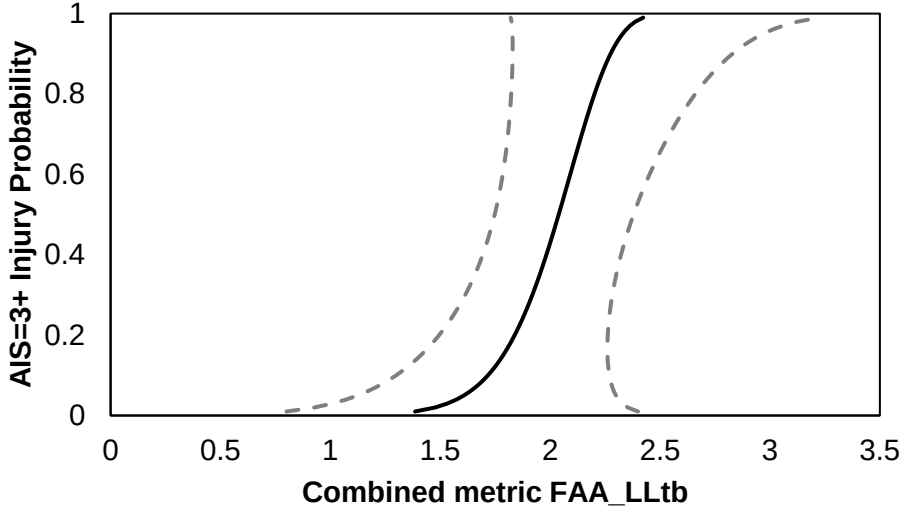
Quality index (Petitjean et al. 2015)	NCIS values for 95th confident interval
Good	0 to 0.5
Fair	0.5 to 1
Marginal	1 to 1.5
Unacceptable	over 1.5

Rationale for selecting CV at 80%

- In the present study, the intercept values for the combined metrics were derived from the individual risk curves taken at 50%, 60%, 70%, 80%, 90% and 100%.

Injury prob.	FAA-LL_{tb}_50	FAA-LL_{tb}_60	FAA-LL_{tb}_70	FAA-LL_{tb}_80	FAA-LL_{tb}_90	FAA-LL_{tb}_100
0.05	0.87	0.83	0.78	0.73	0.70	1.85
0.10	0.68	0.65	0.61	0.57	0.52	1.54
0.25	0.44	0.43	0.41	0.38	0.34	1.35
0.50	0.33	0.32	0.31	0.31	0.32	1.01
0.75	0.35	0.35	0.35	0.36	0.42	1.25
0.90	0.43	0.42	0.42	0.44	0.53	1.65
0.95	0.48	0.47	0.47	0.49	0.59	2.05
% Chance for injury occurrence	50%	60%	70%	80%	90%	100%

FAA-H3 Lspine risk curve



Risk	Mean	95% confidence interval		NCIS	Quality index
		UL	LL		
0.05	1.61	2.30	1.12	0.73	Fair
0.10	1.72	2.27	1.30	0.57	Fair
0.25	1.88	2.27	1.56	0.38	Good
0.50	2.04	2.38	1.75	0.31	Good
0.75	2.17	2.60	1.82	0.36	Good
0.90	2.27	2.83	1.83	0.44	Good
0.95	2.33	2.97	1.83	0.49	Good

**Note: This is a research value and has not been proposed for certification at this time

1. Karthik Somasundaram, John R. Humm, Narayan Yoganandan, David M. Moorcroft & Frank A. Pintar (2022) Tension-bending risk curves for the ATD lower lumbar spine subjected to oblique impact under FAA emergency landing conditions, International Journal of Crashworthiness, https://doi.org/10.1080/13588265.2022.2130611

ATD risk curves evaluation

Other ATD Runs

- ATD runs which did not have matched paired PMHS tests and FE runs were considered as unknown or other ATD runs.
- The metrics were calculated for these runs based on the estimated critical values.
- The corresponding probability values based on the risk curves were determined.

FAA-H3 tests for evaluation

ATD with 3 pt-belt and armrest

ATD with 3 pt-belt

ATD_ 3 pt-belt and airbag cases					
Test ID	Severity	Seat Angle	Pelvis restraint	Leg_ Const	Arm-rest
16034	100	45°	3 pt - belt	Y	Y
16035	100	45°	3 pt - belt	Y	Y
16036	100	45°	3 pt - belt	Y	NA
16037	100	45°	3 pt - belt	Y	NA
16038	100	45°	3 pt - belt	Y	Y
16039	100	45°	3 pt - belt	Y	Y
16041	100	45°	Lap-belt + airbag	Y	NA

ATD with developmental lap-belt fitted airbag

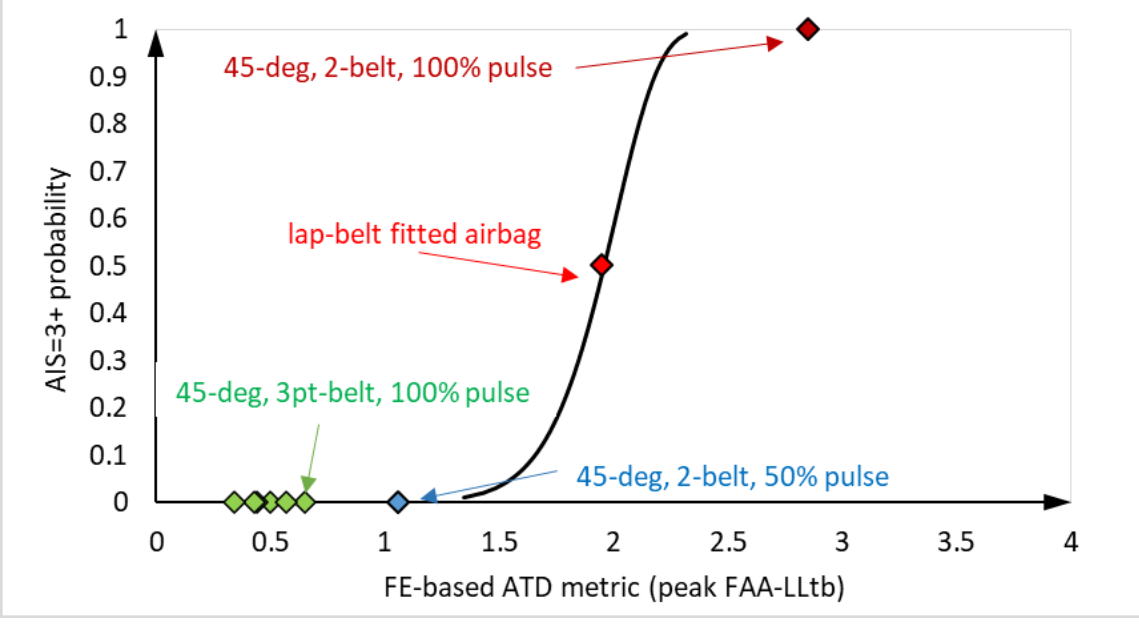
Occupant kinematic

ATD run with 3 pt-belt and armrest

ATD run with 3 pt-belt

ATD run with lap-belt fitted with airbag

FAA-LLtb risk curve



Summary

- The developed risk curve is defined as AIS=3+ injury probability curve.
- At risk levels 5%, 25% and 50% the combined metric values were 1.6, 1.8, and 2.0, respectively.
- The combined metric was estimated to be a better criterion than the single function and/or force-based combined function for assessing the injury to lower lumbar spine and pelvis.

Summary

- The present study also demonstrated the applicability of a computational model in estimating the injury status for metric development.
- The tests considered for metric development were performed with a frontal loading vector.
- Therefore, the estimated criterion can be extended to automotive applications, which have similar crash pulses albeit lower delta V.

Acknowledgement

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- Any views expressed in this manuscript are those of the authors and are not necessarily representative of the funding organizations.

Questions/Discussion