Estimating Variability of Injuries in Underbody Blast Live-fire Testing for Evaluating Modeling and Simulation

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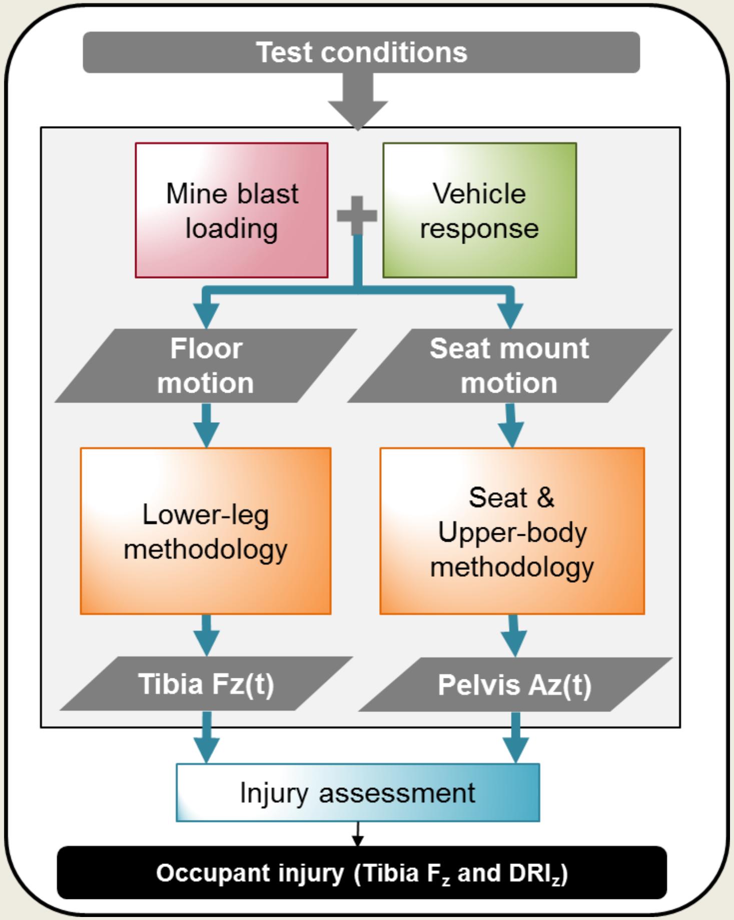
Underbody Blast Methodology (UBM)

UBM is…

- a joint program led by the Army Research Laboratory.
- how the Army is doing M&S of underbody blast (UBB) against ground vehicles.
- a toolset and methodology to simulate and predict occupant injury.
- a methodology that uses LS-DYNA along with custom ARL-developed codes.
- deterministic, as are its injury predictions.



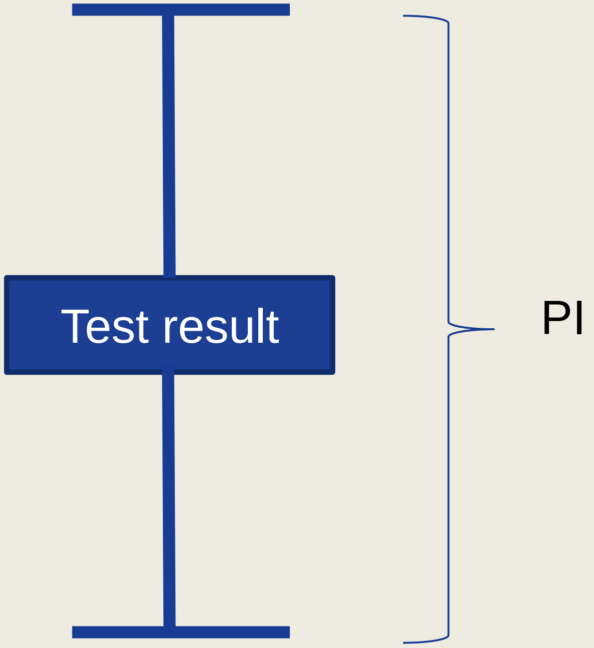
Issue

- UBM is undergoing VV&A to support Army evaluations of ground vehicles.
- UBM will be evaluated by comparing its deterministic injury predictions to live-fire (LF) test results which contain stochastic variability inherent in UBB testing.
- The variability of LF test results is not well defined.

Objective

Quantify variability of LF test results in the form of prediction intervals (PIs) to support model-to-test comparisons

- PIs denote a band in which a new observation in a group is expected to lie given a certain level of confidence.
- For this specific application, UBM predictions can be evaluated against PIs surrounding test results that represent variability in LF testing.



Approach

Estimate the injury variability inherent in LF UBB testing by combining variabilities from two independent sources:

1. Repeat testing
2. Expert opinion

Pros and cons of each data source:

- Repeat testing is few in number but objective
- Expert opinion is subjective but informed by years of experience

Why aggregate estimates from both sources?

- They supplement each other.
- They are independent sources and so provide a double blind test to corroborate the other's estimate.

Injury metrics

- Injury metrics of interest are lower tibia compressive force (tibia F_z) and vertical Dynamic Response Index (DRI_z).
- These injuries are assessed from measurements made with an anthropomorphic test device (ATD) positioned in the vehicles.
- Injury measurements are quantified by relative index (RI) – a ratio of the assessed maximum response of a given injury metric compared to the established injury threshold.

Therefore, variability of injury is that of RI for either tibia F_z or DRI_z.

Repeat test data

13 *sets* of repeat tests with about 4 *groups* each.

- Hundreds of tests were reviewed but few are repeats because tests are so expensive.
- Some repeat tests had different but allowable conditions (e.g. test range, director, vehicle serial number, design changes).
- All tests were for wheeled, armored vehicles subjected to TNT charges buried in soil in accordance with approved test procedures*.
- RI values for tibia F_z and DRI_z from each ATD in the repeat tests were compiled.

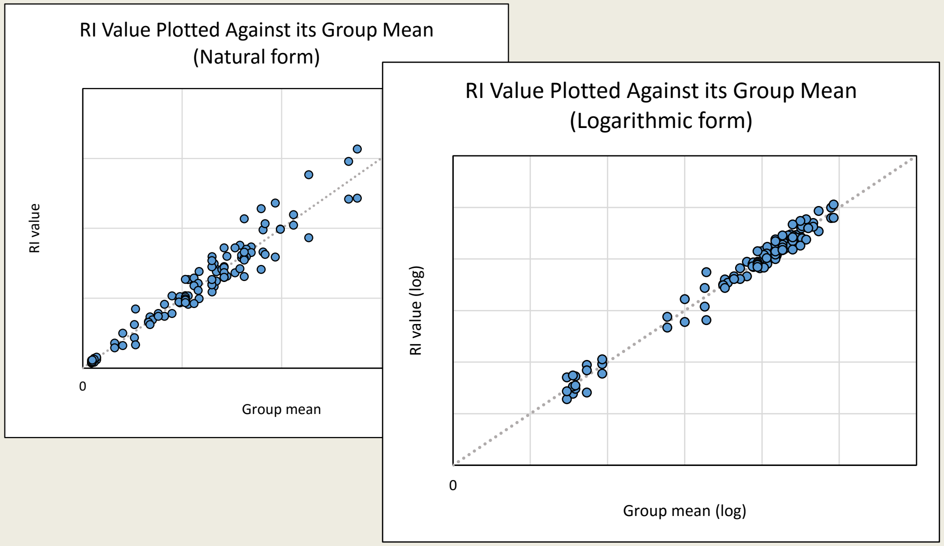
A ***set*** consists of two or more tests conducted under repeated conditions roughly defined by the vehicle and the threat size, type, and location.

A ***group*** is defined by an occupant position in a vehicle against a UBB that was repeated a number of times.

*"FR/GE/UK/US International Test Operations Procedure (ITOP) 4-2-508 Vehicle Vulnerability Tests Using Mines". US Army Aberdeen Test Center. ITOP 4-2-508. April 14, 2005.

Standard deviation from repeat tests

- Standard deviation was used to characterize and quantify RI variability.
- RI data revealed that the standard deviation increased as a function of each group's mean.
- Therefore RI data was analyzed in logarithmic form to calculate a constant standard deviation.
- In logarithmic form, standard deviation was calculated as the square root of the pooled variance (see equation).



$$\hat{\sigma} = \sqrt{{S_p}^2} = \sqrt{\frac{SSE}{df}} = \sqrt{\frac{\sum_{i=1}^{k}(n_i - 1){s_i}^2}{df}}$$

		DRI_z	Tibia F_z
Logarithmic	$\hat{\sigma}$	A	C
Natural	$e^{\hat{\sigma}}$	B	D

A, B, C, D – actual values have been masked for public distribution but are presented in the forthcoming technical report

Expert opinion

*"Expert elicitation refers to a systematic approach to synthesize subjective judgments of experts on a subject where there is uncertainty due to insufficient data, when such data is unattainable because of physical constraints or lack of resources."**

Relative to this study, there is uncertainty in the variability of injuries from LF UBB testing due to insufficient data.

A workshop was held to extract expert intuition.

- 15 experts in attendance offering a collective 158 years of experience with UBB testing and about 1,700 UBB tests observed, analyzed, or evaluated (28 experts were invited and all reviewed the output).
- Organizations represented: ARL-SLAD, ARL-WMRD, ATC, WIAMan, IDA, TARDEC, DOT&E, ATEC, MCOTEA, MSCS, and JPO MRAP.
- However, experts were asked to not represent any particular organization but instead to represent their own personal experiences and perspectives.

*Slottje, P; Sluijs, J.P.; Knowl, A. B. "Expert Elicitation: Methodological suggestions for its use in environmental health impact assessments." National Institute for Public Health and the Environment. 2008

Question posed to experts

"Consider a large set of hypothetical repeated LF UBB tests (say, 100 tests) for a specific vehicle. For the same occupant position, assume that an average RI of a particular injury metric value was calculated. Given that average RI value, what are the bounds above and below it for which you expect 95% of the injury values from the large set of hypothetical repeated tests?"

- Experts were asked to estimate these bounds for three nominal cases: a low, medium, and high average RI value (each assigned a certain value) focused first on tibia F_z and then on DRI_z.

- Estimating a 95% bounds helped to calculate a constant standard deviation in logarithmic units.

Workshop output

- The workshop consisted of discussions within 3 small groups followed by a large group discussion.

- Despite the expectation that experts would be hesitant in voicing an estimate of variability most participants were pleasantly surprised and encouraged to find that their intuitive estimates of variability were close to others'.

- Qualitatively, experts were generally in agreement.

- Quantitatively, expert estimates were averaged to calculate a constant standard deviation in logarithmic form.

	DRI_z	Tibia F_z
Logarithmic	A	C
Natural	B	D

A, B, C, D – actual values have been masked for public distribution but are presented in the forthcoming technical report

Combining variability from repeat test analysis and expert opinion

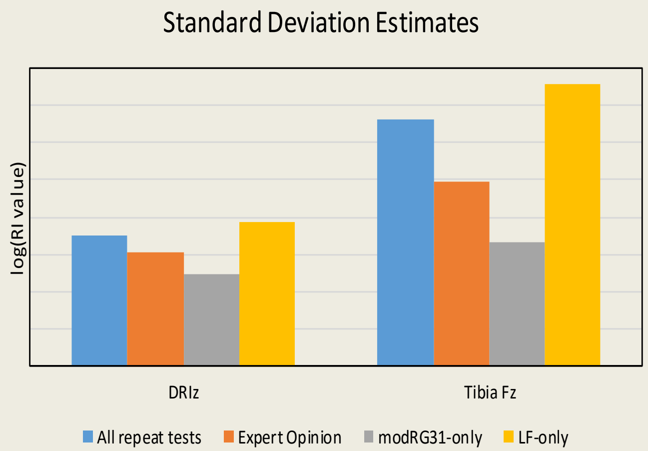
The estimates of standard deviation from repeat test analysis and expert opinion are close in value and consistent in terms of trends – they corroborate one another.

	DRI_z	Tibia F_z
Repeat Tests	A	C
Expert Opinion	B	D

Repeat tests were separated out based on expectation of variability:

- Experimental tests were conducted against a single vehicle, were more controlled, and therefore expected to show less than the true LF variability for a specific vehicle.
- Live-fire-only tests were conducted against a range of vehicles, less controlled and therefore expected to show more than the true LF variability for a specific vehicle.

Expert opinion falls between these two.



Therefore a combined variability was calculated as the average from the two sources.

	DRI_z	Tibia F_z
Logarithmic	W	Y
Natural	X	Z

A, B, C, D, W, X, Y, Z – actual values have been masked for public distribution but are presented in the forthcoming technical report

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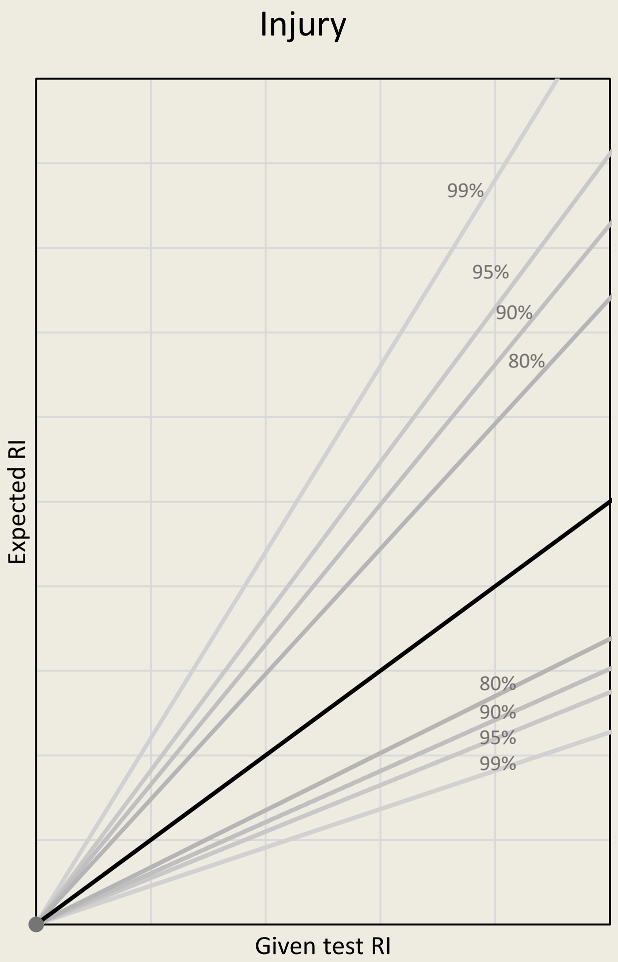
Calculating prediction intervals

ARL

PI width (log and natural):

$$y \pm z_{\left(\frac{\propto}{2}\right)}\sqrt{2}\sigma \qquad e^{z_{\left(\frac{\propto}{2}\right)}\sqrt{2}\sigma}$$

- PIs surround a data point identifying the range in which a new data point is expected to lie.
- The width of a PI is dependent on a confidence level and number of previous observations (for our purposes this is 1).
- In logarithmic units the interval is uniform, in natural units it is like a multiplier relative to a given RI value.



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Evaluating UBM using PIs: Ex. 1

ARL

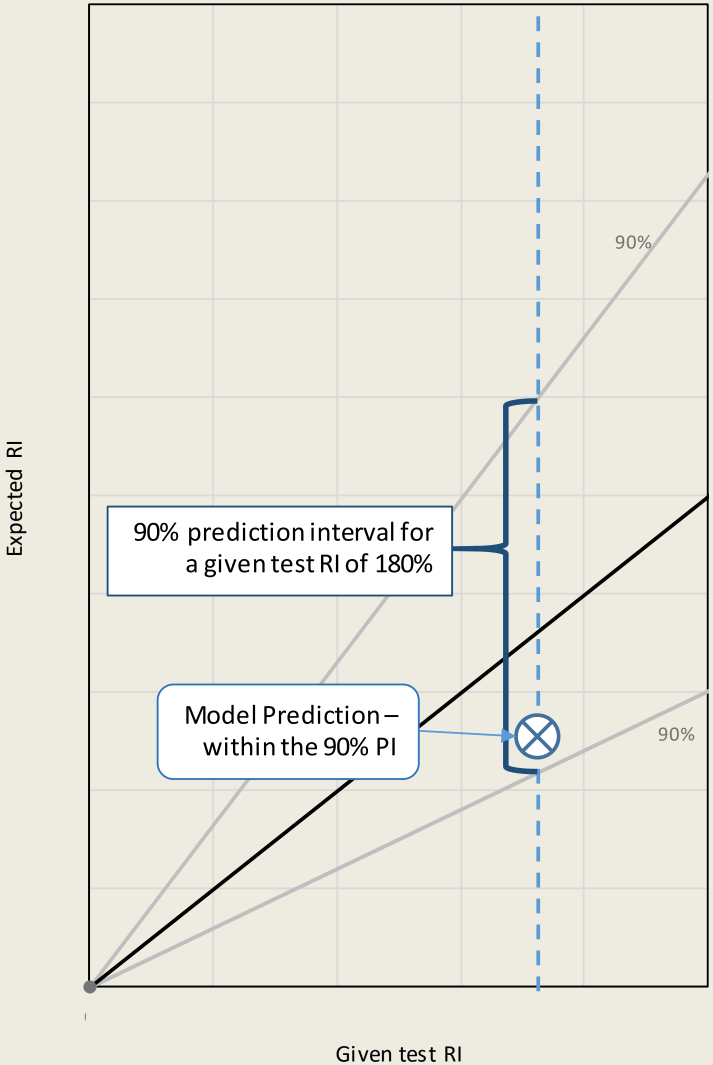
<u>Scenario</u>: An evaluator decides to asses UBM based on its predictions being within PIs of 90% confidence.

- This assessment criteria yields a PI width multiplier for tibia F_z of X.

<u>Application</u>: The test RI is 180, the UBM prediction is 120.

- PIs with 90% confidence around the test RI are 180/X and 180*X.
- (Assume X is such that) The UBM prediction of 120 is within this range.
- Therefore, UBM passes this evaluation!

Expected RI of a New Test Observation (at 90% confidence level) Given a Single Test RI



Evaluating UBM using PIs: Ex. 2

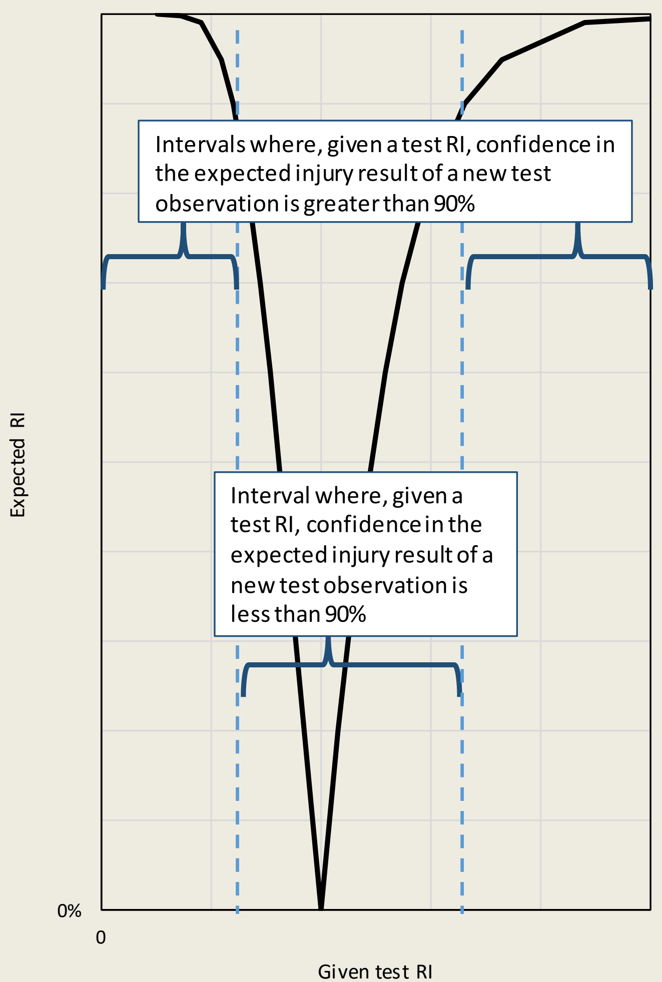
Scenario: An evaluator decides to assess UBM based on its ability to predict the assessment of injury from a test (i.e. RI is above or below 100).

- This evaluation is chosen to only be performed for test points that yield a confidence of injury assessment more than 90%.

Application: The test RI is 180, the UBM prediction is 120.

- (Assume) The test RI of 180 is in the >90% injury confidence level
- UBM prediction agrees with the assessment of injury from the test.
- Therefore, UBM passes this evaluation!

Confidence of Expected Injury Result of New Test Observation Given a Single Test RI



Conclusion/summary

- **Variability of tibia F_z and DRI_z for LF testing was quantified in the form of standard deviation estimates.**
- **Standard deviations were produced using two independent sources: repeat tests and expert opinion.**
- **These two sources yielded similar values for a given injury metric and consistent trends across the two injury metrics.**
- **One set of aggregated estimates were produced from the two sources.**
- **The standard deviation estimates were used to generate PIs which can be used to support the comparison of UBM predictions to LF test results for evaluation of UBM.**

Additional comments:

- Standard deviation estimates were generated for LF tests against a specific vehicle – they should be modified for a different vehicle.
- Additionally, estimates were made for tests conducted in different soil types.

Organization Acronyms

ARL-SLAD: Army Research Laboratory's Survivability/Lethality Analysis Directorate

ARL-WMRD: Army Research Laboratory's Weapons & Materials Research Directorate

ATC: Aberdeen Test Center

WIAMan: Warrior Injury Assessment Manikin

IDA: Institute for Defense Analysis

TARDEC: Tank Automotive Research, Development, and Engineering Center

DOT&E: Director, Operational Test and Evaluation

ATEC: Army Test and Evaluation Command

MCOTEA: Marine Corps Operational Test & Evaluation Activity

MSCS: Marine Corps System Command

JPO MRAP: Joint Program Office, Mine Resistant Ambush Protected Vehicles