U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT COMMAND – ARMAMENTS CENTER

A DOE Case Study: Multidisciplinary Approach to Design an Army Gun Propulsion Charge

Melissa Jablonski & Sarah Longo

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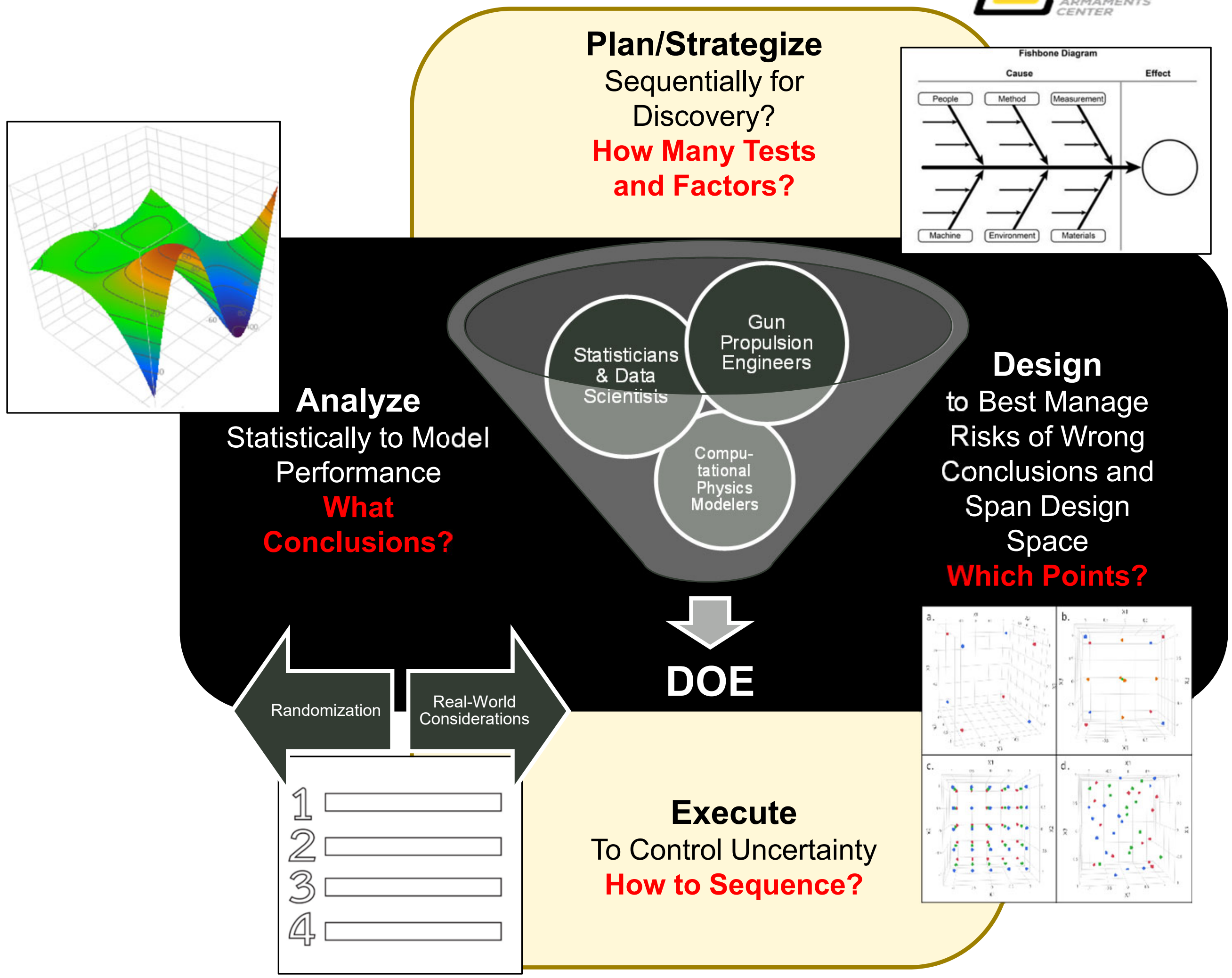
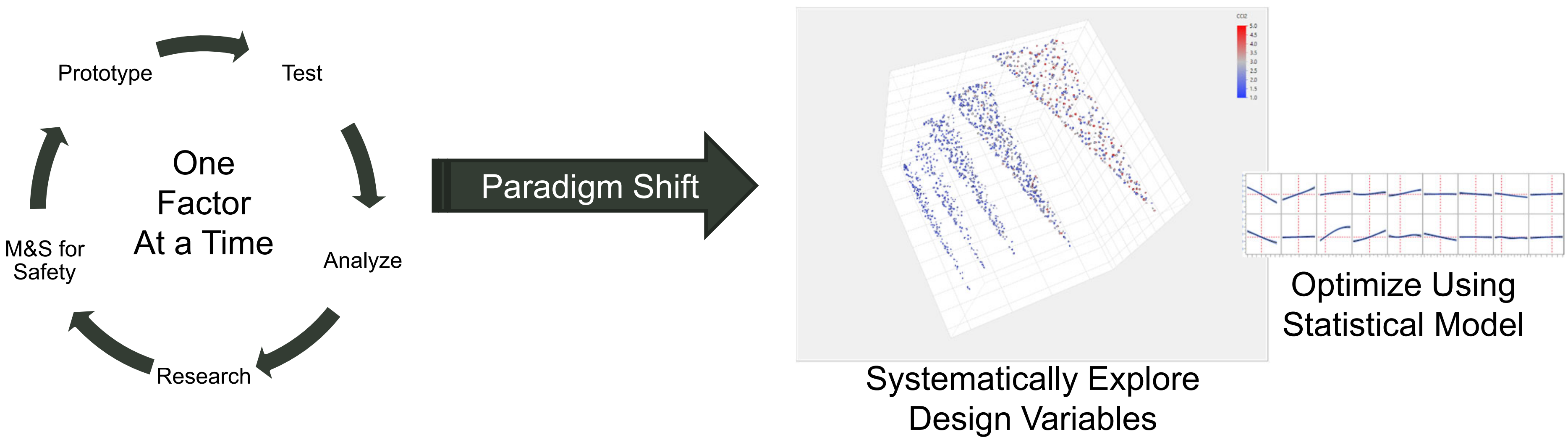
OUTLINE

- **Background**
  - The Army Gun Propulsion Charge
  - Data Sources
  - DOE Approach
- **Phase I DOE**
  - Planning
  - Design
  - M&S
  - Analysis
  - Results
- **Phase 2 DOE**
  - Planning
  - Design
  - M&S/Testing
  - Analysis
  - Results
- **Lessons Learned**
- **Future Work**



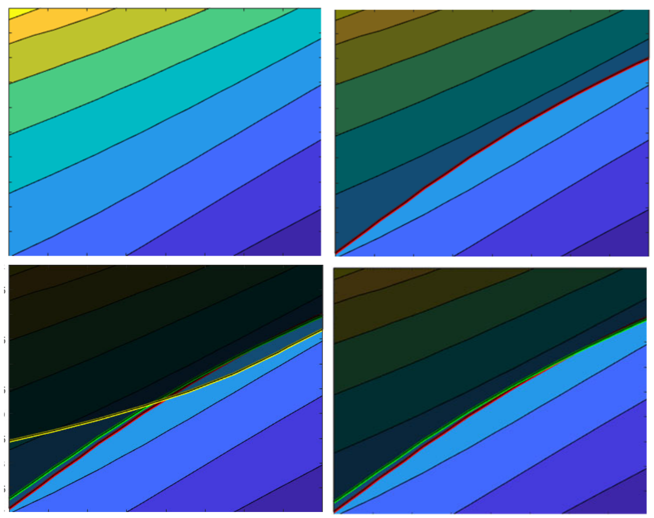
BACKGROUND: THE ARMY GUN PROPULSION CHARGE

- **Gun propulsion charge functions in ~20 ms in a dynamic environment (volume, pressure, temperature, phase)**
- **A year to design propulsion charge for confirmatory gun firing test**
  – Ignition train was the major focus
- **First time using interior ballistics M&S with a design of experiments (DOE) approach**
  – Previously OFAT or SME-judgment-designed sequential prototyping and testing

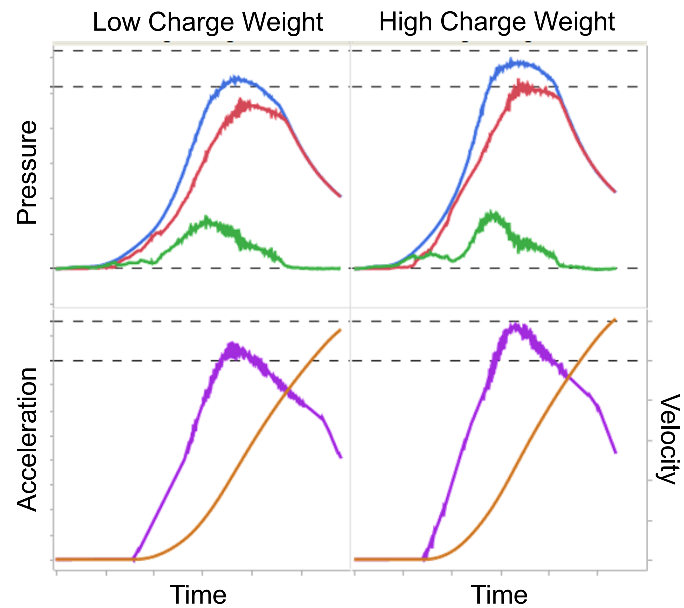


BACKGROUND: OBJECTIVE

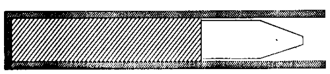
- **Design a propulsion charge that will maximize muzzle velocity while not exceeding maximum pressure or acceleration limits of the system**

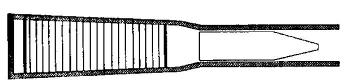


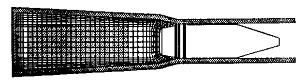
Muzzle Velocity as Function of Propellant Geometry and Charge Weight (with system constraints)

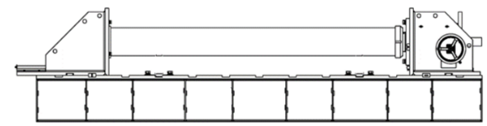


BACKGROUND: RESOURCES AND DATA SOURCES









Lumped Parameter M&S → Two Phase/1D M&S → Two Phase/2D M&S → Ballistic Simulator Live Testing

Lumped Parameter M&S

- Simplest, quickest calculations, PC run time < 1 second
- Used to obtain the big picture response: how does propellant weight affect results?
- No ability to differentiate between different charge configurations

Two Phase/1D M&S

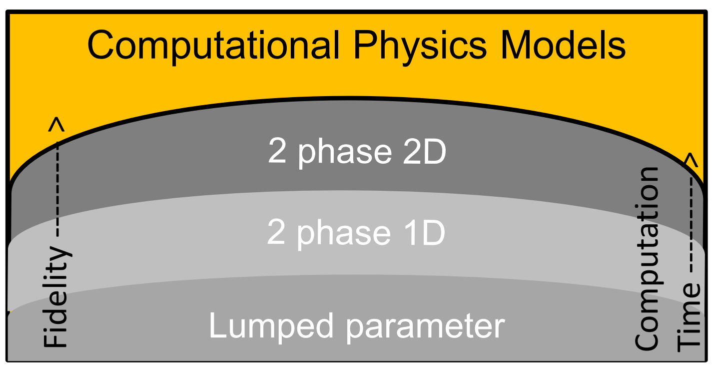
- Slightly more complex, PC run time < 5 minutes
- Used to consider the effects of different charge configurations
- Several assumptions still in the model (dimensionality, igniter table)

Two Phase/2D M&S

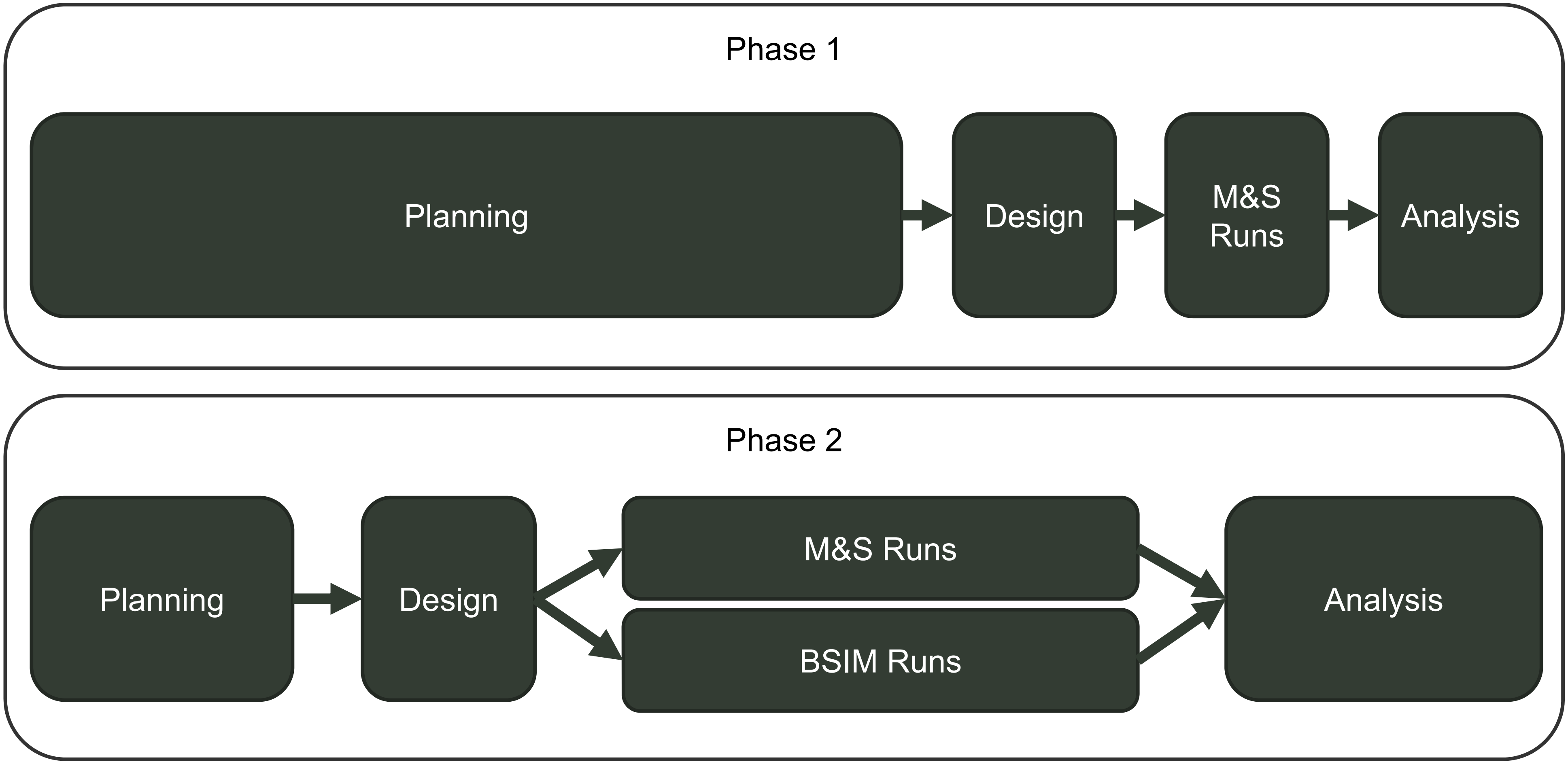
- Most accurate computer simulation, PC run time < 1 day
- Used to refine and correct inaccuracies in 1D M&S due to model assumptions

Ballistic Simulator Live Testing

- Real world test, a handful of shots every two weeks
- Used to correct M&S inaccuracies
- Ballistic Simulator (BSIM) captures the very early part of a true gun firing; Two Phase/2D M&S is then matched to the early ignition pressure traces and high speed video to predict the full gun launch cycle



BACKGROUND: DOE APPROACH



PHASE 1: PLANNING

- **Initial variable list presented at first meeting, with the resources for about 20 total tests**
  - Charge Configuration Factors (11 ea.)
    - Propellant amount
    - Propellant type
    - Propellant length
    - Propellant geometry
    - Bag/combustible case
    - Combustible case composition
    - Charge diameter
    - Charge length
    - Number of charge segments
    - Length of charge segments
    - Segment offset
  - Ignition Configuration Factors (7 ea.)
    - Igniter placement within charge
    - Igniter amount
    - Igniter material
    - Center core geometry
    - Number of center cores
    - Base pad geometry
    - Number of base pads
  - Outside Factors (4 ea.)
    - Projectile weight
    - Chamber volume
    - Ignition method
    - Ambient Temperature
- **Large time and effort investment into**
  - Defining variables for the statisticians (what is a charge segment?)
  - Defining variable relationships (the DOE constraints)
  - Narrowing down the initial list (programmatic constraints, resource limitations, overdefined design, etc.)
- **This planning phase required input and collaboration from many different areas (Statisticians, Propulsion Engineers, Computational Physics Modelers, Experimental Technicians)**
  - Idea presented to use Modeling and Simulation to augment limited available testing
  - Decided on 2 phases of DOE, M&S only in Phase I, reduced variables for Phase II with testing

PHASE 1: PLANNING

Final variable list (19)

	Name	Description	Type
	W1	Charge Weight	continuous
Charge Segment Variables	S1	Number of charge segments	discrete
	S2	Mean Segment Length	continuous
	S3	Segment Length Range/Direction	continuous
	S4	Segment Length Configuration (for S3)	categorical
	S5	Length of offsets between segments	continuous
Base Pad Igniter Variables	BPI1	Number of Base Pad Igniter (BPI) bags	discrete
	BPI2	Mean Amount of igniter per BPI bag	continuous
	BPI3	Igniter in BPI bags Range/Direction	continuous
	BPI4	BPI bag Configuration (for BPI3)	categorical
	BPI5	BPI Placement	categorical
Center Core Igniter Variables	CCI1	Number of Center Core Igniter (CCI) bags	discrete
	CCI2	Mean Amount of igniter per CCI bag (oz)	continuous
	CCI3	Igniter in CCI bags Range/Direction	continuous
	CCI4	CCI Configuration (for CCI3)	categorical
	CCI5	CCI Placement	categorical
Center Core Diameter Variables	CCID1	Mean Diameter of CCI Bag	continuous
	CCID2	Diameter Range/Direction of CCI Bags	continuous
	CCID3	CCI Diameter Configuration (for CCID2)	categorical

Final constraint list

(24 descriptively listed, turned into 30 constraint equations)!

- $descriptively\ charge\ diameter \leq a$
- $total\ charge\ length \leq b$
- $total\ charge\ length \geq c$
- $smallest\ segment \geq d$
- *no out to middle with less than 3 segments*
- $\#\ of\ base\ pad\ igniters \leq \#\ of\ segments$
- $igniter\ mass\ in\ largest\ base\ pad\ igniter \leq e$
- $igniter\ mass\ in\ smallest\ base\ pad\ igniter \geq f$
- $charge\ must\ have\ at\ least\ one\ igniter\ (base\ pad\ or\ center\ core)$
- $if\ there\ is\ less\ than\ 2\ base\ pad\ igniters, range = 0$
- *no out to middle with less than 3 base pad igniters*
- *when bags are placed every other, only 2 or 3 base pad igniters*
- *when bags are placed every other with less than 5 segments, only 2 base pad igniters*
- *when bags are placed every other,* $\#\ of\ segments \geq 3$
- $\#\ of\ center\ core\ igniters \leq \#\ of\ segments$
- $igniter\ mass\ in\ largest\ center\ core\ igniter \leq e$
- $igniter\ mass\ in\ smallest\ center\ core\ igniter \geq f$
- $if\ there\ are\ less\ than\ 2\ center\ core\ igniters, range = 0$
- *no out to middle with less than 3 center core igniters*
- *when bags are placed every other, only 2 or 3 center core igniters*
- *when bags are placed every other with less than 5 segments, only 2 center core igniters*
- *when bags are placed every other,* $\#\ of\ segments \geq 3$
- $\max center\ core\ igniter\ diameter \leq g$
- $nth\ center\ core\ length \leq nth\ segment\ length$

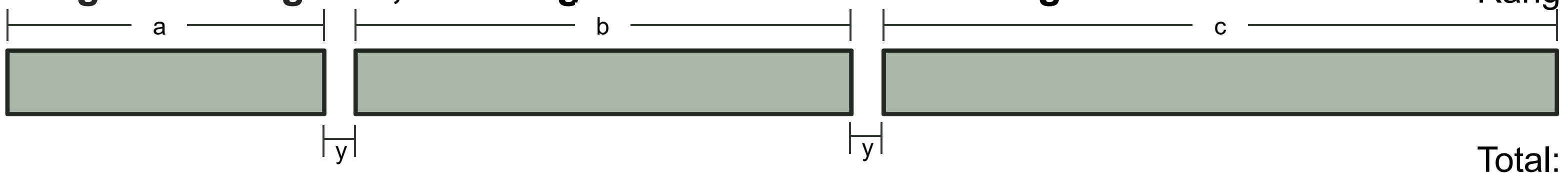
PHASE 1: PLANNING

How the 5 segment variables define the segments

S1: Total Segment Length = x, S2: Number of segments = 3, S5: Offset between segments = y

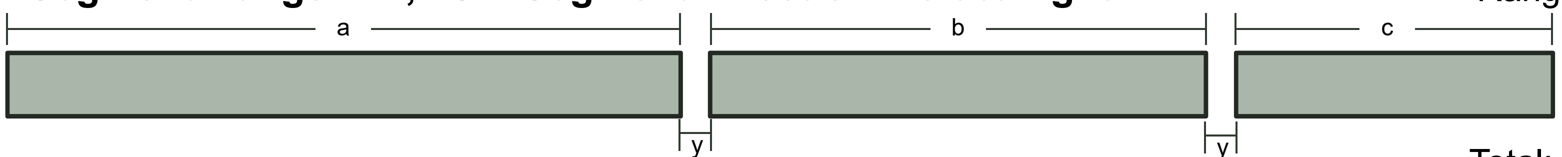
S3: Segment Range = z, S4: Segment Direction= left to right

Total: $a + b + c = x$
Range: $c - a = z$



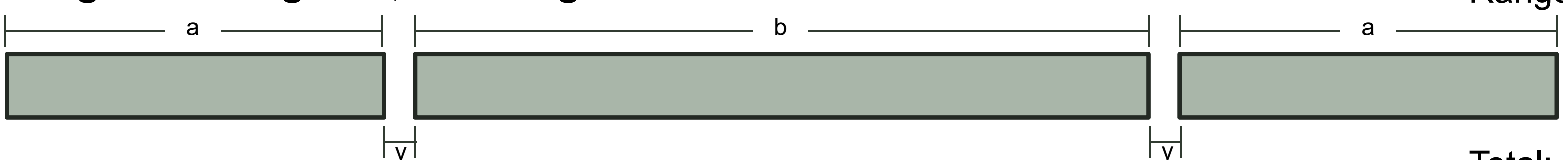
S3: Segment Range = -z, S4: Segment Direction= left to right

Total: $a + b + c = x$
Range: $c - a = -z$



S3: Segment Range = z, S4: Segment Direction= out to middle

Total: $a + b + a = x$
Range: $b - a = z$



S3: Segment Range = -z, S4: Segment Direction= out to middle

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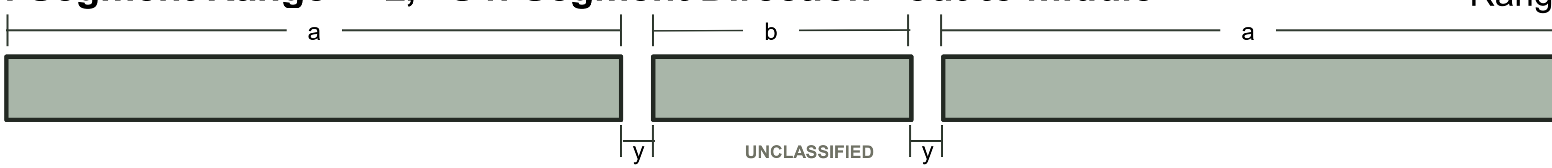
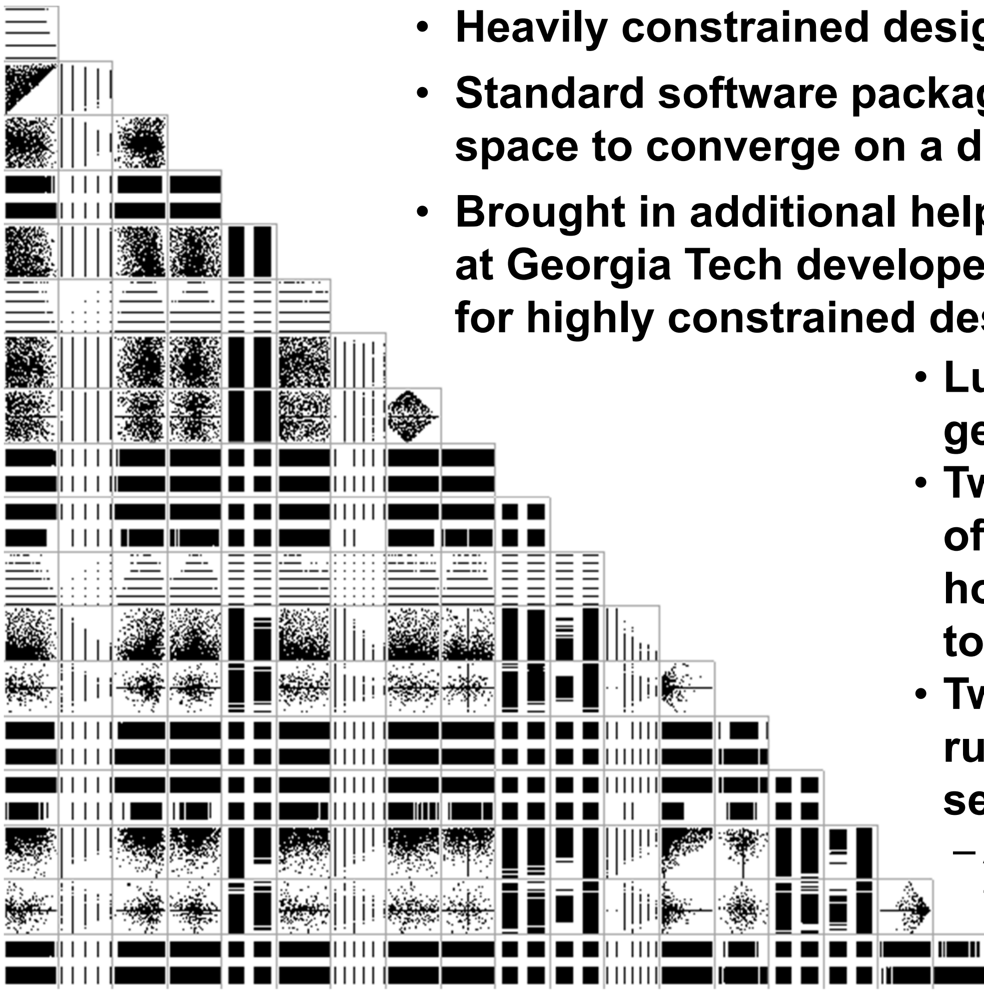


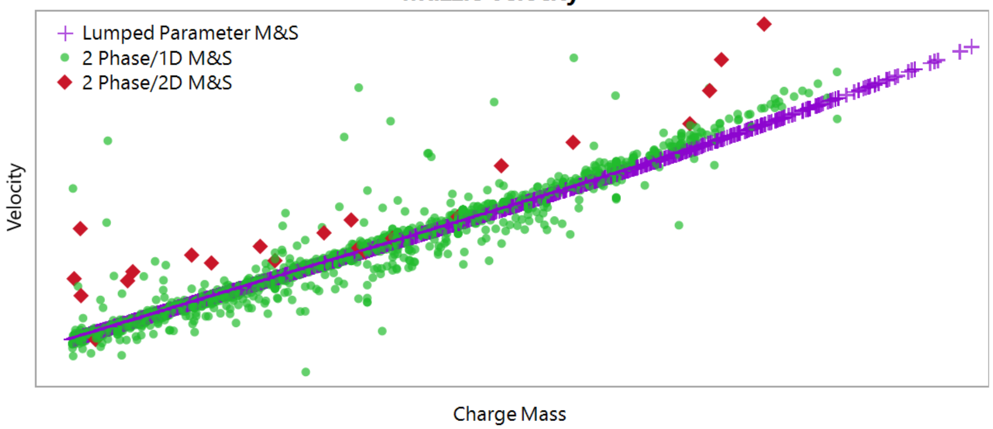
PHASE 1: DESIGN



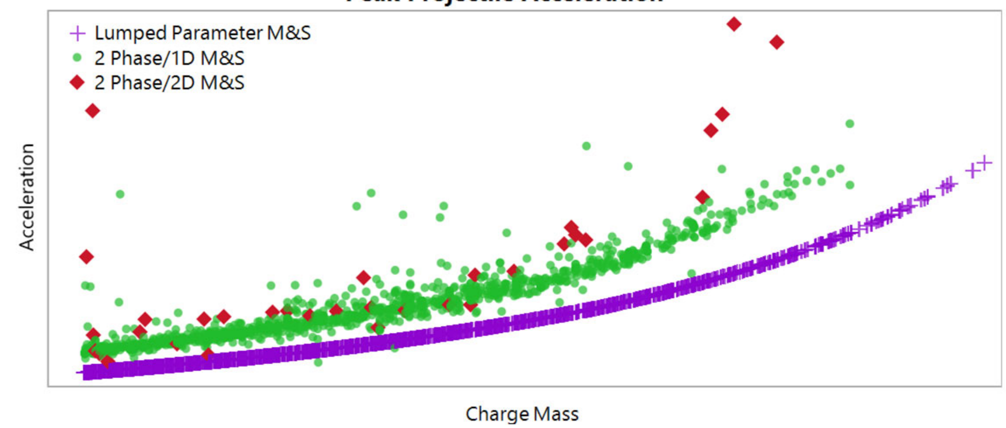
- **Heavily constrained design**
- **Standard software packages couldn't generate enough points in the design space to converge on a design**
- **Brought in additional help- Dr. Roshan Joseph and his graduate students at Georgia Tech developed an algorithm to generate space filling designs for highly constrained design spaces**
  - **Lumped Parameter used the full 2000 run design generated by Dr. Joseph**
  - **Two Phase/1D M&S design initially used a subset of 400 runs chosen from the entire 2000 run set; however, we found the code was efficient enough to run all 2000 no problem**
  - **Two Phase/2D M&S design used a subset of 40 runs chosen I-optimally from the entire 2000 run set**
    - All main effects and select interactions included based on the 1D M&S results

PHASE 1: MODELING AND SIMULATION

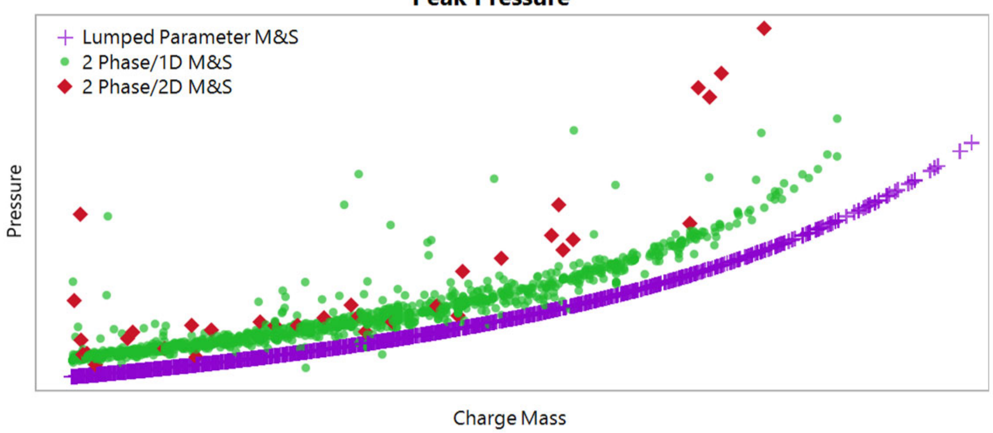
Muzzle Velocity



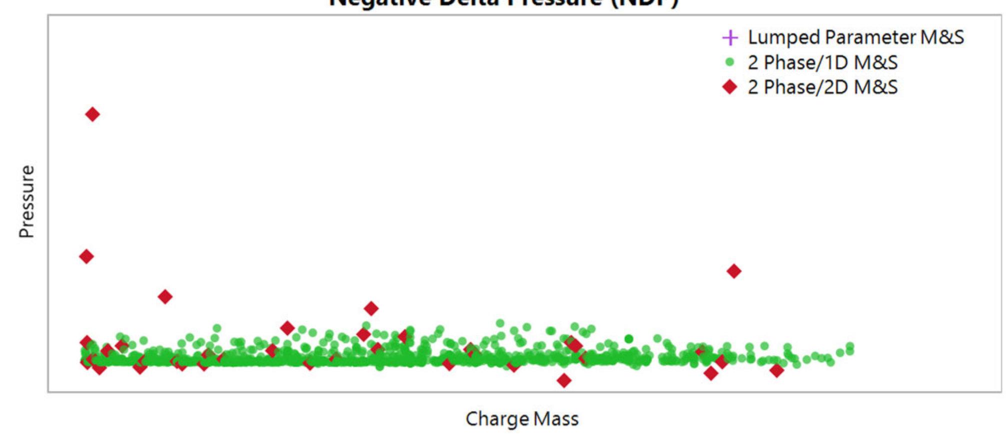
Peak Projectile Acceleration



Peak Pressure



Negative Delta Pressure (NDP)



PHASE 1: ANALYSIS

- **M&S results are actually functional data although specific values (summary values) in these data were most important**
  - Velocity-time curve -> muzzle velocity
  - Acceleration-time curve -> peak projectile acceleration
  - Pressure-time curves -> peak pressure and maximum negative delta pressure (NDP)
- **For the first analysis phase, several models were fit to the data**
  - Separate functional data analysis for each of the lumped parameter and 1D M&S results
  - Separate (summary value) data analysis for each of the 3 M&S codes
  - Combined (summary value) data analysis for the 3 M&S codes with the code as a separate factor
- **Goal of the analysis was to identify important/unimportant variables, not necessarily create the most accurate prediction model**
- **"Lessons learned" during this process carried over to phase 2 planning**
  - Understanding that the functional data analysis with this data is a very time consuming process (large time effort into data pre-processing) -> decision to relay on summary data for phase 2 (considering functional data only as time permitted)
  - Idea of what the data would look like -> helped guide the phase 2 designs

PHASE 1: RESULTS

Predictor	NGEN sensitivites MV Rank	NGEN sensitivities 1st Max NDP Rank	NGEN sensitivities Breech Pressure Rank
W1	1	5	1
S1	3	10	3
S1xS2	2	1	2
S3	5	2	6
S4	14	17	7
S5	8	4	12
BPI1	13	7	10
BPI2	11	6	14
BPI3	12	9	16
BPI4	15	18	18
BPI5	17	19	17
CCI1	6	12	5
CCI2	4	8	4
CCI3	9	13	13
CCI4	16	16	15
CCI5	19	15	19
CCID1	10	3	11
CCID2	7	11	8
CCID3	18	14	9

Reduced design space

- 11 variables carried forward (out of 19)
- Reduced to viable ranges (within system constraints)

PHASE 2: PLANNING

Final variable list (12)

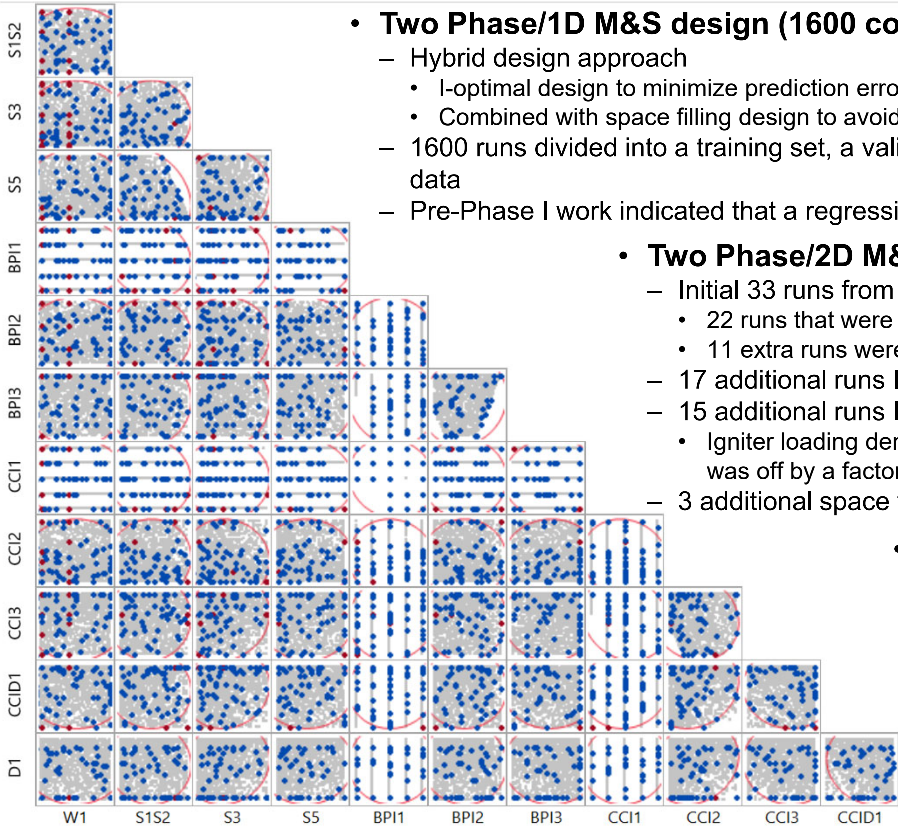
	Name	Description	Type	Details
	W1	Charge Weight	continuous	greatly reduced range
Charge Segment Variables	~~S1~~	~~Number of charge segments~~	~~discrete~~	over-defined
	S1S2	Total Segment Length	continuous	modified variable def.
	S3	Segment Length Range/Direction	continuous	reduced range
	~~S4~~	~~Segment Length Configuration (for S3)~~	~~categorical~~	eliminated
	S5	Length of offsets between segments	continuous	
Base Pad Igniter Variables	BPI1	Number of Base Pad Igniter (BPI) bags	discrete	reduced range
	BPI2	Mean Amount of igniter per BPI bag	continuous	
	BPI3	Igniter in BPI bags Range/Direction	continuous	reduced range
	~~BPI4~~	~~BPI bag Configuration (for BPI3)~~	~~categorical~~	eliminated
	~~BPI5~~	~~BPI Placement~~	~~categorical~~	eliminated
Center Core Igniter Variables	CCI1	Number of Center Core Igniter (CCI) bags	discrete	reduced range
	CCI2	Mean Amount of igniter per CCI bag (oz)	continuous	
	CCI3	Igniter in CCI bags Range/Direction	continuous	reduced range
	~~CCI4~~	~~CCI Configuration (for CCI3)~~	~~categorical~~	eliminated
	~~CCI5~~	~~CCI Placement~~	~~categorical~~	eliminated
Center Core Diameter Variables	CCID1	Mean Diameter of CCI Bag	continuous	
	~~CCID2~~	~~Diameter Range/Direction of CCI Bags~~	~~continuous~~	eliminated
	~~CCID3~~	~~CCI Diameter Configuration (for CCID2)~~	~~categorical~~	eliminated
	D1	Density of igniter	continuous	added

Final constraints (12)

1. $total\ charge\ length \leq a$
2. $total\ charge\ length \geq b$
3. $smallest\ segment \geq c$
4. $igniter\ mass\ in\ largest\ base\ pad \leq d$
5. $igniter\ mass\ in\ smallest\ base\ pad \geq e$
6. $if\ there\ is\ only\ 1\ base\ pad, range = 0$
7. $igniter\ mass\ in\ largest\ center\ core \leq d$
8. $igniter\ mass\ in\ smallest\ center\ core \geq e$
9. $if\ there\ is\ only\ 1\ center\ core, range = 0$
10. $1st\ center\ core\ length \leq 1st\ segment\ length$
11. $last\ center\ core\ length \leq last\ segment\ length$
12. $\#\ of\ base\ pads\ or\ \#\ or\ center\ cores \geq f$

PHASE 2: DESIGN

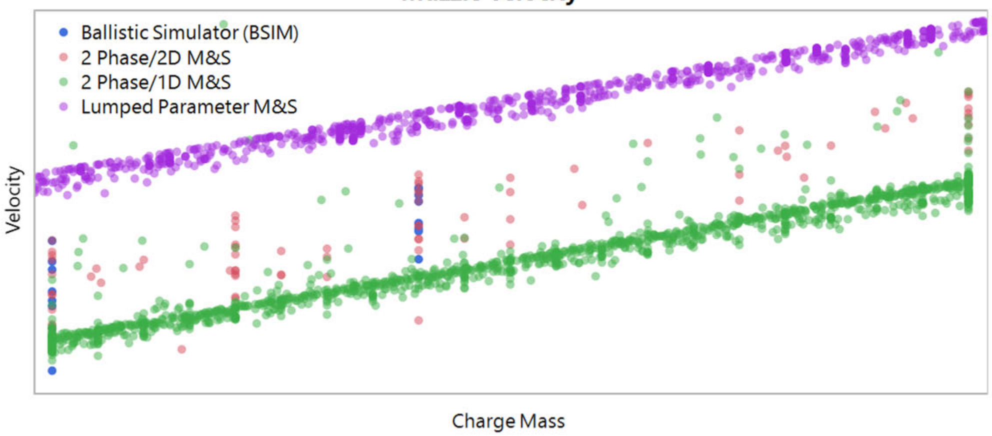
- **Lumped Parameter M&S design (0 new configurations simulated)**
  - Carried over data and results from Phase I work
  - ~900 runs in the Phase I charge weight range
  - More than enough data for our Phase I model (only 1 input variable)



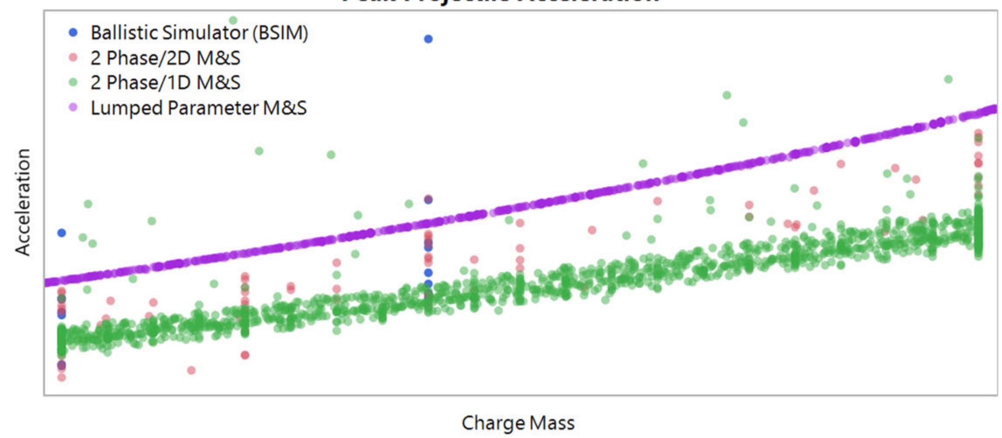
- **Two Phase/1D M&S design (1600 configurations simulated)**
  - Hybrid design approach
    - I-optimal design to minimize prediction errors in a regression model
    - Combined with space filling design to avoid overfitting and leave the option for other types of model fitting techniques
  - 1600 runs divided into a training set, a validation set, and a test set to aid in model fitting and avoid overfitting to noise and outliers in the data
  - Pre-Phase I work indicated that a regression model using validation data would work best to fit the data
- **Two Phase/2D M&S design waves (80 configurations simulated)**
  - Initial 33 runs from BSIM design (see below)
    - 22 runs that were actually tested in the BSIM
    - 11 extra runs were BSIM design configurations with different charge weights
  - 17 additional runs I-optimal augmentation
  - 15 additional runs I-optimal augmentation
    - Igniter loading density added in as an additional factor after we started building charges and realized the initial estimate was off by a factor of 2
  - 3 additional space filling augmentations of 5 runs each
- **Ballistic Simulator (BSIM) design (22 unique configurations tested, 25 total shots)**
  - BSIM design had unique constraints related to the manufactured stick lengths
    - Less than 20 unique combinations of segment lengths could reasonably be cut and built
  - Built a huge table of those unique segment lengths combined with all possible combinations of the other DOE variables
  - Final 22 unique BSIM runs were chosen as a subset of those possible combinations
    - Main effects model only
  - IPT chose 3 runs of interest to replicate to obtain 25 total shots

PHASE 2: M&S AND TESTING

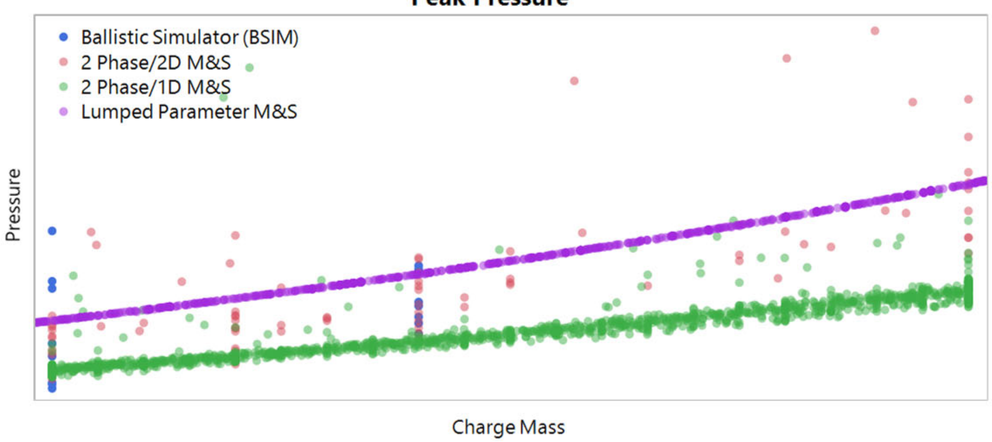
Muzzle Velocity



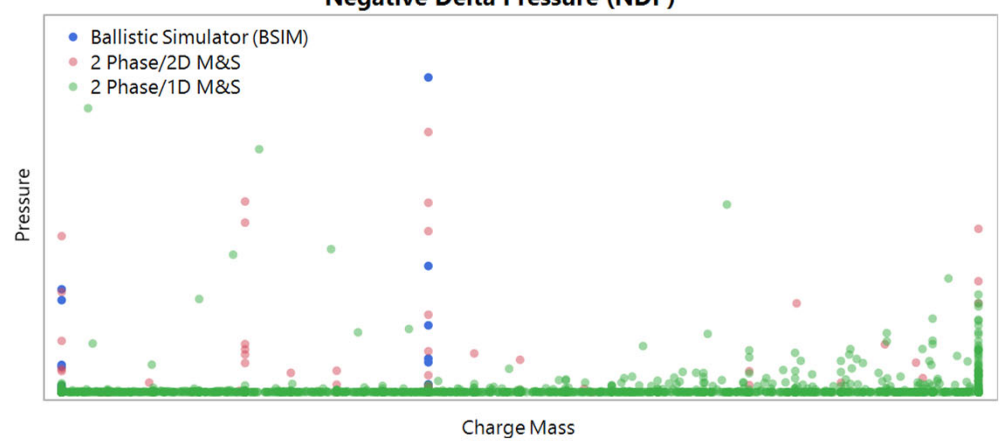
Peak Projectile Acceleration



Peak Pressure



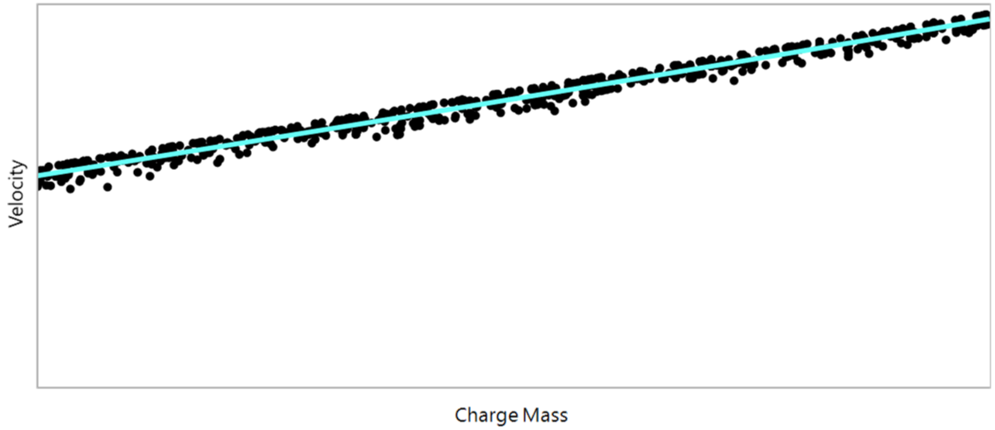
Negative Delta Pressure (NDP)



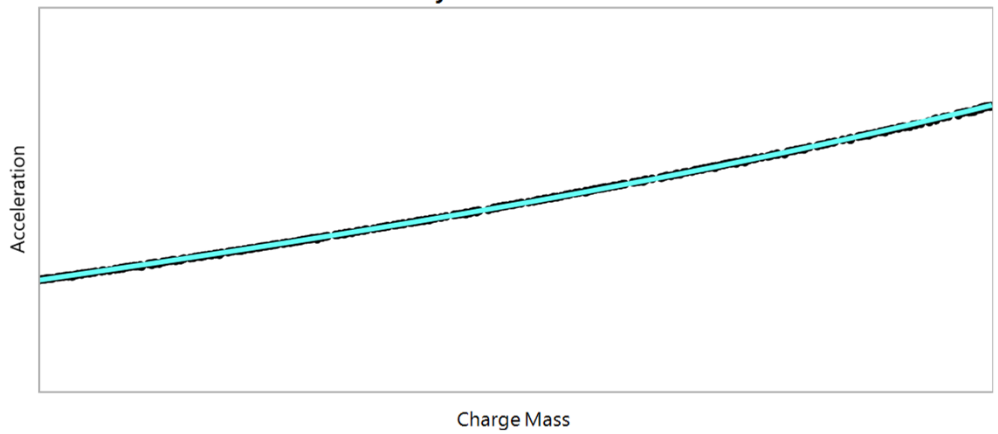
PHASE 2: ANALYSIS

Lumped Parameter M&S

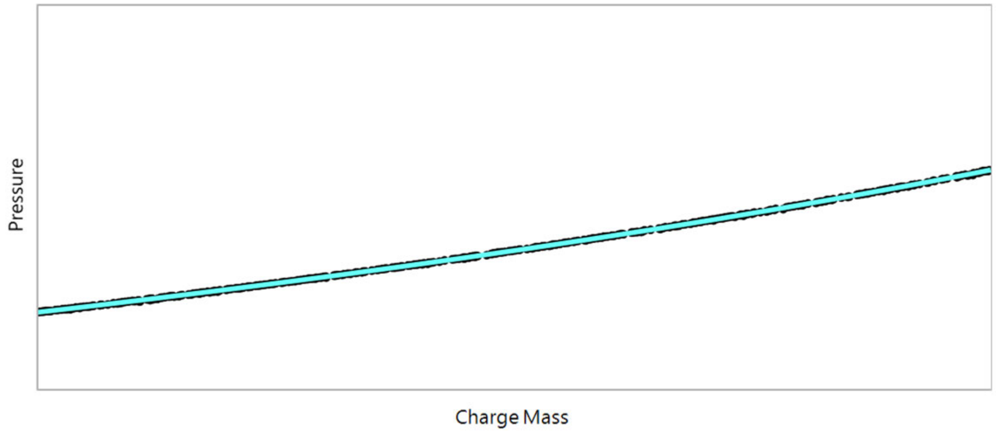
Muzzle Velocity



Peak Projectile Acceleration



Peak Pressure

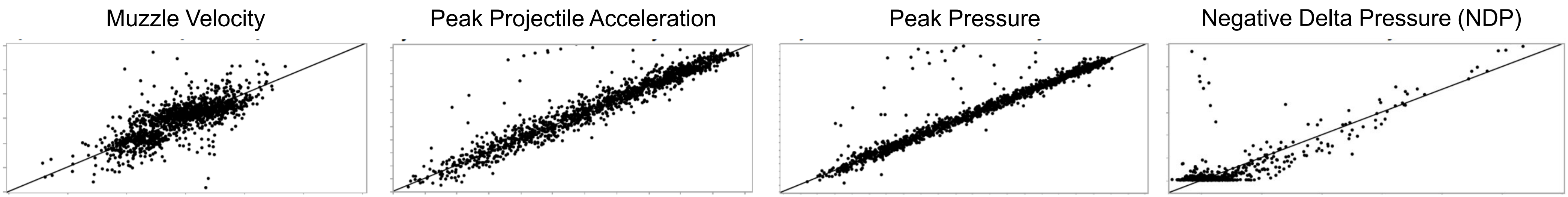


Linear regression used to predict velocity, acceleration, and peak pressure as a function of charge mass

PHASE 2: ANALYSIS

Two Phase/1D M&S

- **Considered the adjustment from the lumped parameter results**
  - i.e. what is the difference between these results and the lumped parameter predictions
  - 1D Adjustment= 1D Result- Lumped Parameter Prediction
  - Prediction Model fit to the 1D Adjustment
  - 1D Prediction = Lumped Parameter Prediction + 1D Adjustment Prediction
- **3rd order stepwise regression used to fit the data with the validation runs used for term selection and the test runs used as an extra "check" on overfitting**
- **Plots below show the model predictions on the x-axis vs the actual M&S results on the y-axis**

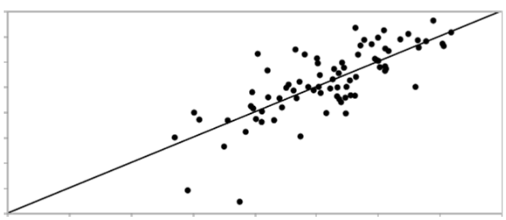


PHASE 2: ANALYSIS

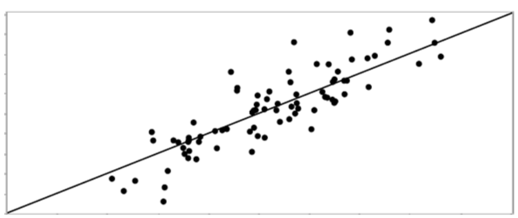
Two Phase/2D M&S

- **Considered the adjustment from the 1D results**
  - i.e. what is the difference between these results and the 1D prediction
  - 2D Adjustment= 2D Result- 1D Prediction
  - Prediction Model fit to the 2D Adjustment
  - 2D Prediction= Lumped Parameter Prediction + 1D Adjustment Prediction + 2D Adjustment Prediction
- **Two separate prediction models fit to each response:**
  - Stepwise response surface regression with 11 extra BSIM configurations and last 2 augmentations used as validation
  - Gaussian process model
- **Final model taken as the average of the 2 prediction models**
- **Plots below show the model (jackknifed) predictions on the x-axis vs the actual M&S results on the y-axis**

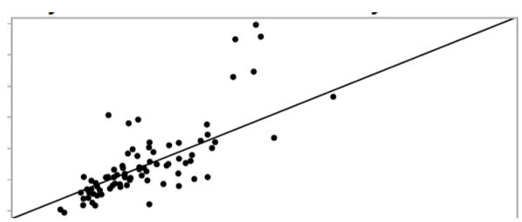
Muzzle Velocity



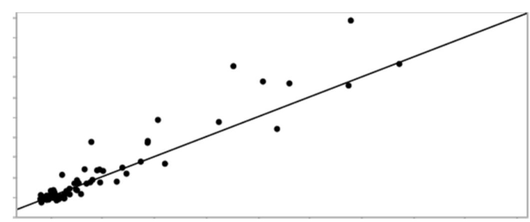
Peak Projectile Acceleration



Peak Pressure



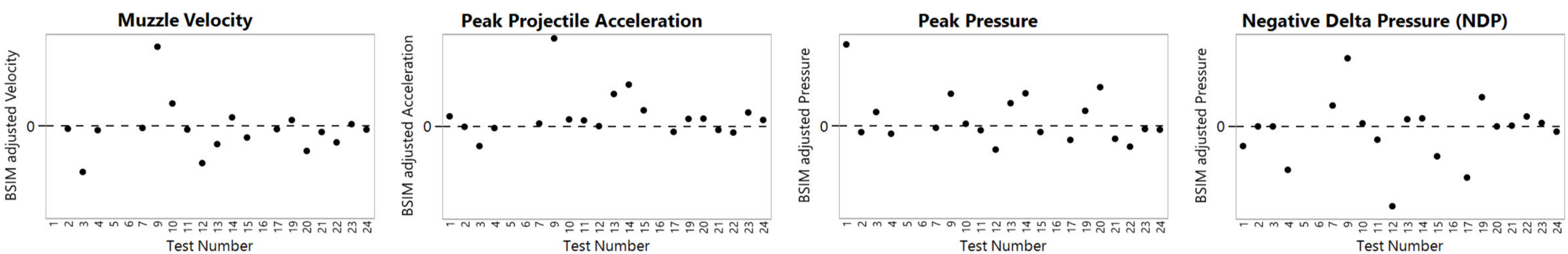
Negative Delta Pressure (NDP)



PHASE 2: ANALYSIS

Ballistic Simulator (BSIM)

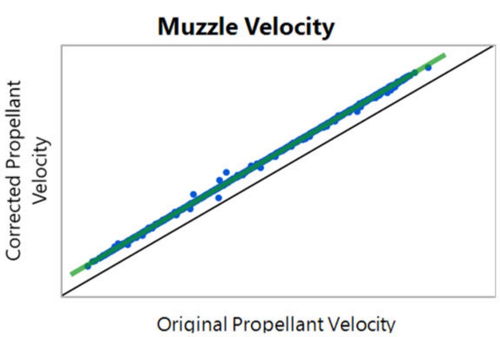
- **BSIM adjustment calculated by subtracting the pre-BSIM NGEN predictions from the BSIM adjusted NGEN predictions**
- **Note that we do not have data for all 25 runs (replicates were not simulated and some runs did not ignite or complete in NGEN)**
- **We do observe some differences in the BSIM adjustment data, but the data does not support these as being more than random noise**
  - No significant terms when a regression model was fit to the data

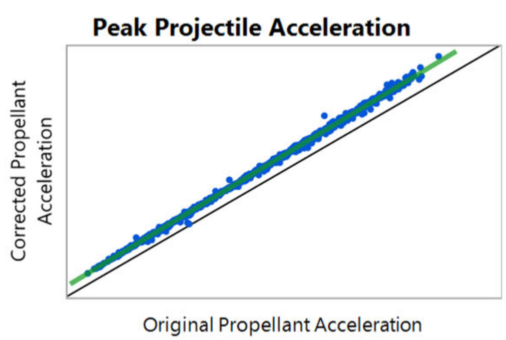


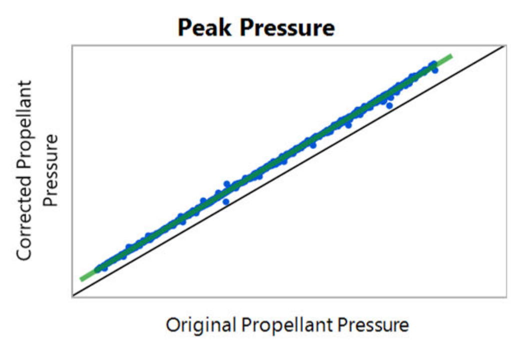
PHASE 2: ANALYSIS

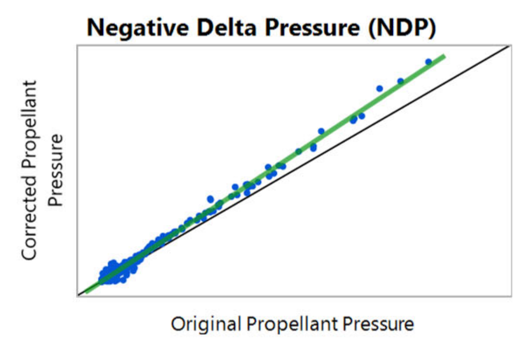
Final Propellant Adjustment

- **We found a small difference in how the modelers were defining the propellant grain based on initial assumptions and the actual grains we were receiving from the contractor**
- **Infeasible to re-run all our 2D runs, but very quick and easy to re-run 1600 1D M&S DOE**
- **Plots below show the model results with the original grain definition vs the corrected grain definition**
  - Slight increase in predicted results with new definition
- **This linear relationship was then applied to the 2D models to adjust those final predictions for this new propellant definition**



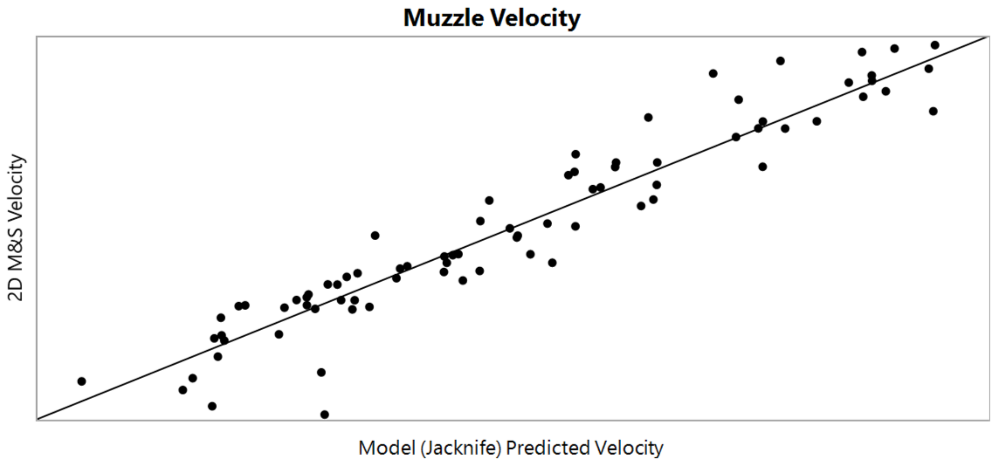


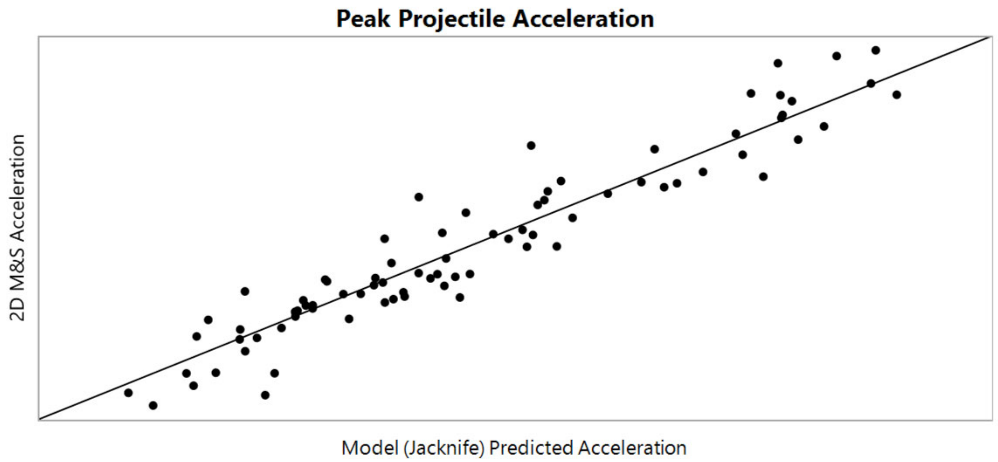


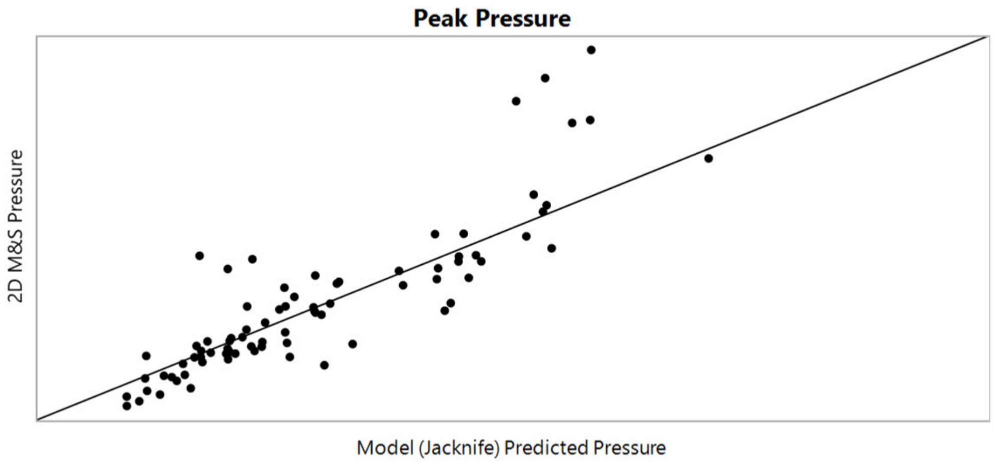


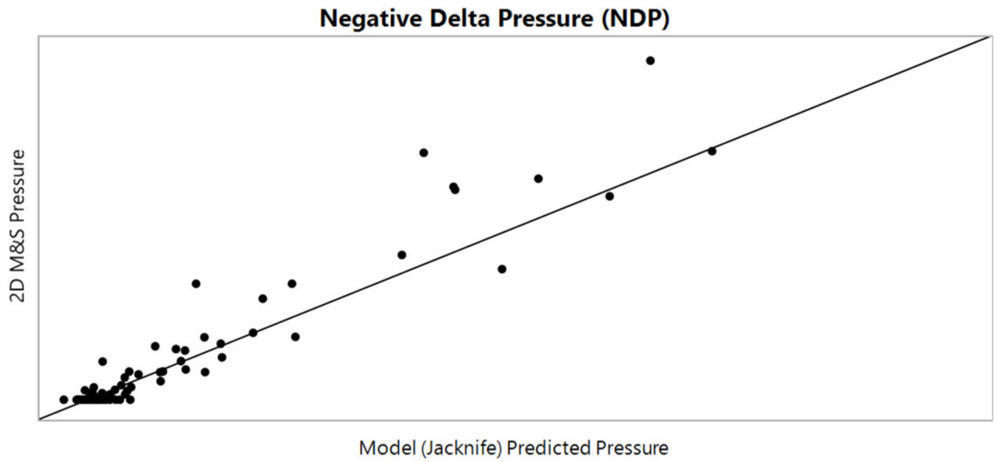
PHASE 2: ANALYSIS

Final Model Evaluation









PHASE 2: RESULTS

Variable Importance

Name	Description
W1	Charge Weight
S1S2	Total Segment Length
S3	Segment Length Range/Direction
S5	Length of offsets between segments
BPI1	Number of Base Pad Igniter (BPI) bags
BPI2	Mean Amount of igniter per BPI bag
BPI3	Igniter in BPI bags Range/Direction
CCI1	Number of Center Core Igniter (CCI) bags
CCI2	Mean Amount of igniter per CCI bag (oz)
CCI3	Igniter in CCI bags Range/Direction
CCID1	Mean Diameter of CCI Bag
D1	Density of igniter

	Objectives		Desirability	
Predictor	Portion	Rank	Portion	Rank
W1	0.7790	1	0.9136	1
S1S2	0.0168	6	0.0030	6
S3	0.0292	4	0.0029	7
S5	0.0050	9	0.0020	8
BPI1	0.0045	10	0.0018	9
BPI2	0.0050	8	0.0010	10
BPI3	0.0013	11	0.0004	11
CCI1	0.0220	5	0.0051	5
CCI2	0.0125	7	0.0137	4
CCI3	0.0354	3	0.0171	3
CCID1	0.0894	2	0.0394	2

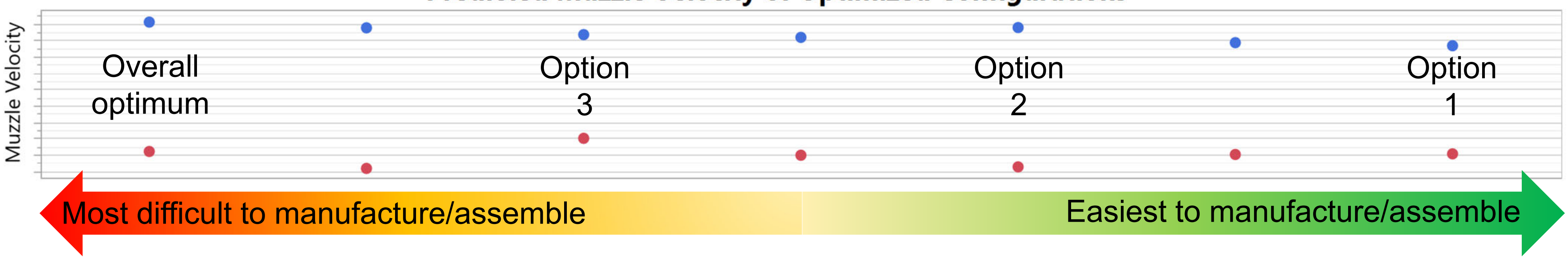
	Muzzle Velocity		Peak Projectile Acceleration		Peak Pressure		Negative Delta Pressure (NDP)	
Predictor	Portion	Rank	Portion	Rank	Portion	Rank	Portion	Rank
W1	0.8385	1	0.8029	1	0.6644	1	0.0069	10
S1S2	0.0143	7	0.0744	2	0.0190	6	0.3295	1
S3	0.0021	9	0.0581	3	0.0537	4	0.0868	4
S5	0.0167	6	0.0142	5	0.0101	7	0.1227	3
BPI1	0.0187	5	0.0075	7	0.0032	9	0.0333	8
BPI2	0.0474	2	0.0001	11	0.0043	8	0.0102	9
BPI3	0.0052	8	0.0026	9	0.0015	11	0.0346	7
CCI1	0.0302	3	0.0138	6	0.0447	5	0.0762	6
CCI2	0.0010	10	0.0028	8	0.0019	10	0.2177	2
CCI3	0.0250	4	0.0230	4	0.1201	2	0.0774	5
CCID1	0.0010	11	0.0005	10	0.0771	3	0.0048	11

PHASE 2: RESULTS

Design Optimization

- **Simultaneously searched for designs that met the following conditions:**
  - At a high propellant weight
    - Peak Projectile Acceleration < threshold level
    - Peak Pressure < threshold level
    - 1st NDP near 0
  - At a low propellant weight
    - Peak Projectile Acceleration < objective level
    - Peak Pressure < objective level
    - 1st NDP near 0
  - Maximized muzzle velocity at both conditions
- **Found the overall best design**
- **Also considered several alternatives of "simpler" charges that were easier to manufacture and assemble**

Predicted Muzzle Velocity of Optimized Configurations



- **Choose to consider a few configurations to simulate in 2D M&S:**
  - Option 1: segment length=manufactured propellant length (easiest to manufacture)
  - Option 2: segments of equal length with the same igniter configuration (slightly more difficult to manufacture, easy to assemble)
  - Option 3: segments of equal length with different, optimized igniter configurations (slightly more difficult to manufacture and assemble)
- **Performance gains for other alternatives are marginal and do not warrant the increased manufacturing/operating complexity**

PHASE 2: RESULTS

Design Optimization: 2D M&S results

Option 1

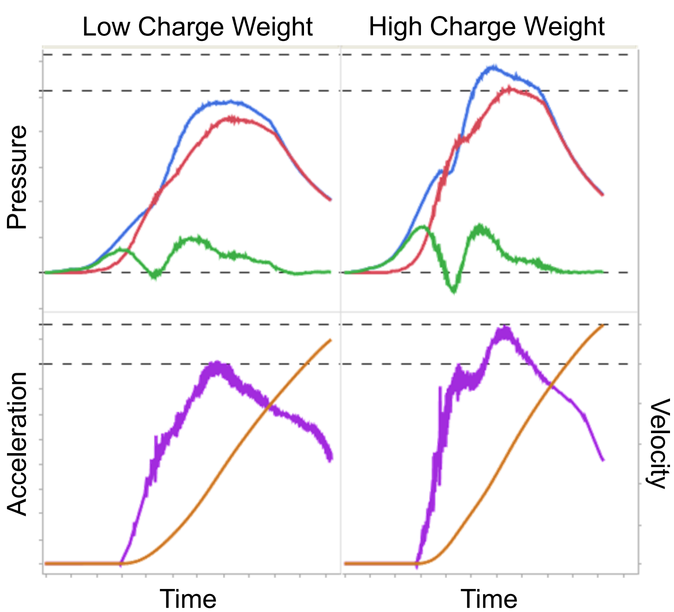
- Hitting pressure and acceleration targets pretty well
- Small NDP (green) and decently shaped curves at lower charge weight
- Issues with higher charge weight (NDP and bumpier curves)

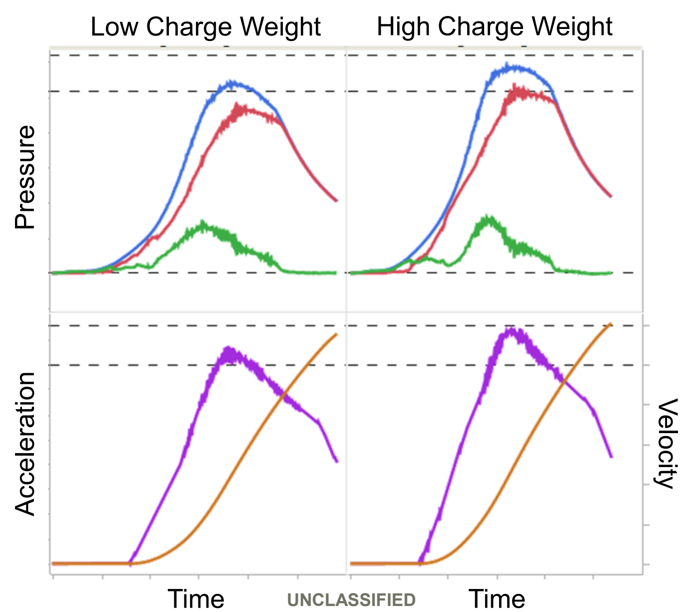
Option 2

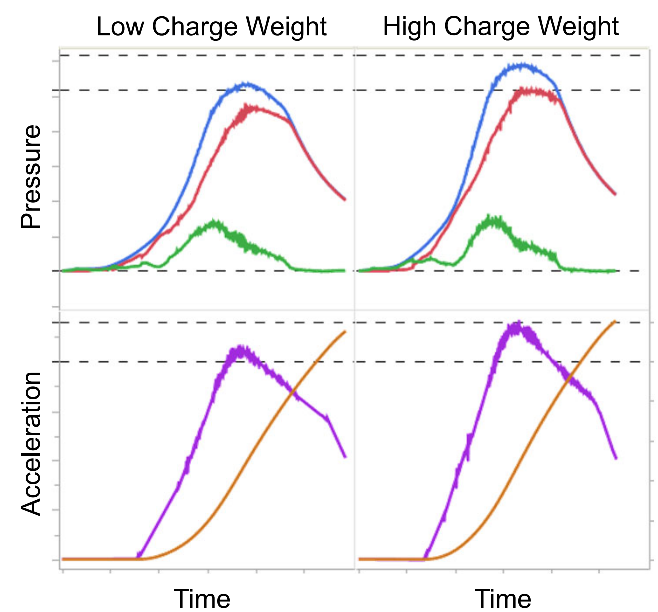
- No NDPs for either scenario
- Smoother, move ideal pressure and acceleration curves
- Slightly above pressure and acceleration targets at low charge weight, but weight can be adjusted to account for that

Option 3

- Very little difference compared to Option 2
- No reason to add additional complexity to final configuration

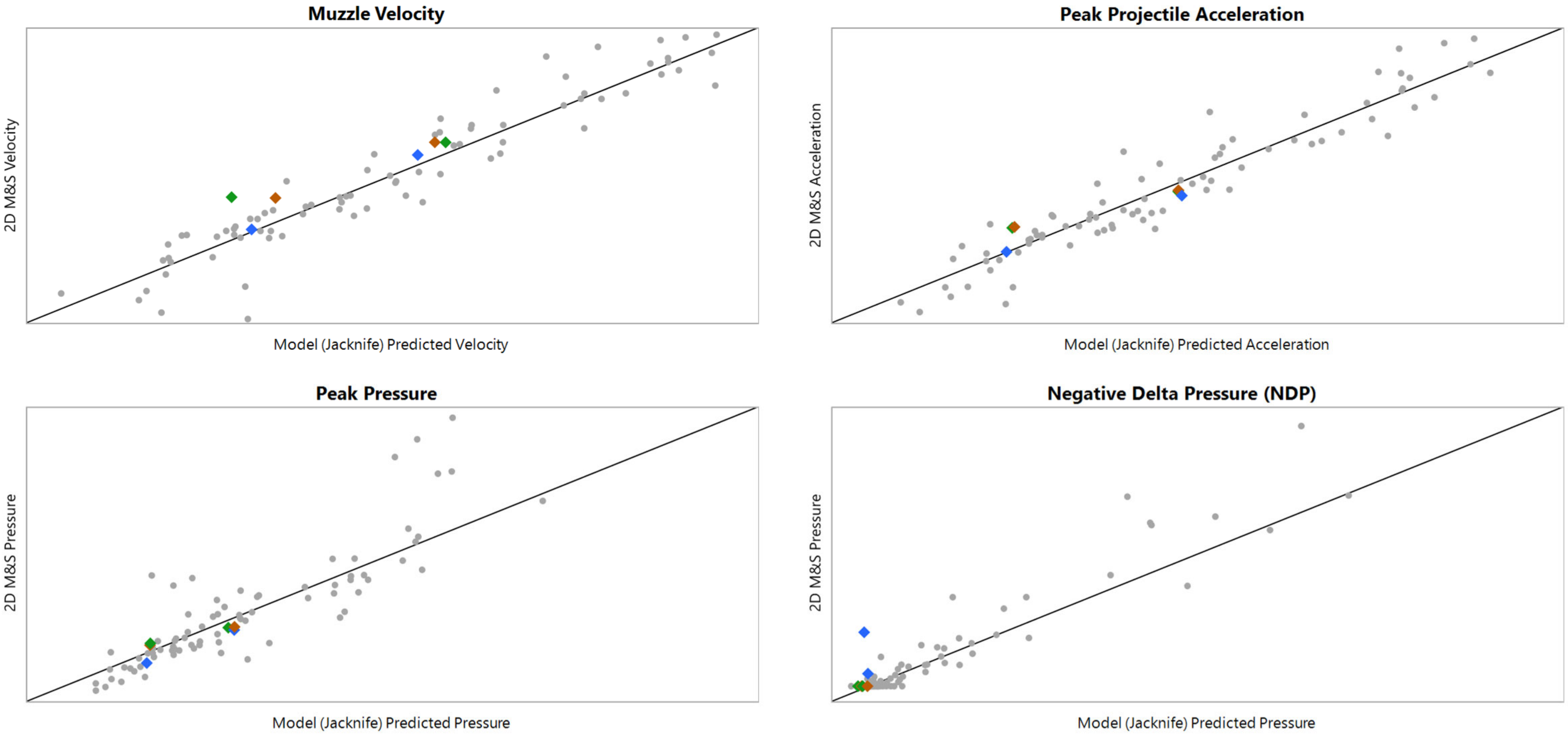






PHASE 2: RESULTS

Optimized Configuration Predictions



LESSONS LEARNED

- **Planning an interdisciplinary effort takes time**
- **Open lines of communication between/within disciplines is critical**
- **When in doubt include a variable!**
- **When working with domain experts new to these strategies, get into the weeds with test planning and execution**
  - When multiple lots of subcomponents need to be used, randomize!
  - Support the test if questions come up along the way to be able to advise with best practice
- **Replacing nominal DOE levels with real-world measurements may improve prediction accuracy**
- **Strip out configuration identifiers from “build sheets” for technicians**
  - They are very skilled at making their work more efficient (this is bad for randomization!)
- **Budget time for after the models are fit to make good use of them**
  - Multiple responses and goals make the optimization process more involved
  - The entire team should be working together on this step

IMPACT & FUTURE WORK

- **Good news story, well received at all levels**
- **Optimal propulsion charge likened to finding a "needle in a haystack"**
- **Expecting follow on basic research and applied research efforts using methodologies described herein**
  - Within gun propulsion domain
  - Between domains within system boundary (i.e., trade study level analyses)