Tires

A Design of Experiments (DOE) Case Study

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Overview

- What's the problem?
- What's the solution?
  - Start with the problem
  - Plan to explicitly achieve goals with efficiency and added value
- How can I do that?

Ken Johnson

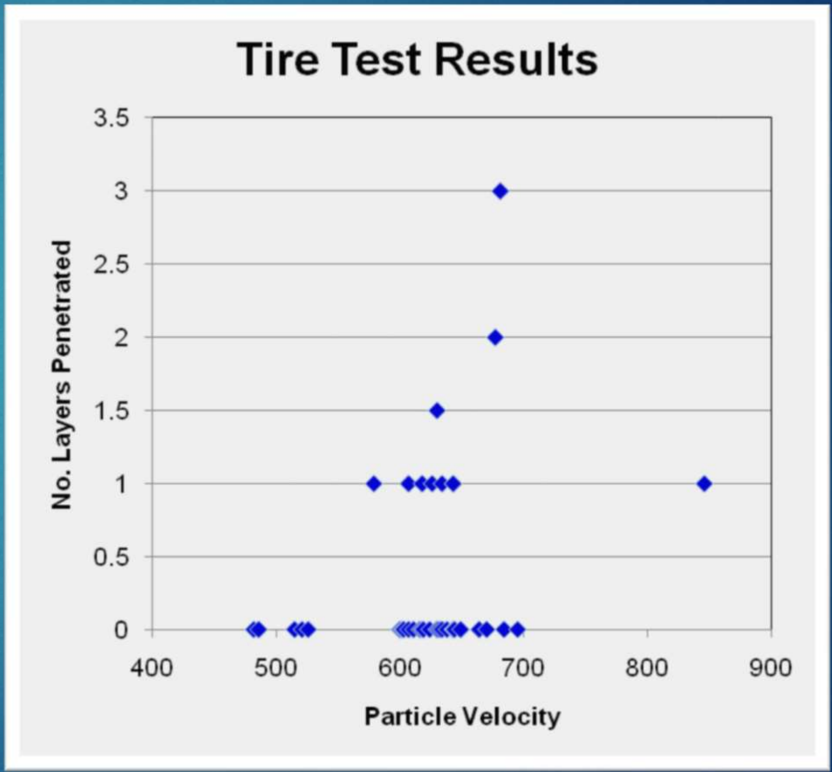
- Statistical Engineer
  - NASA Engineering and Safety Center (NESC)
    - NESC Integration Office (NIO)
  - Lead, NASA Statistical Engineering Team (NSET)
  - Core member, Systems Engineering Technical Discipline Team
- Specialties
  - Design of experiments (DOE), variation reduction, process control and optimization, general and **forensic statistics**
- Education
  - MS Operations Research, Univ. of AL Huntsville (applied stats)
  - Chemistry, business
- Experience
  - NESC (Civil Service) since 2006
  - MSFC S&MA (contractor) from 2001
  - Industrial coatings/ aluminum and steel coil coating/ urethane foam production
    - Management – quality control and improvement projects – product design – field customer service

Is this a NASA Problem?

- **NO!**
  - Typical in industry, academia, government
  - Typical in science, business, economics, politics, engineering
- Because efficient methods for conducting experiments
  - … are not taught in universities, colleges, high schools and grade schools and …
  - … are often actively discouraged in education and culture
  - … so less-efficient methods are very, very common
- … but yes
  - (sigh)
- You don't hear others present this type of study more often because non-government examples tend to be hidden
  - NASA's mission is advancement
  - **We want to help you advance**

Original Test Data

- A Project test owner presented data to a small group of NESC analysts that he couldn't make sense of
  - Wanted to know the 95% confidence minimum velocity that would puncture 3 ribbed tire plies, considering this test data
  - "Too variable"
  - Needed analysis **immediately**



The Data

- Test series was **not planned**
  - Parameter changes decided in real time (“**Let’s try this …**”)
- Responses **not analyzable** using quantitative methods
  - **What are the responses?**
  - **What are the factors?**

Primary Response

Responses & Inputs

Tire No	Layers Penetrated	Date	Speed ft/ sec	Projectile Press psi	Tire Orientation	Notes
1	0	20-Jun	482	79	Center	Scuff on ribs 2, 3 & 4
1	0	20-Jun	486	80	Rotated Right	Lighter scuffs on ribs 2 and 4, with deeper scuff on rib 3
1	0	20-Jun	515	84	Rotated Left	
1	0	20-Jun	526	83	Rotated Right	single scuff/gouge
1	0	20-Jun	521	83	Center	Scuff and gouge
1	0	20-Jun	600	96	Rotated Right	
2	0	21-Jun	602	96	Rotated Left	Projectile hit part and rolled up. Ding below ribs, scuff on rib 1, light scratch on rib 2
2	0	21-Jun	616	96	Rotated Left	Backside of projectile hit target (smiling), ding on rib 7, slightly deeper ding on rib 8
2	0	21-Jun	607	96	Rotated Right	Edge backside of projectile impacted. Scuff on rib 2, light ding on rib 6 and deeper ding on rib 7
3	1	21-Jun	846	139	Rotated Right	Fragment impacted and peeled up a single layer of the material
3	1	24-Jun	579	94	Rotated Right	Backside of projectile tip dragged across rib 1 and gouged rib 2. Only 1st layer of material appears breached
3	0	24-Jun	695	109	Center	Backside of projectile slid over tire and ribs 1 & 2. Missed rest of structure and hit aft peeling material up
3	0	24-Jun	664	107	Center	Backside of projectile tip slid across ribs 3 & 4 and impacted rib 5, leaving a scuff/gouge
3	0	24-Jun	643	108	Rotated Slight Left	Projectile hit tire and turned horizontal and dinged ribs 6 & 7
3	2	24-Jun	677	109	Rotated Left	Projectile scratched tire, then rotated into ribs 6 & 7 with worst case impact angle (or very close to). Damage on rib 6 Appears to breach the 1st and 2nd material layers, but not the 3rd
4	0	24-Jun	670	109	Center	Projectile hit at a frown on ribs 10 and 11
4	0	24-Jun	649	109	Center	Projectile nicked tire and tumbled to create scuff/ding on rib 6
4	0	25-Jun	611	100	Rotated Right	Projectile hit edge of tire, rotated to hit tire area leaving a small ding, and jumped over the structure
4	0	25-Jun	619	100	Rotated Right	Projectile hit tire area, rotated and hit ribs 3 and 4 leaving smaller dings
	0	25-Jun	618	100	Rotated Right	Tip of projectile scratched tire, rotating projectile to a smile, back edge of smile puts scuff on rib 3
	0	25-Jun	603	100	Rotated Right	Projectile hit as frown, dings on ribs 4, 5 and 6, with 4 being a little deeper than the others

The Data, cont'd (~40 Trials Total)

- **This is an analyst's nightmare.**

Tire No	Layers Penetrated	Date	Speed ft/ sec	Projectile Press psi	Tire Orientation	Notes
4	0	25-Jun	684	109	Center	Projectile hit tire area with tip, projectile tumbled across the structure
4	3	25-Jun	681	109	Center	Projectile hit rib 2, leaving a ding, rotated up and left a gouge that breached all 3 layers of material on rib 8
4	1-2	25-Jun	630	100	Rotated Right	Projectile hit the edge of the tire (in IRE-07g gouge) and rotated up impacting rib 1. Appears 1st layer of material breached, possibly 2nd, definitely not 3rd.
	0	25-Jun	638	100	Rotated Right	Projectile hit the edge of the tire, rotated to hit tire
	0	25-Jun	634	100	Rotated Right	Tip of projectile dragged across ribs 3 and 4, leaving smaller dings. Projectile then rotated to hit rib 9, leaving a larger gouge, no obvious breach of 1st material layer
	1	26-Jun	643	100	Rotated Right	Projectile rolled up the structure, leaving dings on ribs 4 and 5, and a gouge on rib 8 with a small breach in the first layer of material
	1	26-Jun	626	100	Center	Projectile tip nicked the tire, dinged rib 1 and gouged rib 2 leaving a pin hole breach in the first material layer
	1	26-Jun	643	100	Center	Tip edge of the projectile impacted rib 3 peeling the 1st layer of material with breach. Appears limited to 1st layer. Small scratches on ribs 4 & 5, and backside of projectile scuffed rib 6
	0	26-Jun	630	100	Rotated Left	Tip of projectile scratched the tire
	1	26-Jun	634	100	Rotated Left	Front edge of projectile hit rib 6 leaving a deeper gouge, unable to tell if first layer breached, and hit rib 7, breaking through the first layer of material, scuffing the second layer, but not breaching
	0	26-Jun	632	100	Rotated Right	Projectile's tip impacted and scratched the tire, the projectile rotated and dinged rib 10
	0	26-Jun	624	100	Rotated Right	Projectile scratched tire, no structure impact
	1	26-Jun	618	100	Rotated Right	Projectile dinged rib 2, and gouged rib 5 peeling back the first layer of material, second layer does not appear to be breached
	0	26-Jun	644	100	Rotated Right	Tip of projectile dinged/scuffed ribs 2 and 3
	0	26-Jun	643	100	Rotated slight right	Tip of projectile scratched the tire, rotated the projectile and put a ding on rib 10
	0	26-Jun	602	100	Center	Edge of projectile scuffed ribs 2 & 3
	1	26-Jun	607	100	Slight left	Edges of projectile impacted ribs 5 & 6, removing the first layer of material in both locations
	0	26-Jun	643	100	Rotated Left	Projectile left a scratch on the tire and a light impression/scuff on rib 8
	0	26-Jun	630	100	Rotated Left	Projectile tip left a scratch on tire, no structure impact

Failure to Plan is a Plan for Failure

- Three (**3!**) applied stats SMEs applied to the task
  - Data proved completely inscrutable
    - … Even using data mining techniques

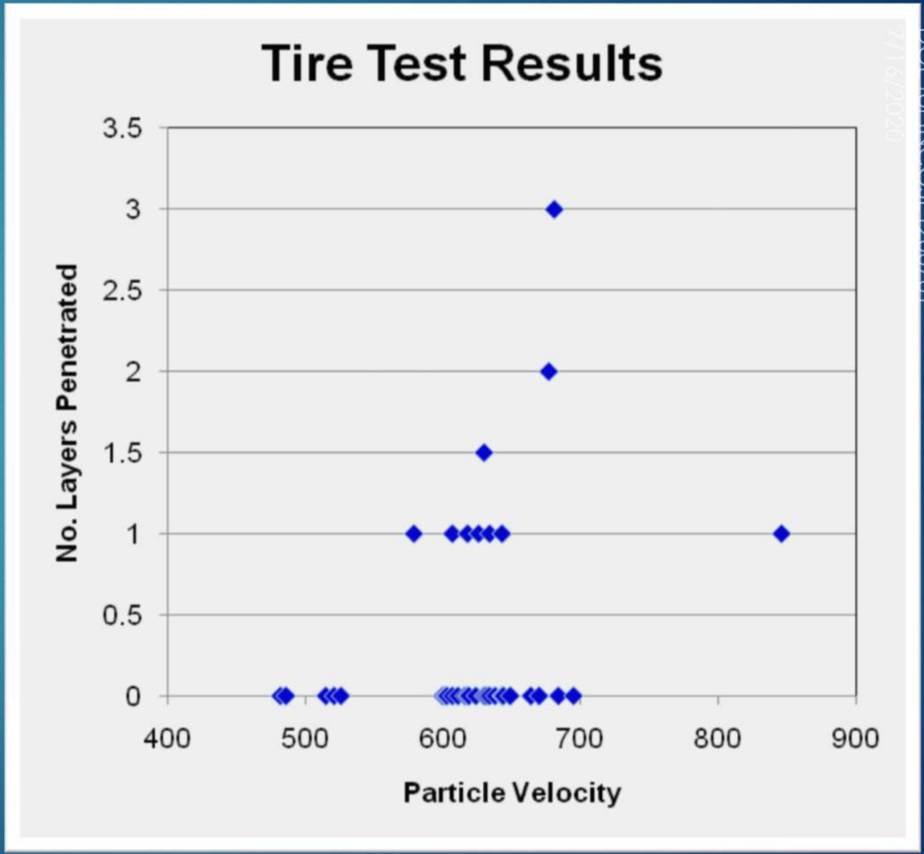
Last resort!

- <u>First act:</u> tried to negotiate
  - Run more trials?
    - Test team offered three more trials – not nearly enough to fix problems
  - Can response data be defined/ remeasured with higher fidelity?
    - **"No."**
- <u>Second act:</u> tried to tell the Program the data was unanalyzable
  - Not acceptable, even though true
- <u>Third act:</u> worked over a weekend to come up with a bound using engineering judgment
  - Conservatism believed adequate

Resort AFTER the last resort!

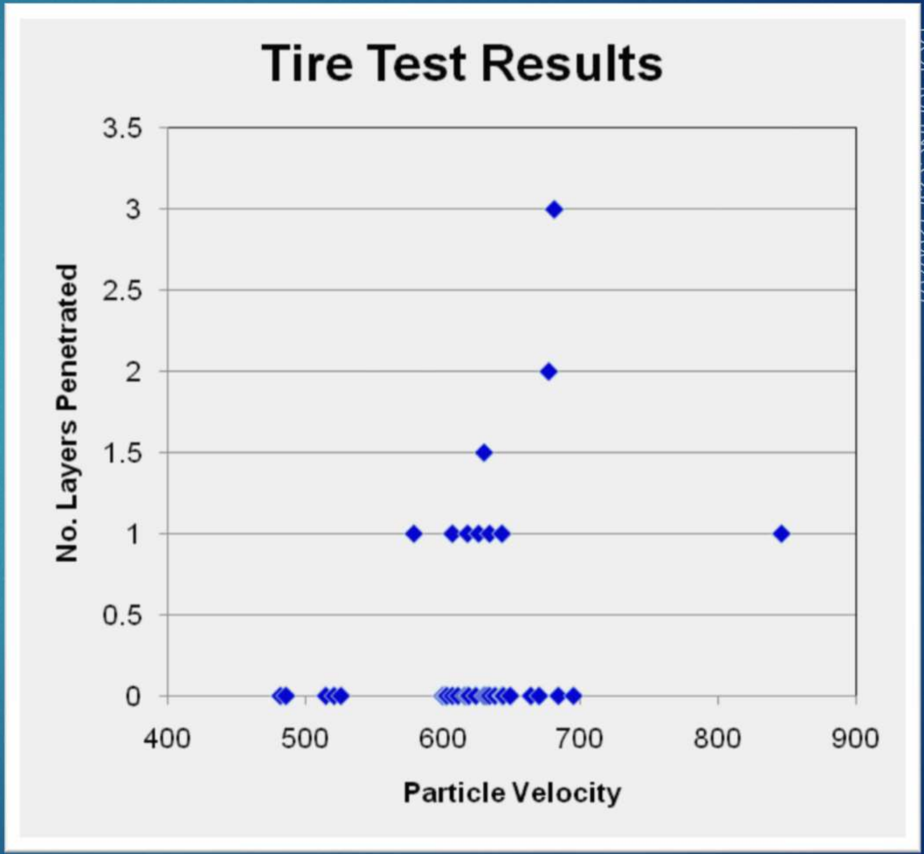
Problems that Doomed Analysis

- Response variable
  - Poor resolution
    - Very rough measurement (plies) **decreased signal and added noise**
  - Censored data
    - Particles that go completely through all three plies get a "3"
    - **Decreased signal**
- Input factors
  - Impossible to include effects of parameter changes in analysis
  - … so effects of inputs remain in the data as **noises and biases**



Other Issues

- Trials focused on region of interest, but not enough output variability within this region to be able to cut through variability
- Test matrix **added noises**
  - Inputs confounded, correlated, unbalanced and poorly measured
- Lack of randomization/ blocking; no time series data supplied
  - **Rogue factors** could have affected data



Other Issues

- Not all information supplied to analysts at outset
  - Analysts expected to work without much knowledge of the data and its etiology
  - Some information and data missing from original data dump
  - Had to play “20 questions”, chase after test owner
- Overall inefficient use of time, dollars and other resources

Act 4

- Test planning/ DOE SMEs asked to be included **immediately** in planning a similar experiment

45-Minute Meeting with Task Lead

- **Statement of Problem: what is the minimum velocity required to cause a failure**, with 50% and 95% confidence?
  - Estimate **impact depth** as a **function** of **velocity** and **orientation**
  - **Failure** is defined by a through depth penetration of (TBA) microinches
- **Negotiated agreements**
  - Factor levels locked
    - **No more changes on the fly!**
    - Questions? ASK – renegotiate -
  - Balanced test matrix
  - Randomization of trials' order of performance
  - Follow-on testing may be required and/or desirable
    - Sequence of tests instead of one-and-done

Thanks to Pete Parker, PhD, NASA/ LaRC

SE Approach to Conducting a Test

- **Only solve only the problem**: leave out unneeded cost/ complexity
  - Experimental setup used a flat 2-ply test article impacted at 90°
- Response
  - Through thickness penetration depth, microinches
    - Precision adequate to achieve goals
- Factors
  - Velocity of the projectile ranging from 500 to 1200 ft/sec
    - **Previous testing** shows 50% failure rate in the range of 800-860 ft/sec (Build on existing knowledge)
  - Projectile Orientation
    - **First experiment**: only KE and Flat (believed to bound the worst and best case for inducing failure)
- DOE SME used **standard software** to plan test matrix

One Hour Later: a Test Matrix

- Summary of design and execution protocol
  - 5 equally spaced levels of velocity
  - 2 levels of orientation
  - **Replication** at the mid-point (3 reps) and extremes (2 reps at each) of the velocity space for each orientation to estimate the experimental error and detect if it is a function of velocity and/or orientation
  - Execute in the completely **randomized** run-order supplied
  - If it requires more than a day to execute, the design should be blocked (*renegotiation*)
  - Set point levels of velocity do not need to be exact if they are measured (*record this information*)
  - Consecutive identical factor settings should be reset between runs
  - Record time and date information

Specified Run Order	$Velocity_{goal}$ ft/sec	Orienta-tion	Impact Depth in
1	500	Flat	
2	1200	KE	
3	500	KE	
4	850	Flat	
5	850	KE	
6	850	KE	
7	1200	KE	
8	850	Flat	
9	1200	Flat	
10	850	Flat	
11	500	KE	
12	1200	Flat	
13	500	Flat	
14	1025	Flat	
15	675	KE	
16	675	Flat	
17	1025	KE	
18	850	KE	

18 trials

Analysis **Plan**

- Don't read this. It's math.
- Bottom line: Analysis was …
  - Pre-planned
  - Used standard methods
  - **Straightforward**

- Model estimated from experimental data

$$d = f(v,z) + \varepsilon$$
$$d = \beta_0 + \beta_1 v + \beta_2 z + \beta_3 zv + \varepsilon$$

- This model allows for prediction of impact depth as a function of velocity for both orientations
- Five levels of velocity allow this simple linear model to be extended to a cubic relationship, while still retaining some lack-of-fit degrees of freedom
- To answer the inverse question - What velocity causes a specified impact depth (equivalent to failure)? - we invert the relationship as follows:

$$\hat{v} = f(d,z)$$

- …where v-hat is the mean velocity given y (depth defined as failure)
- We can then estimate the 50% and 95% confidence intervals on v-hat

Imperfect Implementation Didn't Hurt Much

- Best-laid plans …
  - Randomized run order ignored
    - Independence not fully achieved: important assumption couldn't be assessed
  - Unplanned factor added by test engineers
    - Caught before it became a problem
  - Ended test early without consulting test design SMEs
    - Didn't hurt this time (we don't think)
- The DOE planning and analysis process is **robust** enough to these flaws to have produced valuable information

Specified Run Order	Actual Run Order	$Velocity_{goal}$ ft/sec	$Velocity_{act.}$ ft/sec	Orienta-tion	Impact Depth in
5	1	850	851	KE	0.082
6	2	850	839	KE	0.080
18	3	850	818	KE	0.085
8	4	850	829	Flat	0.012
14	5	1025	1045	Flat	0.023
9	6	1200	1194	Flat	0.032
12	7	1200	1190	Flat	0.024
1	8	500	466	Flat	Missing
13	9	500	487	Flat	0.014
16	10	675	668	Flat	0.015
4	11	850	838	Flat	0.023
10	12	850	844	Flat	0.021
2	13	1200	1186	KE	0.122
7	14	1200	1192	KE	Missing
17	15	1025	1020	KE	0.095
15	16	675	671	KE	0.055
3	17	500	472	KE	0.032
11	18	500	482	KE	Missing

Results Summary

- Delivered **< 4 hours** after data confirmed
- Analysis results based on nearly complete test (15 data points)
  - Effects of factors (speed, orientation) are linear and predictable within the range tested
  - Speed is a significant predictor of depth of impact damage for both flat and knife-edge particle orientation
  - Significant difference found between damage caused by flat and knife-edge orientation of particle at a given speed
  - Knife-edge particles depth of damage increases significantly faster with speed than flat particles (interaction)
  - One complete puncture (1200 fpm, knife-edge orientation)

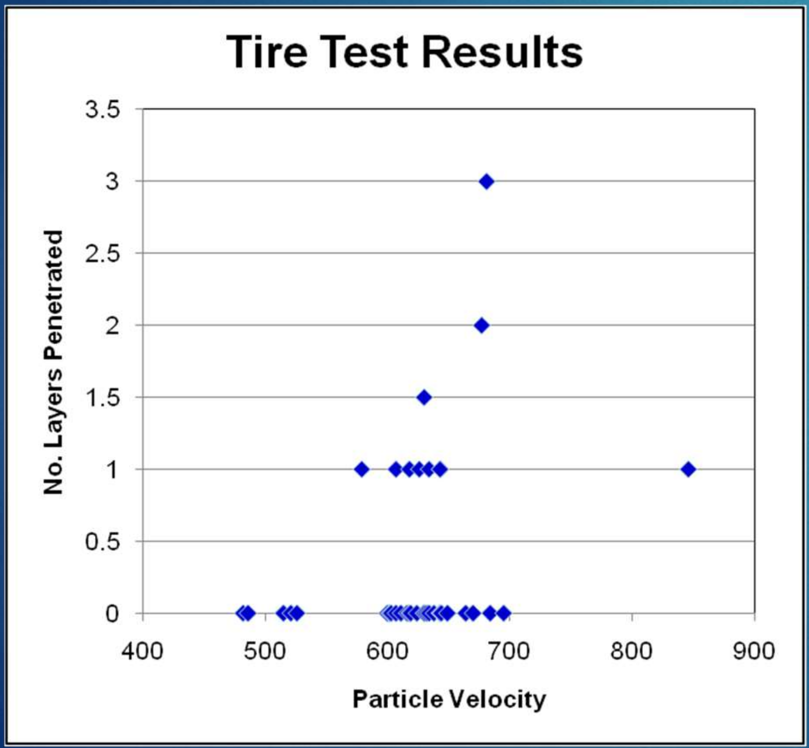
Calculator Supplied to Customer

Inverse Prediction of Velocity Given Impact Depth				
Orientation	KE			
Impact Depth	0.080	inches	**<- input depth to failure**	
Predicted Velocity	847	ft/sec		
Velocity Confidence Intervals (ft/sec)		**Interval**	**Interval**	
	1/2 Int Width	**Low**	**High**	
Std Error in Pred Mean	16	831	863	
V50	12	835	859	50% CI
V95	42	805	889	95% CI
Velocity Prediction Intervals (ft/sec)		**Interval**	**Interval**	
	1/2 Int Width	**Low**	**High**	
Std Error in Pred Individual	46	801	893	
V50	33	814	880	50% PI
V95	118	729	965	95% PI

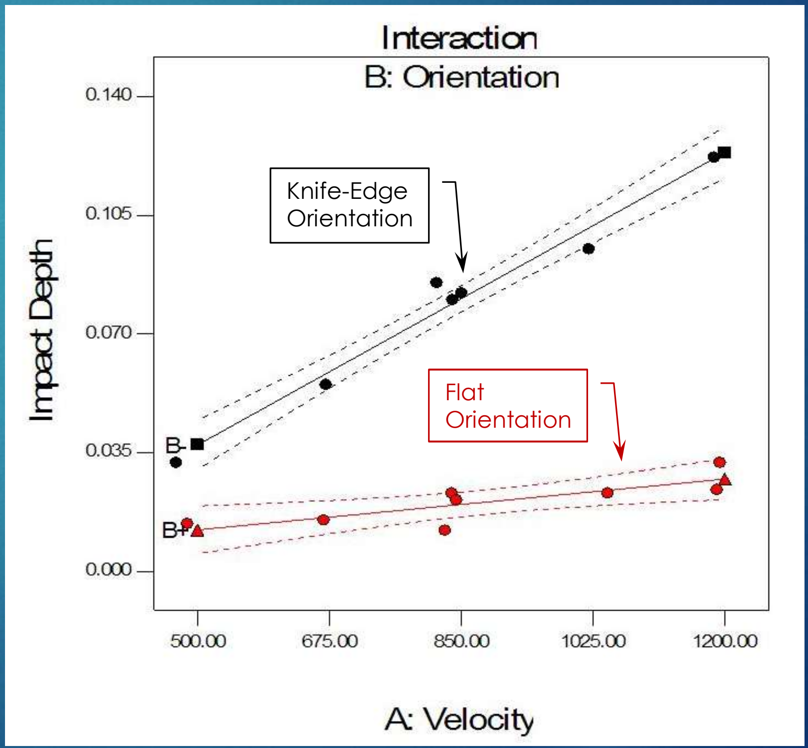
- **Delivered to customer:**
  - Graph of results; story (left)
  - Calculator
    - Gives prediction limits for knife-edge case
    - Blue: inputs
    - Yellow: outputs (predictions)

Improved Clarity, Value of Information

Results of Test Designed On the Fly (Let's Try …)



Results of Test Planned with Help from a Test Design SME



Summary

- Original "Let's Try" test did not answer the question
  - **40** runs
- Efficiently designed experiment did
  - **15** runs
  - Lower cost, smaller schedule, less drain on SMEs
  - **Clear link between inputs and response**
  - High engineering and management value of the information gained
  - **Learned something**

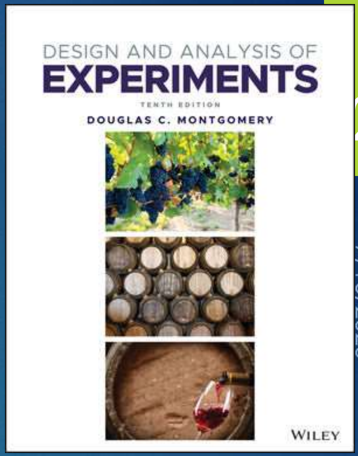
How You Can Do This

Bottom line:

- **Learn**
- **Get help**
- **DO IT**

Hands-on is
CRITICAL,
VITAL
and
ALL-IMPORTANT

How You Can Do This: **Learn**



Good

- Take a class offered by a highly-rated teacher tuned to your needs
  - Maybe e.g. a UHouston professor who will do a class aimed at petrochem at your plant
  - Presenter has a short list of consultants who adapt DOE classes kenneth.l.johnson@nasa.gov
- Classes at accredited colleges, universities
  - UHD, UHouston, Rice
  - Distance learning: MIT, Old Dominion, Univ. of Alabama in Hsv …
  - Math and stats prerequisites typical

Works

- Learn from a mentor
  - *You'll want to know more*
- American Society for Quality (ASQ) and other organizations
  - Tends to be generic, not hands-on; but good
- Read a book
  - Montgomery: Design and Analysis of Experiments
- Online classes and software vendors
  - Caveat emptor!

NASA: contact me or Tim Brady

How You Can Do This

Get Help

- Easy-ish … but a lot of tricks
  - Basic experimental designs straightforward, but not all problems are basic
  - Number of moving parts daunting at first
  - Requires statistical thinking
- **Get a mentor**
- Use software
  - **Design Expert** purpose-built DOE software (phenomenal)
  - Minitab, JMP, …

DO IT

- Practice makes better and better
- Geek around with the software
  - Try their examples
- Design an experiment at home
  - Popcorn, cookies, beer …
- Design an experiment with your **mentor**
- … and then another one
- … and then another one …

Thank You

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Data Mining

- Definition: finding patterns in found data
  - Dependent variables (factors) correlated, even completely confounded
  - "Empty cells" – combinations of factors without observations
  - Many effects, particularly interactions between factors, not analyzable
  - Must make assumptions to draw conclusions
  - *Not typically sufficient to prove causality*

What Is a Statistical Engineer?

- **Engineers**, as practitioners of engineering, are professionals who invent, design, analyze, build and test machines, complex systems, structures, gadgets and materials to fulfill functional objectives and requirements while considering the limitations imposed by practicality, regulation, safety and cost.
  - A professional engineer is competent by virtue of his/her fundamental education and training to apply the scientific method and outlook to the analysis and solution of engineering problems.
  - S/he is able to assume personal responsibility for the development and application of engineering science and knowledge, notably in research, design, construction, manufacturing, superintending, managing and in the education of the engineer.
  - Her/his work is predominantly intellectual and varied and not of a routine mental or physical character.
  - It requires the exercise of original thought and judgement and the ability to supervise the technical and administrative work of others.
  - His/her education and training will have been such that s/he will have acquired a broad and general appreciation of the engineering sciences as well as thorough insight into the special features of his/her own branch.

Yeah, yeah. Whatever.

https://en.wikipedia.org/wiki/Engineer, including an excerpt from a definition by the 1961 Conference of Engineering Societies of Western Europe and the United States of America.

What's StatEng?

- The process of **utilizing** knowledge and principles to design, build, and analyze (stuff).

- http://www.businessdictionary.com/definition/engineering.html