Six-Sigma Implications of Particulate Mass Measurement at a Milligram per Mile

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Assessment Overview for
6σ Particulate Measurement Capability

Consumer Driven
6-Sigma

AVL

Black Belts:	**Dan Meyer, Colin Chisholm** (advisor)
Project Leader:	**Bill Silvis**
Project Champions:	**Jimmy Williamson / Siegfried Roeck**
Master Black Belt:	**none**
Management:	**Sean Egmon / Rick Karaschin**
Additional Team Members:	**John Bushkuhl**
Financial Analyst:	**Jennifer Foulk**
Organization:	**AVL TSI (CAPS)**
Close Date:	**December 31, 2015**

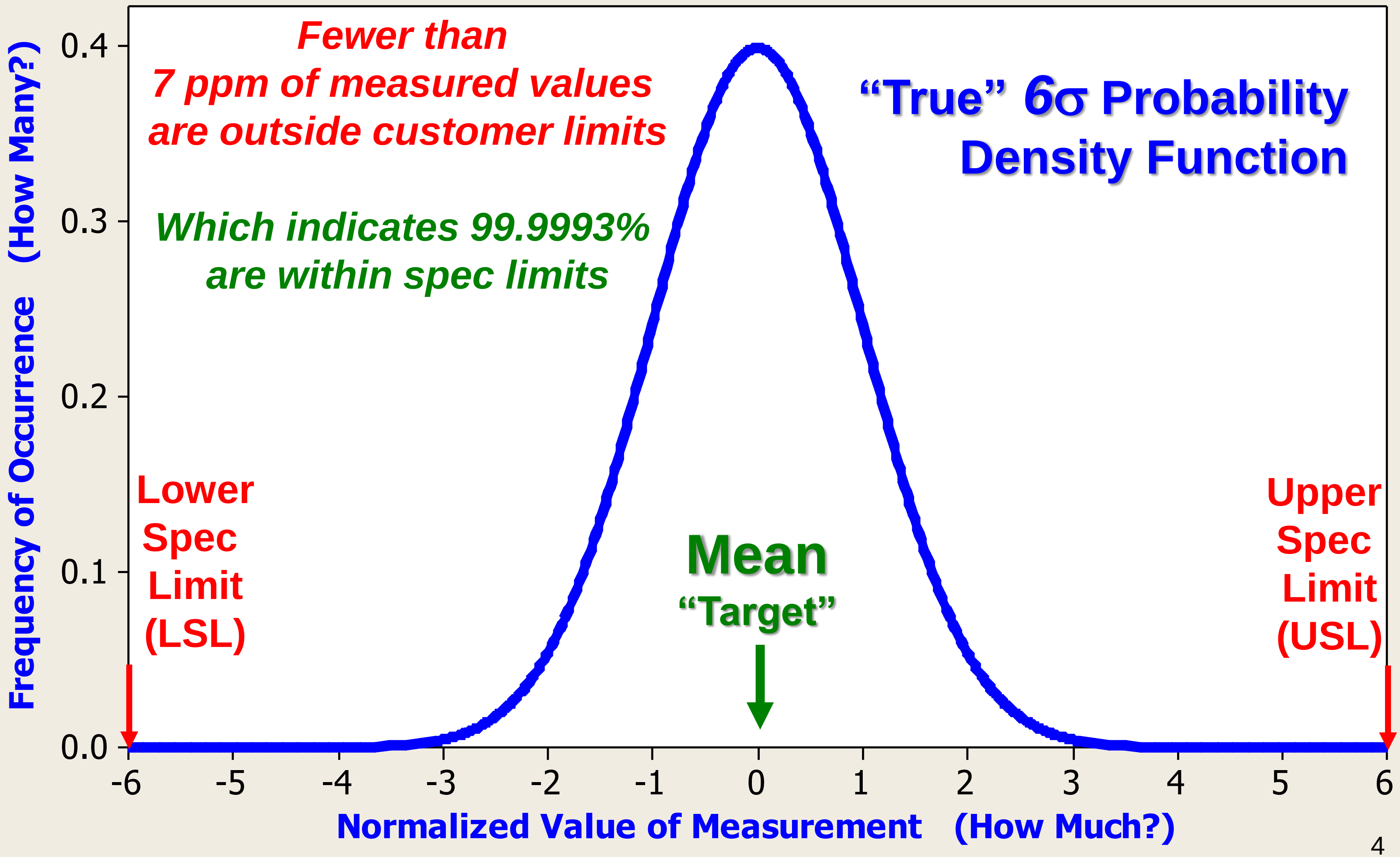
Engineering & Business Methodology to:

1. Improve quality of products and services.
2. Assess and minimize variation.
3. Deliberately search to identify defects.
   (Defect defined as any customer dis-satisfier.)
4. Attempt to drive all defects to zero.
   (True Six-Sigma process is 99.9993% defect free.)
5. Estimate value of reducing defects.

Reference: Anthony, Jiju, *"Pros and Cons of Six Sigma: An Academic Perspective," May 1, 2008

Six-Sigma Performance – a closer look

"Standard Normal," Gaussian Distribution



Particulate DEFECT or Failure Mode Definition:

Measured values that are outside target tolerance range.

Scope of Analysis:

- *Process Capability*
- *Resolution*

Investigate & Identify Improvements required for:

- *True Six-Sigma tolerance*
- *Reliable measurements of low-level PM (~1mg/mile)*

Challenges:

1. *No particulate reference standard currently exists.*
2. *Normal measurement system analysis might not apply.*
3. *Particulate constituents, i.e. variables have not been isolated.*

Actual PM **Vehicle Data** FTP Phase 3

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D M A I C

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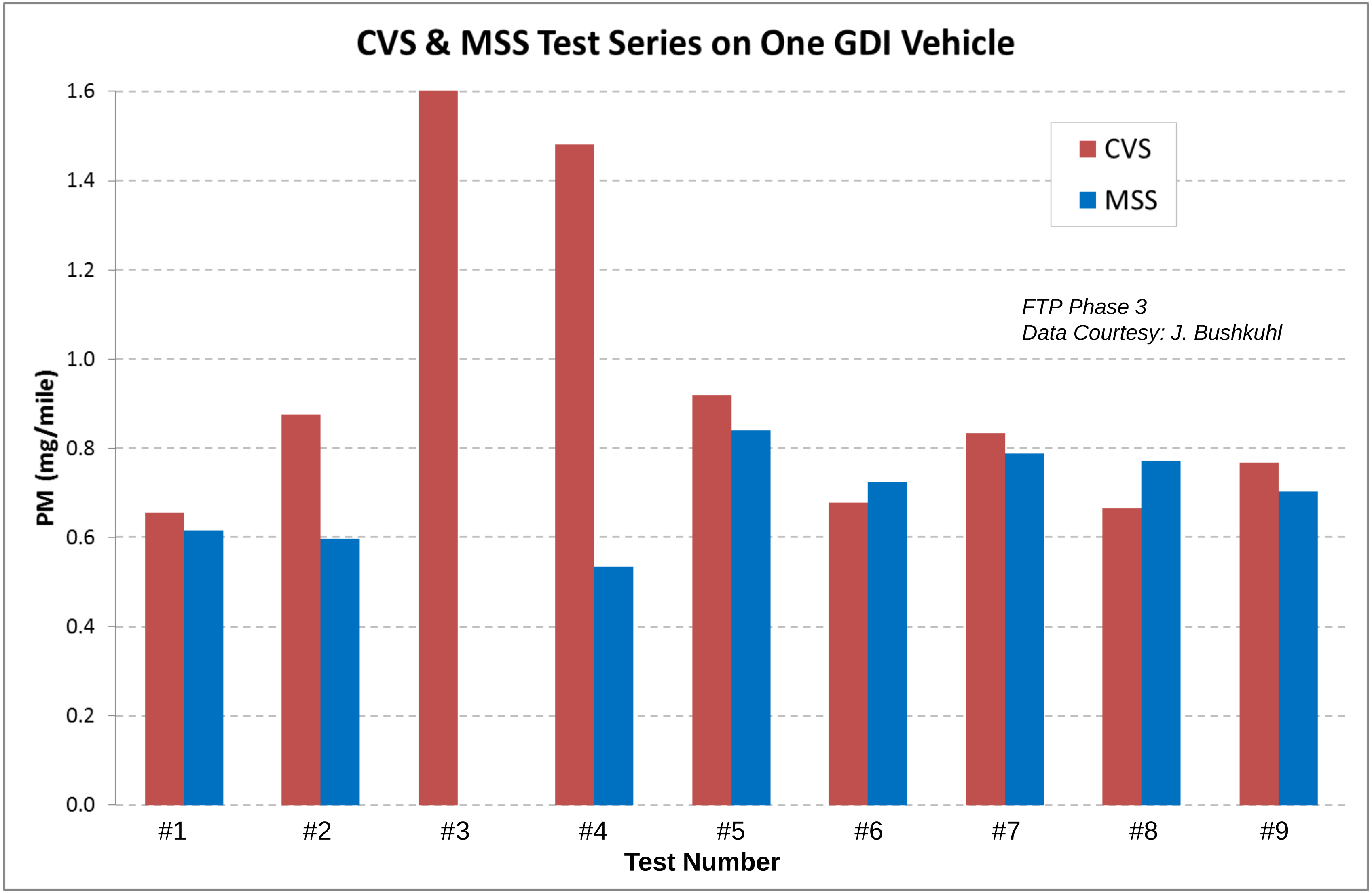
1. Particulate levels at or near 1 mg / mile *AND*
2. At least 8 sample runs for each measuring device



Vehicle **Particulate Mass** Emissions Statistics – **CVS** Phase 3

D – M – A – I – C

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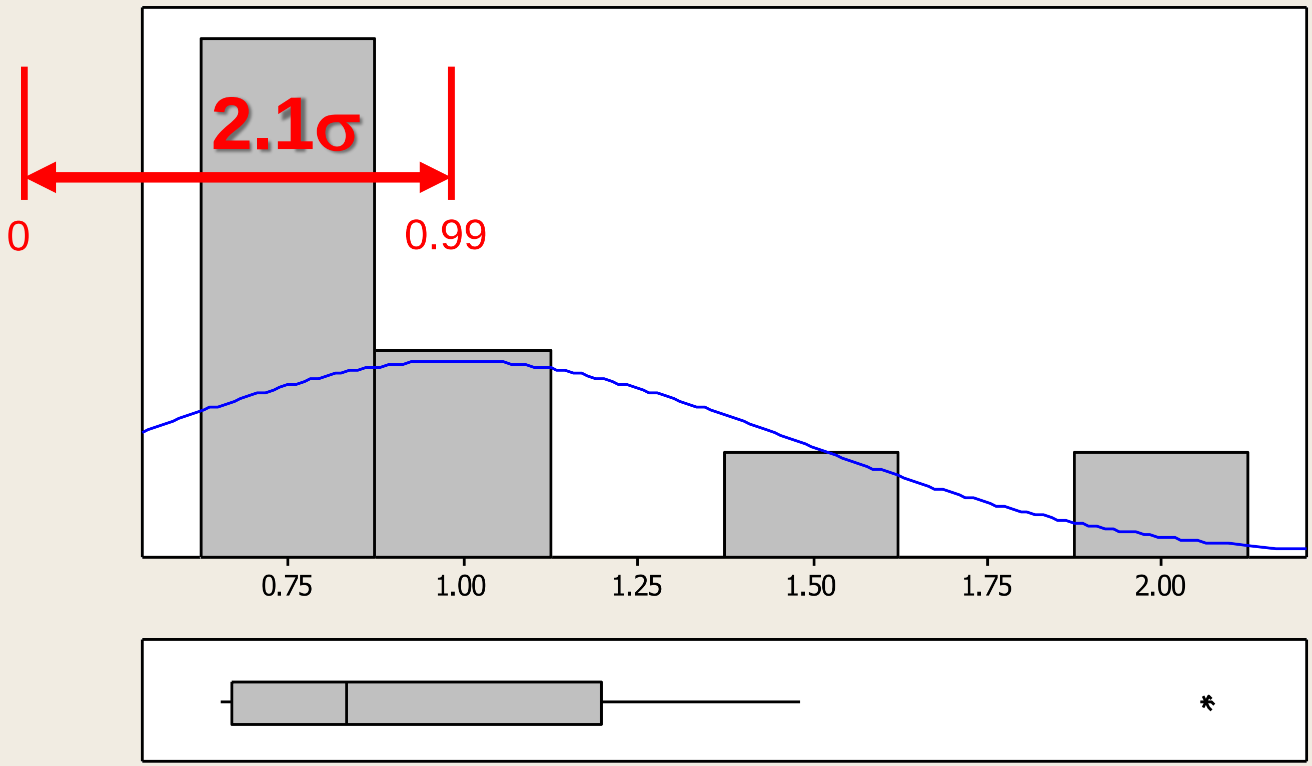
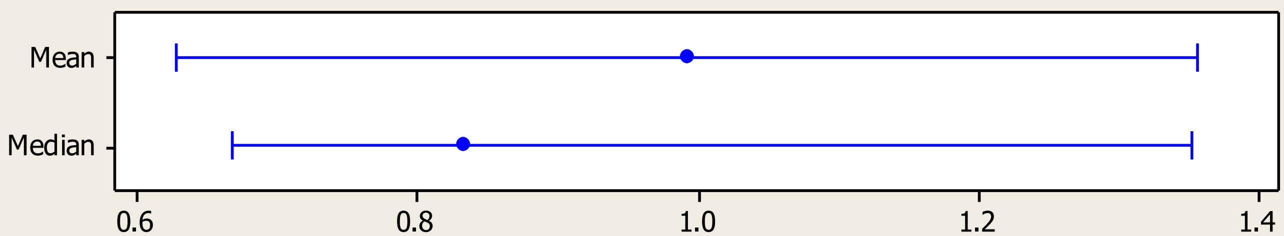
Summary: CVS - Phase 3

Only 2.1σ from Zero to Mean



95% Confidence Intervals



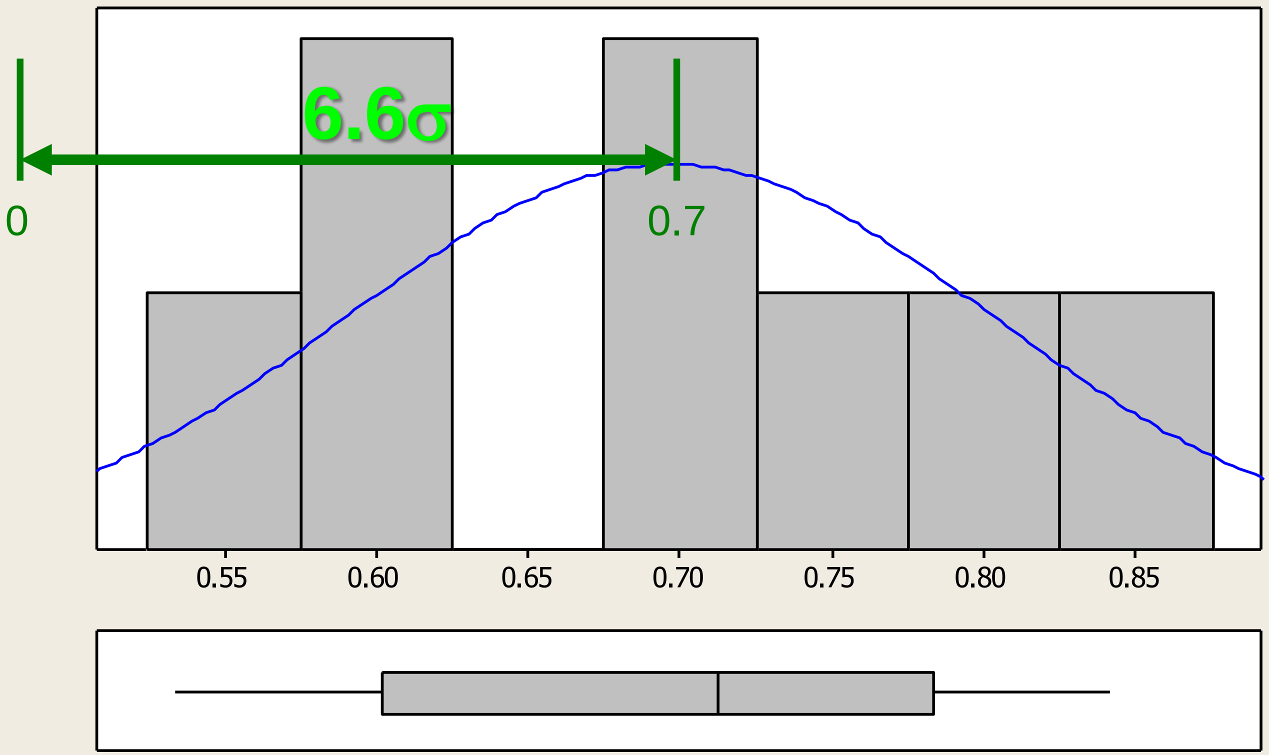
Fails Normality Test?

Anderson-Darling Normality Test	
A-Squared	1.06
P-Value <	0.005
Mean	0.99282
StDev	0.47430
Variance	0.22496
Skewness	1.83443
Kurtosis	2.86124
N	9
Minimum	0.65535
1st Quartile	0.67110
Median	0.83352
3rd Quartile	1.19996
Maximum	2.06254
95% Confidence Interval for Mean	
0.62824	1.35740
95% Confidence Interval for Median	
0.66794	1.35303
95% Confidence Interval for StDev	
0.32037	0.90864

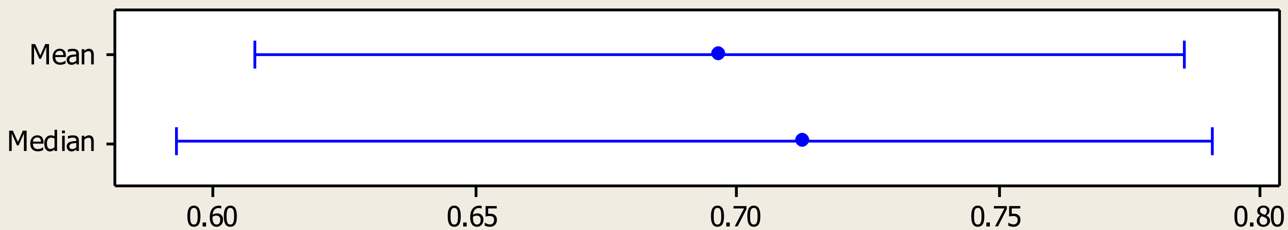
Raw Data Courtesy: J. Bushkuhl
Minitab Data Analysis: D. Meyer

Summary: MSS - Phase 3

Over 6σ from Zero to Mean



95% Confidence Intervals

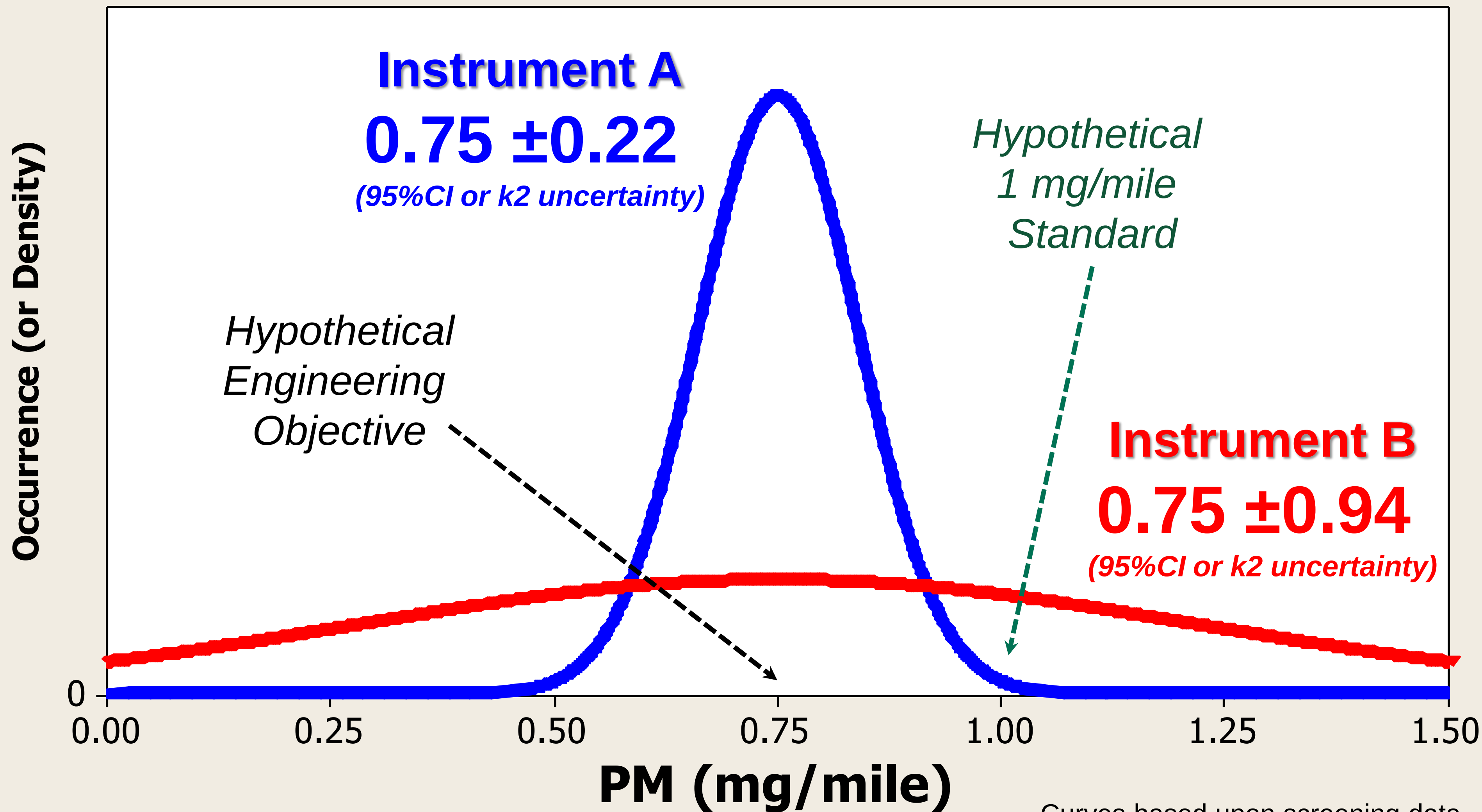


Anderson-Darling Normality Test	
A-Squared	0.21
P-Value	0.799
Mean	0.69662
StDev	0.10578
Variance	0.01119
Skewness	-0.26219
Kurtosis	-1.12987
N	8
Minimum	0.53373
1st Quartile	0.60201
Median	0.71275
3rd Quartile	0.78357
Maximum	0.84083
95% Confidence Interval for Mean	
0.60819	0.78505
95% Confidence Interval for Median	
0.59320	0.79084
95% Confidence Interval for StDev	
0.06994	0.21528

Raw Data Courtesy: J. Bushkuhl
Minitab Data Analysis: D. Meyer

Emissions Engineering-Objective Example

How can we be confident we are meeting the standard, in the fewest number of tests?



Curves based upon screening data.

Vehicle Data Prediction

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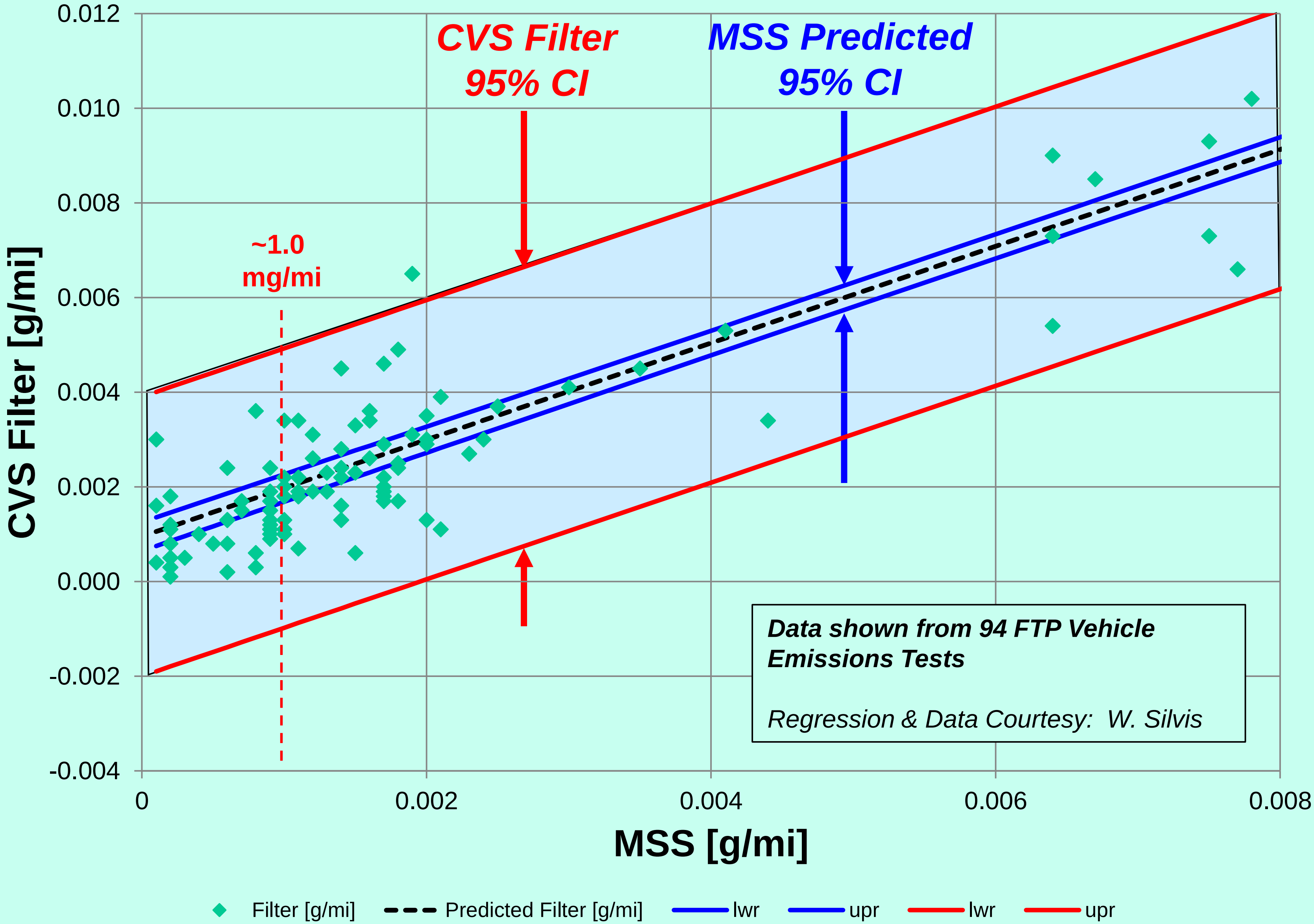
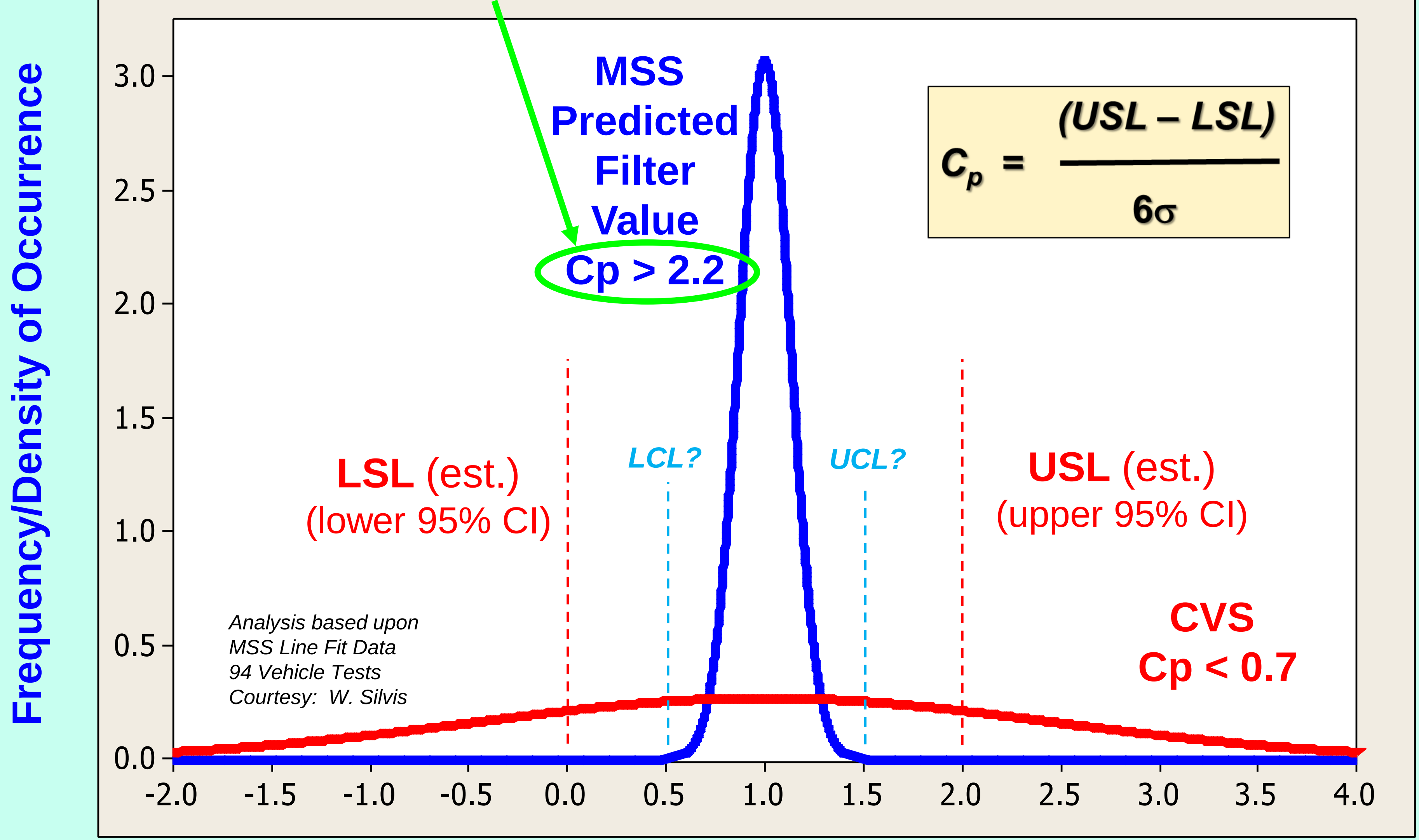
MSS [g/mi] - CVS Filter Prediction, Regression Line Fit of Vehicle Data



Copy of Regressions of MSS vs filter data_DLM.xlsx

***Cp** value greater than 2.0 indicates a true **6σ** capability at 1 mg/mi.*



Mean Value of Filter Data, mg/mile (CVS)

RESOLUTION: *(Standard Deviation dependent)*

What is the smallest DISCERNABLE DIFFERENCE between two actual measured values (or means) that can be reliably detected?

Why a measurement **RESOLUTION** requirement?

- Needed to quantify <u>accuracy</u> or "trueness"
- Influences the <u>lowest measurement</u> capability
- Impacts <u>sample size</u> for a given confidence

Power analysis is used to calculate the minimum sample size required so that one can be reasonably likely to detect an effect of a given size.

Minitab Power and Sample Size (CVS)

1-Sample t Test

Testing mean = null (versus not = null)
Calculating power for mean = null + difference
Alpha = 0.05 Assumed standard deviation = **0.474**

Difference	**Sample Size**	Target Power	Actual Power
0.25	$\boxed{31}$	0.8	0.810969

Power analysis is used to calculate the minimum sample size required so that one can be reasonably likely to detect an effect of a given size.

Minitab Power and Sample Size (MSS)

1-Sample t Test

Testing mean = null (versus not = null)
Calculating power for mean = null + difference
Alpha = 0.05 Assumed standard deviation = **0.11**

Difference	**Sample Size**	Target Power	Actual Power
0.25	**4**	0.8	0.844016

Projected Financial Benefits:

(Baseline CVS vs using MSS)

- **Tests required to evaluate:** *(@ 0.25 mg/mile diff. & 0.8 power)*
  - **31 tests vs 4 tests** *(1 regulatory emissions test = 1 "sample")*
- **Cost of testing to evaluate:** *($500/hr x 2 hr/test = $1000/test)*
  - **$31K vs $4K per powertrain evaluation**
  - **$6.2M vs $0.8M per year** *(200 lab evaluations per year*)*
- **Projected Annual Laboratory Savings: $5.4M**

*40 powertrains per year, 1 certification and 4 development evaluations per powertrain

**Approx. Capital Cost Comparison for Reference: PSS-$170K, MSS(Std)-$108K, both in addition to CVS HW

Thank you for your time and attention.