

# Cummins M11EGR Precision/BOI Matrix Analysis

Report to

M11EGR Task Force

August 9, 2001

# Significant Effects

- **Lab**
  - Crosshead Wear
  - Average Engine Sludge
  - Adjusting Screw Weight Loss
  - Rod Bearing Weight Loss
  - Average Wear Step
- **Base oil**
  - Crosshead Wear
- **Technology**
  - Rod Bearing Weight Loss
  - Average Wear Step
- **Base oil/Technology**
  - Oil Filter Differential Pressure
  - Average Engine Sludge

# Experimental design

Lab A		Lab B	Lab D	Lab G	
S1	S2	S1	S1	S1	S2
B	A	B <sup>a</sup>	C <sup>a</sup>	A	C <sup>b</sup>
E	E	D	D	E	E
E	E	E	E	E	E
F	J	J	H	F	G
G				H	

<sup>a</sup> Replaced oil filter due to low oil gallery pressure

<sup>b</sup> Terminated at 228 hrs. due to low oil gallery pressure (only included in OFDP analysis)

		Base stock		
		1	2	3
Technology	X	A	B	C
	Y	D	E	F
	Z	G	H	J
		Group II	Group II	Group I

# Crosshead Wear

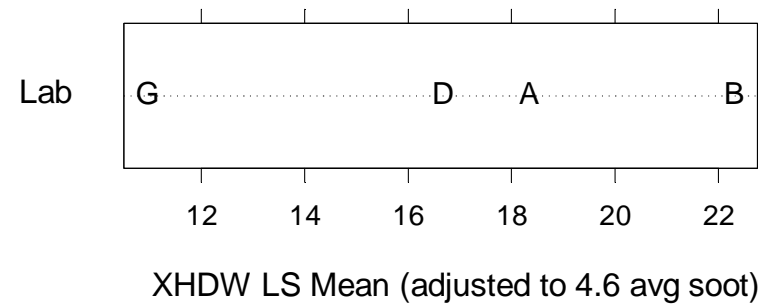
- Crosshead wear is transformed and adjusted to 4.6 average soot.

$$XHDW_{adj} = 10^{\log(XHDW) - 0.2575(avSoot - 4.6)}$$

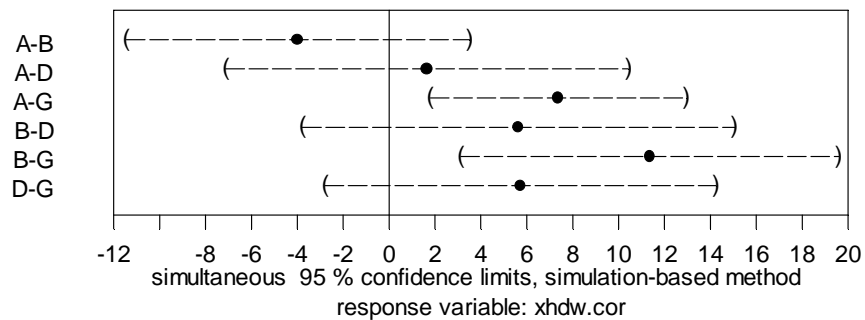
- Lab and base oil are significant
  - Lab G has lower wear than labs A and B
  - base oil 1 has lower wear than base oil 3
- RMSE = 3.7 (adj mg)
- $R^2 = 0.74$
- No highly influential observations

# Crosshead Wear (lab effect)

- Lab effect is due to Lab G having lower wear than Labs A and B



## Confidence intervals for lab differences



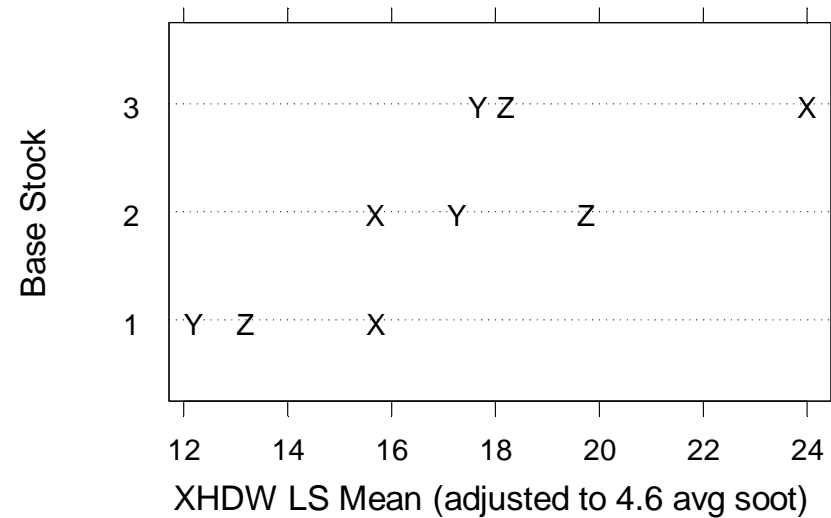
## Lab LS Means

Lab	A	B	D	G
LS Mean	18.3	22.3	16.7	11.0

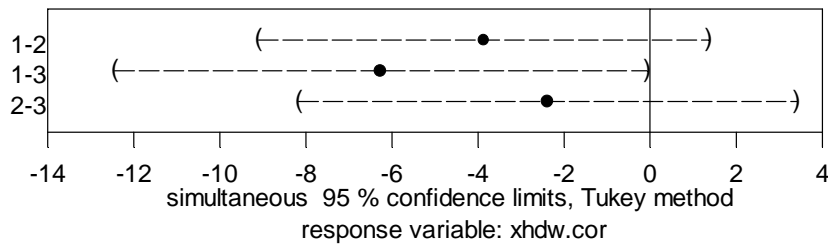
# Crosshead Wear

## (base oil effect)

- Base oil effect is due to lower wear in base oil 1 than in base oil 3



### Confidence intervals for base oil differences

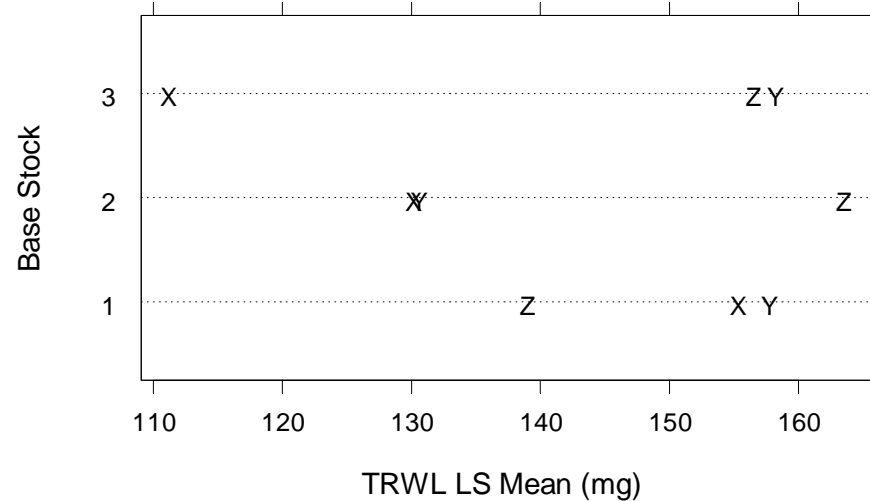


### Oil LS Means

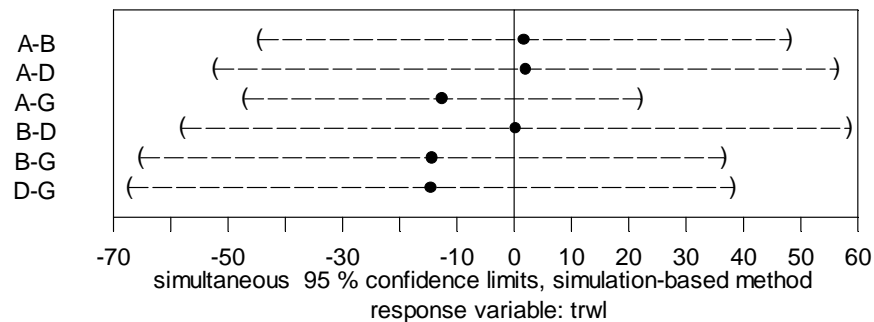
BS \ Tech	X	Y	Z
1	15.7	12.2	13.2
2	15.7	17.3	19.7
3	24.0	17.7	18.2

# Top Ring Weight Loss

- No significant effects
- No transform necessary
- RMSE = 22.9
- $R^2 = 0.49$
- No highly influential observations



## Confidence intervals for lab differences



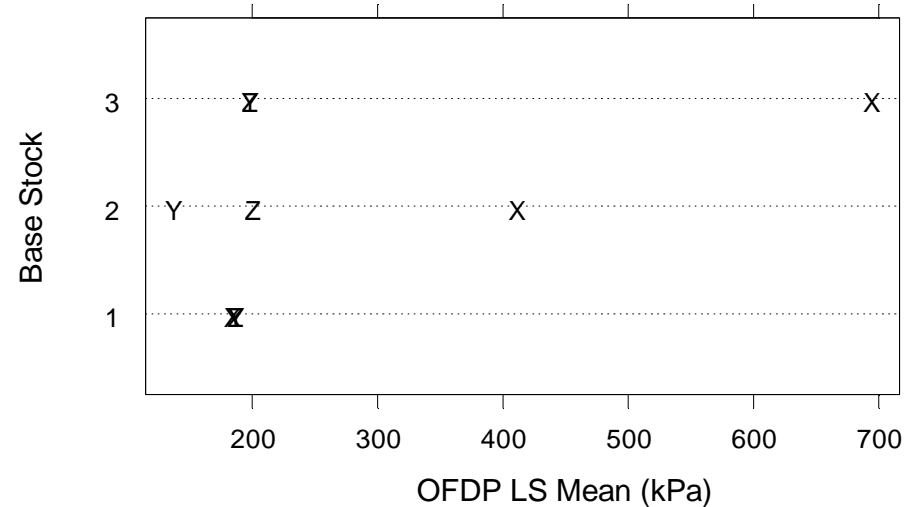
## Oil LS Means

BS \ Tech	X	Y	Z
1	156.3	157.9	140.1
2	131.5	131.7	162.8
3	111.3	161.5	158.2

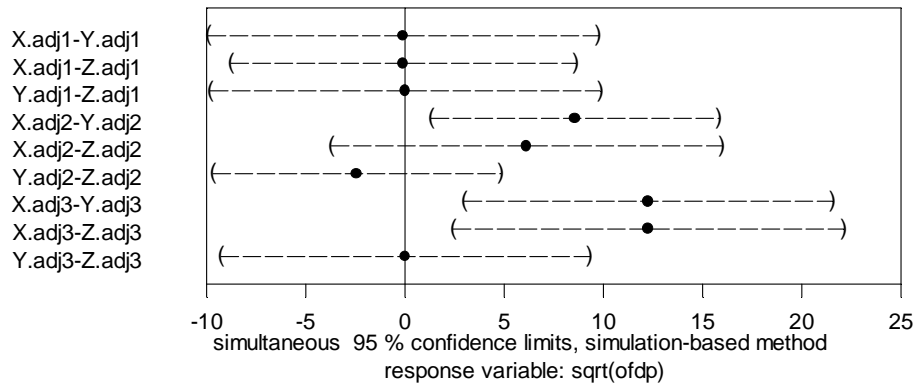
# Oil Filter Differential Pressure

## (including extreme values)

- Significant base oil/technology interaction
- Square root transformation
- RMSE = 2.7 (sqrt kPa)
- $R^2 = 0.81$



### Confidence intervals for technology differences



### Oil LS Means

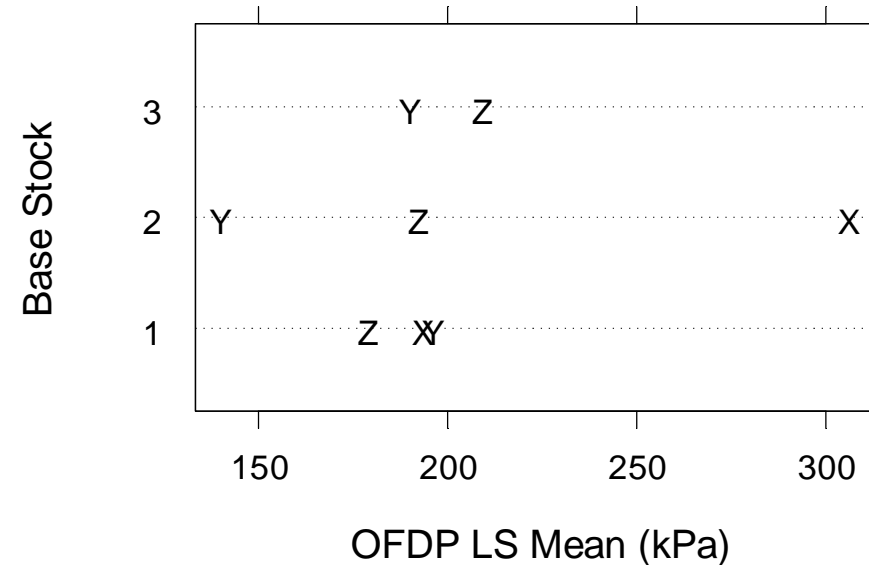
BS \ Tech	X	Y	Z
1	184.1	186.9	186.7
2	411.2	137.3	200.2
3	694.2	198.3	198.1



# Oil Filter Differential Pressure

(excluding extreme values)

- This excludes
  - CMIR 38972 (oil B, lab B)
  - CMIR 38965 (oil C, lab D)
  - CMIR 38958 (oil C, lab G)
- Collectively these observations are highly influential
- Nothing significant
- No transformation necessary
- RMSE = 67
- $R^2 = 0.46$



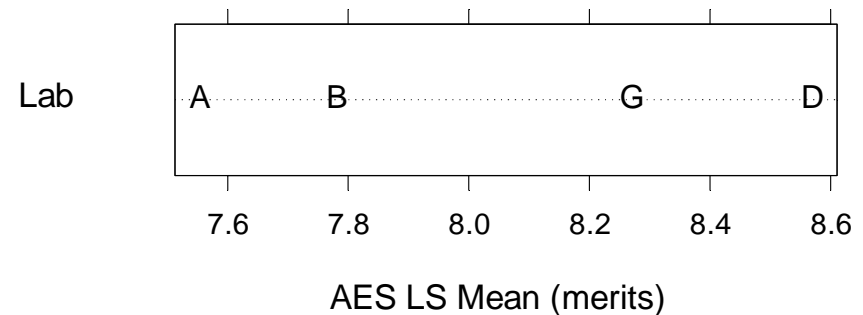
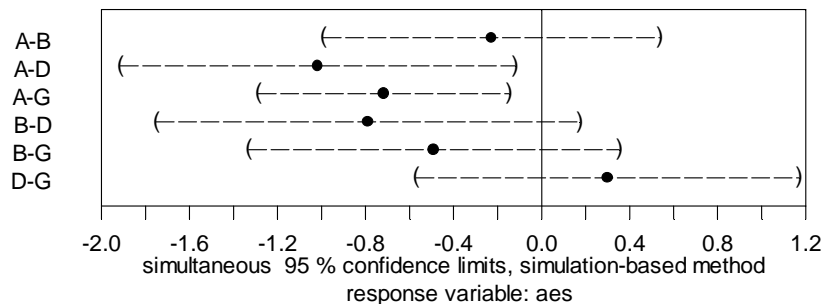
Oil LS Means

BS \ Tech	X	Y	Z
1	193.4	196.1	178.9
2	306.0	139.9	192.3
3	NA	189.9	209.2

# Average Engine Sludge

- Significant lab differences and technology/base stock interaction
  - Lab effect is due to Lab A having lower sludge than Labs D and G
  - Interaction is due to low sludge rating for technologies Y and Z in base oil 1
- No transformation necessary
- RMSE = 0.38
- $R^2 = 0.82$
- No highly influential observations

Confidence intervals for lab differences

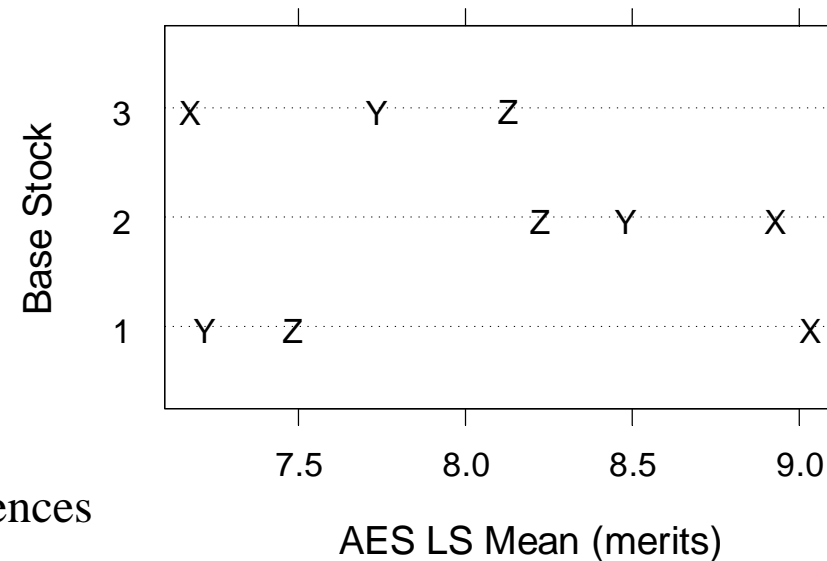


Lab LS Means

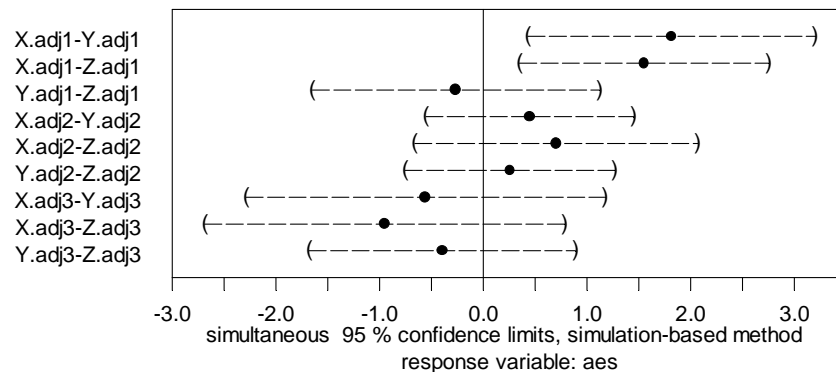
Lab	A	B	D	G
LS Mean	7.6	7.8	8.6	8.3

# Average Engine Sludge (technology/base oil interaction)

- Low sludge rating for technologies Y and Z in base oil 1



## Confidence intervals for technology differences



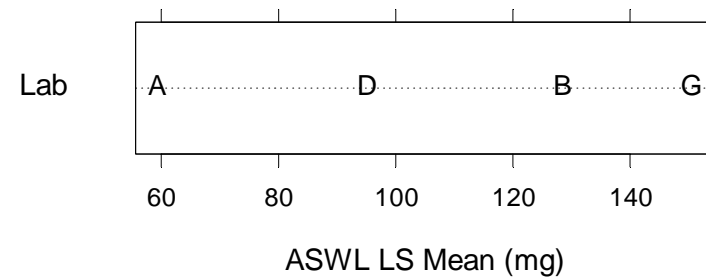
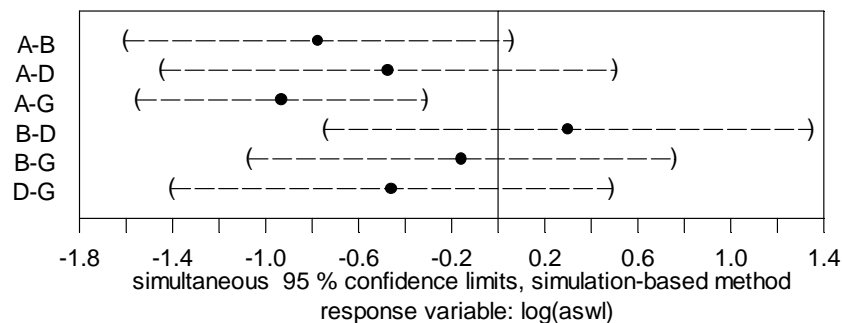
## Oil LS Means

BS \ Tech	X	Y	Z
1	9.0	7.2	7.5
2	8.9	8.5	8.2
3	7.2	7.7	8.1

# Adjusting Screw Weight Loss

- Lab is significant, with Lab A having lower wear than labs B and G
- Base oil is close to significant
- Ln transformation
- RMSE = 0.41 (ln mg)
- $R^2 = 0.74$

Confidence intervals for lab differences

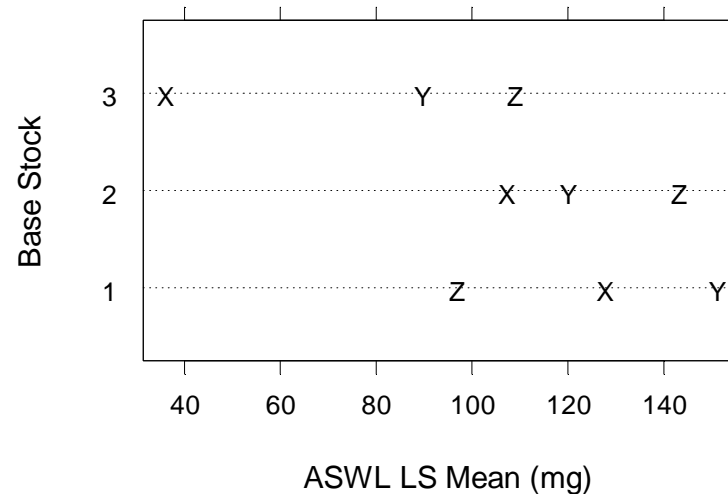


Lab LS Means

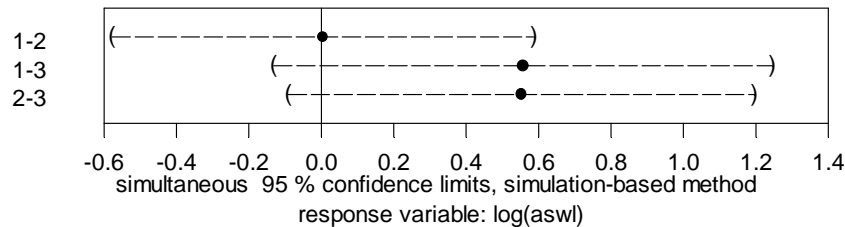
Lab	A	B	D	G
LS Mean	59.3	128.5	95.1	150.4

# Adjusting Screw Weight Loss (base oil)

- While not statistically significant, base oil 3 appears to have slightly lower wear than base oils 2 and 3



## Confidence intervals for base oil differences

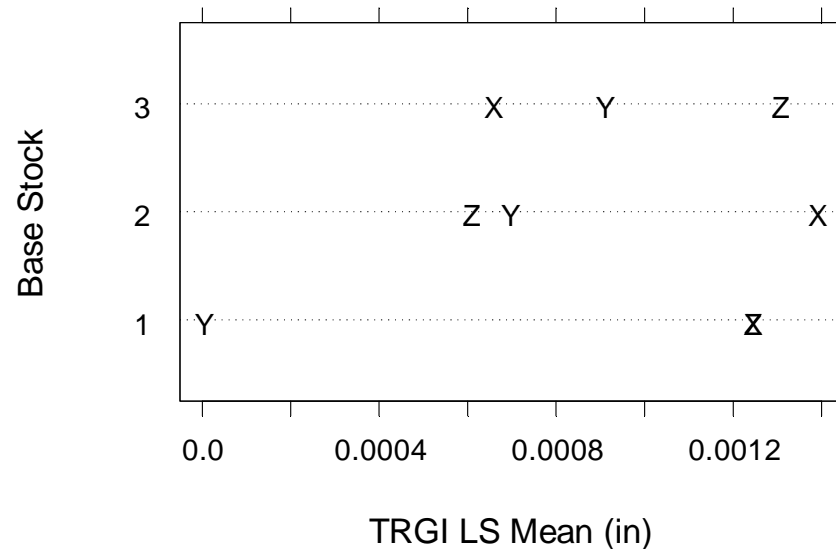


## Oil LS Means

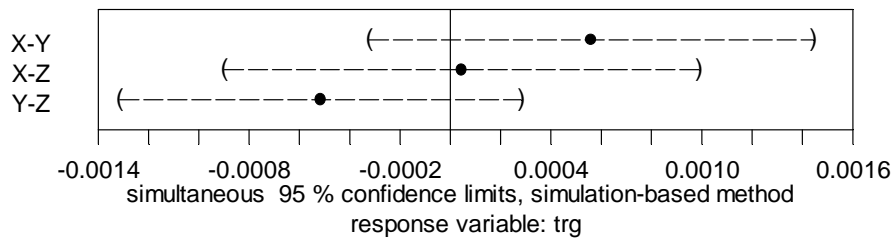
BS \ Tech	X	Y	Z
1	127.7	151.2	96.8
2	107.2	120.1	143.2
3	36.0	89.7	109.0

# Top Ring Gap Increase

- Nothing is significant
- Does not correlate with TRWL
- No transformation necessary
- RMSE = 0.00056
- $R^2 = 0.43$



## Confidence intervals for technology differences

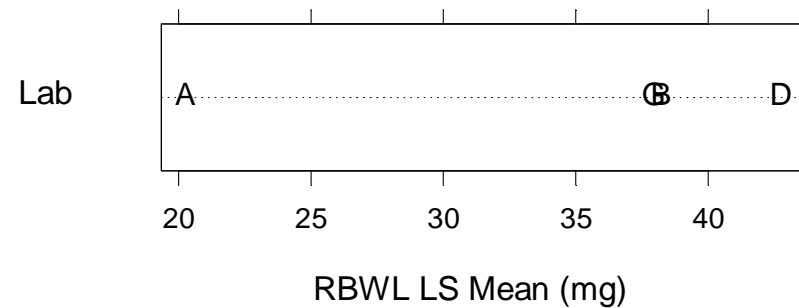


## Oil LS Means

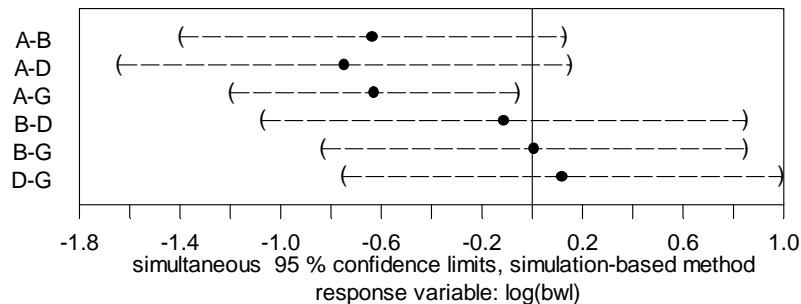
BS \ Tech	X	Y	Z
1	0.0013	0.0000	0.0013
2	0.0014	0.0007	0.0007
3	0.0006	0.0009	0.0013

# Rod Bearing Weight Loss

- Lab and technology are significant
  - Lab A has lower weight loss than labs B, D, and G
  - Technology X has higher weight loss than Technologies Y and Z
- Ln transformation
- RMSE = 0.38 (ln mg)
- $R^2 = 0.73$



## Confidence intervals for lab differences

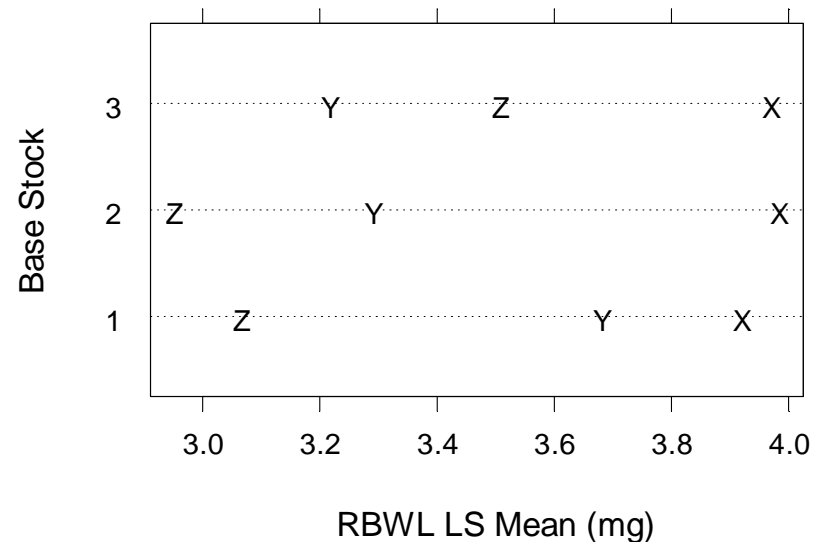


## Lab LS Means

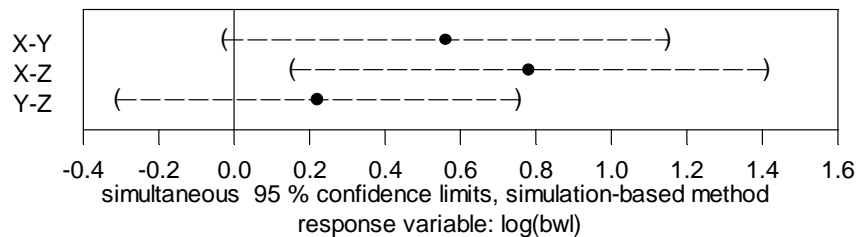
Lab	A	B	D	G
LS Mean	20.2	38.2	42.7	37.9

# Rod Bearing Weight Loss (technology effect)

- Technology effect is due to technology X having higher weight loss than technologies Y and Z



## Confidence intervals for technology differences



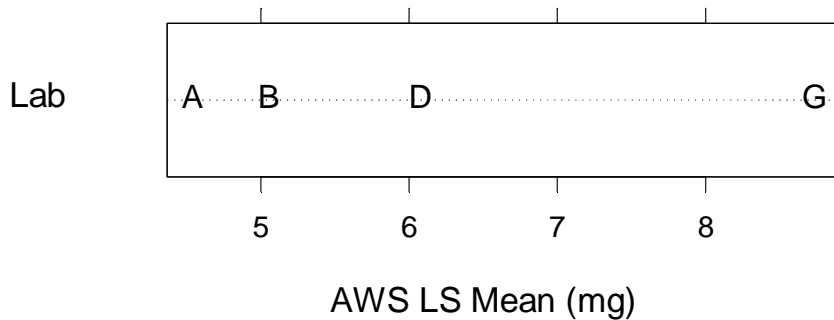
## Oil LS Means

BS \ Tech	X	Y	Z
1	50.4	39.7	21.5
2	53.7	26.9	19.1
3	53.0	25.0	33.4



# Average Wear Step

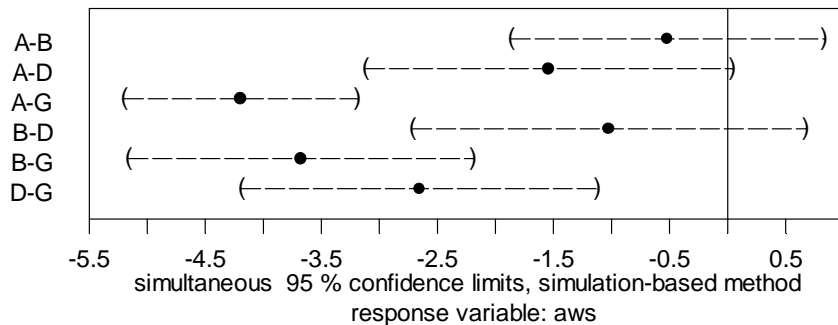
- Lab is highly significant
  - Labs G has much higher than Labs A, B, and D
- No transformation
- RMSE = 0.67
- $R^2 = 0.94$



Lab LS Means

Lab	A	B	D	G
LS Mean	4.5	5.1	6.1	8.7

Confidence intervals for lab differences



Oil LS Means

BS \ Tech	X	Y	Z
1	5.3	6.2	6.4
2	5.9	5.9	7.0
3	5.5	6.4	6.2



# Oil LS means and standard deviations

<b>Oil</b>	<b>adjXHDW</b>	<b>TRWL</b>	<b>sqrt(OFPD)</b>	<b>AES</b>	<b>ln(ASWL)</b>	<b>TRGI</b>	<b>ln(RBWL)</b>	<b>AWS</b>
A	15.7	156.3	13.5673	9.0	4.8499	0.0012	3.9209	5.3
B	15.7	131.5	20.2788	8.9	4.6749	0.0014	3.9836	5.9
C	24.0	111.3	26.3477	7.2	3.5832	0.0007	3.9706	5.5
D	12.2	157.9	13.6704	7.2	5.0184	0.0000	3.6820	6.2
E	17.3	131.7	11.7164	8.5	4.7883	0.0007	3.2919	5.9
F	17.7	161.5	14.0805	7.7	4.4964	0.0009	3.2178	6.4
G	13.2	140.1	13.6620	7.5	4.5729	0.0012	3.0668	6.4
H	19.7	162.8	14.1506	8.2	4.9642	0.0006	2.9523	7.0
J	18.2	158.2	14.0751	8.1	4.6913	0.0013	3.5089	6.2
std dev	3.7	22.9	2.7	0.38	0.4100	0.00056	0.3804	0.67

# Data set

	CMIR	oil	base	tech	lab	xhdw	trwl	ofdp	aes	aswl	trgi	rbwl	aws
1	38932	E	2	Y	A	23.609126	172.0	127	7.4	108.4	0.0010000000	16.2	4.2
2	38967	B	2	X	A	18.860696	125.0	308	8.8	43.7	0.0010000000	30.1	3.9
3	38969	G	1	Z	A	12.024254	124.5	175	7.3	68.2	0.0010000000	18.6	4.7
4	38935	E	2	Y	A	17.497106	128.9	97	8.1	85.0	0.0001666667	22.3	4.1
5	38970	F	3	Y	A	20.770668	134.2	186	7.0	42.7	0.0010000000	17.6	4.3
6	38933	E	2	Y	A	11.403427	115.5	66	8.0	51.2	0.0011666667	7.6	5.3
7	38966	J	3	Z	A	20.313626	170.5	265	7.7	71.8	0.0010000000	23.8	4.5
8	38934	E	2	Y	A	16.018042	139.1	143	7.6	82.1	0.0000000000	17.1	4.5
9	38968	A	1	X	A	20.292868	144.5	288	8.9	56.6	0.0001666667	25.0	4.4
10	38936	E	2	Y	B	23.283084	147.2	246	8.7	116.6	0.0005000000	36.2	3.8
11	38971	D	1	Y	B	19.409366	144.7	191	6.9	196.6	0.0003333333	42.0	5.7
12	40920	J	3	Z	B	22.573732	139.7	179	7.8	120.7	0.0015000000	32.4	5.3
13	38972	B	2	X	B	19.005164	131.8	601	8.3	191.9	0.0016666667	66.2	5.3
14	38931	E	2	Y	D	15.914587	112.8	118	9.1	98.9	0.0011666667	37.2	6.4
15	38963	D	1	Y	D	9.810164	162.9	224	7.8	136.1	0.0000000000	54.8	5.7
16	38965	C	3	X	D	23.597374	107.1	606	7.7	33.5	0.0008333333	67.7	5.5
17	38964	H	2	Z	D	22.282757	164.0	184	8.6	155.8	0.0008333333	20.9	7.0
18	38927	E	2	Y	G	11.739236	104.1	178	9.0	160.5	0.0000000000	26.2	8.2
19	38962	F	3	Y	G	9.698728	196.9	171	8.2	160.9	0.0005000000	24.3	9.6
20	38930	E	2	Y	G	11.478874	148.2	190	8.4	96.6	0.0003333333	21.9	9.1
21	38960	H	2	Z	G	10.702293	167.7	175	8.6	180.4	0.0006666667	25.4	9.6
22	38959	A	1	X	G	6.245662	176.2	76	8.9	246.2	0.0020000000	69.8	7.3
23	38928	E	2	Y	G	14.913275	143.7	111	8.9	139.0	0.0003333333	28.1	9.0
24	38929	E	2	Y	G	12.098821	129.5	55	8.8	404.0	0.0013333333	62.6	8.0
25	38958	C	3	X	G	NA	NA	706	NA	NA	NA	NA	NA
26	38961	G	1	Z	G	9.496053	163.8	160	7.4	117.4	0.0011666667	17.0	9.1