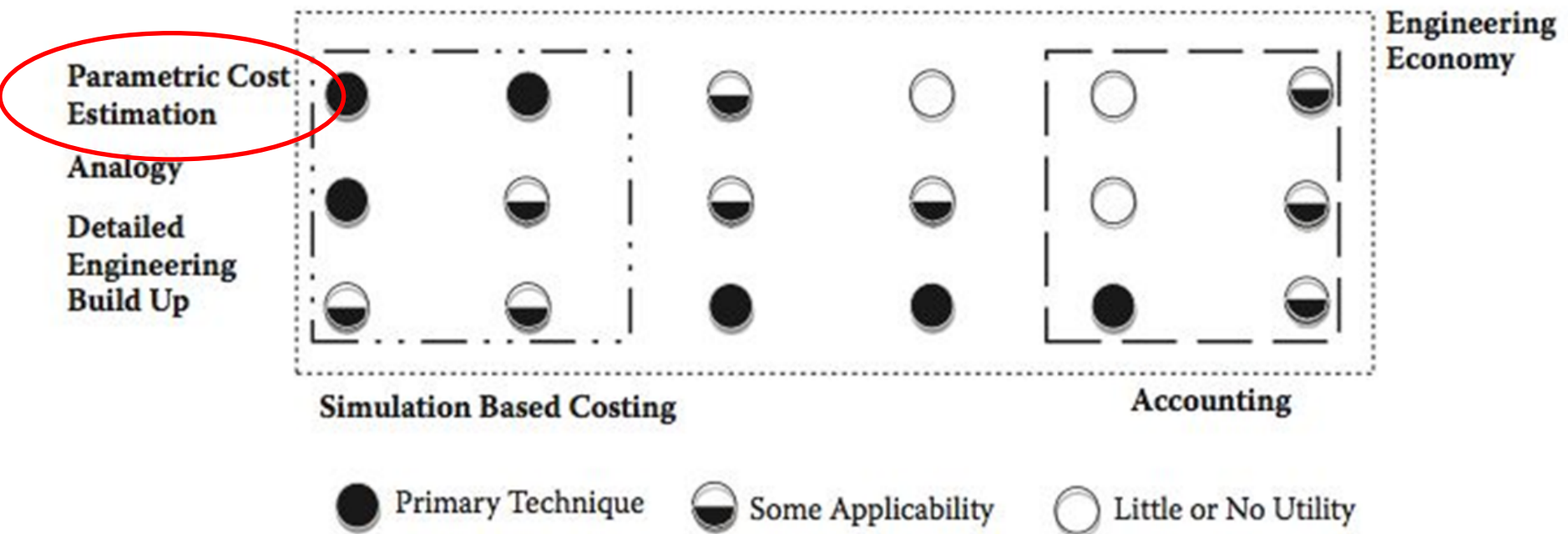
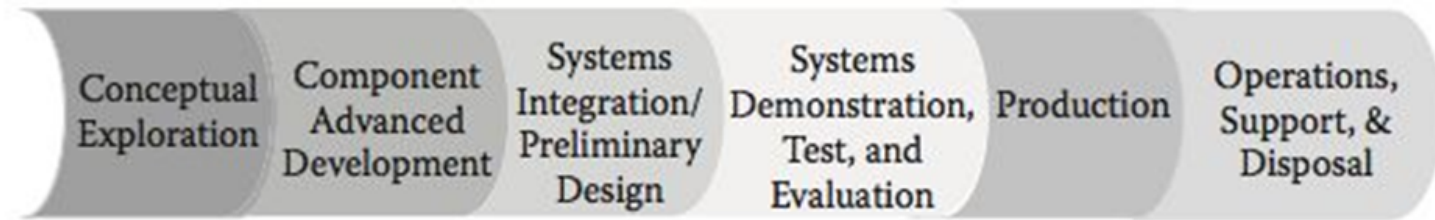


Costing Complex Systems



Methods, processes, and tools used in costing complex systems.

Primary Text

Engineering Economics of Life Cycle Cost
Analysis by Farr/Faber

Chapter 9 – Cost Estimating Techniques

9.1 INTRODUCTION

Previous Topics

- Cost and Project Estimating Methods
- Cost drivers (not just monetary value)
- Fixed vs. variable Costs
- Cost Analysis (Account analysis, High-low method, Scatter graph method, and Regression analysis)

Parametric cost estimating (PCE) – Key Terms

- Parametric cost estimate: Estimate derived from statistical correlation of historic system costs with **performance** and/or **physical attributes** of the system
- Parametric cost model: A mathematical representation of parametric cost estimating relationships that provides a logical and predictable correlation between the physical or functional characteristics of a system and the resultant cost of the system
 - comprises CERs (cost estimating relationships) and other parametric estimating functions, (e g , cost/quantity relationships, inflation factors, staff skills, schedules, etc.)
 - yield product or service costs at designated levels and may provide a departmentalized breakdown of generic cost elements
 - provides a logical and repeatable relationship between input variables and resultant costs

PCE – Key Terms (continued)

- Cost estimating relationship: An algorithm relating the cost of an element to physical or functional characteristics of that cost element or a separate cost element, or relating the cost of one cost element to the cost of another element
 - can be a functional relationship between one variable and another and may represent a statistical relationship between some well-defined program element and some specific cost
 - many costs can be related to other costs or non-cost variables in some fashion, but not all such relationships can be turned into a CER (cost estimating relationship)
- CER: A mathematical expression that describes, for predictive purposes, the cost of an item or activity as a function of one or more independent variables

Some Forms of CER

- Definition: A Cost Estimating Relationship (CER) is a mathematical expression of cost as a function of one or more independent variables
- CERs are often developed using regression analysis to fit an equation to a data set
- Examples of equations used for CERs include:

Linear CER: $y = a + bx$

Nonlinear CERs:

$$y = ax^b$$
$$y = ab^x$$
$$y = a + bx^c$$

where y = Cost
 x = Technical Parameter

FIGURE 9.1 Process for determining parametric cost estimates

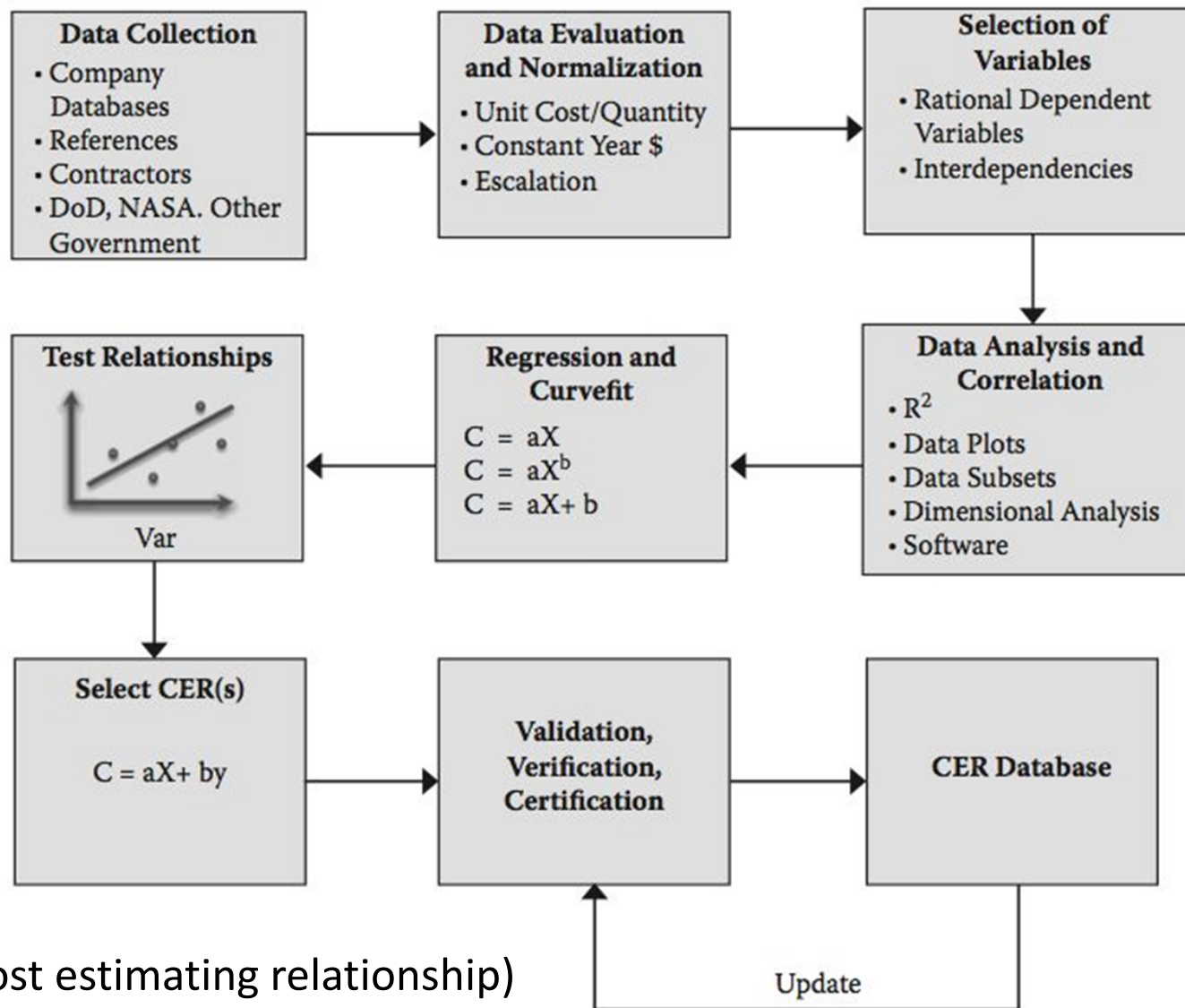


TABLE 9.3

Sample CER Relationships

Product	Independent Variable
Construction	Floor space, roof surface area, wall surface area
Gears	Net weight, percent of scrap, inches of teeth cut, harness, envelope
Trucks	Empty weight, gross weight, horsepower, number of driving axles, loaded cruising speed
Passenger car	Curb weight, wheel base, passenger space, horsepower
Turbine engine	Dry weight, maximum thrust, cruise thrust, specific fuel consumption, bypass ratio, inlet temperature
Reciprocating engine	Dry weight, piston displacement, compression ratio, horsepower
Sheet metal	Net weight, percent of scrap, number of holes drilled, number of rivets placed, inches of welding, volume of envelope
Aircraft	Empty weight, speed, useful load, wing area, power, landing speed
Diesel locomotive	Horsepower, weight, cruising speed, maximum load on standard grade at standard speed

Example 9.1 – Basic CER

Historical information on construction waste disposal costs has been input into a computer with statistical software. The statistical package generated the following CER equation:

$$C = 200 + 275D_{10} + 325D_{30} + 0.75M$$

where:

C = cost (in dollars) to dispose of construction waste

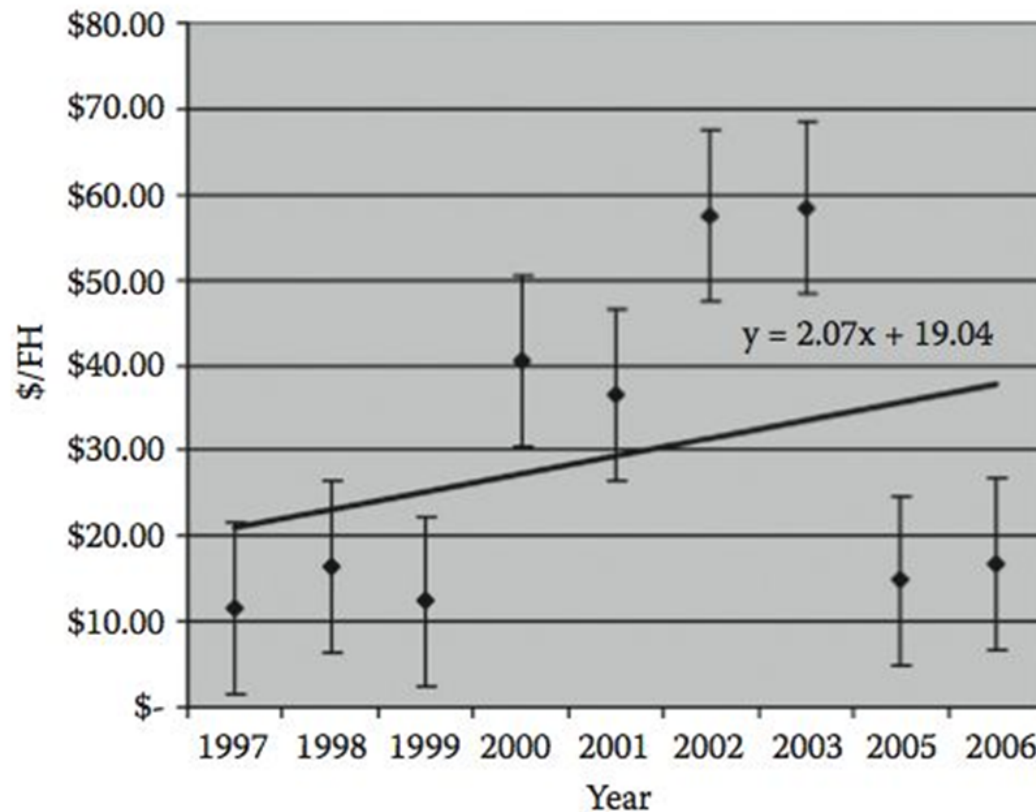
D_{10}, D_{30} = number of 10-cubic-yard or 30-cubic-yard rolls off dumpsters

M = number of miles between waste location and waste disposal facility

This is an example of linear regression model

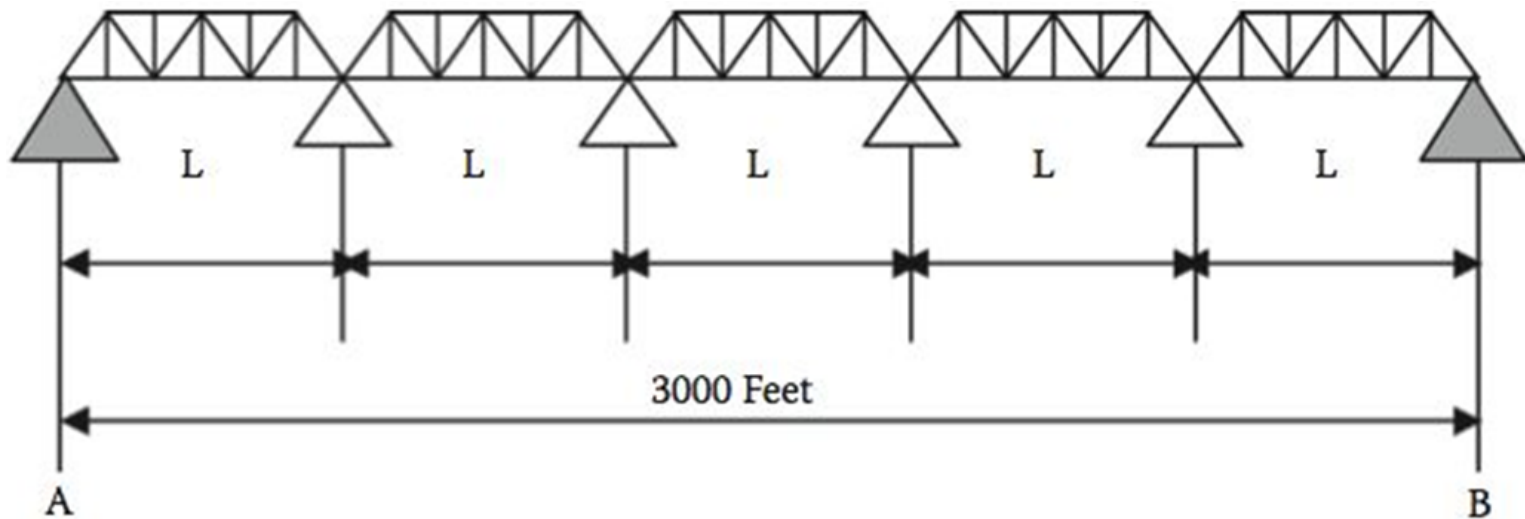
Example 9.3 – Impact of Consumables

FH = flight hour



The radar's consumables include all of the internal cable assemblies, low-cost power supplies, and other various low-cost components that fail. This relationship covers only the O&S costs for consumable components and piece parts. It does not include consumables such as fuel, lubricants, corrosion treatment solutions, etc. Even for a low-maintenance item such as radar, there can be significant hidden costs.

Example 9.4 – Project Estimation



- A bridge is to be constructed to span a distance of 3000 feet across a shallow river, as shown above.
- A preliminary study concluded that a series of equal- span simple trusses is most suitable. It is estimated that the two end piers, A and B, will cost \$400,000 each.
- The remaining piers, which will be located in water, can be constructed anywhere in the crossing at a cost of \$800,000 per pier. Each bridge truss of length L (feet) costs 80 times L^2

Example 9.4 Solution

Thus, the number of interior piers, n , is given by

$$n = \frac{3000}{L} - 1$$

Count them

and the expected cost of the bridge, C , becomes

$$\begin{aligned} C &= 2(400,000) + n(800,000) + (n + 1)8L^2 \\ &= 800,000 + \frac{3000}{L} - 1 * 800,000 + \frac{3000}{L} * 80L^2 \end{aligned}$$


Truss strength based on length

Example 9.4 – CER (Truss Length)

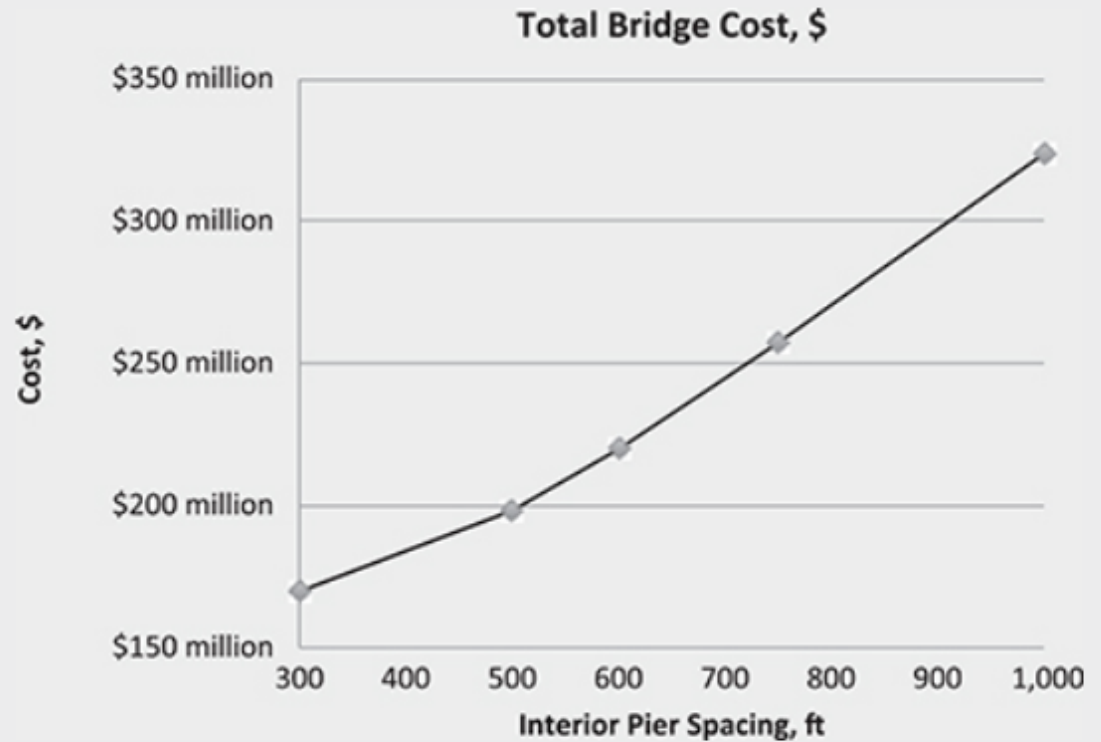
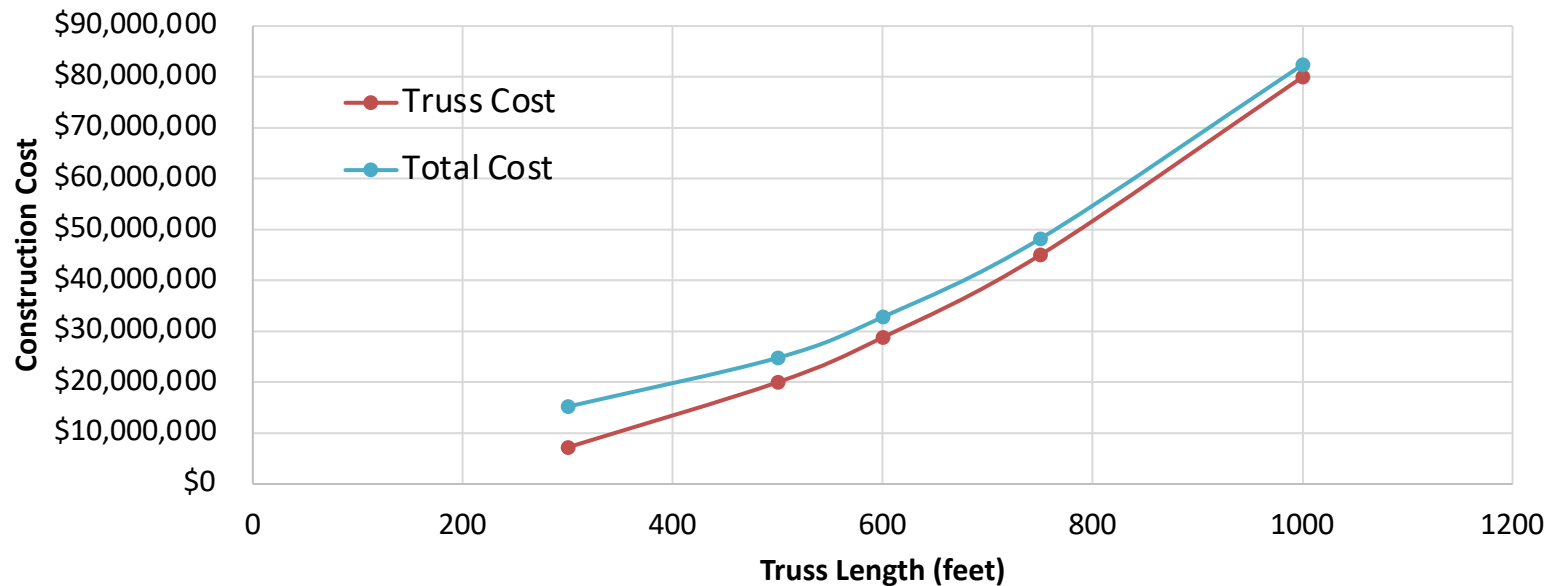


Figure 9.3 CER for cost as a function of interior truss length

Why not evenly spaced data points? Why is it near linear?

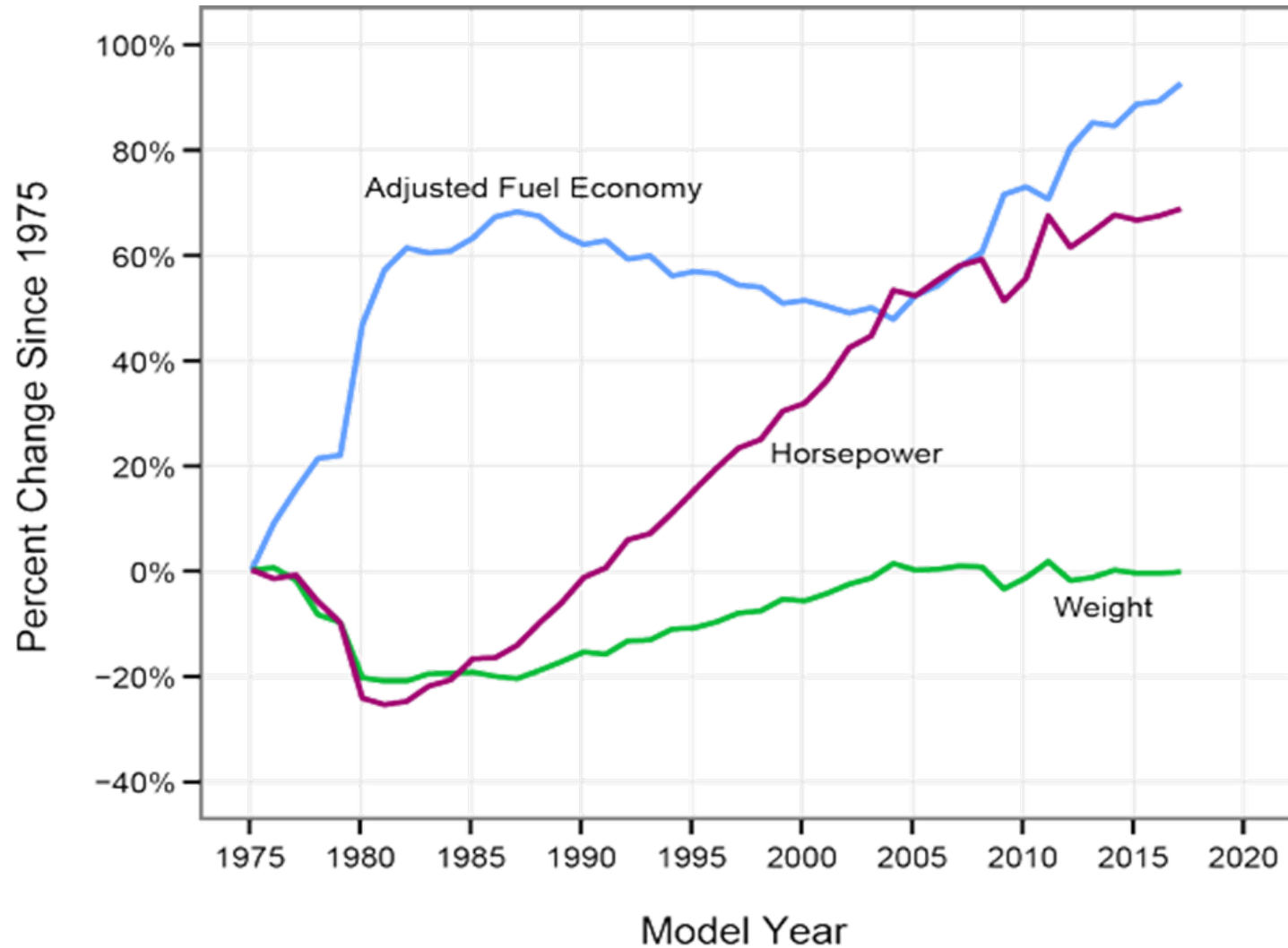
Checked with Excel

Qty	Unit \$	Item					
3000		Span Distance					
		Truss length (L)	300	500	600	750	1,000
		Interior Piers (n)	9	5	4	3	2
	\$80	Truss Cost $80L^2$	\$7,200,000	\$20,000,000	\$28,800,000	\$45,000,000	\$80,000,000
	\$800,000	Interior Pier Cost	\$7,200,000	\$4,000,000	\$3,200,000	\$2,400,000	\$1,600,000
2	\$400,000	End Piers	\$800,000	\$800,000	\$800,000	\$800,000	\$800,000
		Total Cost	\$15,200,000	\$24,800,000	\$32,800,000	\$48,200,000	\$82,400,000

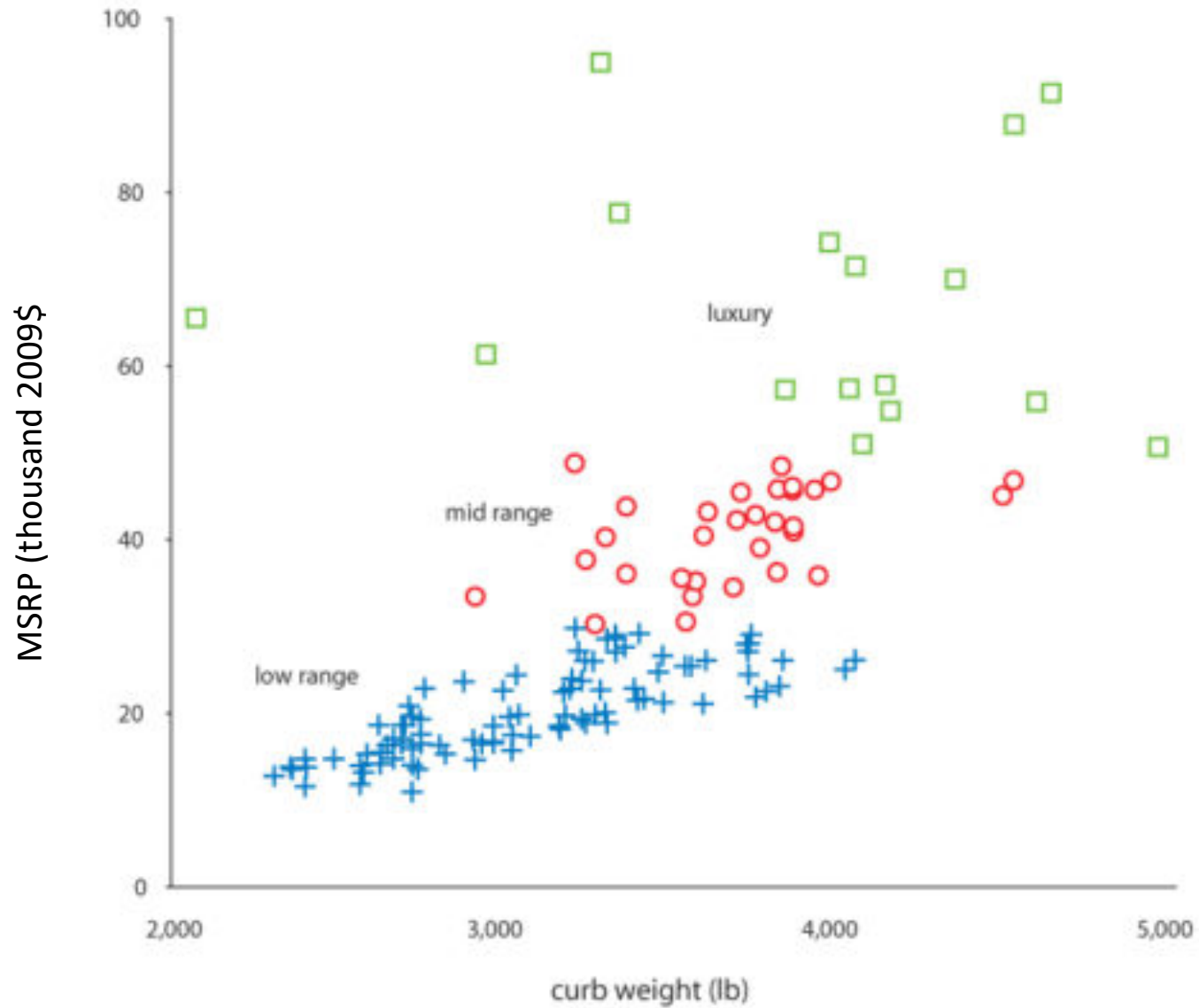


Observe: Shorter truss – more piers costs less

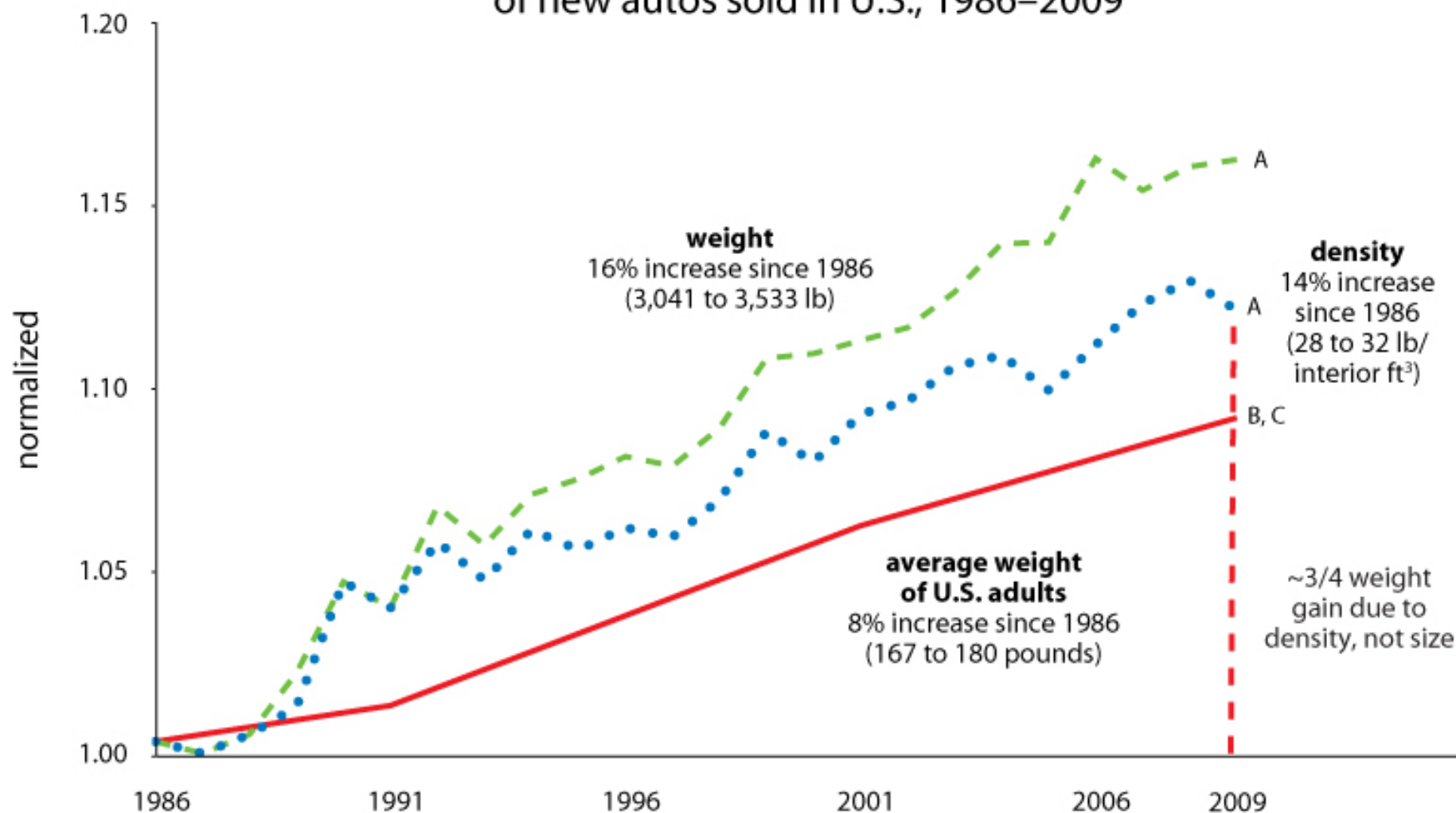
Behavior of Physical Properties



Vehicle retail price and curb weight, new U.S. car sales, model year 2010



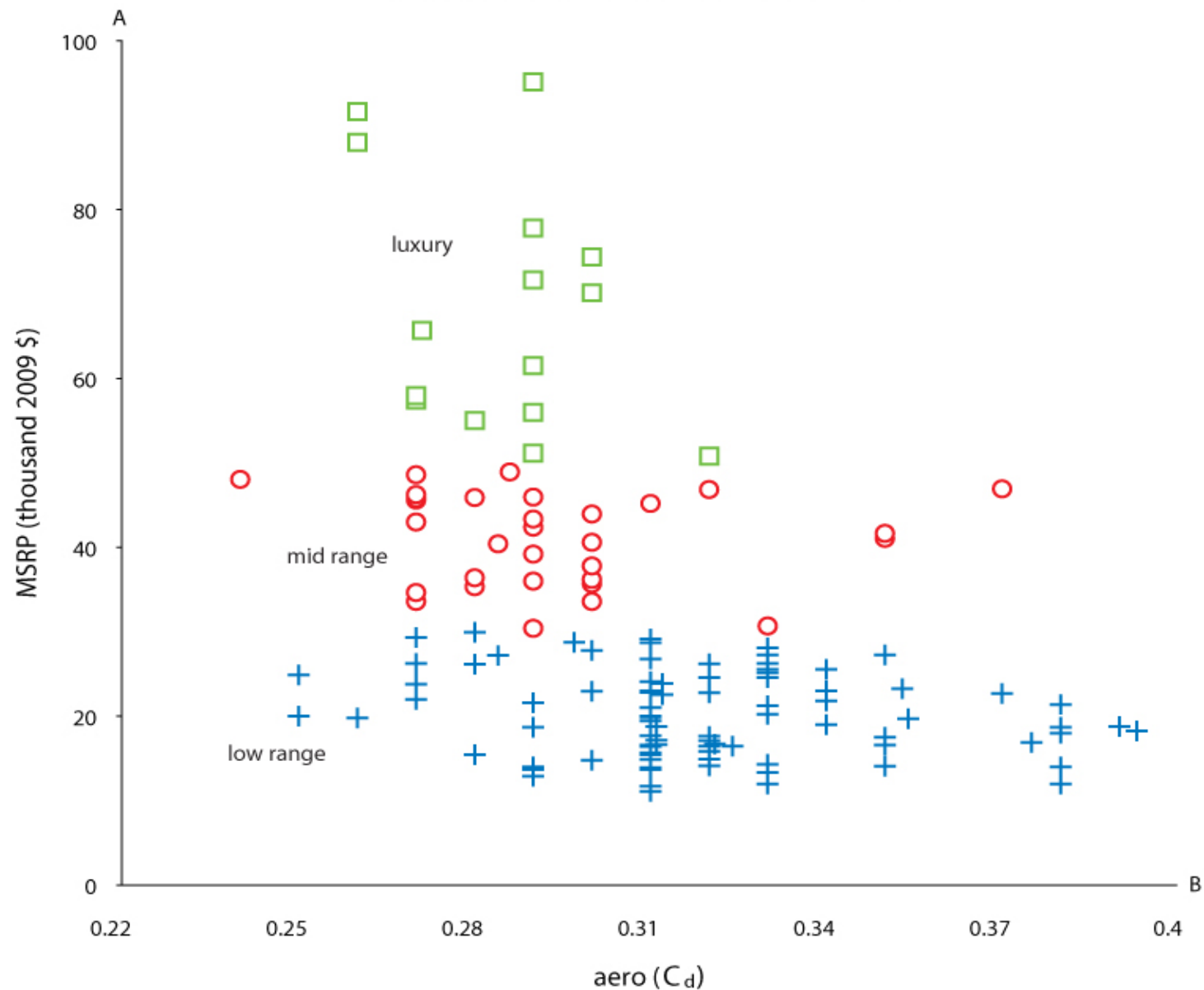
Sales-weighted curb mass and density of new autos sold in U.S., 1986–2009



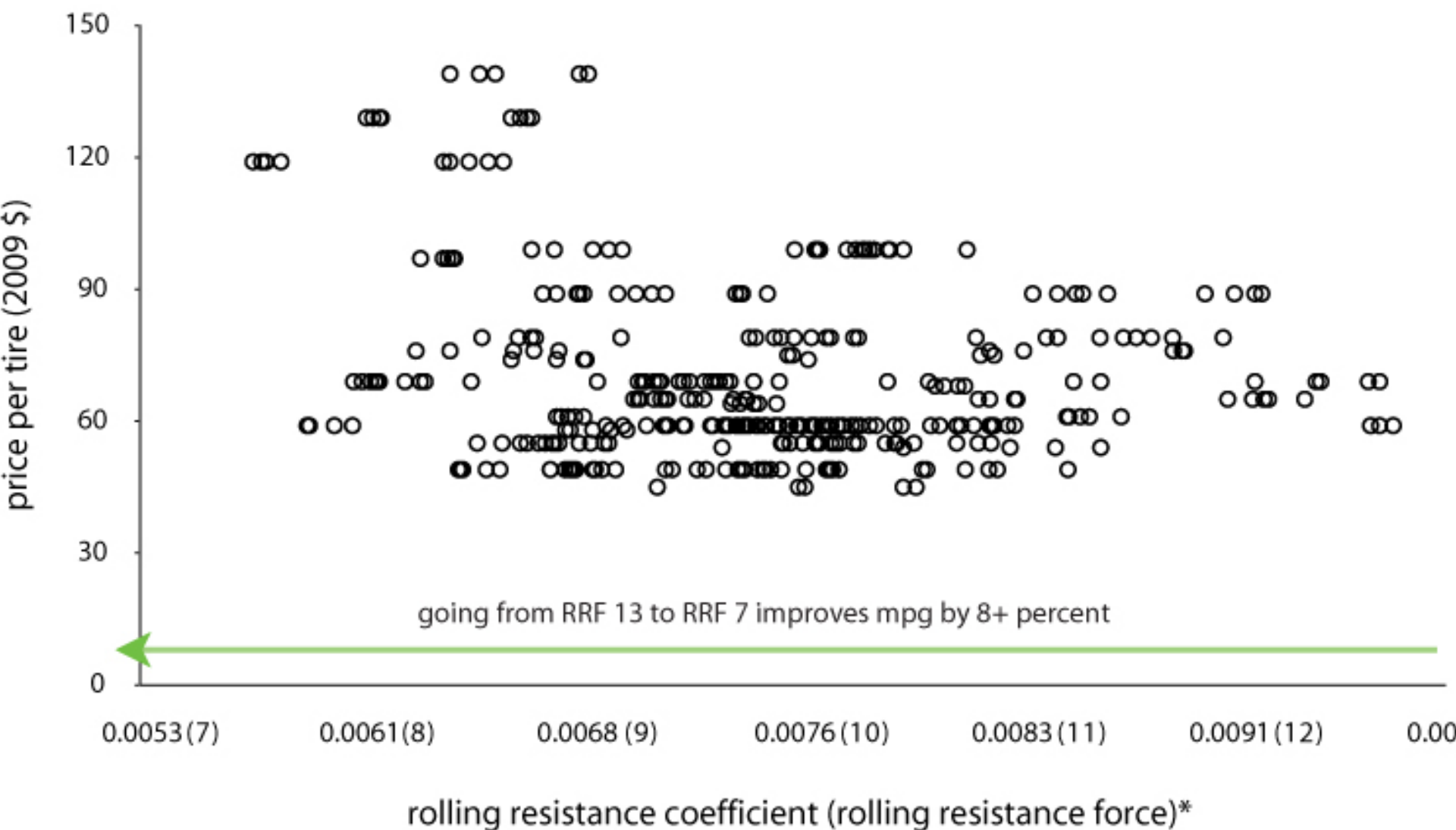
Lettered sources in chart are detailed below.

Rocky Mountain Institute © 2011. For more information see www.RMI.org/ReinventingFire.

Drag coefficient and retail price, new U.S. car sales model year 2010

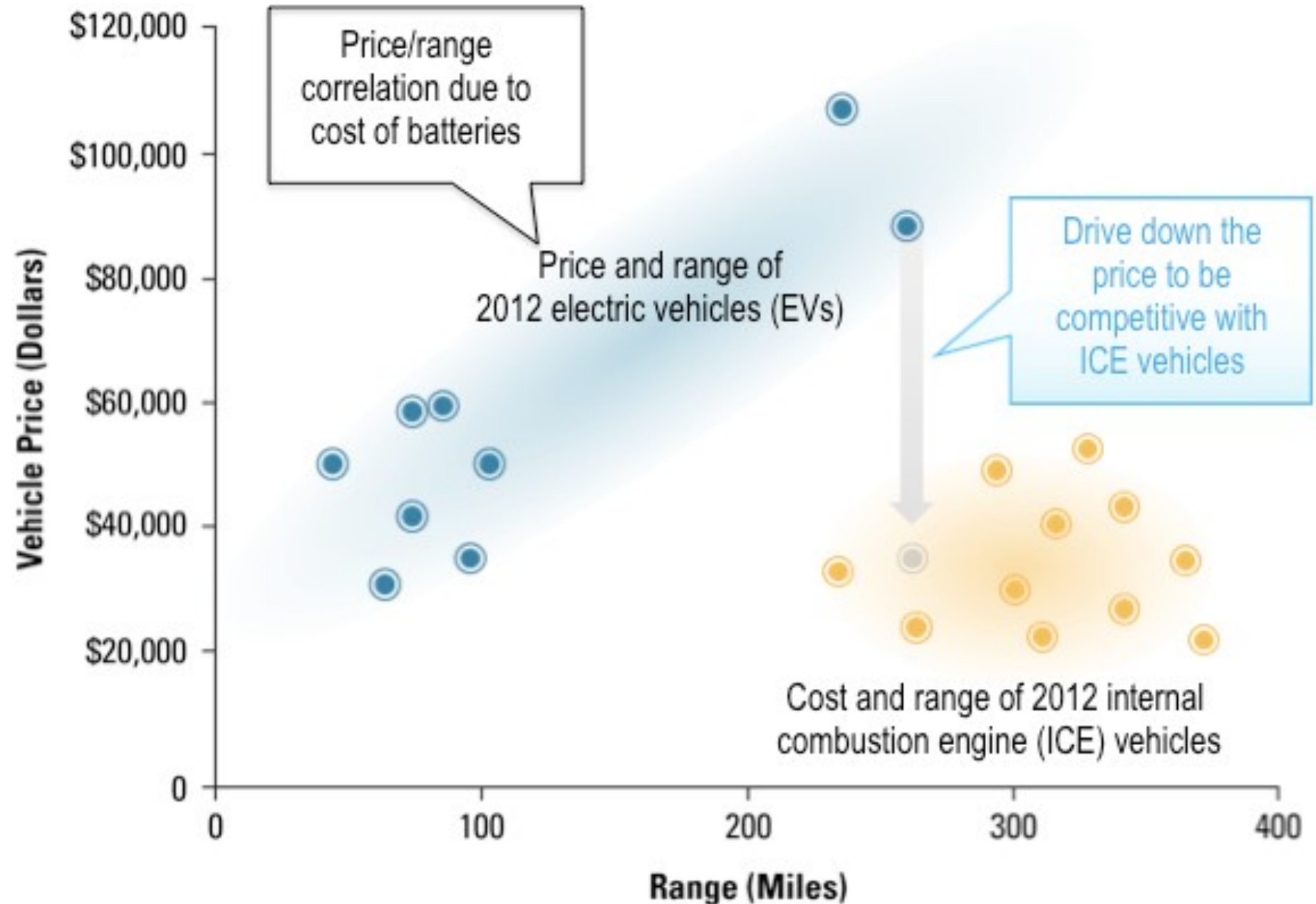


Tire price and rolling resistance coefficient

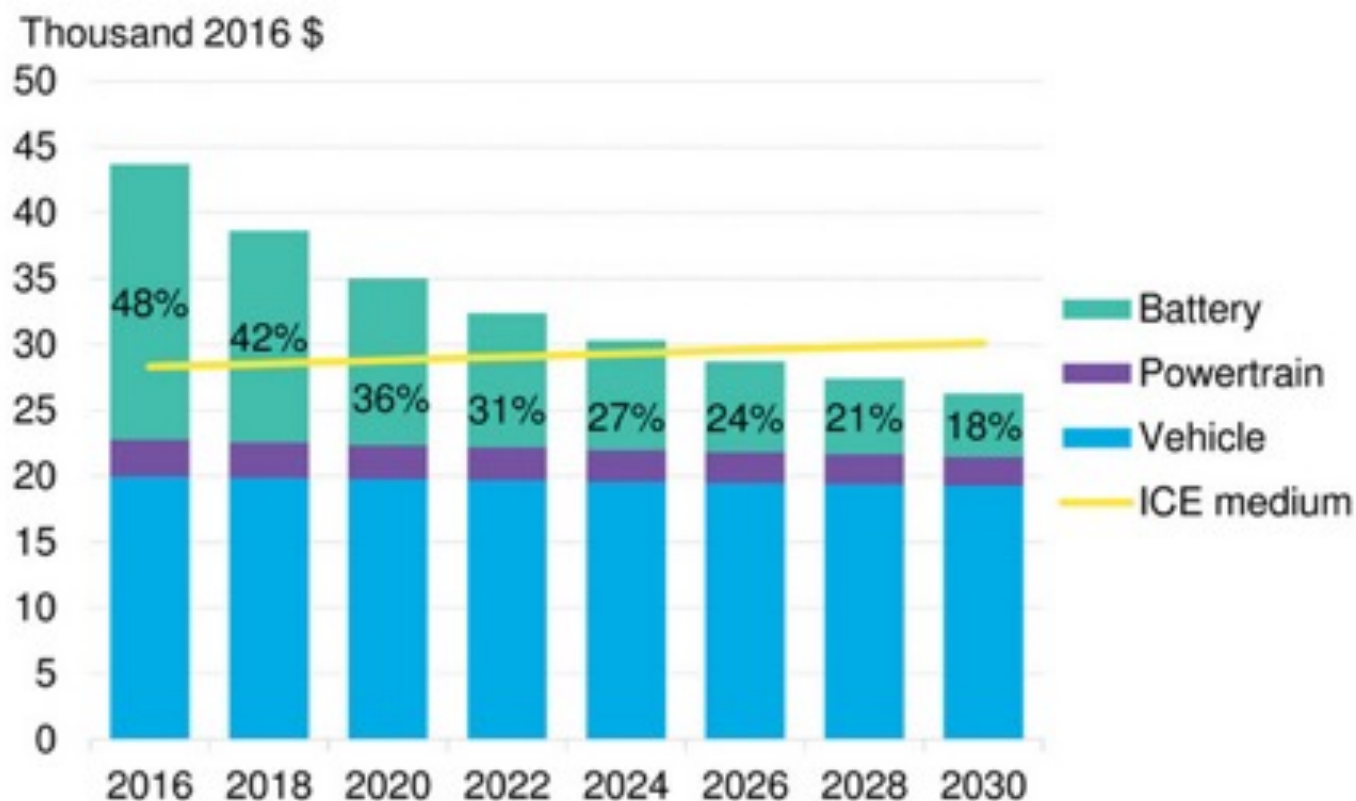


*conversion from RRF to RRC based on average load index of 90 (1,323 pounds)

Impact of Physical Attribute



U.S. medium segment vehicle price estimates



Source: Bloomberg New Energy Finance

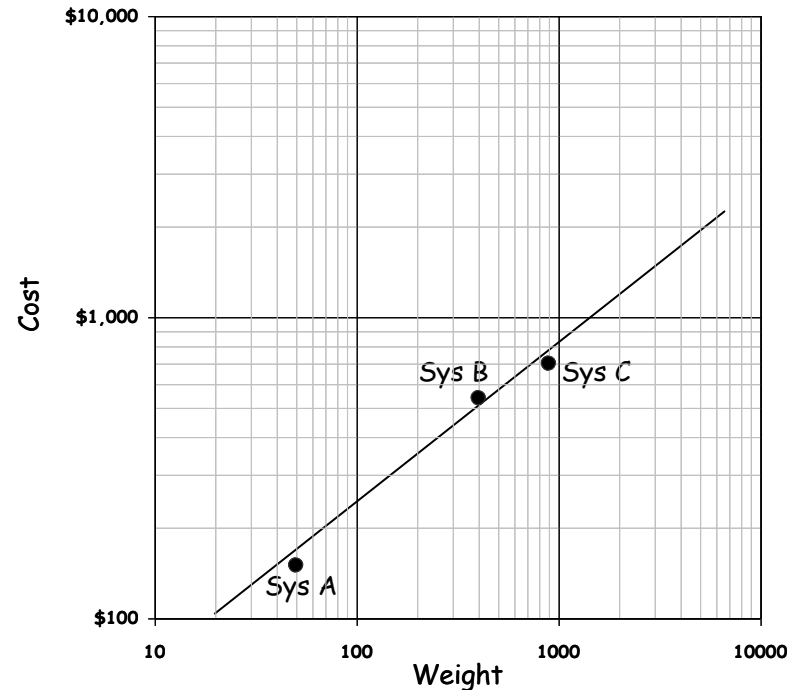
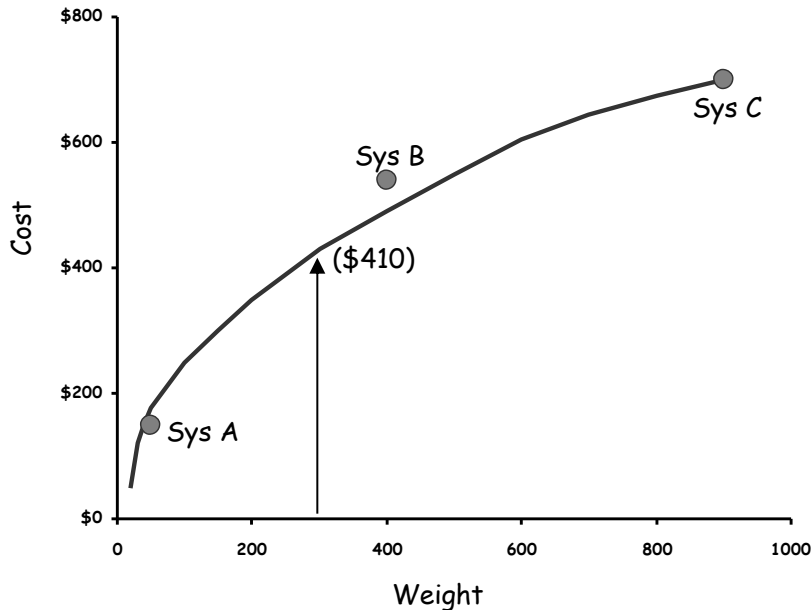
Note: Estimated pre-tax retail prices

How do you get the CER?

- Reliable historical cost, schedule, and technical data or a set of data points
- Work Breakdown Structure (WBS), WBS dictionary, product tree, and/or physical architecture
- Analysis to determine significant cost drivers
- Knowledge of basic statistics and software

Comparison of Linear / Log-Log Plots

- ◆ Left side shows the an example CER and data points. Since this is a second order equation (not a straight line) the relationship is a curve.
- ◆ A second order equation plots to log-log graph as a straight line and is convenient for the user, especially when the data range is wide.



Resulting CER:

$$\text{Cost} = 25 * W^{.5} \text{ (Slope} = .5\text{)}$$

Generic CER form:

$$\text{Cost} = a + bX^c$$

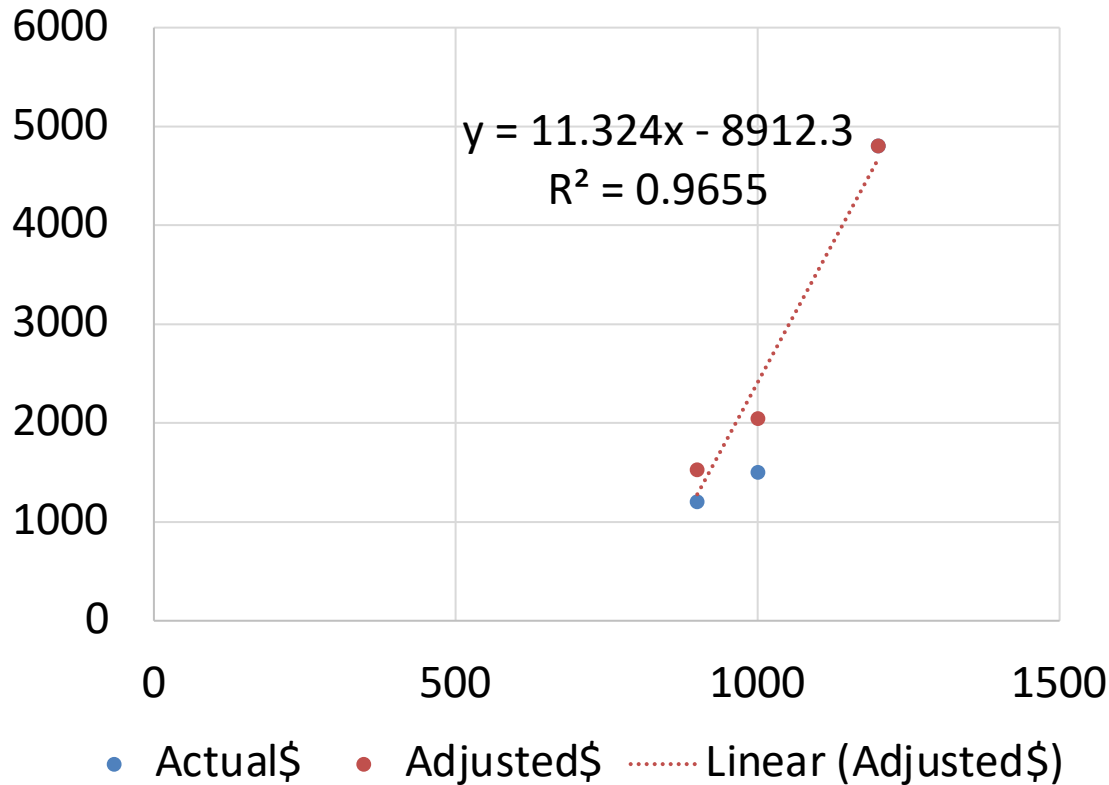
Make sure you normalize historical data!

Be sure inflation effects removed!

Historical Data in RY \$						Historical Cost Data in 1991 CY \$		
Year	SYS A	SYS B	SYS C	Inflation Rate	1991 Inflation Factor	SYS A	SYS B	SYS C
1981	\$11.1			10%	1.882	\$20.9		
1982	\$22.2			9%	1.711	\$38.0		
1983	\$33.3	\$53.9		9%	1.57	\$52.3	\$84.6	
1984	\$22.4	\$80.8		8%	1.44	\$32.3	\$116.4	
1985	\$5.0	\$107.7		6%	1.333	\$6.7	\$143.5	
1986		\$80.8	\$72.2	6%	1.258		\$101.6	\$90.8
1987		\$53.9	\$144.4	5%	1.187		\$64.0	\$171.4
1988		\$26.9	\$216.7	5%	1.13		\$30.4	\$244.9
1989			\$144.6	4%	1.076			\$155.6
1990			\$36.1	3.5%	1.035			\$38.4
Total	\$94.0	\$404.0	\$614.0			\$150.2	\$540.5	\$701.1
Cost Adjustment						~60%	~34%	~14%
Make Sense?								

Note: NASA publishes an inflation table (NASA2003_inflation_index.xls)

Adjusting Historical Prices to Constant\$



Project	Weight	Actual\$	Year	Adjusted\$	Year	Adjust CPI
A	1000	1500	1995	2041	2007	1.360512
B	900	1200	1998	1526	2007	1.272037
C	1200	4800	2007	4800	2007	1

Use of Complexity Factors

Complexity is an adjustment to a CER to compensate for a project's unique features that aren't accounted for in the CER historical data.

Description	Complexity Factor
System is "off the shelf" ; minor modifications	.2
System's basic design exists; few technical issues; 20% new design and development	.4
System's design is similar to an existing design; some technical issues; 20% technical issues; 80% new design and development	.7
System requires new design, development, and qualification; some technology development needed (normal system development)	1.0
System requires new design, development, and qualification; significant technology development; multiple contractors	1.3
System requires new design, development and qualification; major technology development	1.7
System requires new design, development and qualification; major technology development; crash schedule	2.0

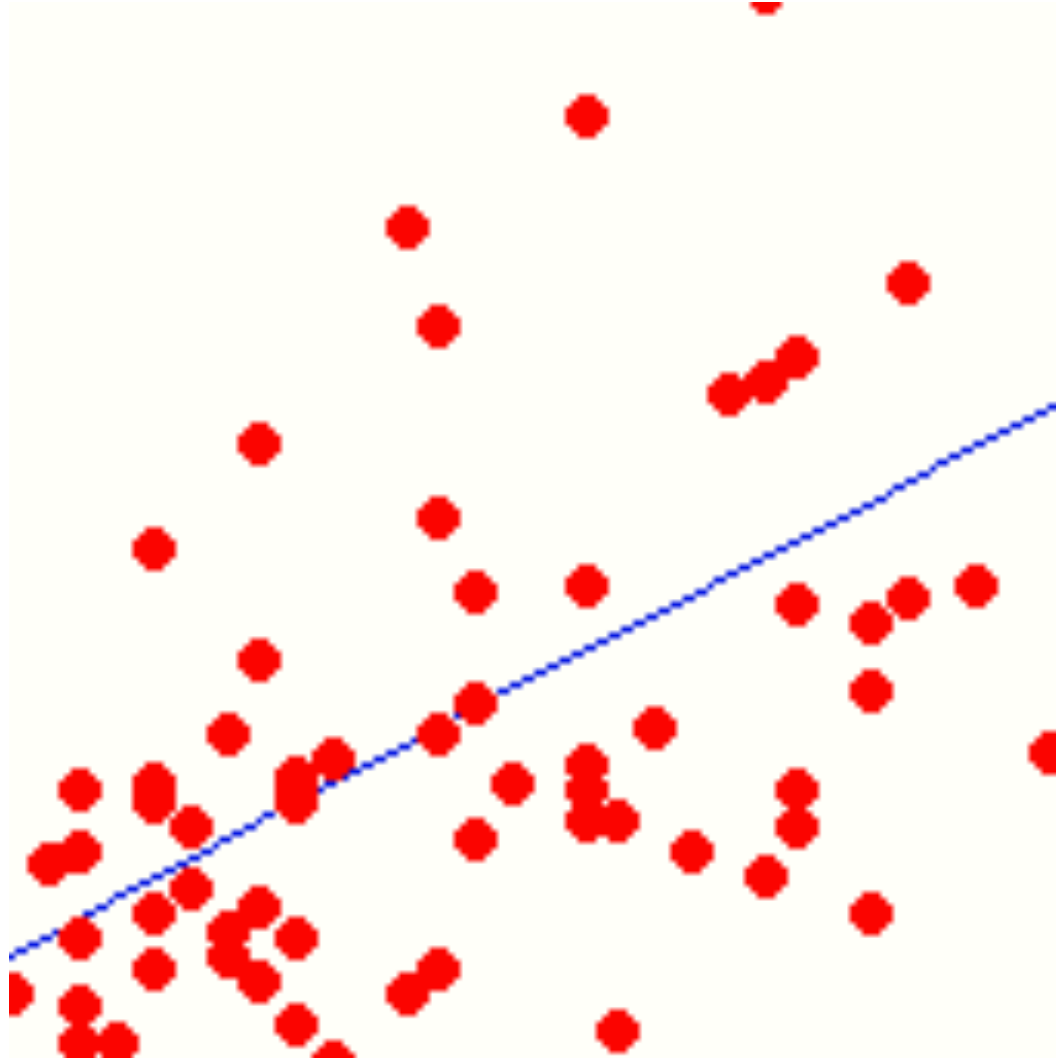
9.3.1 ROLE OF STATISTICS

Statistical Approaches

- Regression (Excel) – right-click data point on x-y scatter plot – add trendline
- Many techniques: simple, multiple, and curvilinear regression
- Complex methods: neural networks, genetic algorithms

Biggest challenge: understanding the goodness of fit for the data and the validity of the equations even for statistically significant models

Find the Underlying Driver – Don't Believe Your Statistics



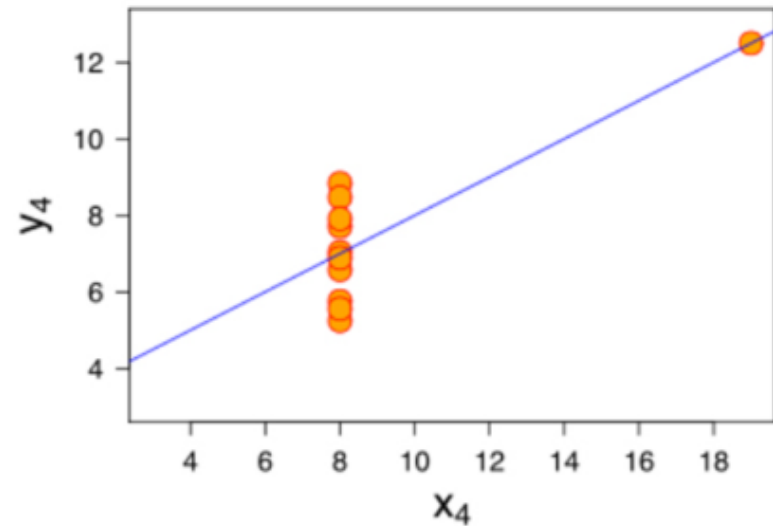
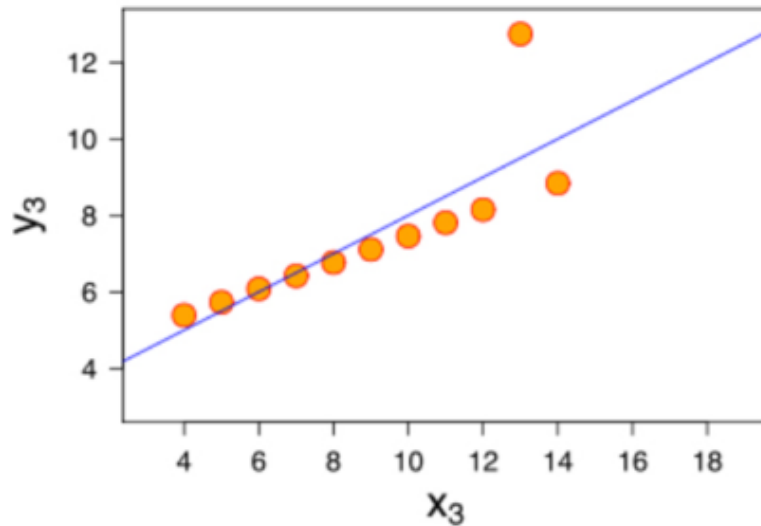
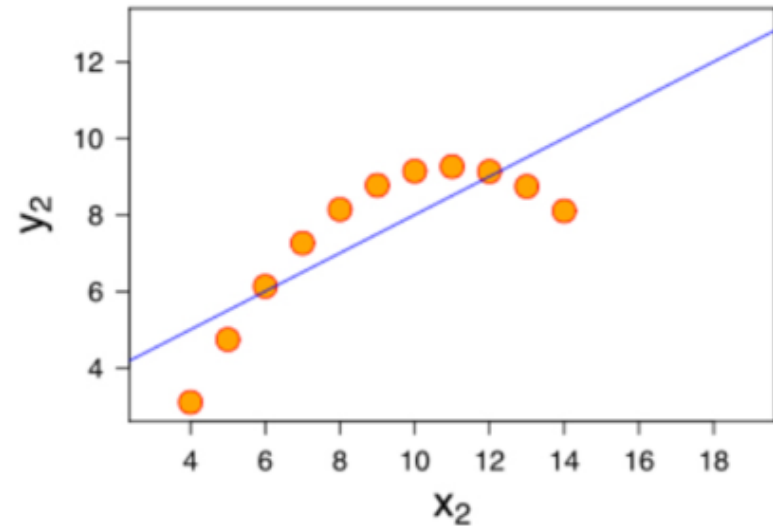
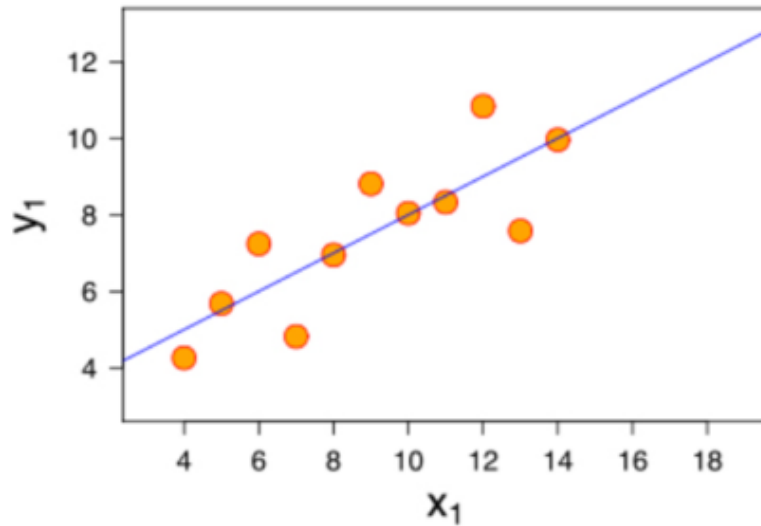
Let's look at some data...with statistical analysis

I		II		III		IV	
x	y	x	y	x	y	x	y
10	8.04	10	9.14	10	7.46	8	6.58
8	6.95	8	8.14	8	6.77	8	5.76
13	7.58	13	8.74	13	12.74	8	7.71
9	8.81	9	8.77	9	7.11	8	8.84
11	8.33	11	9.26	11	7.81	8	8.47
14	9.96	14	8.1	14	8.84	8	7.04
6	7.24	6	6.13	6	6.08	8	5.25
4	4.26	4	3.1	4	5.39	19	12.5
12	10.84	12	9.13	12	8.15	8	5.56
7	4.82	7	7.26	7	6.42	8	7.91
5	5.68	5	4.74	5	5.73	8	6.89
9	--	9	--	9	--	9	--
11	--	11	--	11	--	11	--
--	7.5	--	7.5	--	7.5	--	7.5
--	4.122		4.122		4.122		4.122
0.816	0.816	0.816	0.816	0.816	0.816	0.816	0.816
$y = 3 + 0.5x$	$y = 3 + 0.5x$	$y = 3 + 0.5x$	$y = 3 + 0.5x$	$y = 3 + 0.5x$	$y = 3 + 0.5x$	$y = 3 + 0.5x$	$y = 3 + 0.5x$

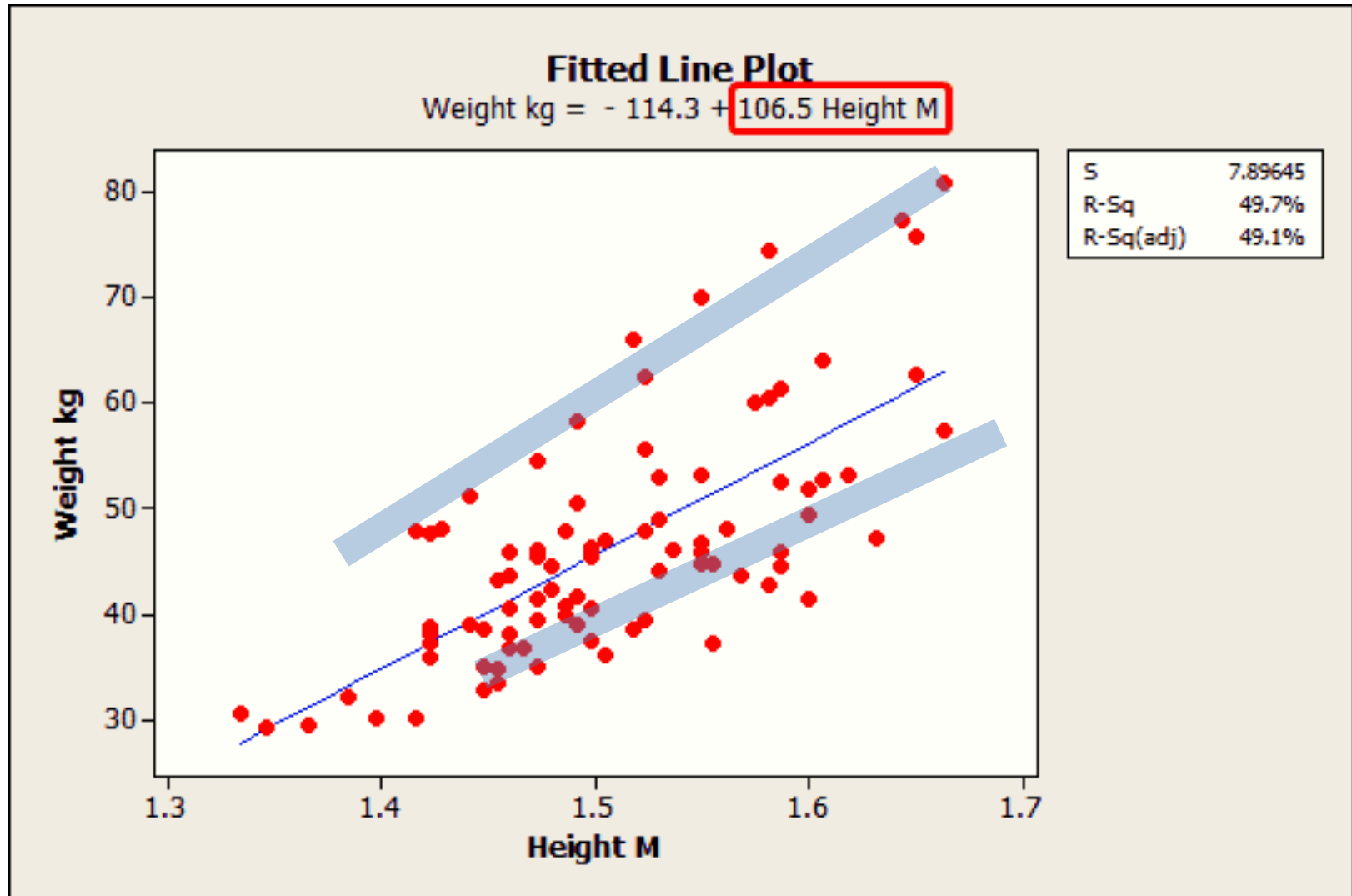
Mean of x
Variance of x
Mean of y
Variance of y
Correlation between x and y
Linear regression line

Let's look at some data ... visually!

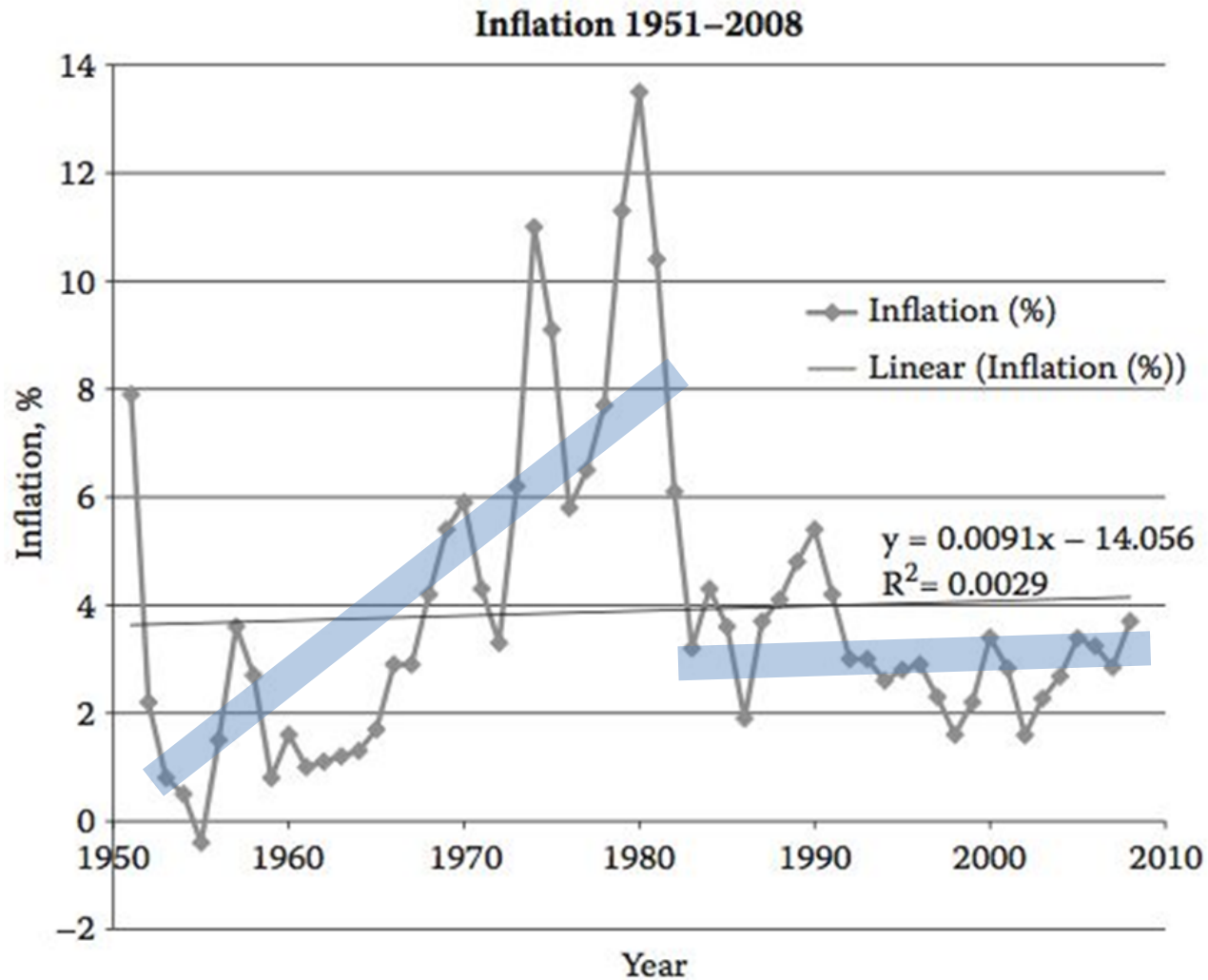
“Anscombe's Quartet”



See the Big Picture



Example 9.5



Visual Indicator of Predictive Ability

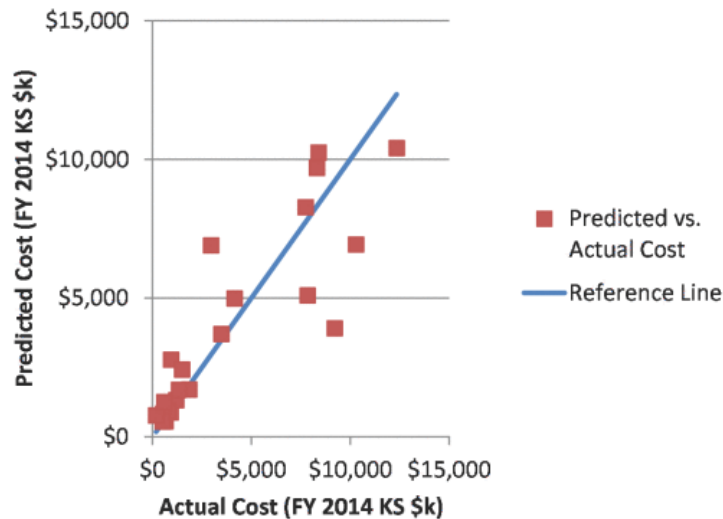


Figure A.1. Predicted vs. actual cost—construct or rehabilitate taxiway.

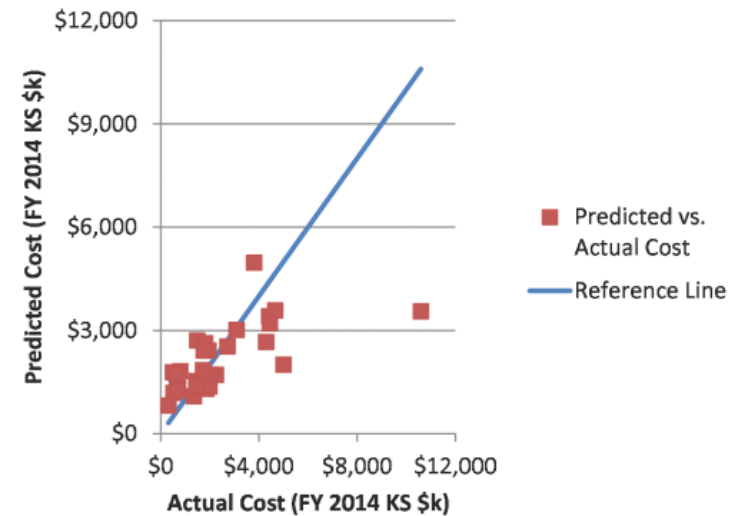


Figure A.3. Predicted vs. actual cost—construct, extend or rehabilitate runway.

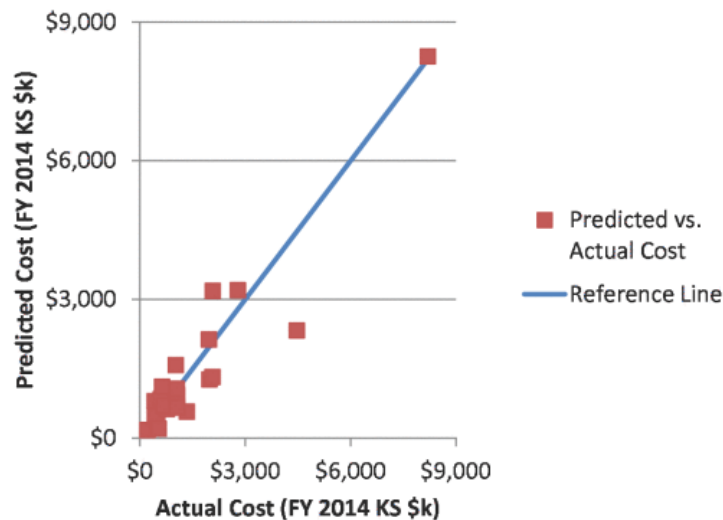


Figure A.2. Predicted vs. actual cost—construct, expand, or rehabilitate apron.

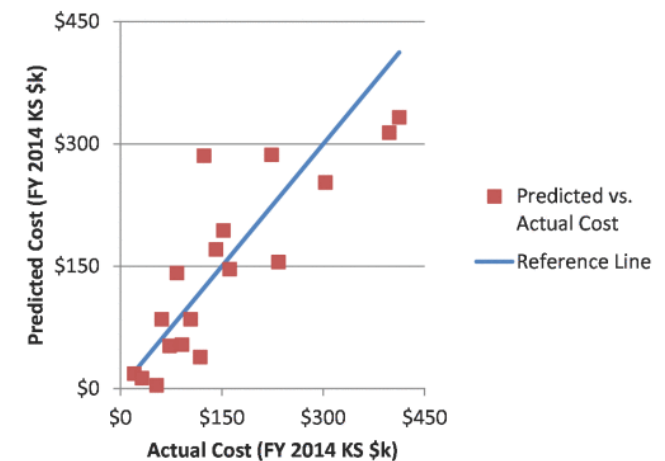
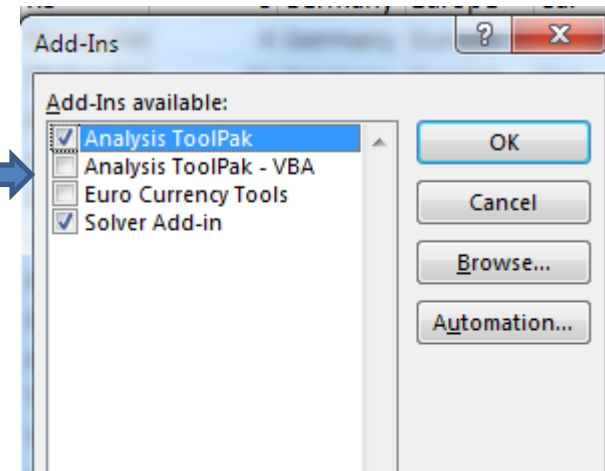
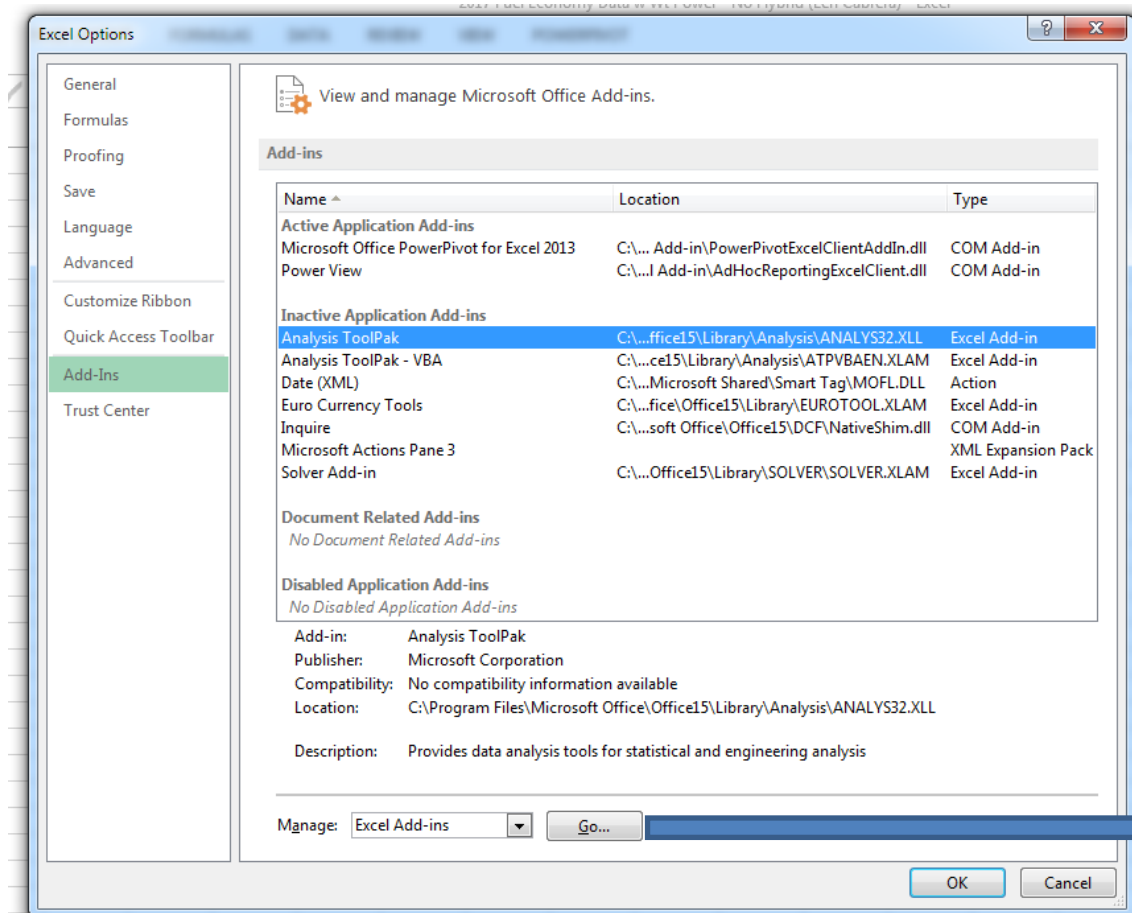
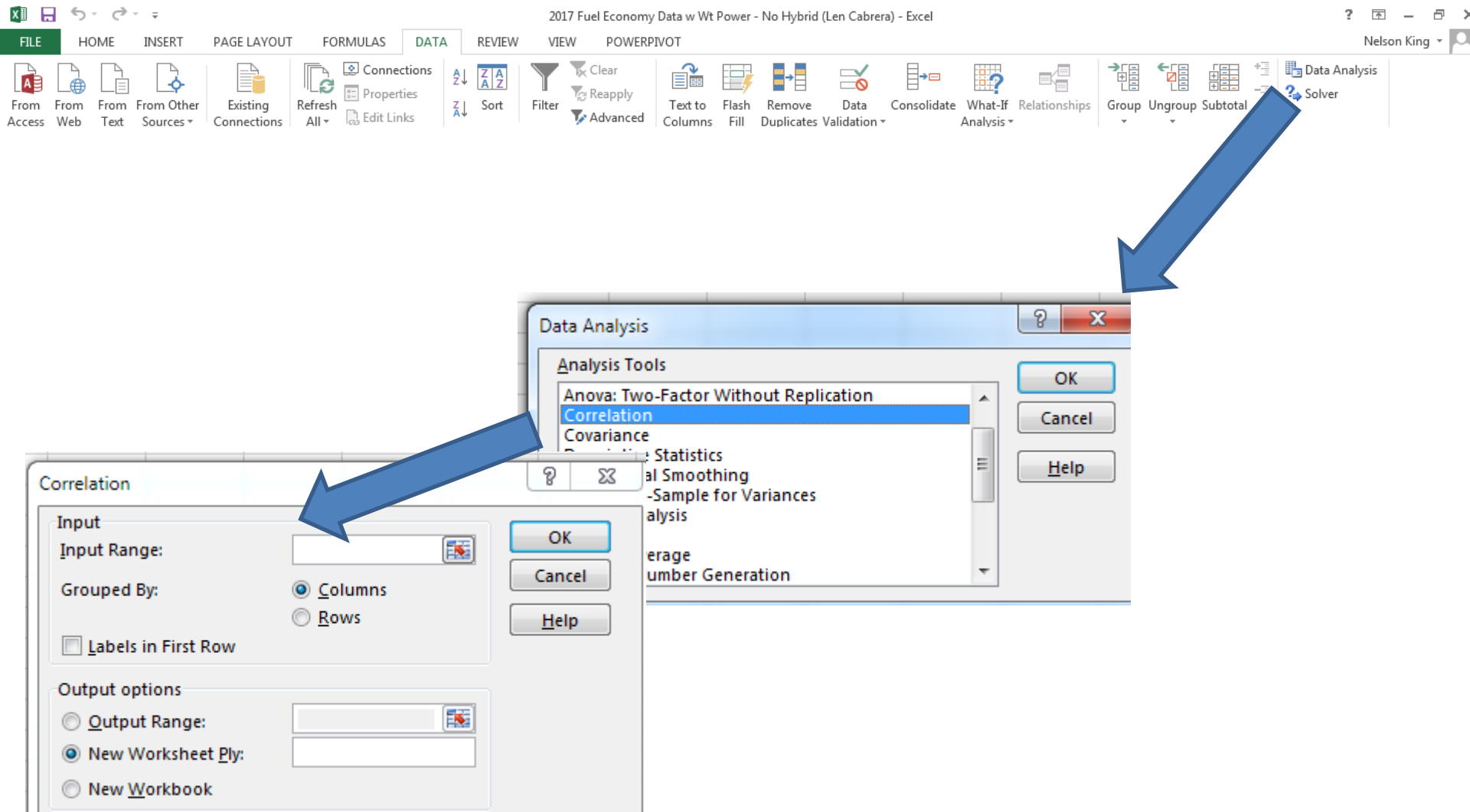


Figure A.4. Predicted vs. actual cost—install perimeter fencing.

Load the Analysis ToolPak



Select Data Analysis



CAR PRICE CER IN EXCEL

Selecting the Data

	A	B	C	D	E	F	G	H	I	J
1	Base Price	Curb weight (lbs)								
2	28940	3093								
3	39150	3765								
4	32950	3483								
5	36400	3585								
6	61400	4003								
7	55400	3969								
8	57495	2465								
9	38990	3636								
10	73595	3822								
11	40990	3768								
12	164150	3737								
13	176350	3957								
14	47950	3164								
15	32150	3197								
16	38550	3428								
17	41250	3627								
18	35150	3362								
19	49550	4046								
20	43150	3583								
21	42150	3493								

?

✕

Correlation

Input

Input Range: 

Grouped By: ☒ Columns ☐ Rows

☒ Labels in first row

Output options

☒ Output Range: 

☐ New Worksheet Ply:

☐ New Workbook

OK

Cancel

Help

Regression – Raw Data

With Zeros

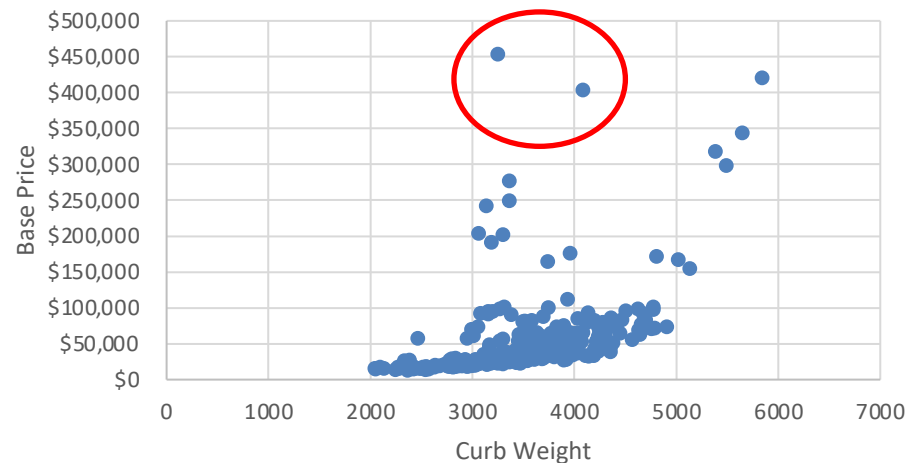
Linear R2	Curb weight (lbs)	Base Price
	1	
Curb weight (lbs)		
Base Price	0.417899	1

130	3378	90390
131	3894	26995
132		
133	4190	32995
134		
135	4232	38995
136	4108	33395
137		
138	4448	64195
139		
140	4279	50195
141	3362	249150
142	3362	276450
143	3750	153750

Remove Zeros

Linear R2	Curb weight (lbs)	Base Price
	1	
Curb weight (lbs)		
Base Price	0.482614	1

Inspecting Data for CER



Regression – Sort (by Weight - Remove Outliers)

	A	B	C
382	Jetta GLI	3153	28715
383	Passat	3263	23260
384	Passat	3571	30115
385	Golf Alltra	3422	27770
386	Golf Alltra	3422	26670
387	Golf Sport	3120	23500
388	Golf Sport	3063	22400
389	Golf Sport	3415	25750
390	Golf Sport	3358	24650
391	S60 R-Des	3862	48395
392	S60 Cross	3913	45195
393	S60 Inscrip	3798	39795
394	S60 Inscrip	3703	37795
395	S60 Polest	3862	60995

Add Level
Delete Level
Copy Level
Options...
☒ My data has headers

Column	Sort On	Order
Sort by	Curb weight (lbs)	Values
		Largest to Smallest

OK
Cancel

	A	B	C
382	VERSA	2363	12875
383	YARIS	2335	18895
384	MX-5	2332	25790
385	YARIS	2315	18095
386	SPARK AC	2312	18045
387	SPARK	2278	14975
388	SPARK AC	2266	16945
389	SPARK	2246	13875
390	Smart fort	2127	15640
391	MIRAGE	2095	16830
392	Smart fort	2050	14650
393	MIRAGE	2040	15630
394	Challenge	0	34495
395	Challenge	0	40495
396	Challenge	0	65695
397	Challenge	0	51695

	A	B	C
1	Model	Curb weight (lbs)	Base Price
2	Phantom	5840	420325
3	Dawn	5644	343875
4	Ghost	5490	298350
5	Wraith	5380	317700
6	M760i xDr	5128	154795
7	S 550 4MA	5017	167195
8	G90 AWD	4905	73175
9	S 600	4806	171745
10	G90 AWD	4784	71575

Regression – Sort (by Weight - Remove Outliers)

By Weight

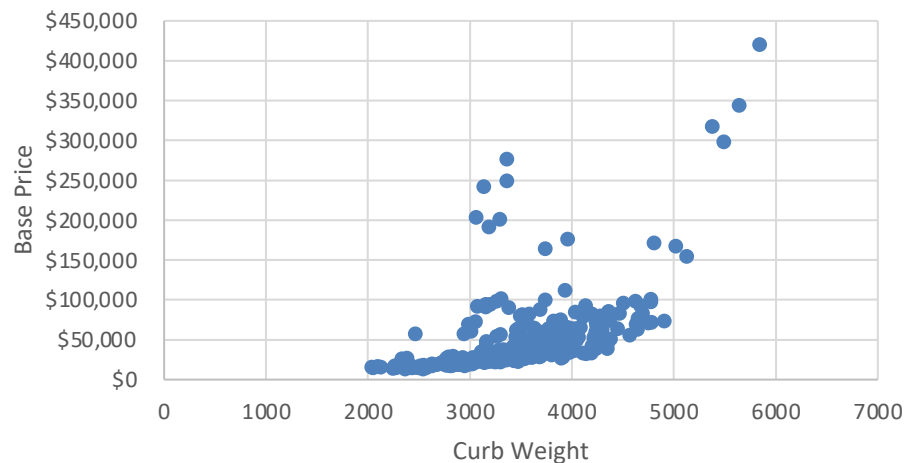
	A	B	C
1	Model	Curb weight (lbs)	Base Price
2	Phantom	5840	420325
3	Dawn	5644	343875
4	Ghost	5490	298350
5	Wraith	5380	317700
6	M760i xDr	5128	154795
7	S 550 4MA	5017	167195
8	G90 AWD	4905	73175
9	S 600	4806	171745
10	G90 AWD	4784	71575
11	S 550	4773	97595
12	S 550 4MA	4773	100595

By Base Price (and Weight)

	A	B	C
1	Model	Curb weight (lbs)	Base Price
2	Ford GT	3250	453750
3	Phantom	5840	420325
4	Aventado	4085	402995
5	Dawn	5644	343875
6	Wraith	5380	317700
7	Ghost	5490	298350
8	488 Spider	3362	276450
9	488 gtb	3362	249150
10	Huracan	3135	241995
11	Huracan 2	3062	202795

Linear R2	Curb weight (lbs)	Base Price
Curb weight (lbs)	1	
Base Price	0.551811	1

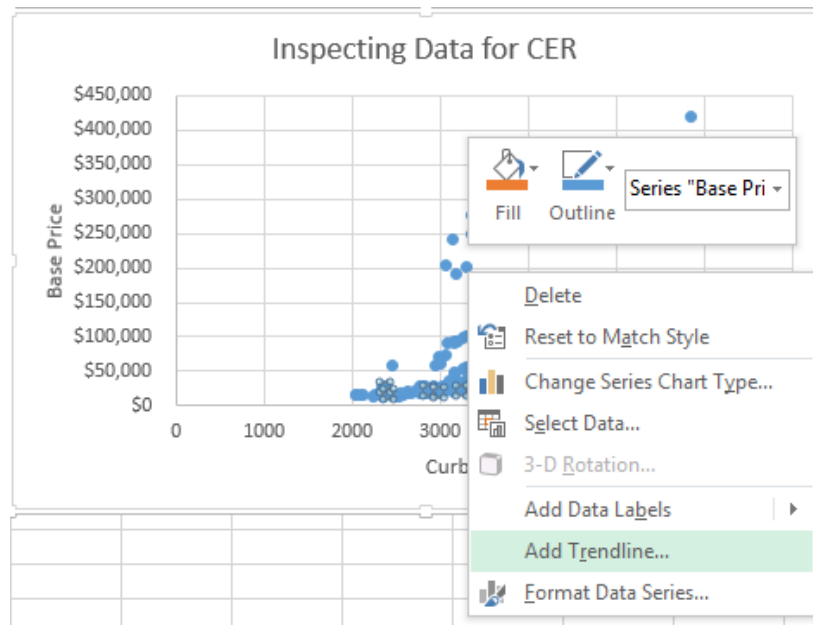
Inspecting Data for CER



Excel

(right click on data point)

Add Trendline



Options

Format Trendline ▼ ✕

TRENDLINE OPTIONS ▼

▲ TRENDLINE OPTIONS

☐ Exponential

☒ Linear

☐ Logarithmic

☐ Polynomial Order

☐ Power

☐ Moving Average Period

Trendline Name

☒ Automatic Linear (Base Price

☐ Custom

Forecast

Forward period

Backward period

☐ Set Intercept

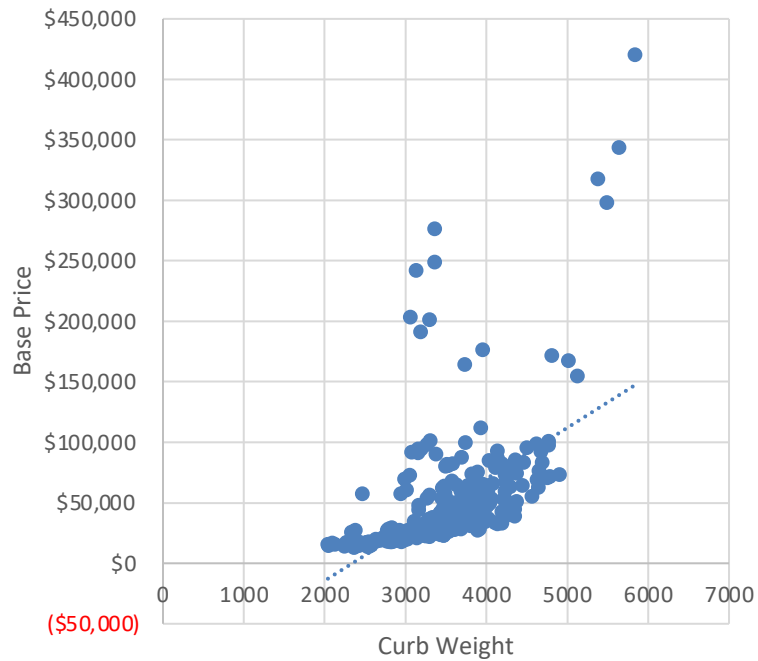
☐ Display Equation on chart

☐ Display R-squared value on chart

Trendline Results

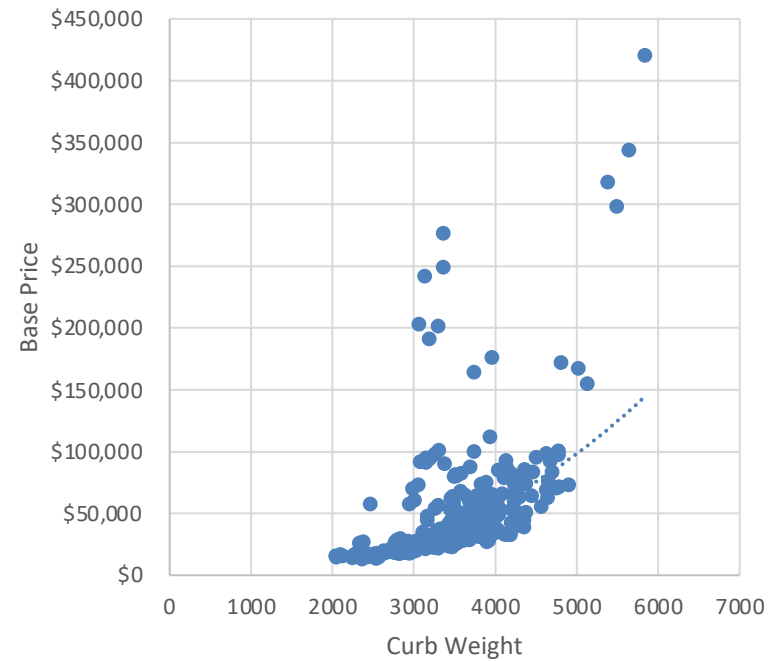
Linear

Inspecting Data for CER

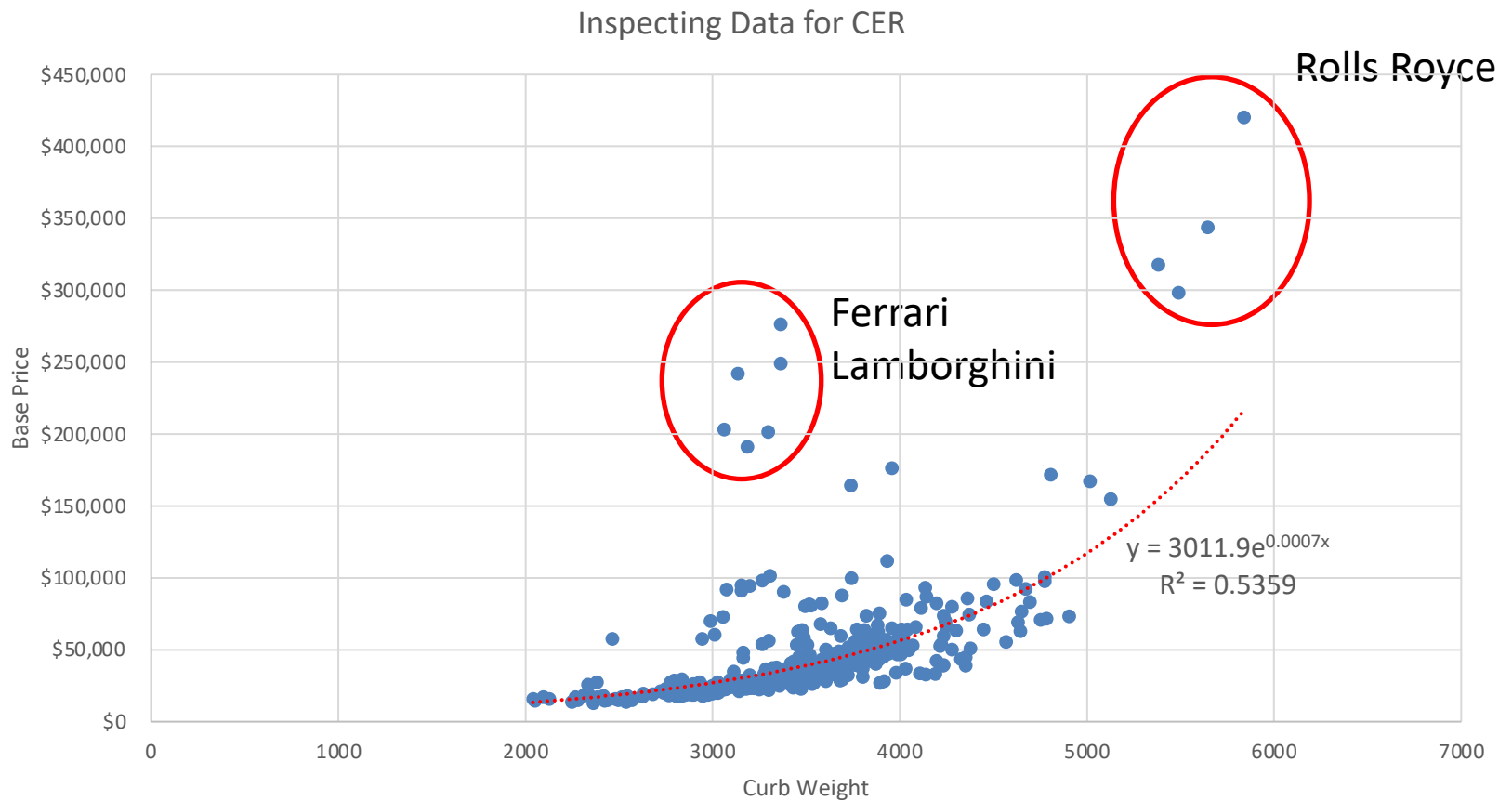


Power

Inspecting Data for CER



Exponential Trendline – Realistic?



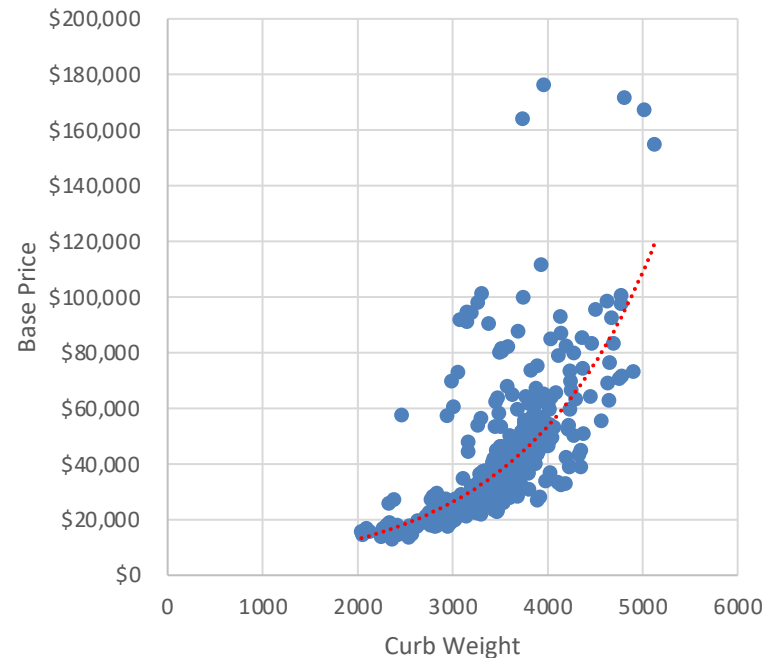
Remove Outliers: Zero data, Expensive cars (Rolls Royce, Lamborghini, McLaren)

Expensive Removed

1	Model	Curb weight (lbs)	Base Price
2	Ford GT		
3	Phantom	5840	420325
4	Aventador Coupe		
5	Dawn	5644	343875
6	Wraith	5380	317700
7	Ghost	5490	298350
8	488 Spider	3362	276450
9	488 gtb	3362	249150
10	Huracan	3135	241995
11	Huracan 2	3062	203295
12	570GT	3296	201450
13	570S Coup	3186	191100
14	R8 Spyder	3957	176350
15	S 600	4806	171745
16	S 550 4MA	5017	167195
17	R8	3737	164150
18	M760i xDr	5128	154795
19	GT S	3833	111600

Exponential

Inspecting Data for CER



Linear R2	Curb weight (lbs)	Base Price
Curb weight (lbs)	1	
Base Price	0.662035	1

Next Step? More Outliers or Trends

After Remove Outliers: Zero data, Expensive cars (Rolls Royce, Lamborghini, McLaren)

