Volkswagen Emissions Scandal

DESIGN OF EXPERIMENTS (DOE)
FINAL PRESENTATION

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Agenda

- Problem Statement
- Overview of Volkswagen Company
- Problems Identified and COPQ
- Root Cause Analysis
- Design of Experiment
  - 8 Steps of DOE using T-table
  - DOE using Minitab
- Conclusion

Problem Statement

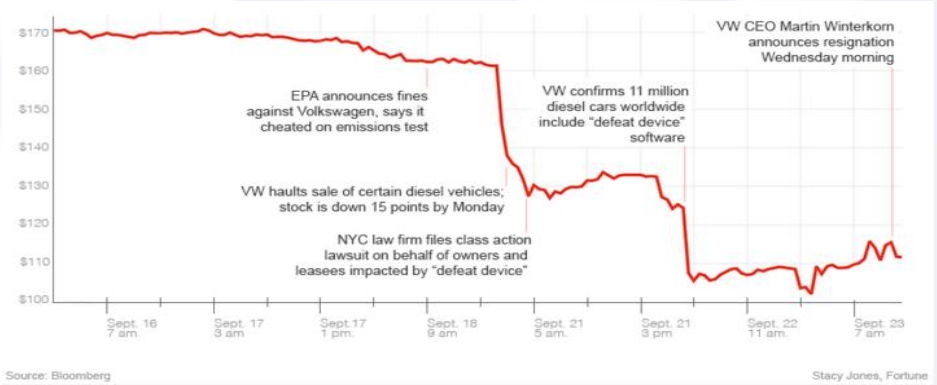
“ In September 2015, **the Environmental Protection Agency (EPA)** found that many Volkswagen cars being sold in America had a "defeat device" - or software - in diesel engines that could detect when they were being tested, changing the performance accordingly to improve results.”

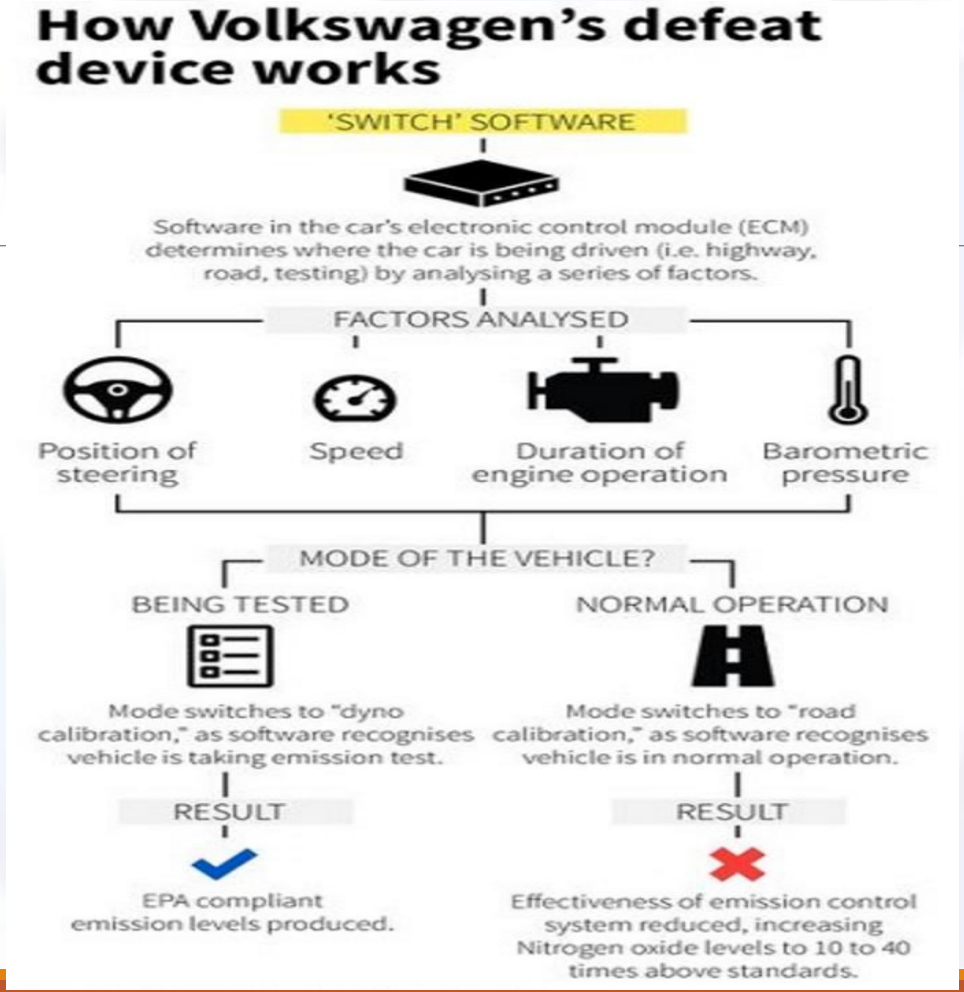
Overview of Volkswagen Company

- Headquartered in Wolfsburg, Germany
- Until January 2016, the largest manufacturer of cars in the world
- Makers of some of the most iconic cars such as VW Beetle and Minibus.
- Owns brands such as
  - Audi
  - Bugatti
  - Porsche
  - Lamborghini
  - Ducati
  - Bentley

Scandal

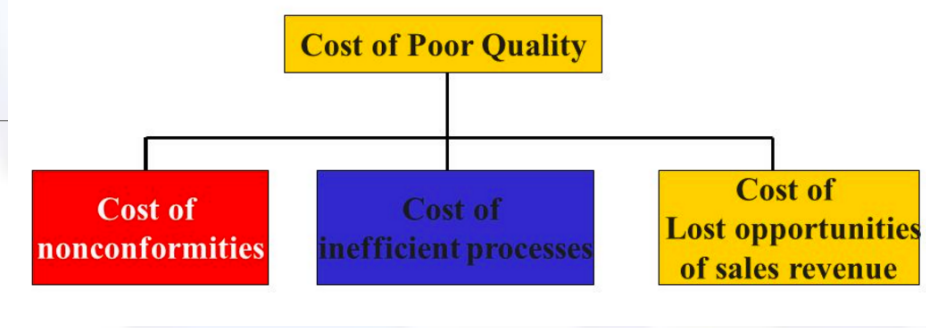
- VW diesel cars had “defeat device” software installed in them
  - Could detect when cars were being tested and accordingly improve emission results
- EPA discovered emission discrepancies in Sept 2015
  - 500K cars in the US
  - 11 Million cars worldwide
- “Defeat Device” found in Porsche and Audi models as well
- Stocks plummet

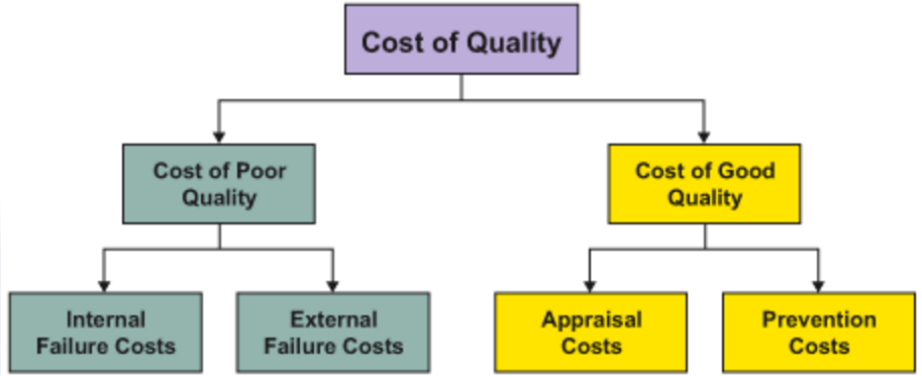



How Volkswagen's defeat device works
'SWITCH' SOFTWARE
Software in the car's electronic control module (ECM) determines where the car is being driven (i.e. highway, road, testing) by analysing a series of factors.
FACTORS ANALYSED
Position of steering
Speed
Duration of engine operation
Barometric pressure
MODE OF THE VEHICLE?
BEING TESTED
NORMAL OPERATION
Mode switches to "dyno calibration," as software recognises vehicle is taking emission test.
Mode switches to "road calibration," as software recognises vehicle is in normal operation.
RESULT
RESULT
EPA compliant emission levels produced.
Effectiveness of emission control system reduced, increasing Nitrogen oxide levels to 10 to 40 times above standards.

Cost of Poor Quality

- Non Conformities
  - Emission standards not met by diesel engines
  - Nitrogen Oxide(NO) emissions 40 times higher than the permissible limit
- Inefficient Processes
  - Lack of transparency and accountability
  - Lack of proper quality checks
- Lost Opportunities
  - Heavy costs incurred due to car recalls
  - Stock prices crashed
  - Brand value jeopardized

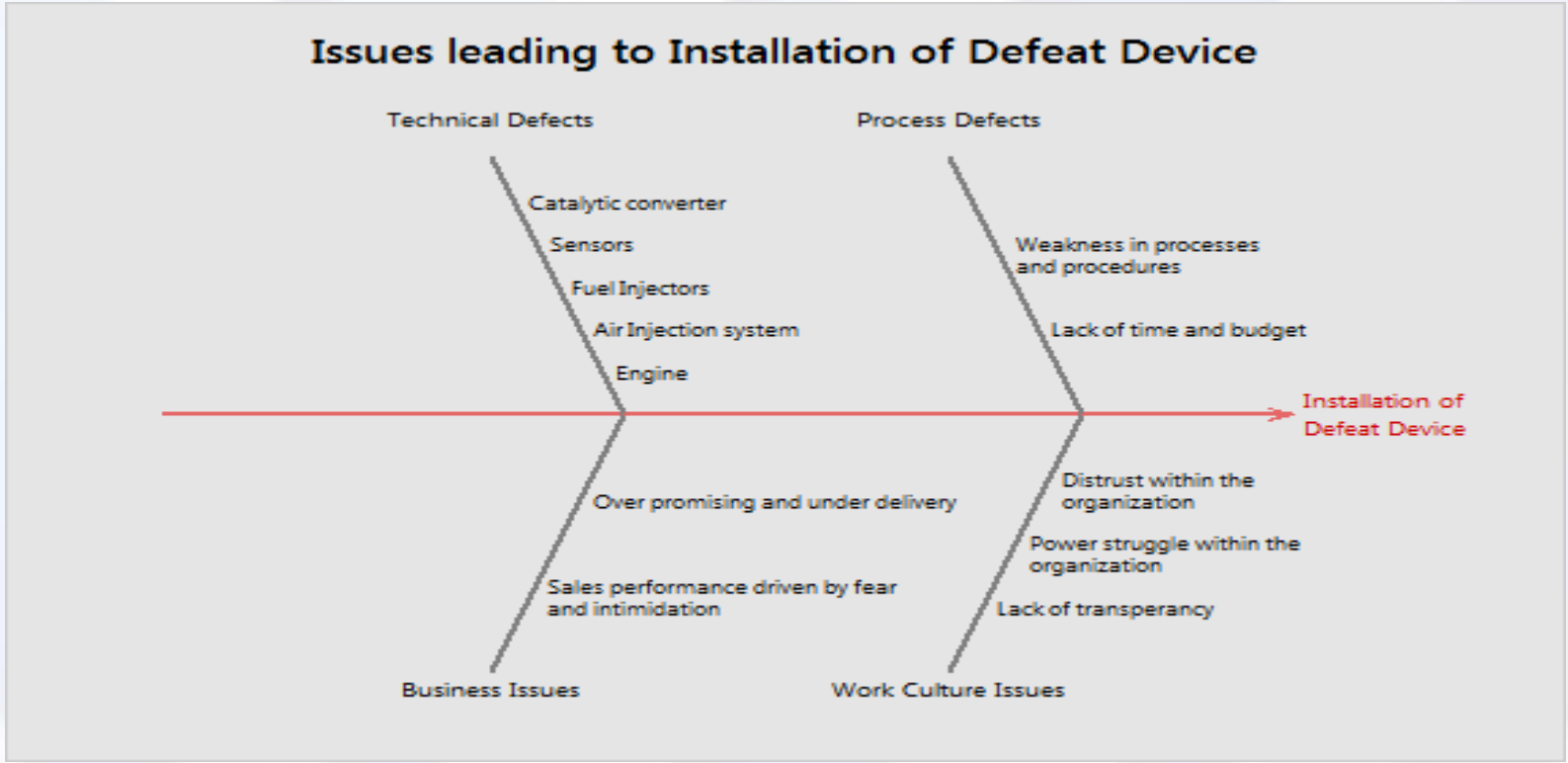




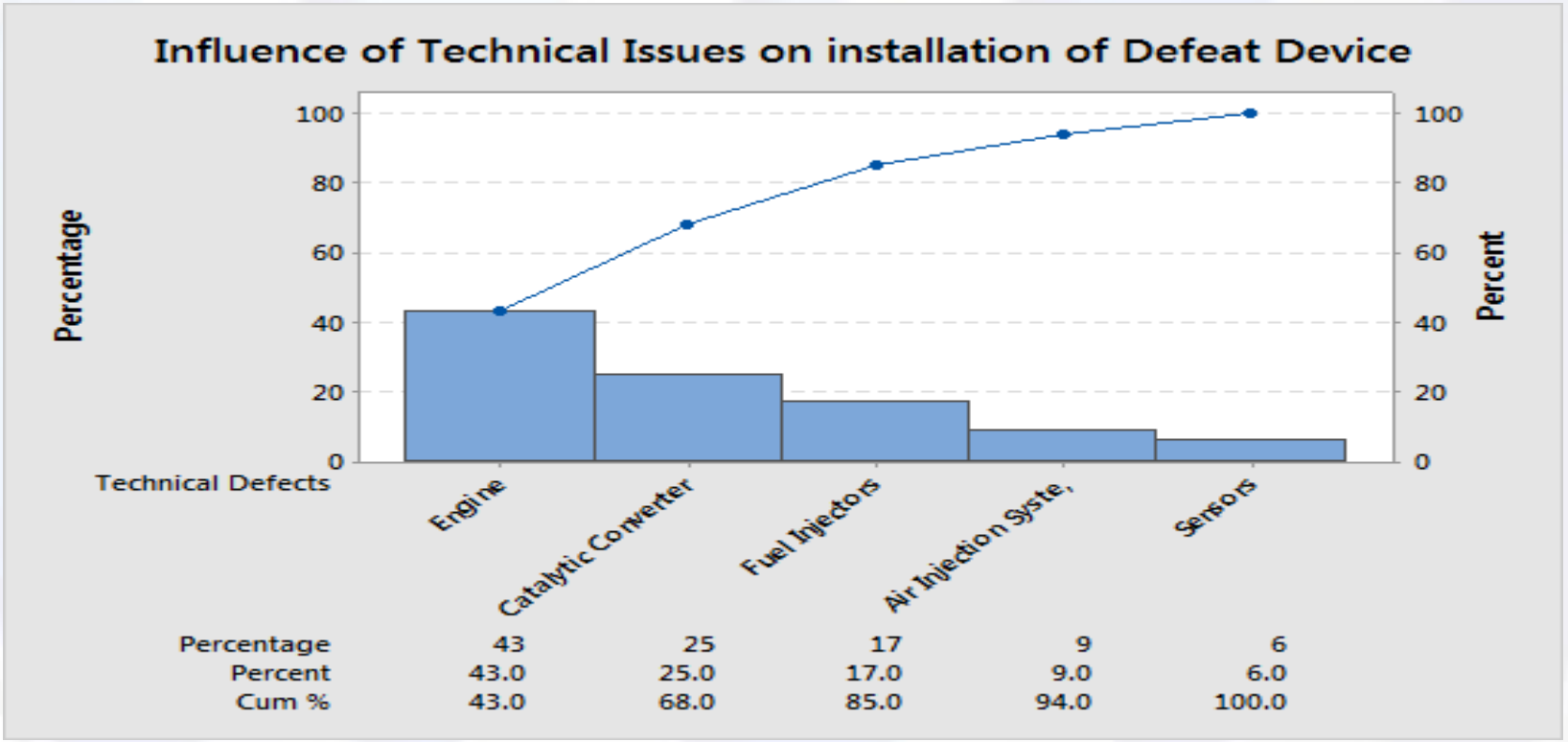
Items of Concern from COPQ

- Not met standards set by regulatory body
- No quality assessments by 3rd party vendors
- Lack of transparency in the organization
- Company chose to build “Defeat Device” rather than tackle the emission problem
- Huge losses for company and stakeholders
- Company needs a lot of time and budget to manage the recalls and correcting the emission problem

Root Cause Analysis - Fishbone Chart



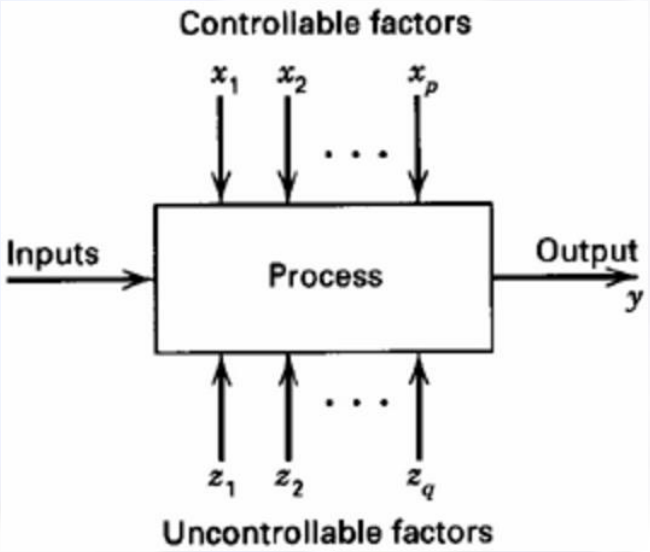
Root Cause of Technical Issues - Pareto Chart



Percentage	43	25	17	9	6
Percent	43.0	25.0	17.0	9.0	6.0
Cum %	43.0	68.0	85.0	94.0	100.0

Design of Experiment

- Based on Pareto chart
  - 43% cause of emission from Engine
  - If Engine is corrected, emissions will reduce significantly
- Further analyzing the Engine, the factors that affect emissions
  - Engine Type
    - 4 cylinder engine vs 6 cylinder engine
  - Weight
    - Small car (1 Ton) vs Large car (3.5 Tonnes)
  - Average Speeds
    - City Traffic (30 MPH) vs Highway Traffic (60 MPH)
- The cars will undergo on-road emission testing to avoid discrepancies from in-house testing



Design of Experiments Cont…

- Create a 2^3 experiment (3 Factors)
- We consider 2 replicates for each run

	Factor A	Factor B	Factor C
	Engine Type	Weight	Avg Speed
Low	V4	1 Tonn	30 MPH
High	V6	3.5 Tonnes	60 MPH

Run	Engine Type	Weight	Avg Speed	Emission-1	Emission-2
1	-1	1	1	8.77	9.36
2	-1	1	-1	5.49	8.19
3	1	1	1	9.5	8.97
4	1	-1	1	5.9	6.45
5	-1	-1	-1	3.06	3.7
6	-1	-1	1	5.06	5.69
7	1	1	-1	6.01	7.63
8	1	-1	-1	3.69	6.6

Steps for Analysis of Effects in a DOE

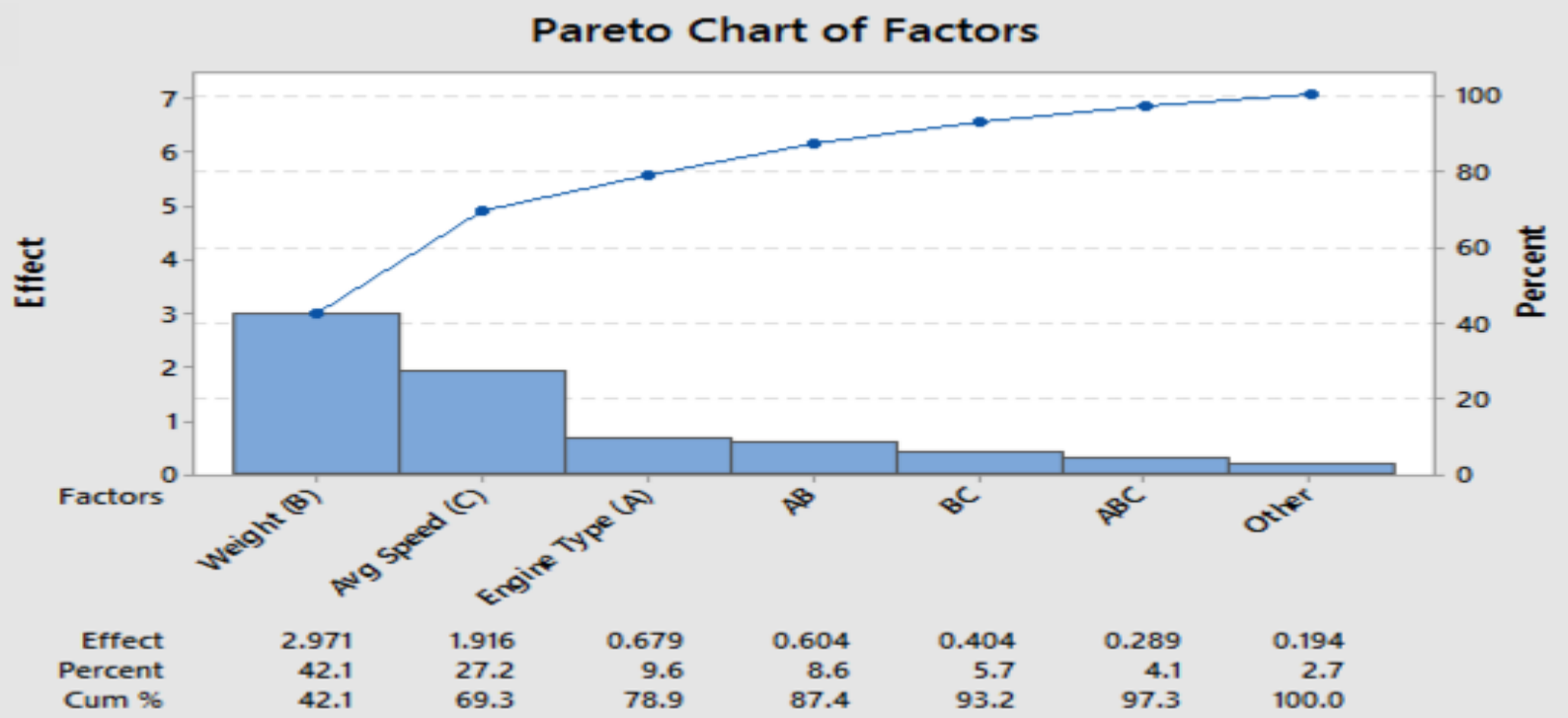
I. Calculate the effects
II. Calculate the Pareto chart
III. Calculate the Standard Deviation of the experiment, S_e
IV. Calculate the standard deviation of the Effects, S_{eff}
V. Determine the T-statistic
VI. Calculate the decision limits and determine the significant effects
VII. Graph significant effects
VIII. Model the significant effects

Step 1 - Calculate the effects

- **Effects of Individual factors**
  - Engine Type: **0.67875**
  - Weight: **2.97125**
  - Avg Speed: **1.91625**
- **Effects of two level interactions**
  - Engine and Weight: **-0.60375**
  - Engine and Avg Speed: **-0.19375**
  - Weight and Avg Speed: **0.40375**
- **Effects of three level interaction**
  - Engine, Weight and Avg Speed: **0.28875**

Run	Engine Type (A)	Weight (B)	Avg Speed (C)	AB	AC	BC	ABC	Emission-1	Emission-2	Average	Variance
1	-1	-1	-1	1	1	1	-1	3.06	3.7	3.38	0.2048
2	1	-1	-1	-1	-1	1	1	3.69	6.6	5.145	4.23405
3	-1	1	-1	-1	1	-1	1	5.49	8.19	6.84	3.645
4	1	1	-1	1	-1	-1	-1	6.01	7.63	6.82	1.3122
5	-1	-1	1	1	-1	-1	1	5.06	5.69	5.375	0.19845
6	1	-1	1	-1	1	-1	-1	5.9	6.45	6.175	0.15125
7	-1	1	1	-1	-1	1	-1	8.77	9.36	9.065	0.17405
8	1	1	1	1	1	1	1	9.5	8.97	9.235	0.14045
Sum Emission +	27.375	31.96	29.85	24.81	25.63	26.825	26.595				
Sum Emission -	24.66	20.075	22.185	27.225	26.405	25.21	25.44				
Avg Emission +	6.84375	7.99	7.4625	6.2025	6.4075	6.70625	6.64875				
Avg Emission -	6.165	5.01875	5.54625	6.80625	6.60125	6.3025	6.36				
Effect	**0.67875**	**2.97125**	**1.91625**	**-0.60375**	**-0.19375**	**0.40375**	**0.28875**				
Regression Coeff	0.339375	1.485625	0.958125	-0.301875	-0.096875	0.201875	0.144375				

Step 2 - Calculate the Pareto Chart



Step 3 - Calculate the Standard Deviation - S_e

- Average variance of the Base 8 Runs
  - $S_b^2 = \frac{0.21+4.23+3.65+1.31+0.19+0.15+0.17+0.14}{8} = 1.26$
- Degree of Freedom for design
  - $d_{fb} = (\#\ of\ runs) * (\#of\ replicates - 1\ )$

    $= 8 * (2 - 1) = 8$
- Calculate S_e^2
  - $S_e^2 = S_b^2 = 1.26$
  - $S_e = \sqrt{1.25} = 1.12$

Run	Engine Type (A)	Weight (B)	Avg Speed (C)	AB	AC	BC	ABC	Emission-1	Emission-2	Average	Variance
1	-1	-1	-1	1	1	1	-1	3.06	3.7	3.38	0.2048
2	1	-1	-1	-1	-1	1	1	3.69	6.6	5.145	4.23405
3	-1	1	-1	-1	1	-1	1	5.49	8.19	6.84	3.645
4	1	1	-1	1	-1	-1	-1	6.01	7.63	6.82	1.3122
5	-1	-1	1	1	-1	-1	1	5.06	5.69	5.375	0.19845
6	1	-1	1	-1	1	-1	-1	5.9	6.45	6.175	0.15125
7	-1	1	1	-1	-1	1	-1	8.77	9.36	9.065	0.17405
8	1	1	1	1	1	1	1	9.5	8.97	9.235	0.14045
Sum Emission +	27.375	31.96	29.85	24.81	25.63	26.825	26.595				
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Step 4 - Calculate the Standard Deviation of the Effects

- $S_{eff} = S_e * \sqrt{\frac{4}{N}}$
  - $1.12 * \sqrt{\frac{4}{8}}$
  - $1.12 * 0.707 = 0.792$

Run	Engine Type (A)	Weight (B)	Avg Speed (C)	AB	AC	BC	ABC	Emission-1	Emission-2	Average	Variance
1	-1	-1	-1	1	1	1	-1	3.06	3.7	3.38	0.2048
2	1	-1	-1	-1	-1	1	1	3.69	6.6	5.145	4.23405
3	-1	1	-1	-1	1	-1	1	5.49	8.19	6.84	3.645
4	1	1	-1	1	-1	-1	-1	6.01	7.63	6.82	1.3122
5	-1	-1	1	1	-1	-1	1	5.06	5.69	5.375	0.19845
6	1	-1	1	-1	1	-1	-1	5.9	6.45	6.175	0.15125
7	-1	1	1	-1	-1	1	-1	8.77	9.36	9.065	0.17405
8	1	1	1	1	1	1	1	9.5	8.97	9.235	0.14045
Sum Emission +	27.375	31.96	29.85	24.81	25.63	26.825	26.595				
Sum Emission -	24.66	20.075	22.185	27.225	26.405	25.21	25.44				
Avg Emission +	6.84375	7.99	7.4625	6.2025	6.4075	6.70625	6.64875				
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Regression Coeff	0.339375	1.485625	0.958125	-0.301875	-0.096875	0.201875	0.144375				

Step 5 - Determine the T-Statistic

- $\alpha = 0.05$
- $d_f = 8$
- $t - value = 1.859$

df/p	0.40	0.25	0.10	0.05	0.025	0.01	0.005	0.0005
1	0.324920	1.000000	3.077684	6.313752	12.70620	31.82052	63.65674	636.6192
2	0.288675	0.816497	1.885618	2.919986	4.30265	6.96456	9.92484	31.5991
3	0.276671	0.764892	1.637744	2.353363	3.18245	4.54070	5.84091	12.9240
4	0.270722	0.740697	1.533206	2.131847	2.77645	3.74695	4.60409	8.6103
5	0.267181	0.726687	1.475884	2.015048	2.57058	3.36493	4.03214	6.8688
6	0.264835	0.717558	1.439756	1.943180	2.44691	3.14267	3.70743	5.9588
7	0.263167	0.711142	1.414924	1.894579	2.36462	2.99795	3.49948	5.4079
8	0.261921	0.706387	1.396815	1.859548	2.30600	2.89646	3.35539	5.0413
9	0.260955	0.702722	1.383029	1.833113	2.26216	2.82144	3.24984	4.7809
10	0.260185	0.699812	1.372184	1.812461	2.22814	2.76377	3.16927	4.5869
11	0.259556	0.697445	1.363430	1.795885	2.20099	2.71808	3.10581	4.4370
12	0.259033	0.695483	1.356217	1.782288	2.17881	2.68100	3.05454	43178
13	0.258591	0.693829	1.350171	1.770933	2.16037	2.65031	3.01228	4.2208
14	0.258213	0.692417	1.345030	1.761310	2.14479	2.62449	2.97684	4.1405
15	0.257885	0.691197	1.340606	1.753050	2.13145	2.60248	2.94671	4.0728
16	0.257599	0.690132	1.336757	1.745884	2.11991	2.58349	2.92078	4.0150
17	0.257347	0.689195	1.333379	1.739607	2.10982	2.56693	2.89823	3.9651

Step 6 - Calculate decision limits and significant effects

$$Decision\ Limit = \pm t * S_{eff} = \pm 1.859 * 0.792 = \pm 1.4723$$

Run	Engine Type (A)	Weight (B)	Avg Speed (C)	AB	AC	BC	ABC	Emission-1	Emission-2	Average	Variance
1	-1	-1	-1	1	1	1	-1	3.06	3.7	3.38	0.2048
2	1	-1	-1	-1	-1	1	1	3.69	6.6	5.145	4.23405
3	-1	1	-1	-1	1	-1	1	5.49	8.19	6.84	3.645
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7	-1	1	1	-1	-1	1	-1	8.77	9.36	9.065	0.17405
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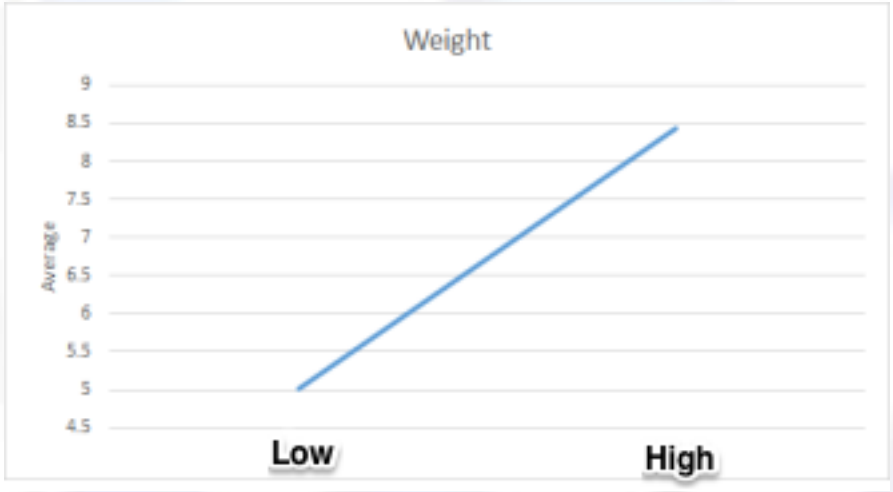
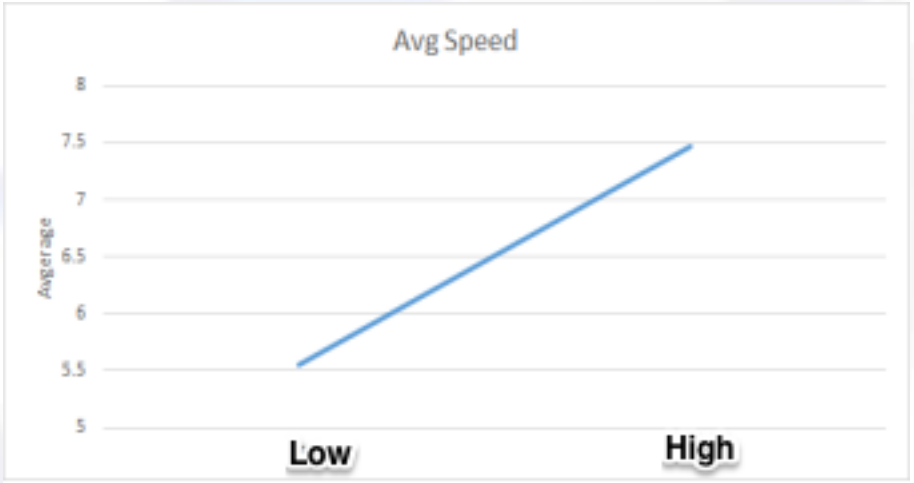
Regression Coeff	0.339375	1.485625	0.958125	-0.301875	-0.096875	0.201875	0.144375				

Factor	Engine Type (A)	Weight (B)	Avg Speed (C)	AB	AC	BC	ABC
Significance	No	Yes	Yes	No	No	No	No

Step 7 - Graph significant effects





Step 8 - Model the significant effects

Weight

$$\hat{\bar{Y}} = \bar{\bar{Y}} + \frac{E(B)}{2} * B =$$

$$6.504 + 2.97125/2 * B =$$

$$6.504 + 1.486B$$

Average Speed

$$\hat{\bar{Y}} = \bar{\bar{Y}} + \frac{E(C)}{2} * C =$$

$$6.504 + 1.91625/2 * C =$$

$$6.504 + 0.958C$$

Minitab for DOE

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	7	54.4379	7.7768	6.18	0.010
Linear	7	54.4379	7.7768	6.18	0.010
Engine Type (A)	1	1.8428	1.8428	1.47	0.261
Mileage (B)	1	35.3133	35.3133	28.08	0.001
Avg Speed (C)	1	14.6881	14.6881	11.68	0.009
AB	1	1.4581	1.4581	1.16	0.313
BC	1	0.6521	0.6521	0.52	0.492
AC	1	0.1502	0.1502	0.12	0.739
ABC	1	0.3335	0.3335	0.27	0.620
Error	8	10.0602	1.2575		
Total	15	64.4982			

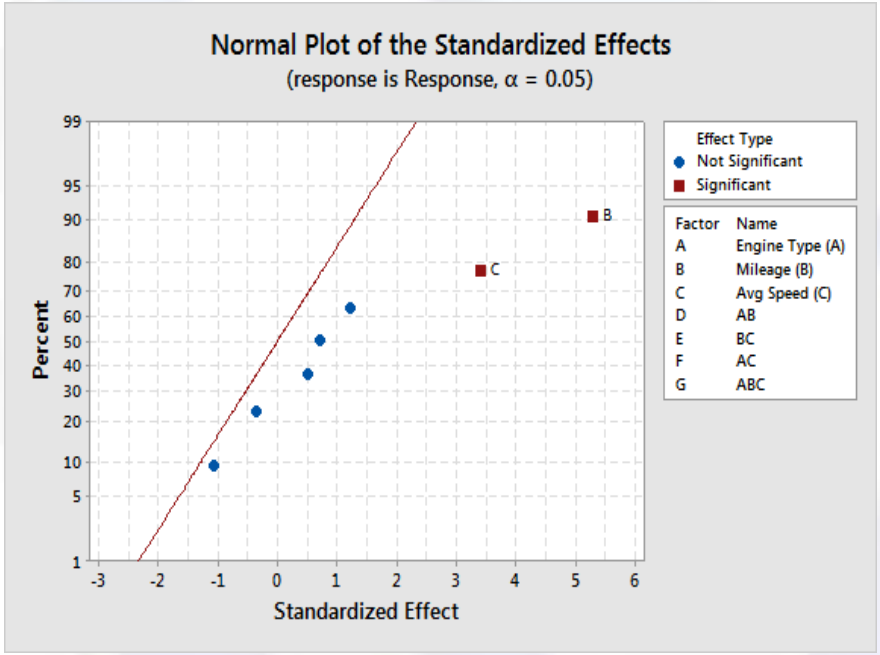
Coded Coefficients

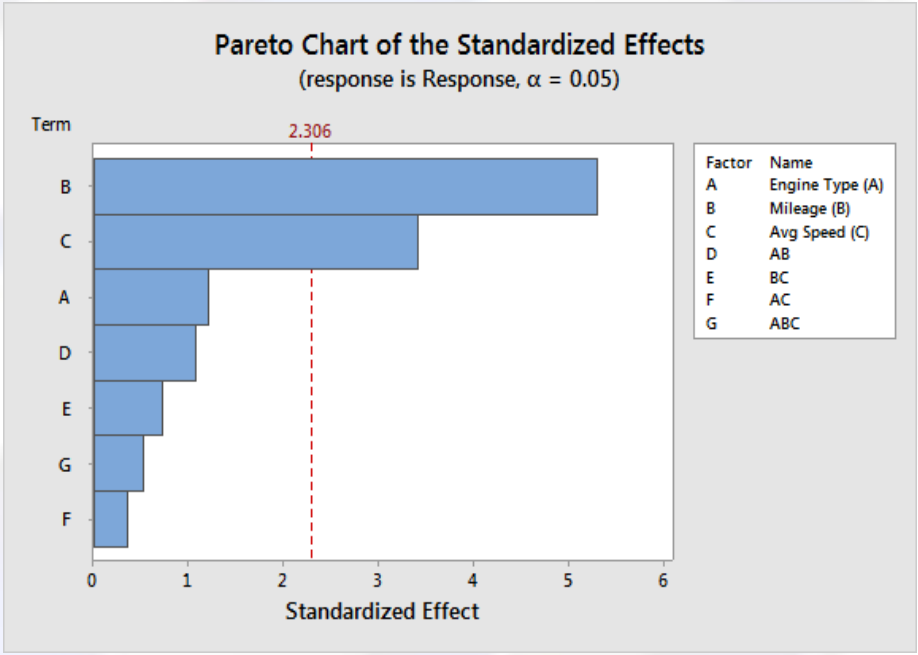
Term	Effect	Coef	SE Coef	T-Value	P-Value	VIF
Constant		6.504	0.280	23.20	0.000	
Engine Type (A)	0.679	0.339	0.280	1.21	0.261	1.00
Mileage (B)	2.971	1.486	0.280	5.30	0.001	1.00
Avg Speed (C)	1.916	0.958	0.280	3.42	0.009	1.00
AB	-0.604	-0.302	0.280	-1.08	0.313	1.00
BC	0.404	0.202	0.280	0.72	0.492	1.00
AC	-0.194	-0.097	0.280	-0.35	0.739	1.00
ABC	0.289	0.144	0.280	0.51	0.620	1.00

Regression Equation in Uncoded Units

Response = 6.504 + 0.339 Engine Type (A) + 1.486 Mileage (B) + 0.958 Avg Speed (C) - 0.302 AB
+ 0.202 BC - 0.097 AC + 0.144 ABC

Plots obtained from Minitab





Conclusion

- Factors that have significant effect on Engine are -
  - Weight
  - Avg Speed
- VW should reduce weight of the car by using light and strong materials
- Improvements in emission equipment such as Exhaust pipe and catalytic converter to counter emissions during high speed

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Questions?