Design of Experiments Applied to Vehicle Dynamics Development

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About the author

Tim Drotar is currently a senior staff engineer in vehicle dynamics at Tesla. Prior to joining Tesla, he spent 30 years at Ford Motor Company where he specialized in chassis systems and vehicle dynamics for passenger cars and light trucks. Tim is a member of SAE, SCCA and The Tire Society. He holds a B.S. in Mechanical Engineering from Lawrence Technological University and a M.S. in Mechanical Engineering from the University of Michigan-Dearborn.

Tim also teaches the following classes for SAE:

- Advanced Vehicle Dynamics for Passenger Cars and Light Trucks
  - https://www.sae.org/learn/content/c0415/
- Fundamentals of Steering Systems
  - https://www.sae.org/learn/content/c0716/

Outline

- Learning Objectives
- What is Design of Experiments (DOE)?
- Why use DOE in Vehicle Dynamics Development
- Terminology
- Books/Software
- Example: Screening DOE for Primary Ride
- Example: RSM DOE for transient handling
- Summary

Learning Objectives

At the end of this presentation, you should be able to:

- Explain what a Design of Experiments (DOE) is/is-not
- Explain why one would use DOE in vehicle dynamics development
- Apply common DOE terminology
- Explain the 3 main types of Classical DOE’s
- Explain the strength and limitation of each type of classical DOE’s

What is DOE?

DOE **is** a statistical methodology to evaluate the effect of multiple factors. These factors are changed simultaneously, according to a predefined pattern, to investigate their effect on the output.

Run	Factor 1	Factor 2	.....	F_n	Response 1	….	R_m
1	Low	Low	…..	High	$R_{1,1}$	….	$R_{1,m}$
2	High	Low	…..	High	$R_{2,1}$	….	$R_{2,m}$
3	Low	High	…..	High	$R_{3,1}$	….	$R_{3,m}$
…..	…..	…..	…..	…..	…..	….	…..
n	Low	Low		Low	$R_{n,1}$	….	$R_{n,m}$

DOE **is not** a “Silver Bullet” approach to solving a problem

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Why use DOE in Vehicle Dynamics Development?

Efficiency:

DOE enables one to extract the maximum amount of information in the minimum amount of time, as compared to the “Silver Bullet” approach or OFAT (One Factor at a Time) testing.

Complexity:

The automotive chassis is very complex; there are a lot of knobs to turn, each with different levels of effectiveness on the response of the vehicle.

Hardpoints (one side):

UCA: 3 attachment points x 3 directions (X, Y, Z) = 9 factors
LCA: 3 attachment points x 3 directions = 9 factors
Tie rod: 2 attachments x 3 directions = 6 factors

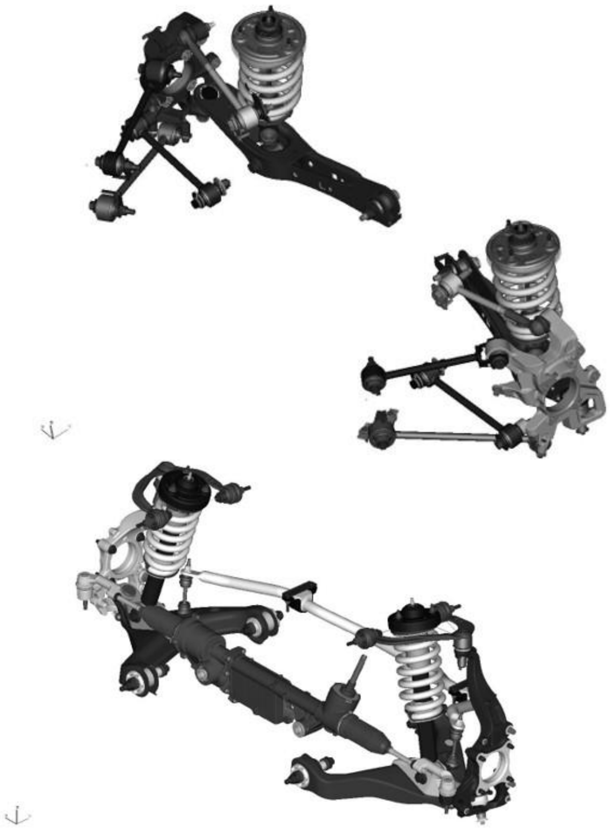
Bushings (one side):

UCA: 2 bushings x 6 stiffness directions (3T/3R) = 12 factors
LCA: 2 bushings x 6 stiffness directions (3T/3R) = 12 factors

24 hardpoint factors and 24 bushing factors = 48 total factors! That’s just the front suspension!

Complexity:

Furthermore, the vehicle dynamics engineer is concerned with several attributes (ride, steering, handling, braking and acceleration) and must find a single chassis setup that balances all the attributes



Factors	**Responses**:
Hardpoints	Ride (Primary/Secondary)
Bushings	Steering (Straight/Cornering/Parking)
Springs	Handling (Steady state/Transient)
Dampers	Error States
Stabilizer bars	NVH (Tactile and Audible)
Steering gear	Durability Road Loads
Tires	

Why use DOE in Vehicle Dynamics Development?

A veteran vehicle dynamics development engineer will be able to “get the vehicle in the box” with just a few part changes to the prototype vehicle. However, for a relatively new engineer or a seasoned engineer with a brand-new suspension, DOE is a useful tool to help point them in the correct direction.

When used in conjunction with Vehicle Dynamics CAE tools, DOE can be used to:

- Provide direction to the design community on up-front decisions regarding suspension architecture, kinematics and compliances.
- Help resolve any conflicts between attributes that arise in the early stages of design and development.

DOE Terminology

Factor: What you are varying
Response: What you measure

Factors (F_n)		Response (R_n)
Spring rate	Vehicle System	Lateral acceleration gain
Hardpoint location		Torque at 0g
Bushing stiffness		Yaw response time

DOE run matrix: Predefined matrix of experimental runs
Setting: Value for the factor
Level: How many factor settings you are evaluating
e.g. low, nominal, high would be 3-level

Types of DOE's

There are 3 main types of DOE methods:

- Classical
- Taguchi
- Optimization

All three methods share the common goal of providing the maximum amount of information about the effect of factor setting on system response, with the least amount of data. The difference between the 3 methods lies in how the experimental design is constructed and how the data is processed. For this discussion, we will concentrate on the “Classical Methods”

There are 3 main types of Classical DOE's:

- Screening
- Factorial
- Response Surface Method (RSM)

Classical Screening DOE

Advantages:

- Allows one to narrow a large number of factors to the "critical few"
  - Prelude to further DOE's
- Obtain information quickly i.e. minimum number of runs

Limitations:

- Lower accuracy than other DOE's
- Can only determine magnitude and direction of factor change on system response
- Can only gather information on the main effect of factor setting, no information on the effect of factor interactions on system response
  - Response = $a_0+a_1F_1+a_2F_2+a_3F_3$
- Typically, only use 2-level factor settings (e.g. low, high)

Some common types:

- Plackett-Burman, Fractional Factorial, Taguchi

Classical Factorial DOE

Advantages

- Fewer factors than the screening DOE
- Obtain information on main effects and 2-way interactions
  - Response = $a_0+a_1F_1+a_2F_2+a_3F_1F_2$

Limitations:

- Allows fewer factors than the screening DOE
- Typically, only use 2-level factor settings (e.g., low, high)
- Linear model of factor setting on system response

Some common types:

- Full Factorial, Fractional Factorial, D-Optimal

Classical Response Surface Method (RSM) DOE

Advantages

- Fewer factors than the screening or factorial
- Can generate a highly accurate, higher order equation of the factor setting effect on system response
  - Response = $a_0 + a_1F_1+a_2F_2+a_3F_1F_2+a_4F_1^2+a_5F_2^2$…….
- Can use 2 or 3 level factors

Limitations:

- Allows fewer factors than the screening or factorial
- Often requires a large number of runs
- Better suited for CAE than physical test

Some common types:

- Box-Behnken, Central Composite, D-Optimal

Classical DOE References

Fortunately for engineers, there are references and software packages that take a lot of the statistical work out of setting up an experiment (e.g. selecting the proper experimental design matrix) and processing the data.

A couple of good books on Classical DOE are:

<u>Statistics for Experimenters: An Introduction to Design, Data Analysis, and Model Building</u>; G. P. Box, W. G. Hunter, J. S. Hunter, Wiley, 1978.

<u>Experimental Designs, 2nd Edition;</u> W. G. Cochran, G. M. Cox, Wiley, 1957

DOE Software

In addition, there are some commercially available DOE software packages that take the statistical labor out setting up the experiment and processing the data:

- HyperStudy – Altair Engineering
- LMS Optimus – Noesis Solutions
- Minitab Statistical Software
- ADAMS/Insight – MSC Software
- DOE Wisdom – Launsby Consulting
- JMP – SAS Institute Inc.
- iSight – Dassault Systemes
- modeFrontier – Esteco (Batch process automation + GA optimization)
- HEEDS – Siemens (Batch process automation + GA optimization)

Example: Screening DOE for Primary Ride

Suppose we were given a small sports sedan with the following nominal chassis (factor) settings:

Parameter	**Units**	**Value**
CoG to front axle	mm	1272
Front Wheel Rate	N/mm	54.2
Rear Wheel Rate	N/mm	58.2
Pitch Radius of Gyration	m	1.13

Use DOE to determine the magnitude and direction of the abovementioned chassis parameter changes on primary ride response, namely pitch and bounce natural frequencies and node locations

A typical screening DOE would be a fractional factorial consisting of 4 factors with 2 levels and 4 responses

Assume a “low” setting is 80% of nominal, “high” is 120% of nominal

Setting up the DOE

Referring to one of the DOE books or statistical software, a fractional factorial DOE run matrix like the one shown below would be appropriate:

Run #	CoG from Front Axle	Front Ride Rate	Rear Ride Rate	Pitch Radius of Gyration
1	-1	-1	-1	-1
2	1	-1	-1	1
3	-1	1	-1	1
4	1	1	-1	-1
5	-1	-1	1	1
6	1	-1	1	-1
7	-1	1	1	-1
8	1	1	1	1

- Note the 2 level factor setting, -1=low, 1=high
- A full factorial would be $2^4 = 16$ runs

Setting up the DOE

In terms of chassis settings:

Run #	CoG from Front Axle	Front Ride Rate	Rear Ride Rate	Pitch Radius of Gyration	CoG from Front Axle	Front Ride Rate	Rear Ride Rate	Pitch Radius of Gyration
1	-1	-1	-1	-1	1018	43	47	0.904
2	1	-1	-1	1	1526	43	47	1.356
3	-1	1	-1	1	1018	65	47	1.356
4	1	1	-1	-1	1526	65	47	0.904
5	-1	-1	1	1	1018	43	70	1.356
6	1	-1	1	-1	1526	43	70	0.904
7	-1	1	1	-1	1018	65	70	0.904
8	1	1	1	1	1526	65	70	1.356

Where -1 = 80% of nominal and 1 = 120% of nominal

Our ‘model’ for this experiment are the natural frequency and amplitude ratio (node) equations from the 2 DOF primary ride model previously presented.

Example – Simplified 2-DOF Undamped Primary Ride Model

(green)	input
(yellow)	calculated

2019 [redacted] @ SSF loading condition

Inputs

a	mm	1169.6	cg to frt axle
b	mm	1552.2	cg to rear axle
M_V	kg	2083.0	mass
$M_{V,F}$	kg	1187.9	front mass
$M_{V,R}$	kg	895.1	rear mass
m_F	kg	118.8	front unsprung mass (assume 10% of total front mass)
m_R	kg	89.5	rear unsprung mass (assume 10% of total rear mass)
M_F	kg	1069.1	front sprung mass (assume 10% unsprung)
M_R	kg	805.6	rear sprung mass (assume 10% unsprung)
M	kg	1874.7	Sprung mass
K_F	N/mm	73.9	2x front suspension rate
K_R	N/mm	81.0	2x rear suspension rate
$K_{T,F}$	N/mm	600.0	2x tire rate
$K_{T,R}$	N/mm	600.0	2x tire rate
K'_F	N/mm	65.8	LF + RF ride rate
K'_R	N/mm	71.3	LR + RR ride rate
l	kgm^2	2721.8	wheelbase
J_V	kgm^2	3526.0	Total vehicle inertia
J	kgm^2	3147.8	Sprung mass pitch inertia

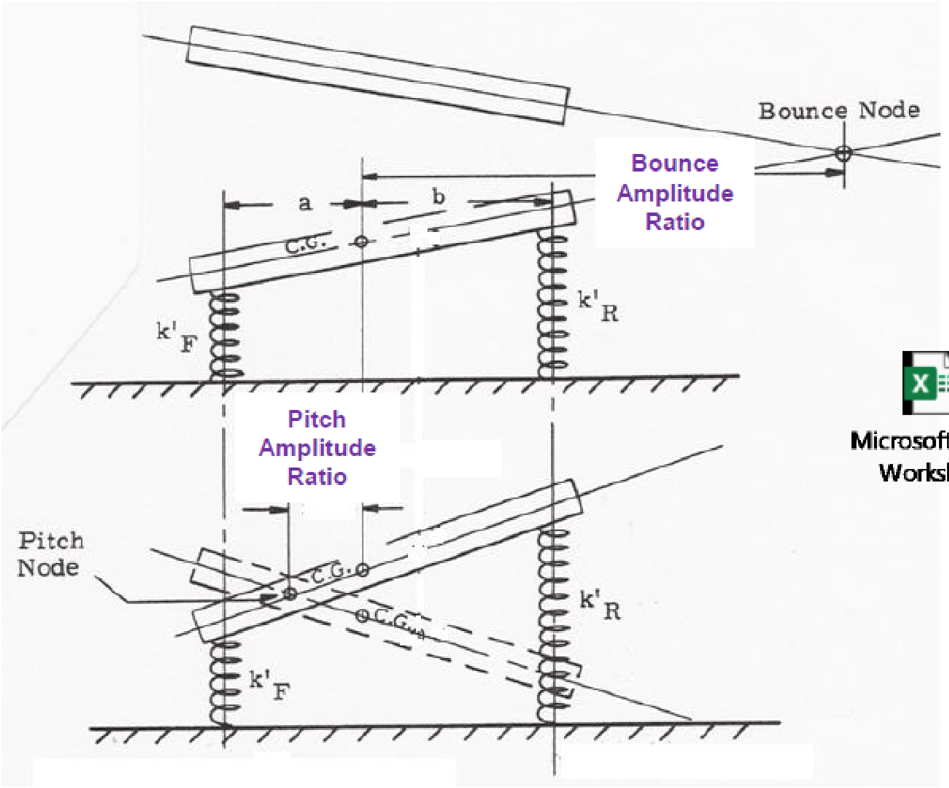
Outputs

Pitch/Bounce Natural Frequencies

ω_1	9.64	rad/s	1.53	hz
ω_2	7.96	rad/s	1.27	hz

Pitch/Bounce Amplitude Ratios

$A_{z1}/A_{\theta1}$	0.91	m/rad	909.44	mm/rad
$A_{z2}/A_{\theta2}$	-1.85	m/rad	-1846.31	mm/rad



Microsoft Excel Worksheet

$$\left(\omega_1, \frac{A_{z1}}{A_{\theta 1}}\right) = (1.53, 909.44)$$

$$\left(\omega_2, \frac{A_{z2}}{A_{\theta 2}}\right) = (1{,}27, -1849.31)$$

Executing the DOE run matrix

Plugging the factor settings for each run into the ‘model equations’ we complete the DOE matrix?

Run #	CoG from Front Axle	Front Ride Rate	Rear Ride Rate	Pitch Radius of Gyration	Bounce frequency	Pitch frequency	Bounce node	Pitch node
1	1018	43	47	0.904	1.659	2.473	-3.220	0.254
2	1526	43	47	1.356	1.731	1.905	-20.289	0.091
3	1018	65	47	1.356	1.929	1.736	21.951	-0.084
4	1526	65	47	0.904	1.876	3.226	5.251	-0.156
5	1018	43	70	1.356	2.249	1.489	1.491	-1.234
6	1526	43	70	0.904	1.874	3.229	-4.594	0.178
7	1018	65	70	0.904	2.030	3.027	-3.220	0.254
8	1526	65	70	1.356	2.118	2.331	-20.206	0.091

Ok, so what do we do with the data?

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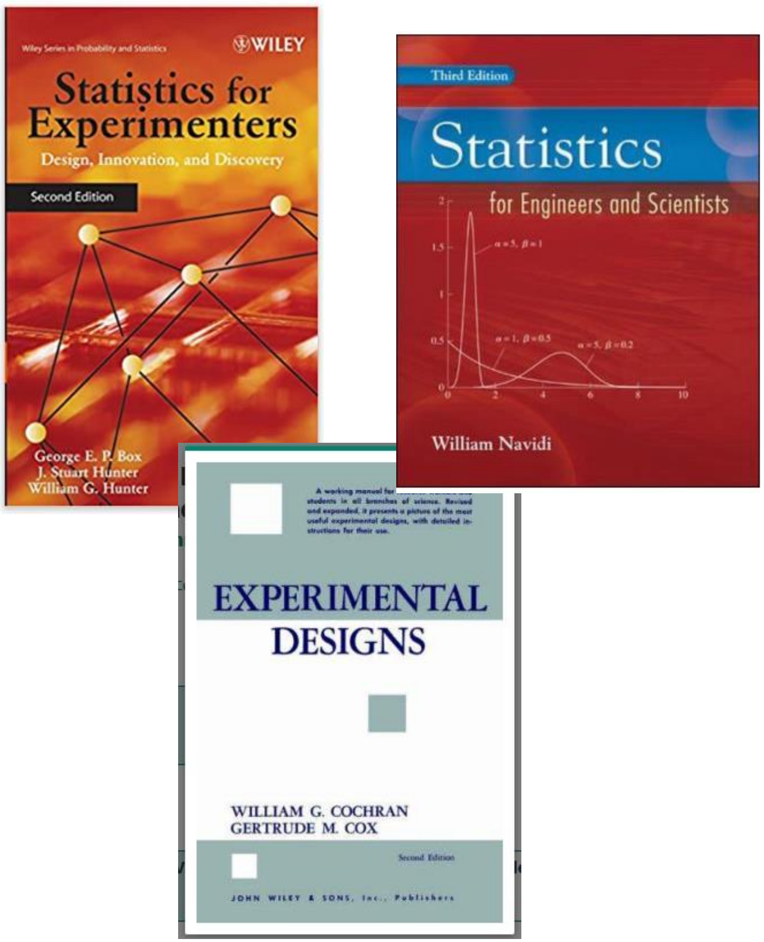
Processing the data

In the old days, we would break out the statistics book and calculate sensitivities, mean, standard deviation, R-squared, t-values, etc. In this example, we will use the statistical software package called **Minitab**



Create Factorial Design: Display Available Designs

Available Factorial Designs (with Resolution)

	Factors													
Run	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
4	Full	III												
8		Full	IV	III	III	III								
16			Full	V	IV	IV	IV	III	III	III	III	III	III	III
32				Full	VI	IV	IV	IV	IV	IV	IV	IV	IV	IV
64					Full	VII	V	IV	IV	IV	IV	IV	IV	IV
128						Full	VIII	VI	V	V	IV	IV	IV	IV

Available Resolution III Plackett-Burman Designs

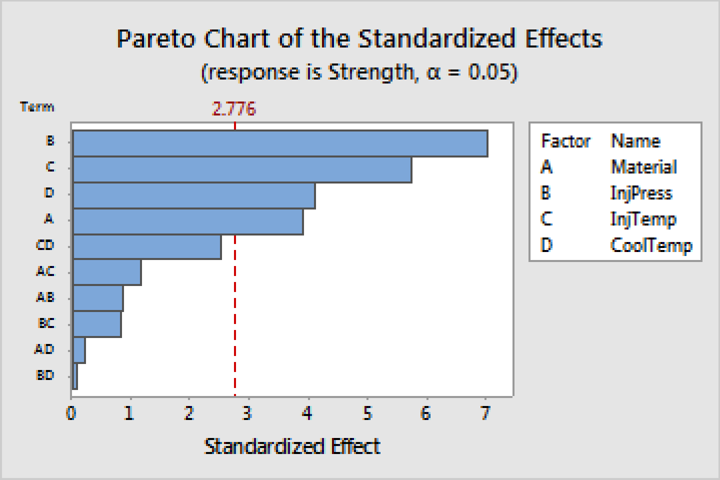
Factors	Runs	Factors	Runs	Factors	Runs
2-7	12,20,24,28,...,48	20-23	24,28,32,36,...,48	36-39	40,44,48
8-11	12,20,24,28,...,48	24-27	28,32,36,40,44,48	40-43	44,48
12-15	20,24,28,36,...,48	28-31	32,36,40,44,48	44-47	48
16-19	20,24,28,32,...,48	32-35	36,40,44,48		

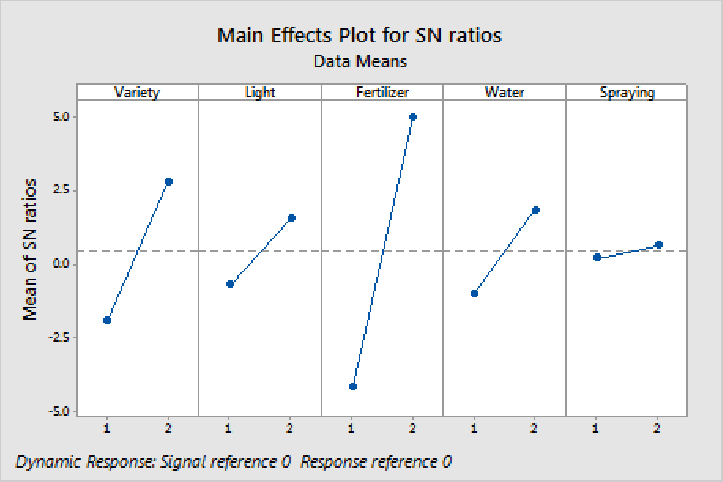
Help OK

Interpreting the results

We can interpret the results of the DOE by using graphical means.

2 common plot types:





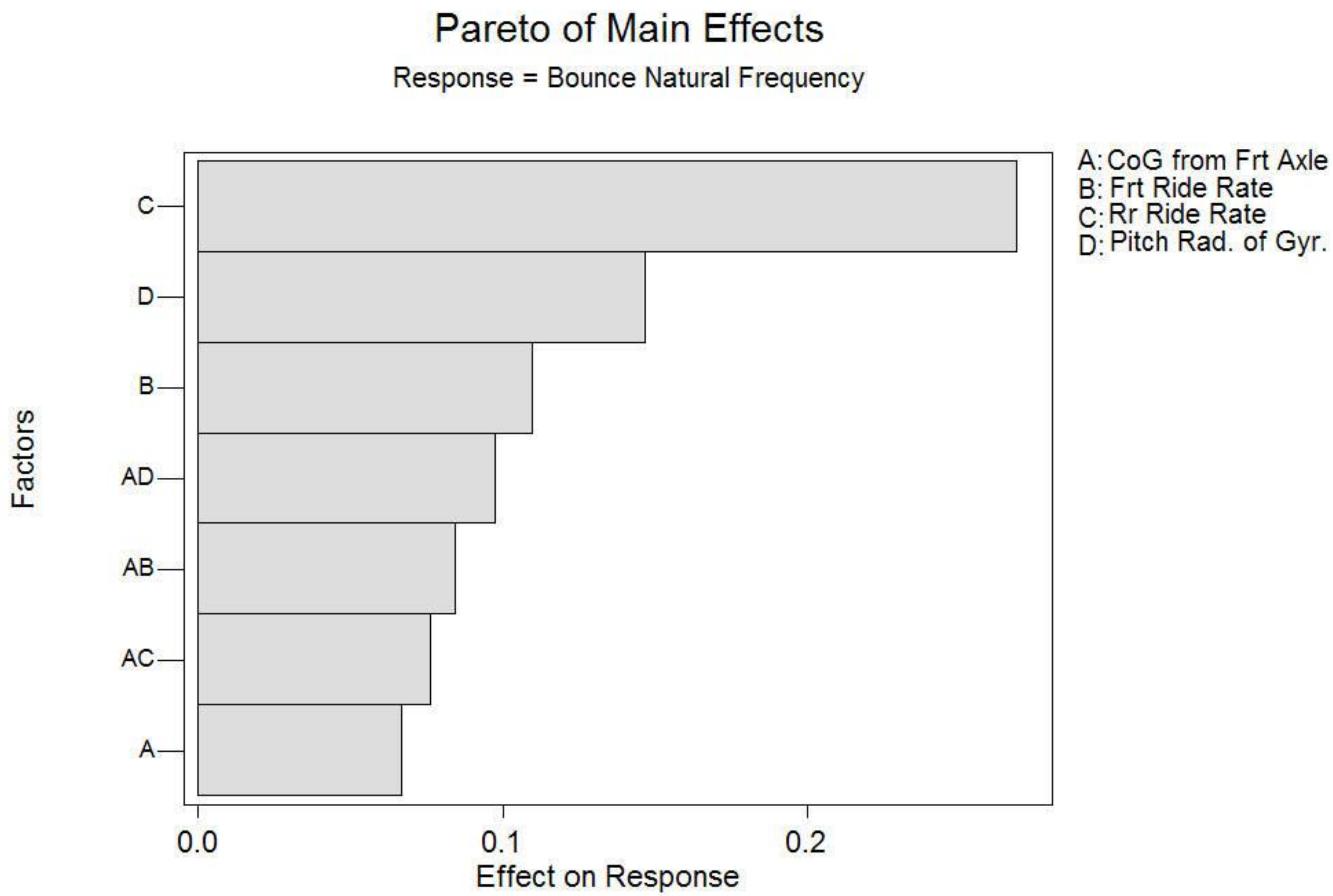
Pareto Chart

Main Effects Plot

Both can be used to assess the relative strength and direction of factor setting on system response

Pareto Charts

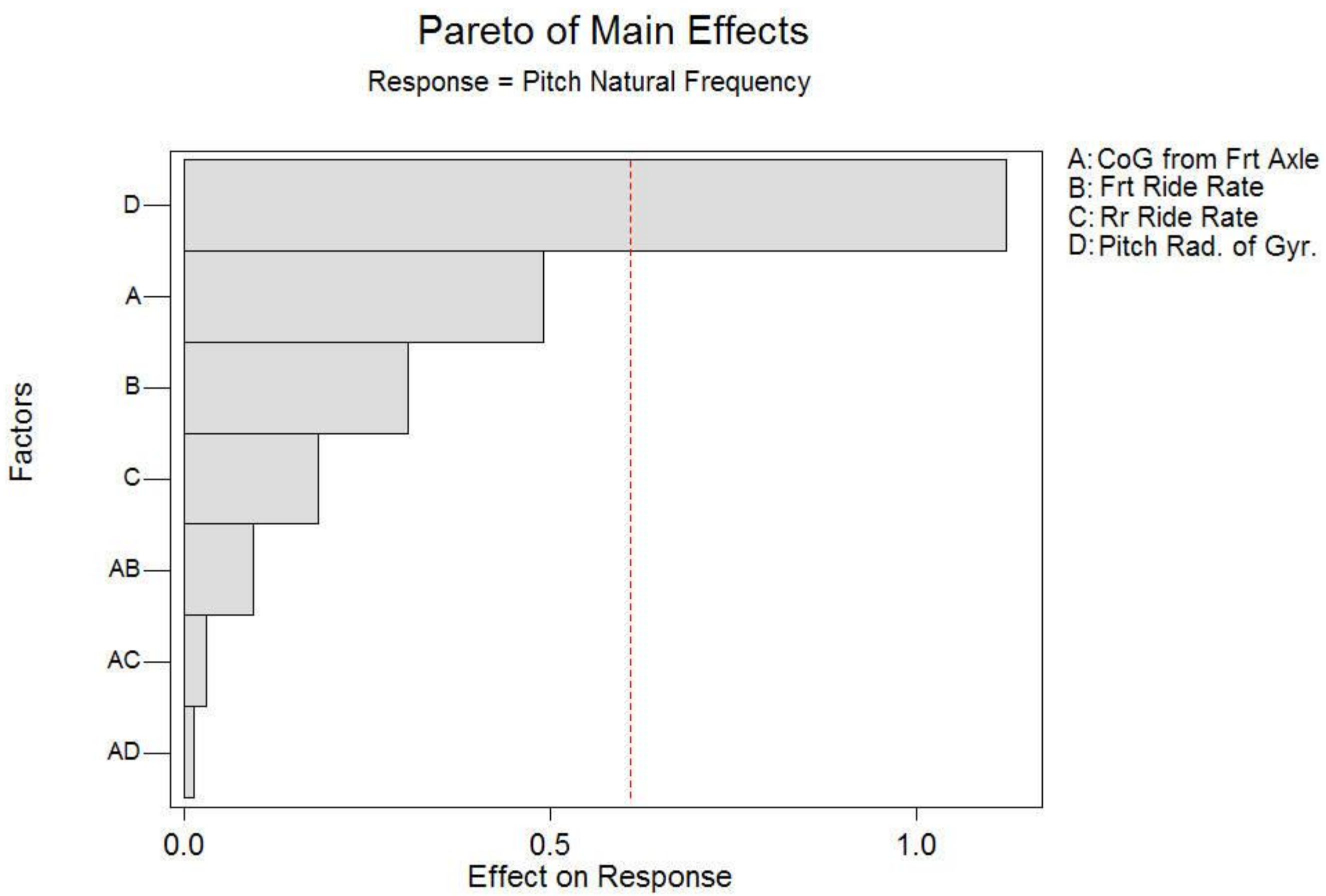
Pareto chart for bounce natural frequency



Interpretation: Changing the rear ride rate from 80% to 120% of nominal has biggest effect on bounce natural frequency, changing it by almost 0.3hz

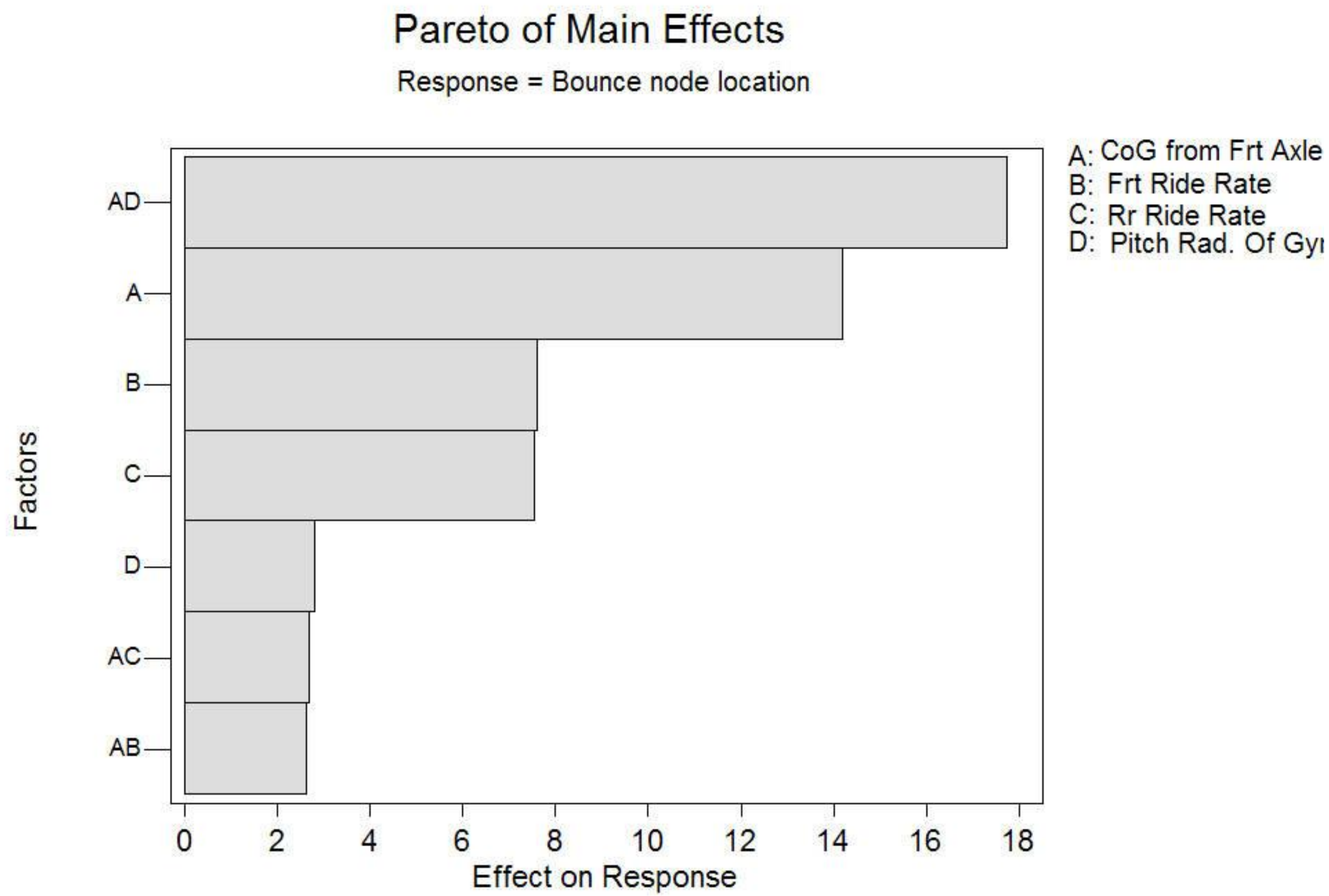
Pareto Charts

Pareto chart for pitch natural frequency



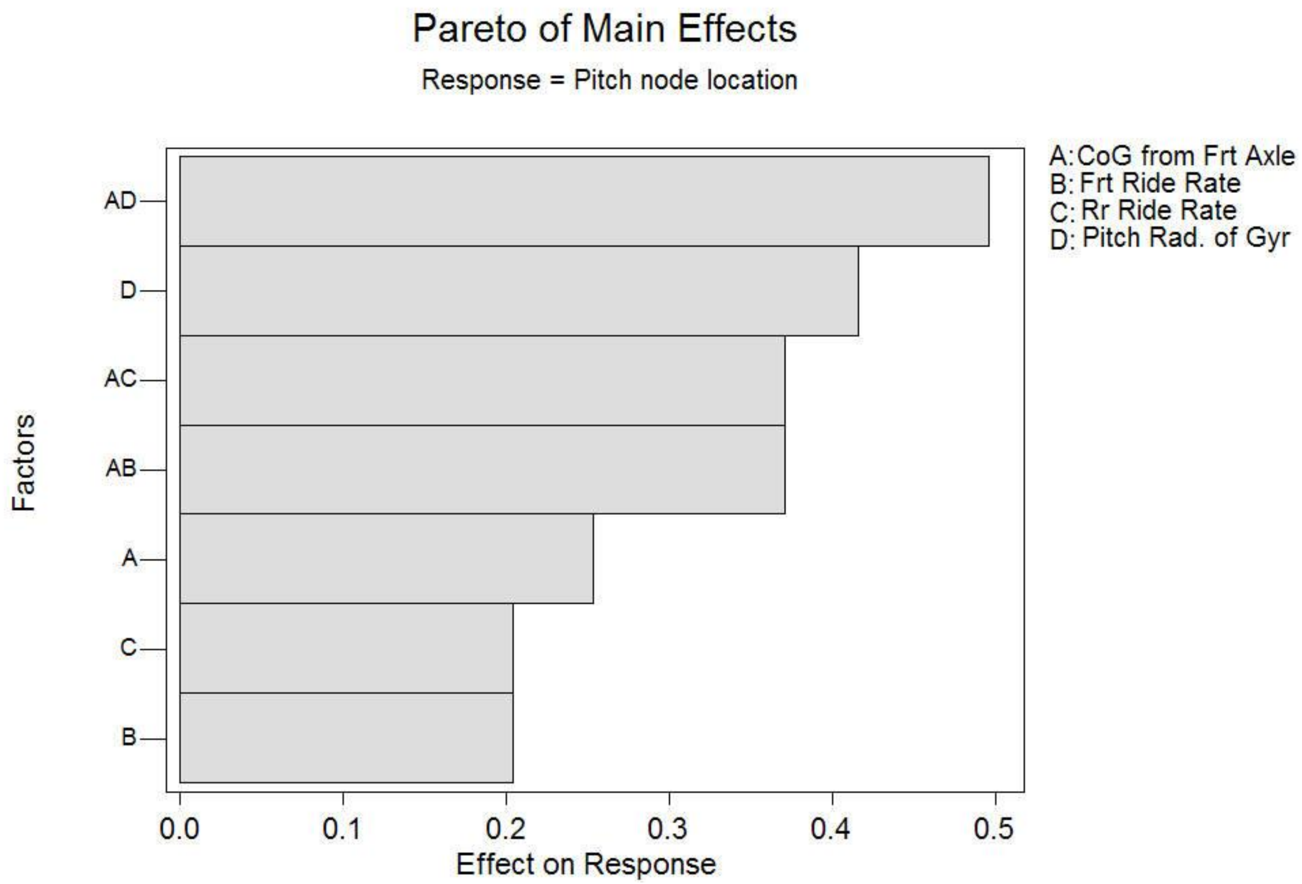
Interpretation: Changing the pitch radius of gyration from 80% to 120% of nominal has the biggest effect on pitch natural frequency, changing it by more than 1 Hz

Pareto chart for bounce node location



Interpretation: The interaction of CoG location and pitch radius of gyration has the biggest effect on bounce node location, changing it by almost 17m

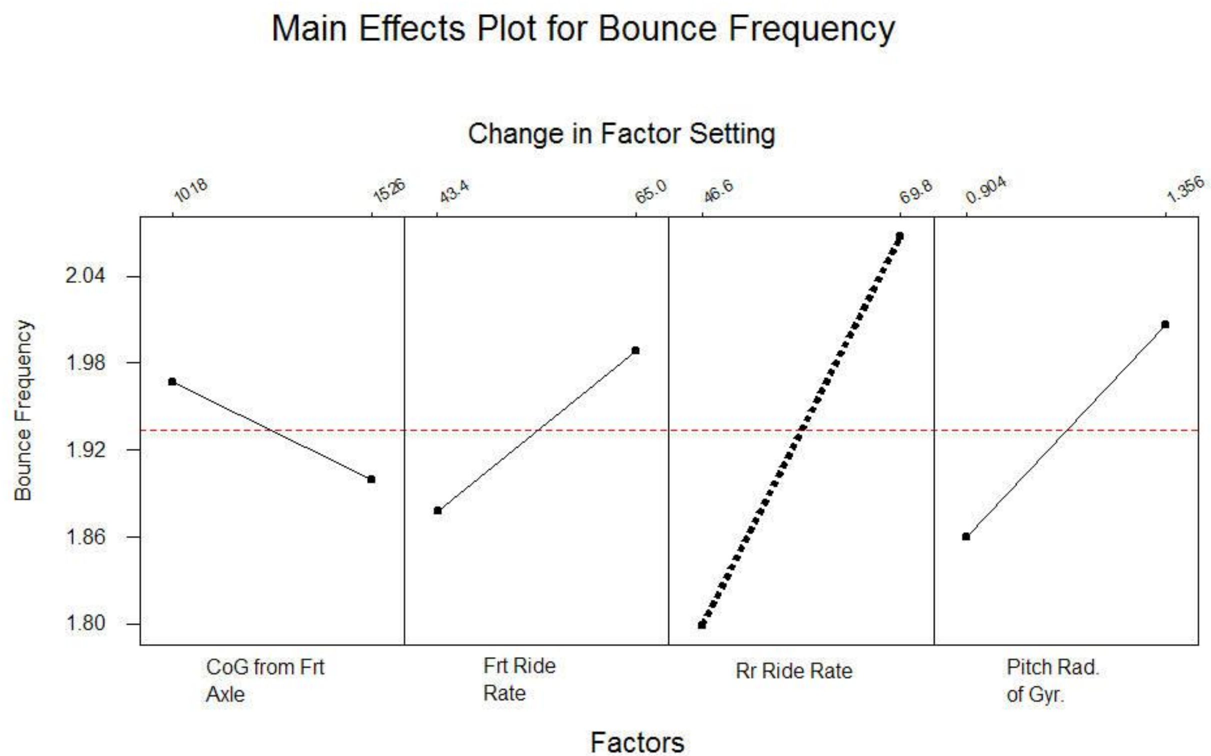
Pareto chart for pitch node location



Interpretation: The interaction of CoG location and pitch radius of gyration has the biggest effect on pitch node location, changing it by almost 0.5m

Main Effects Plot

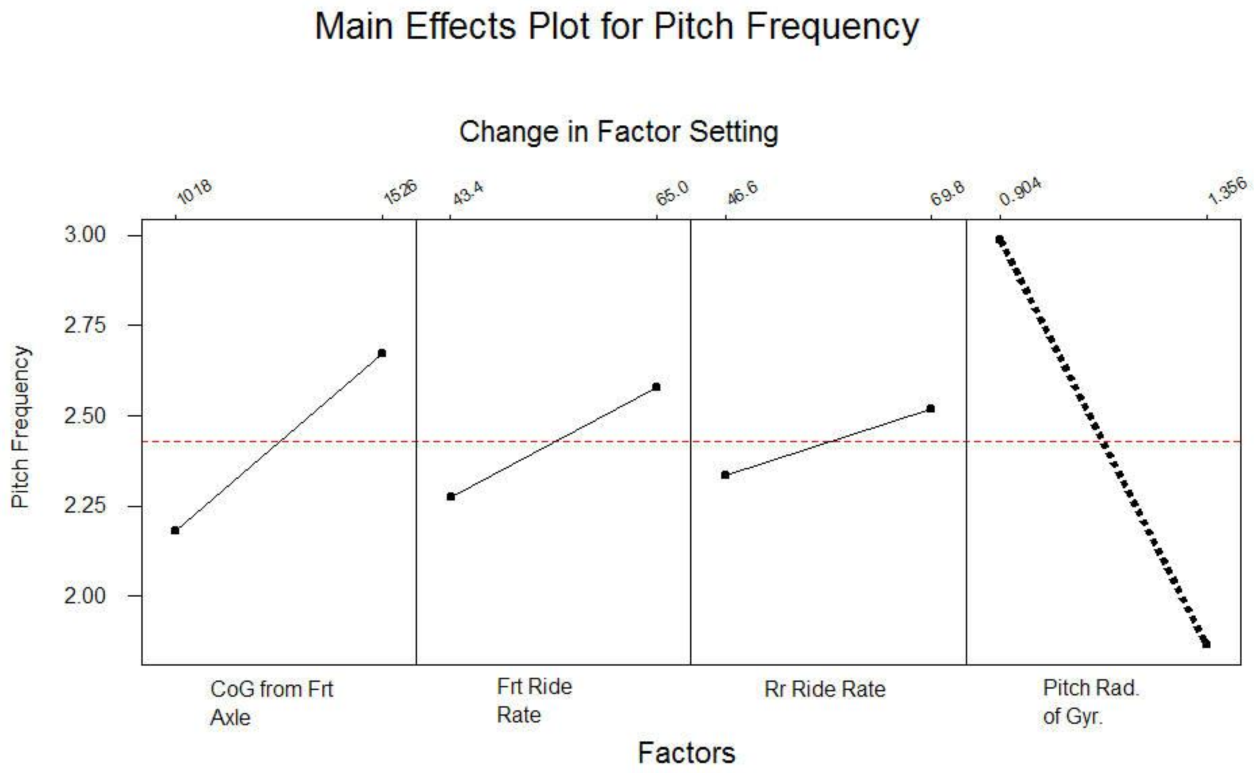
Main effects plot for bounce natural frequency



Interpretation: Changing the rear ride rate from 80 to 120% of nominal has the biggest effect on bounce natural frequency and tends to increase the frequency by almost 0.3Hz

Main Effects Plot

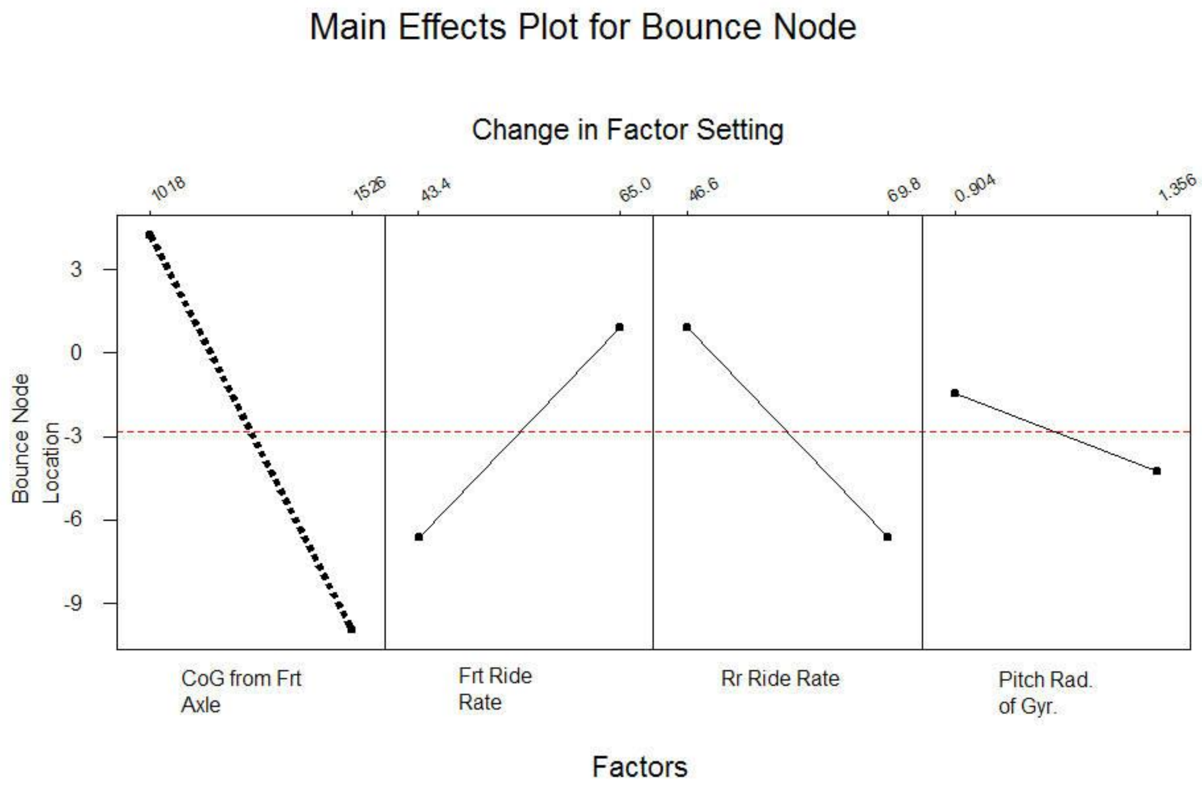
Main effects plot for pitch natural frequency



Interpretation: Changing the pitch radius of gyration from 80 to 120% of nominal has the biggest effect on pitch natural frequency, and tends to decrease the frequency by almost 1Hz

Main Effects Plot

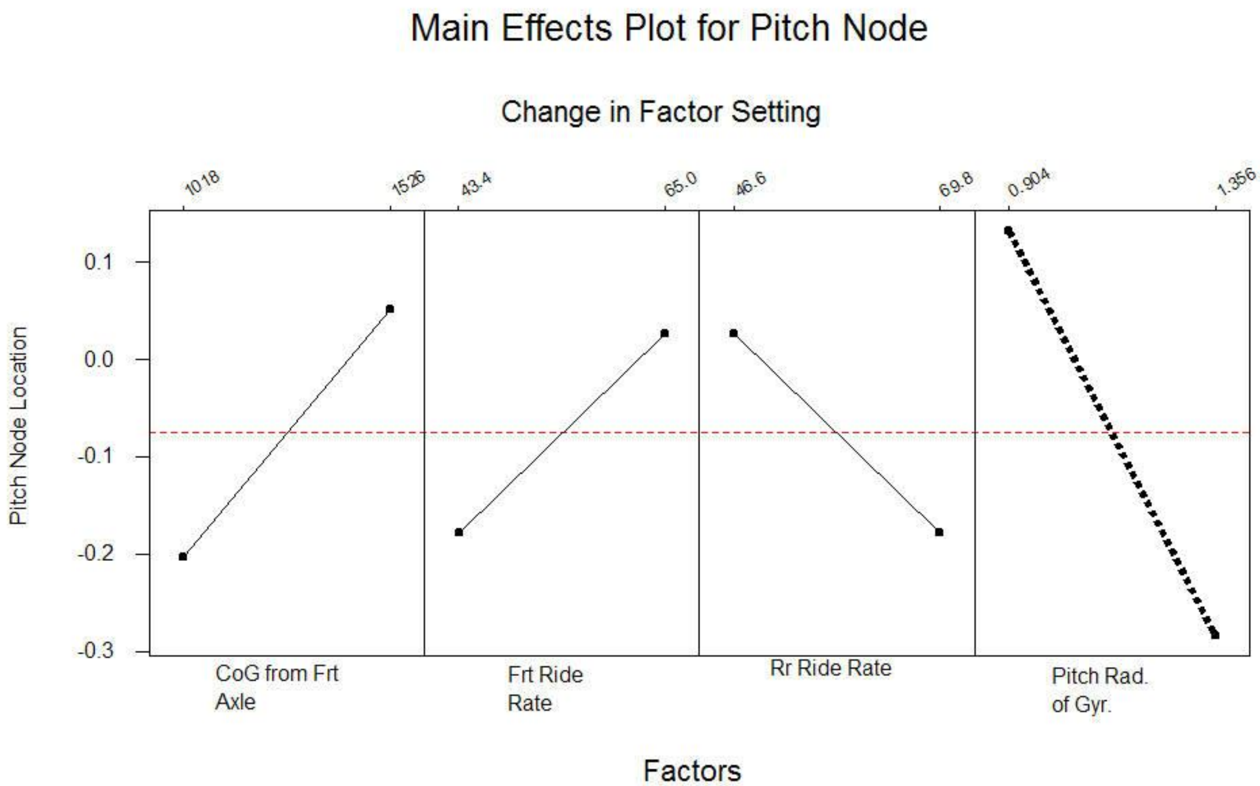
Main effects plot for bounce node location



Interpretation: Changing the CoG location to front axle from 80 to 120% of nominal has the biggest effect on bounce node location, and tends to move the node rearward more than 12m

Main Effects Plot

Main effects plot for pitch node location

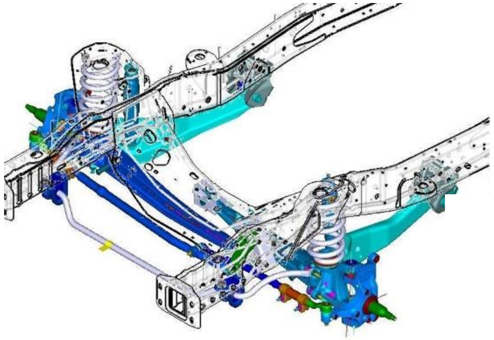


Interpretation: Changing the Radius of Gyration from 80 to 120% of nominal has the biggest effect on pitch node location and tends to move it rearward almost 0.5m

Example – RSM DOE for transient handling

Assume a we ran a prior screening DOE on all the chassis factors that affect handling The results revealed the following parameters had the biggest effect on vehicle response during a step steer test:

- LCA bushing lateral rate
- Front stabilizer bar stiffness
- Front spring rate
- Rear leaf spring first stage rate
- Left front outer tie rod "Z" location
- Right front drag link ball joint "Z" location



Suppose our goal is to reduce the front lateral load transfer while maintaining the current response level of the vehicle. We conduct and use a response surface DOE to determine chassis settings that <u>increases the inside front tire vertical force</u> while <u>maintaining the lateral acceleration response time</u> during a step steer maneuver

Setting up the DOE

Maneuver:

- Step steer right turn 0.5g steady state at 55mph

Factors:

- Front LCA bushing lateral rate
- Front stabilizer bar stiffness
- Front spring rate
- Rear leaf spring first stage rate
- Left front outer tie rod “Z” location
- Right front drag link ball joint “Z” location

Assume a “low” setting is 80% of nominal, “high” is 120% of nominal

Response:

- Minimum inside front tire vertical force (N)
- Lateral acceleration response time (sec)

Setting up the DOE

An ADAMS/Chassis model of a full-size truck was used to simulate a step steer manuver

The ADAMS/Insight DOE software package was used to construct, execute and postprocess a Box-Behnken Response Surface DOE

- 6 factors
- 3 levels (low, nominal, high)
- 54 runs

A full-factorial DOE would be 3^6 = 729 runs! Box and Behnken came up with a design matrix which will give us statistically significant results in much fewer runs

Note: There is no reason why we couldn't have used Minitab for the RSM DOE. I used ADAMS/Insight because it is seamlessly integrated with the ADAMS/Chassis and ADAMS/Car simulation environment.

Setting up the DOE

Box-Behnken DOE Run Matrix

	Factor Level						Factor Values					
Run	LCA bushing lateral stiffness	Stabilizer bar torsional stiffness	Front coil spring rate	Rear leaf spring first stage rate	Left outer tie rod ball joint height to ground	Right outer drag link ball joint height to ground	LCA bushing lateral stiffness (N/mm)	Stabilizer bar torsional stiffness (N-mm/deg)	Front coil spring rate (N/mm)	Rear leaf spring first stage rate (N/mm)	Left outer tie rod ball joint height to ground	Right outer drag link ball joint height to ground
1	-1	-1	0	-1	0	0	4212.80	1432000.00	63.40	29.54	472.28	490.02
2	-1	0	0	-1	-1	0	4212.80	1790000.00	63.40	29.54	467.28	490.02
3	-1	0	0	-1	1	0	4212.80	1790000.00	63.40	29.54	477.28	490.02
4	-1	1	0	-1	0	0	4212.80	2148000.00	63.40	29.54	472.28	490.02
5	0	0	-1	-1	0	-1	5266.00	1790000.00	50.72	29.54	472.28	485.02
6	0	0	-1	-1	0	1	5266.00	1790000.00	50.72	29.54	472.28	495.02
7	0	0	1	-1	0	-1	5266.00	1790000.00	76.08	29.54	472.28	485.02
8	0	0	1	-1	0	1	5266.00	1790000.00	76.08	29.54	472.28	495.02
9	1	-1	0	-1	0	0	6319.20	1432000.00	63.40	29.54	472.28	490.02
.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.
42	1	0	1	0	0	1	6319.20	1790000.00	76.08	36.93	472.28	495.02
43	-1	-1	0	1	0	0	4212.80	1432000.00	63.40	44.32	472.28	490.02
44	-1	0	0	1	-1	0	4212.80	1790000.00	63.40	44.32	467.28	490.02
45	-1	0	0	1	1	0	4212.80	1790000.00	63.40	44.32	477.28	490.02
46	-1	1	0	1	0	0	4212.80	2148000.00	63.40	44.32	472.28	490.02
47	0	0	-1	1	0	-1	5266.00	1790000.00	50.72	44.32	472.28	485.02
48	0	0	-1	1	0	1	5266.00	1790000.00	50.72	44.32	472.28	495.02
49	0	0	1	1	0	-1	5266.00	1790000.00	76.08	44.32	472.28	485.02
50	0	0	1	1	0	1	5266.00	1790000.00	76.08	44.32	472.28	495.02
51	1	-1	0	1	0	0	6319.20	1432000.00	63.40	44.32	472.28	490.02
52	1	0	0	1	-1	0	6319.20	1790000.00	63.40	44.32	467.28	490.02
53	1	0	0	1	1	0	6319.20	1790000.00	63.40	44.32	477.28	490.02
54	1	1	0	1	0	0	6319.20	2148000.00	63.40	44.32	472.28	490.02

Box-Behnken DOE Run Matrix with Results

	Factor Level						Response		
Run	LCA bushing lateral stiffness	Stabilizer bar torsional stiffness	Front coil spring rate	Rear leaf spring first stage rate	Left outer tie rod ball joint height to ground	Right outer drag link ball joint height to ground	Minimum Front Inside Tire Load (N)	Peak Roll Angle (deg)	Time to 90% of peak accel (sec)
1	-1	-1	0	-1	0	0	3017.31	3.23	1.00
2	-1	0	0	-1	-1	0	2990.72	3.14	0.88
3	-1	0	0	-1	1	0	2989.39	3.14	0.88
4	-1	1	0	-1	0	0	2963.83	3.05	0.79
5	0	0	-1	-1	0	-1	3227.28	3.22	0.01
6	0	0	-1	-1	0	1	3232.97	3.21	0.01
7	0	0	1	-1	0	-1	2791.39	3.07	0.50
8	0	0	1	-1	0	1	2792.08	3.07	0.50
.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
45	-1	0	0	1	1	0	3149.90	2.92	0.70
46	-1	1	0	1	0	0	3106.29	2.88	0.64
47	0	0	-1	1	0	-1	3320.47	3.02	1.70
48	0	0	-1	1	0	1	3321.27	3.02	1.72
49	0	0	1	1	0	-1	2939.70	2.91	0.46
50	0	0	1	1	0	1	2940.34	2.91	0.46
51	1	-1	0	1	0	0	3182.71	2.99	0.78
52	1	0	0	1	-1	0	3152.95	2.92	0.72
53	1	0	0	1	1	0	3151.25	2.91	0.72
54	1	1	0	1	0	0	3106.39	2.88	0.66

Interpreting the results

Post-processing the response surface DOE runs in ADAMS/Insight allows us to port the response surface equations to Excel

Factor settings

Tolerance on Factor

Nominal: Response Surface Method analysis

Factor	*Units*	*Nominal*	*Current*	*Tolerance*	*Min*	*Max*
LCA bushing lateral stiffness	% of nom	100	**100.00**	1	80	120
Stabilizer bar torsional stiffness	% of nom	100	**100.00**	1	80	120
Front coil spring rate	% of nom	100	**100.00**	1	80	120
Rear leaf spring first stage rate	% of nom	100	**100.00**	1	80	120
Left outer tie rod ball joint height to ground	diff. from nom	0	**0.00**	0.1	-5	5
Right outer drag link ball joint height to ground	diff. from nom	0	**0.00**	0.1	-5	5

Response	*Units*	*Nominal*	*Estimate*	*Tolerance*	*Description*
Minimum Front Inside Tire Load	N	3073.30	**3073.30**	10.68	Minimum Front Inside Tire Load
Peak Roll Angle	deg	3.02	**3.02**	0.01	Peak Roll Angle
Time to 90% of peak accel (sec)	sec	0.77	**0.77**	0.01	Lat. Accel. Response Time

	Factor Tolerance % Contribution to Total Response Variation					
Tolerance Contributions	*LCA bushing lateral stiffness*	*Stabilizer bar torsional stiffness*	*Front coil spring rate*	*Rear leaf spring first stage rate*	*Left outer tie rod ball joint height to ground*	*Right outer drag link ball joint height to ground*
Minimum Front Inside Tire Load	0%	2%	86%	11%	0%	0%
Peak Roll Angle	0%	29%	24%	47%	0%	0%
Time to 90% of peak accel (sec)	26%	8%	61%	5%	0%	0%

% Contribution of individual tolerance on total variation in response

response

Interpreting the results

Using the solver function in Excel, find a solution that increases the inside tire load 10% while maintaining the current level of lateral acceleration response time

Microsoft Excel
97-2003 Workshee

Factor settings that achieve desired goal

Optimization: Increase minimum front inside wheel load by 10% while maintaining 0.77s lateral acceleration response time

Factor	*Units*	*Nominal*	*Current*	*Tolerance*	*Min*	*Max*
LCA bushing lateral stiffness	% of nom	100	**102.13**	1	80	120
Stabilizer bar torsional stiffness	% of nom	100	**80.68**	1	80	120
Front coil spring rate	% of nom	100	**80.12**	1	80	120
Rear leaf spring first stage rate	% of nom	100	**120.00**	1	80	120
Left outer tie rod ball joint height to ground	diff. from nom	0	**-4.84**	0.1	-5	5
Right outer drag link ball joint height to ground	diff. from nom	0	**5.00**	0.1	-5	5

Response	*Units*	*Nominal*	*Estimate*	*Tolerance*	*Description*
Minimum Front Inside Tire Load	N	3073.30	**3370.00**	9.50	Minimum Front Inside Tire Load
Peak Roll Angle	deg	3.02	**3.10**	0.01	Peak Roll Angle
Time to 90% of peak accel (sec)	sec	0.77	**0.77**	0.05	Lat. Accel. Response Time

	Factor Tolerance % Contribution to Total Response Variation					
Tolerance Contributions	***LCA bushing lateral stiffness***	***Stabilizer bar torsional stiffness***	***Front coil spring rate***	***Rear leaf spring first stage rate***	***Left outer tie rod ball joint height to ground***	***Right outer drag link ball joint height to ground***
Min_Frt_Ins_Tire_Load	0%	5%	81%	14%	0%	0%
Peak_Roll_Ang	0%	17%	48%	35%	0%	0%
Lat_Accel_Resp_Time	44%	34%	0%	22%	0%	0%

We can do the exact same type of analysis using response equations from a DOE set up and postprocessed in Minitab

Vehicle Dynamics / NVH Cross Attribute Optimization Using CAE

Tim Drotar
Vehicle Dynamics

Example of Cross Attribute Optimization: Steady State Handling and Secondary Ride

- Goal was to find a front and rear suspension bushing tuning that met vehicle dynamics requirements for steady state understeer while minimizing impact harshness and brake roughness seat track vibration

- Two CAE Response Surface Method (RSM) Design of Experiments (DOE) were conducted in parallel:
  - Effect of front and rear suspension bushing stiffness on steady state handling response (Vehicle Dynamics)
  - Effect of front suspension bushing stiffness on seat track response for the brake roughness and impact harshness loadcases (NVH)

Example of Cross Attribute Optimization: Steady State Handling and Secondary Ride

- Vehicle Dynamics CAE set up the DOE using ADAMS/Insight

- NVH was given the DOE matrix and asked to run the prescribed bushing combinations in their simulation environment and provide the corresponding vehicle response.

- Vehicle Dynamics CAE post-processed both the handling and brake roughness/impact harshness DOE results in ADAMS/Insight generating:
  - Main effects plots showing the relative magnitude and direction of bushing stiffness change on vehicle response
  - Response surface equations (in Excel) that describe the vehicle response as a function of factor settings

- The response "solver" function in Excel was used find a combination of bushing stiffness that provided target understeer while minimizing seat track response for the brake roughness and impact harshness loadcases

Example of Cross Attribute Optimization: Steady State Handling and Secondary Ride

CAE Response Surface DOE to simultaneously study the effect of changing bushing rates on handling and NVH performance

Yellow is current tuning
Type in new values in Green and see how response changes

Factor	**Units**	**Current**	**Proposed**	**Tolerance**	**Min**	**Max**	**Description**
Pt 1 Axial/Radial Rate Scale Factor	x baseline	1.0	0.6	0.1	0.5	1.5	FUCA front bushing stiffness scale factor
Pt 2 Axial/Radial Rate Scale Factor	x baseline	1.0	0.6	0.1	0.5	1.5	FUCA rear bushing stiffness scale factor
Pt 3 Axial/Radial Rate Scale Factor	x baseline	1.0	1.5	0.1	0.5	1.5	FLCA front bushing stiffness scale
Pt 4 Axial/Radial Rate Scale Factor	x baseline	1.0	1.1	0.1	0.5	1.5	FLCA rear bushing stiffnss scale factor

Response	**Units**	**Current**	**Proposed**	**Tolerance**	**Description**
Brake Roughness Seat Track F/A	mm/s RSS	35.31	20.00	1.91	Drivers Seat Track F/A - Target 20mm/s max
Impact Harshness (lower is better)	VDV	1.22	0.75	0.09	Impact Harshness Seat Track Vertical Vibration - Target 1.5 max
Front Suspension Compliance (Understeer Budget)	deg/g	0.54	0.34	0.05	Front Suspension Compliance (LFCS+ATCS+Camber Compliance)
Total Understeer (Understeer Budget)	deg/g	2.95	2.80	0.04	Total Understeer (Understeer Budget) - Target 2-3 deg/g

Tolerance Contributions	Pt 1 Dynamic Rate Scale Factor	Pt 2 Dynamic Rate Scale Factor	Pt 3 Dynamic Rate Scale Factor	Pt 4 Dynamic Rate Scale Factor
Brake Roughness Seat Track F/A	0%	0%	64%	36%
Impact Harshness	57%	41%	0%	2%
Front Suspension Compliance (Understeer Budget)	8%	8%	46%	46%
Total Understeer (Understeer Budget)	5%	5%	50%	39%

Example of Cross Attribute Optimization: Steady State Handling and Secondary Ride

- Outcome was a proposal for front and rear suspension bushing rates that optimized brake roughness, impact harshness and steady state cornering

- Proposal was verified in physical prototype test and implemented in next round of prototypes

Summary

- DOE is
  - A statistical methodology to evaluate the effect of multiple factors
  - An efficient way to analyze the relative effect of many factors on vehicle response
  - Used to provide direction to the design community on up-front decisions regarding suspension architecture, kinematics and compliances.
  - Used to help resolve any conflicts between attributes that arise in the early stages of design and development.

- There are 3 main types of DOE methods:
  - Classical
  - Taguchi
  - Optimization

Summary

- There are 3 main types of Classical DOE’s:
  - Screening
  - Factorial
  - Response Surface Method (RSM)

- There are several commercially available software packages that take the drudgery out of setting up, executing and analyzing a DOE

- A screening DOE is commonly used to
  - Reduce the list of possible factors to those that have the biggest effect on system response
  - Determine the relative strength and direction of factor effect on system response

Summary

- There are 2 graphical methods commonly used to assess the relative strength and direction of factor setting on system response
  - Pareto chart
  - Main effect plots

- The Response Surface Method DOE is used to generate an equation of system response as a function of factor setting

- A response surface equation can be used to find a setup that optimizes vehicle response(s)

Additional Learning

Does this sound interesting and useful? Want to learn more? Consider taking the SAE course "Design of Experiments for Engineers"

On-demand: https://www.sae.org/learn/content/pd530932/

- 10 hours of instruction for $550/person
- Work at your own pace
- Hands-on exercises using Minitab are part of the training

Virtual instructor-led: https://www.sae.org/learn/content/c0406/

- 16 hours of instruction spread over 4 consecutive days for $1349/person
- Hands-on exercises using Minitab are part of the training

SAE gives a discount for group registration. On-site training is also available.

Optimization Software

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https://www.plm.automation.siemens.com/global/en/products/simcenter/simcenter-heeds.html

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