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# Correlating Suspension K&C Using Multi- Experiment DOE Techniques

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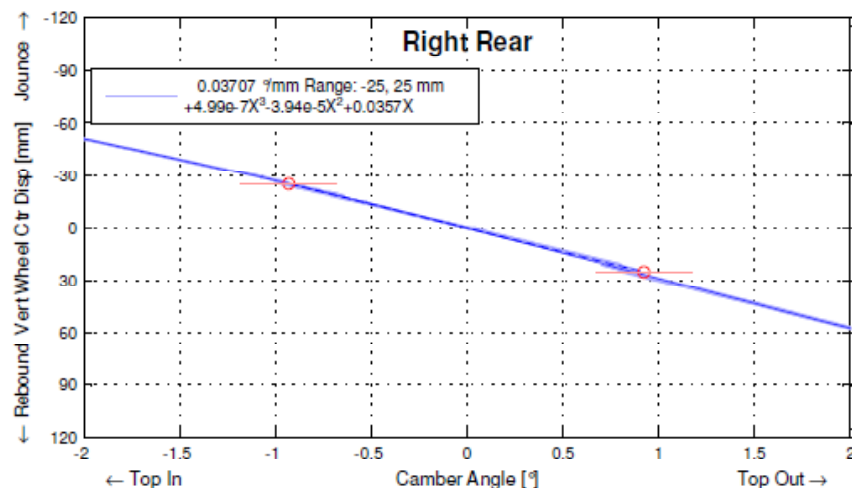
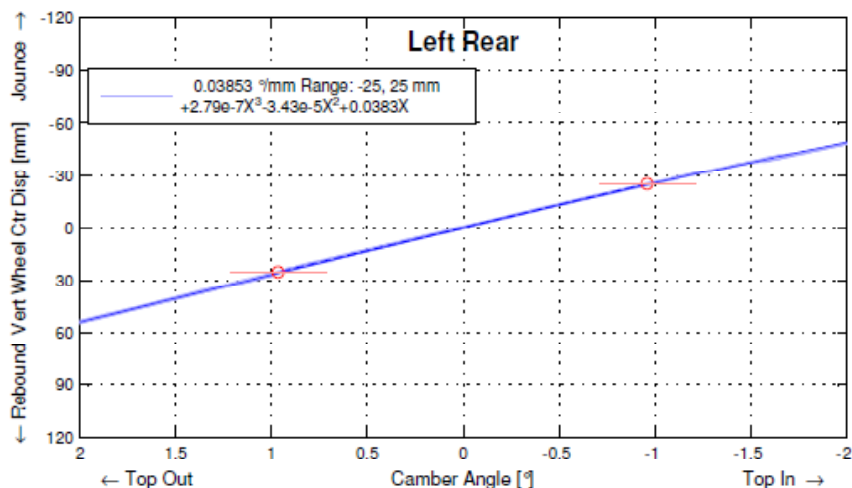
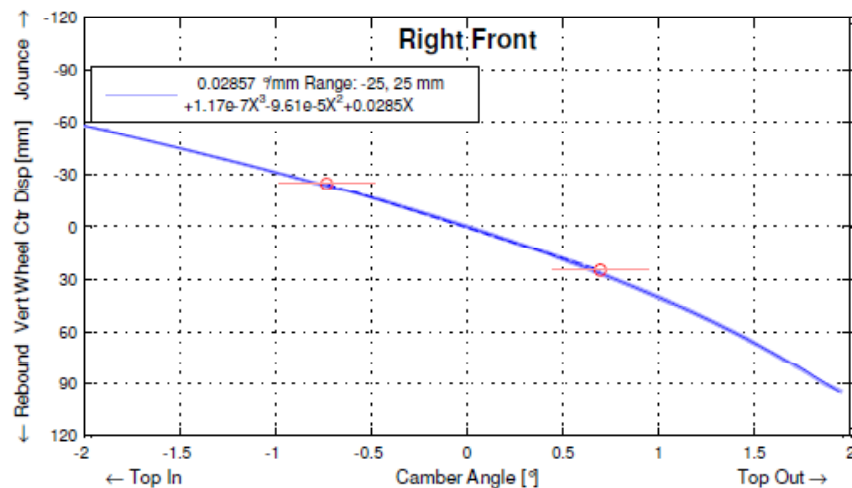
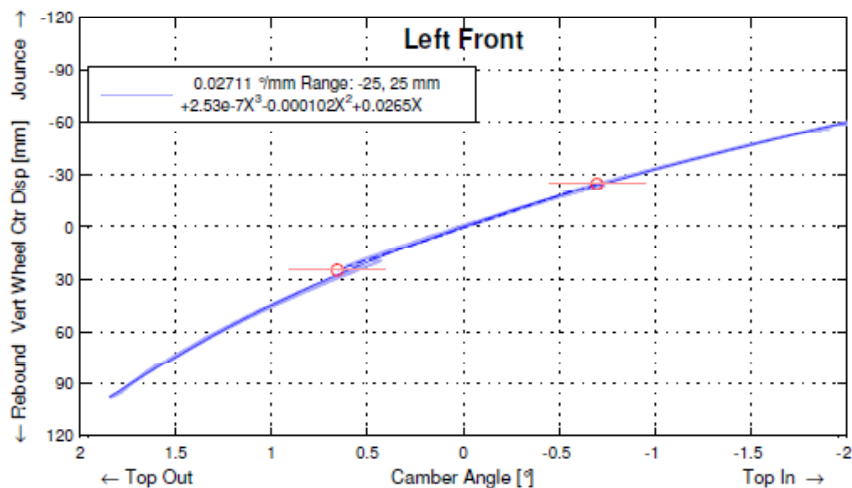
# Background

- This presentation focus on correlating suspension K&C properties to test results
- To reverse engineer a vehicle, a good suspension model is  $\alpha - \Omega$ 
  - K&C testing provides the kinematic and elasto-kinematic properties
    - Toe, camber, caster, roll-center location .... as a function of wheel motion, steering input and applied forces
  - Up to 100 independent variables to be identified
    - Hardpoint locations and bushing stiffness are primary

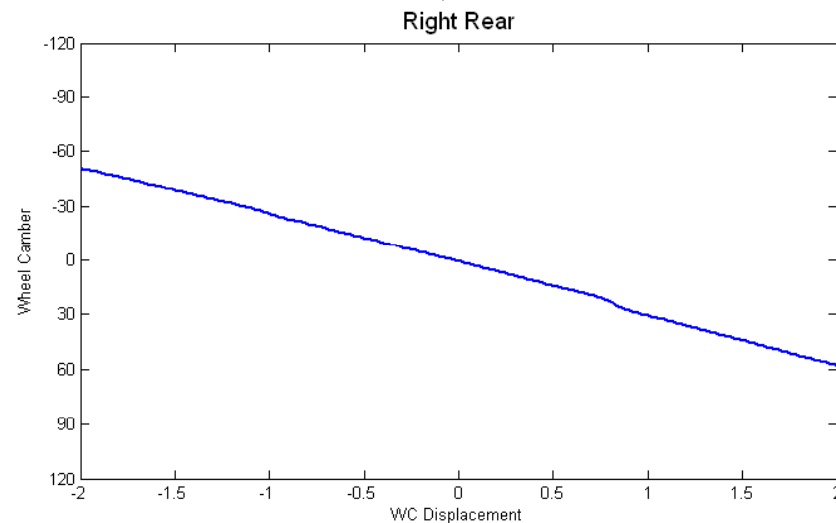
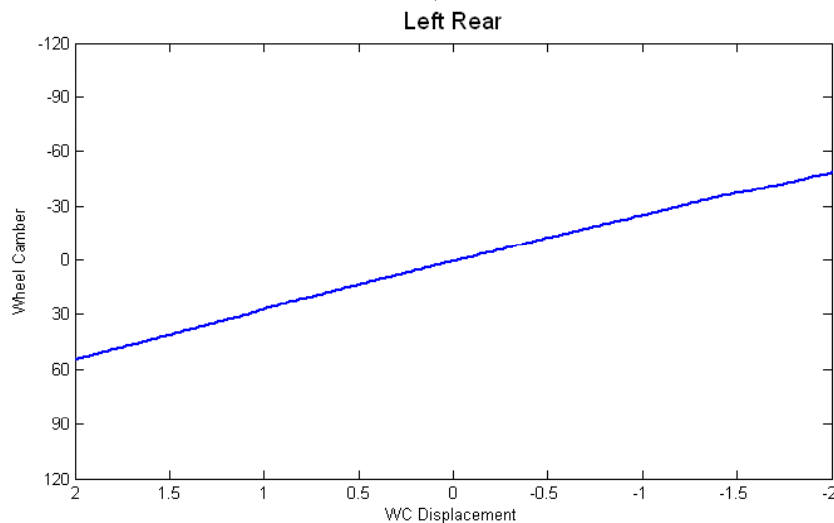
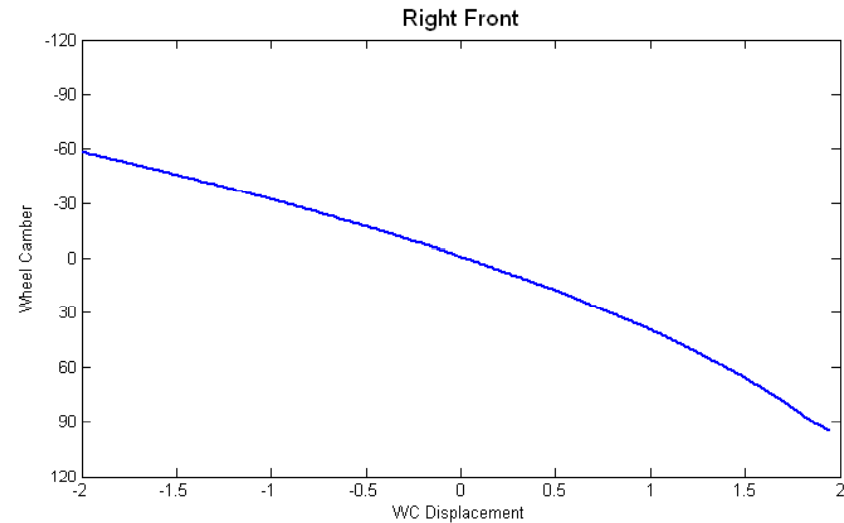
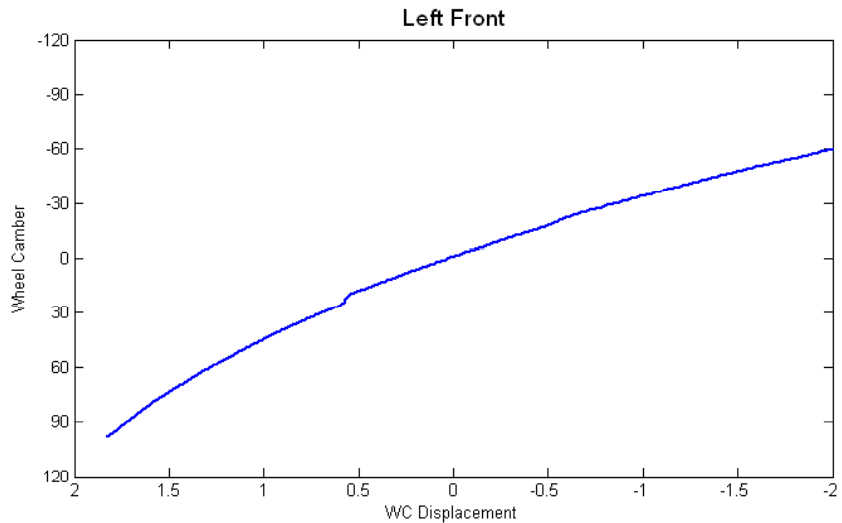
# Kinematics and Compliance testing



# Example results



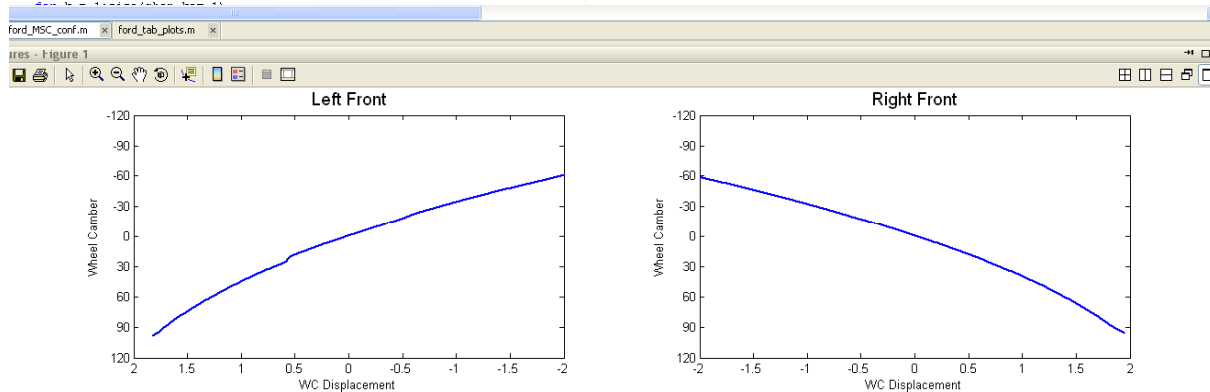
# Using Matlab, convert from K&C Raw data to filtered ADAMS splines



# Use Matlab scripts to write command files

```
%condition creates the field and fills the data with zeros.
waitbar(2,h,'Filtering Data...')
for k = 1:size(chan_key,1)
    if isfield(data,chan_key(k,3))
        data_out=setfield(data_out,chan_key(k,1),chan_key(k,2),'raw_data',(getfield(data,chan_key(k,3))+chan_key(k,5)).*chan_key(k,4));
        [B,A]=butter(3,10/100,'Low');
        data_out=setfield(data_out,chan_key(k,1),chan_key(k,2),'filt_data',filtfilt(B,A,getfield(data_out,chan_key(k,1),chan_key(k,2),'raw_data')));
    else
        data_out=setfield(data_out,chan_key(k,1),chan_key(k,2),'raw_data',zeros(arylen,1));
    end
    data_out=setfield(data_out,chan_key(k,1),[chan_key(k,2),'_Offset'],0);
    waitbar(1/size(chan_key,1))
end

%% Write txt file for reading into A/Car. K&C Comparison. Outputs raw data, not used in favor of fitted data file below
clear data_temp data_temp1
data_temp = [];
chan_temp = [];
output_name = strcat(dirname,'\','PME_',file_info(1)(3,1),'_',file_info(1)(4,1),'_',revision,'.txt');
save('data_temp.mat','data_temp','chan_temp');
```



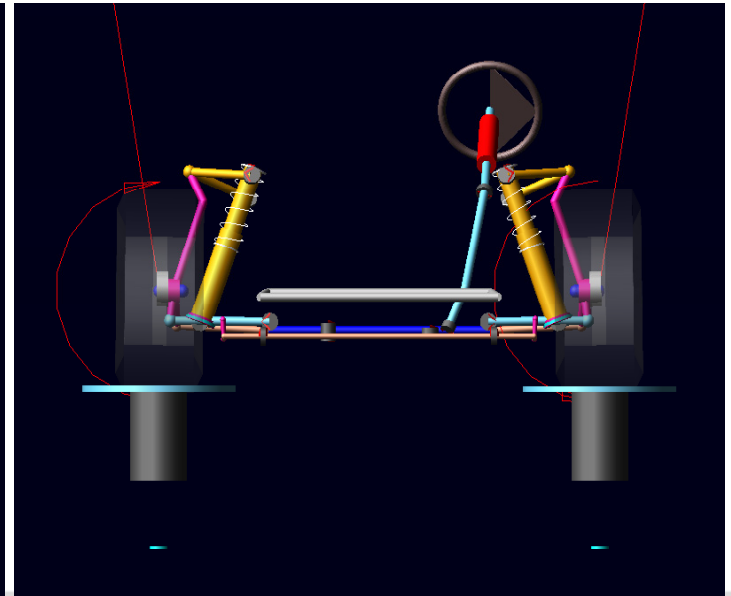
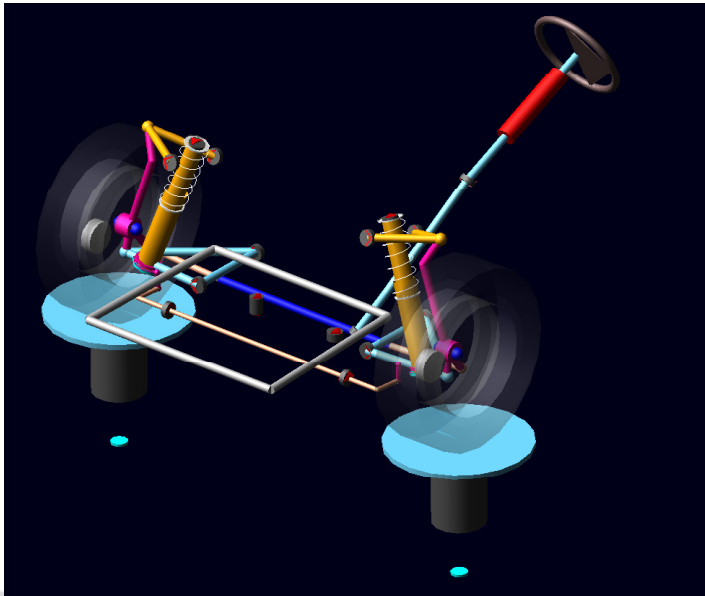
```
data_element modify spline &
    spline_name = 'PME_fr_susp.vert_LF_desired_Camber' &
    units = "no_units" &
x = &
-98.04242,-98.02899,-98.01178,-97.98999,-97.96271,-97.92902,-97.88799,-97.83877,-97.78054,-97.71264,-97.63445,-97.54242,-97.43877,-97.32500,-97.20271,-97.07290,-96.93799,-96.79877,-96.65500,-96.50771,-96.35690,-96.20271,-96.04500,-95.88377,-95.71790,-95.55399,-95.38277,-95.20500,-95.02377,-94.83790,-94.64877,-94.45690,-94.26271,-94.06500,-93.86377,-93.65500,-93.44077,-93.22271,-93.00190,-92.77877,-92.55290,-92.32477,-92.09377,-91.86077,-91.62477,-91.38577,-91.14377,-90.89877,-90.65077,-90.40077,-90.14877,-89.89377,-89.63577,-89.37477,-89.11077,-88.84377,-88.57377,-88.30077,-88.02477,-87.74577,-87.46377,-87.17877,-86.89077,-86.60077,-86.30877,-86.01377,-85.71577,-85.41377,-85.10877,-84.80077,-84.48977,-84.17577,-83.85877,-83.53877,-83.21577,-82.88977,-82.56077,-82.22877,-81.89377,-81.55577,-81.21477,-80.87077,-80.52377,-80.17377,-79.82077,-79.46477,-79.10577,-78.74377,-78.37877,-78.01077,-77.64077,-77.26877,-76.89377,-76.51577,-76.13477,-75.75077,-75.36377,-74.97377,-74.58077,-74.18477,-73.78577,-73.38377,-72.97877,-72.57077,-72.15977,-71.74577,-71.32877,-70.90877,-70.48577,-70.05977,-69.63077,-69.19877,-68.76377,-68.32577,-67.88377,-67.43877,-66.99077,-66.53877,-66.08277,-65.62377,-65.16177,-64.69277,-64.21677,-63.73277,-63.24077,-62.74077,-62.23277,-61.71777,-61.20577,-60.68777,-60.16277,-59.63477,-59.10277,-58.56677,-58.02177,-57.46877,-56.90777,-56.33877,-55.76177,-55.17677,-54.58377,-53.98277,-53.37377,-52.75677,-52.13177,-51.50077,-50.86277,-50.21677,-49.56277,-48.90077,-48.23077,-47.55277,-46.86677,-46.17277,-45.47077,-44.76077,-44.04277,-43.31677,-42.58277,-41.84077,-41.09077,-40.33277,-39.56677,-38.79277,-38.01077,-37.22077,-36.42277,-35.61677,-34.80277,-33.98077,-33.15077,-32.31277,-31.46677,-30.61277,-29.75077,-28.88077,-28.00277,-27.11677,-26.22277,-25.32077,-24.41077,-23.49277,-22.56677,-21.63277,-20.69077,-19.74077,-18.78277,-17.81677,-16.84277,-15.86077,-14.87077,-13.87277,-12.86677,-11.85277,-10.83077,-9.79977,-8.76077,-7.71277,-6.65677,-5.59277,-4.52077,-3.44077,-2.35277,-1.25677,-0.15277,9.85077,10.83277,11.80277,12.76077,13.70677,14.64077,15.56277,16.47277,17.37077,18.25677,19.13077,20.00077,20.85677,21.70077,22.53277,23.35277,24.16077,24.95677,25.74077,26.51277,27.27277,28.02077,28.75677,29.48077,30.19277,30.89277,31.58077,32.25677,32.92077,33.57277,34.21277,34.84077,35.45677,36.06077,36.65277,37.23077,37.79677,38.35077,38.89277,39.42277,39.94077,40.44677,40.94077,41.42277,41.89277,42.35077,42.79677,43.23077,43.65277,44.06077,44.45677,44.84077,45.21277,45.57277,45.92077,46.25677,46.58077,46.89277,47.19277,47.48077,47.75677,48.02077,48.27277,48.51277,48.74077,48.95677,49.16077,49.35277,49.53077,49.69677,49.85077,49.99277,50.12277,50.24077,50.34677,50.44077,50.52277,50.59277,50.65077,50.69677,50.73277,50.76077,50.78077,50.79277,50.79677,50.79277,50.78077,50.76077,50.73277,50.72077,50.71677,50.71277,50.70877,50.70477,50.70077,50.69677,50.69277,50.68877,50.68477,50.68077,50.67677,50.67277,50.66877,50.66477,50.66077,50.65677,50.65277,50.64877,50.64477,50.64077,50.63677,50.63277,50.62877,50.62477,50.62077,50.61677,50.61277,50.60877,50.60477,50.60077,50.59677,50.59277,50.58877,50.58477,50.58077,50.57677,50.57277,50.56877,50.56477,50.56077,50.55677,50.55277,50.54877,50.54477,50.54077,50.53677,50.53277,50.52877,50.52477,50.52077,50.51677,50.51277,50.50877,50.50477,50.50077,50.49677,50.49277,50.48877,50.48477,50.48077,50.47677,50.47277,50.46877,50.46477,50.46077,50.45677,50.45277,50.44877,50.44477,50.44077,50.43677,50.43277,50.42877,50.42477,50.42077,50.41677,50.41277,50.40877,50.40477,50.40077,50.39677,50.39277,50.38877,50.38477,50.38077,50.37677,50.37277,50.36877,50.36477,50.36077,50.35677,50.35277,50.34877,50.34477,50.34077,50.33677,50.33277,50.32877,50.32477,50.32077,50.31677,50.31277,50.30877,50.30477,50.30077,50.29677,50.29277,50.28877,50.28477,50.28077,50.27677,50.27277,50.26877,50.26477,50.26077,50.25677,50.25277,50.24877,50.24477,50.24077,50.23677,50.23277,50.22877,50.22477,50.22077,50.21677,50.21277,50.20877,50.20477,50.20077,50.19677,50.19277,50.18877,50.18477,50.18077,50.17677,50.17277,50.16877,50.16477,50.16077,50.15677,50.15277,50.14877,50.14477,50.14077,50.13677,50.13277,50.12877,50.12477,50.12077,50.11677,50.11277,50.10877,50.10477,50.10077,50.09677,50.09277,50.08877,50.08477,50.08077,50.07677,50.07277,50.06877,50.06477,50.06077,50.05677,50.05277,50.04877,50.04477,50.04077,50.03677,50.03277,50.02877,50.02477,50.02077,50.01677,50.01277,50.00877,50.00477,50.00077,49.99677,49.99277,49.98877,49.98477,49.98077,49.97677,49.97277,49.96877,49.96477,49.96077,49.95677,49.95277,49.94877,49.94477,49.94077,49.93677,49.93277,49.92877,49.92477,49.92077,49.91677,49.91277,49.90877,49.90477,49.90077,49.89677,49.89277,49.88877,49.88477,49.88077,49.87677,49.87277,49.86877,49.86477,49.86077,49.85677,49.85277,49.84877,49.84477,49.84077,49.83677,49.83277,49.82877,49.82477,49.82077,49.81677,49.81277,49.80877,49.80477,49.80077,49.79677,49.79277,49.78877,49.78477,49.78077,49.77677,49.77277,49.76877,49.76477,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# Run ADAMS/Car Suspension Simulation

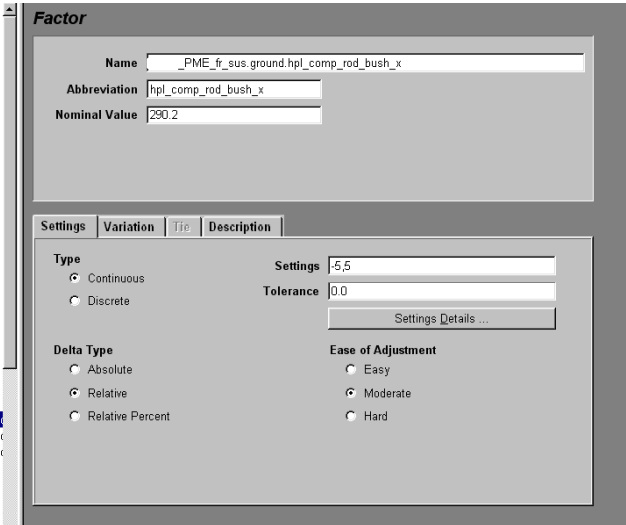
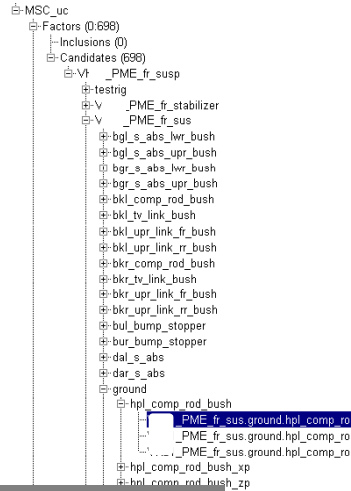
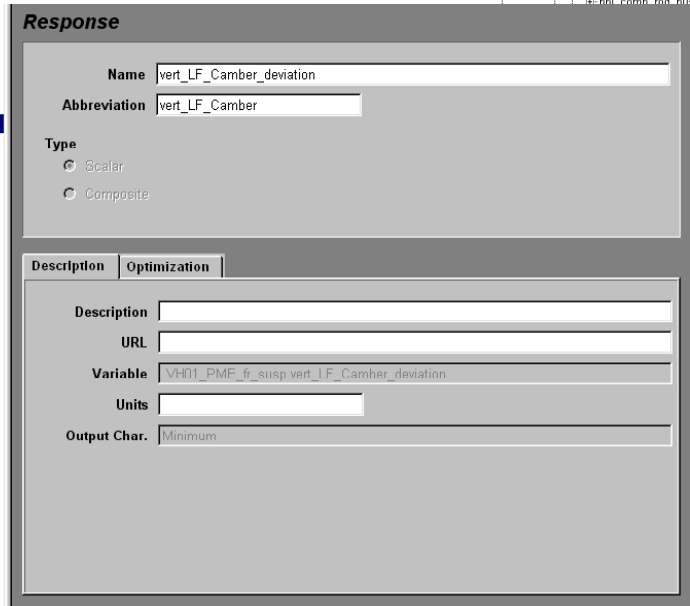
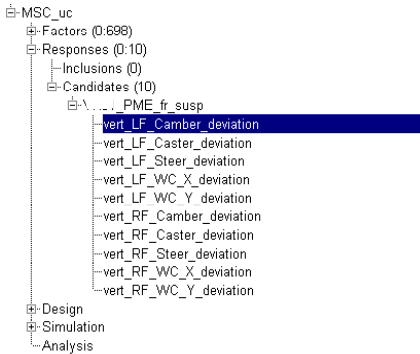


- Possible simulations:
  - Vertical wheel motion
  - Steer
  - Aligning torque
  - Lateral aiding force
  - Lateral opposing force
  - Traction force
  - Braking force
  - Roll motion
  - ...
  - ...
- Each simulation will result in a separate DOE experiment
- Pratt & Miller Engineering's DOETool<sup>®</sup> will be able to optimize across all the experiments



# ADAMS/Insight

- Load the assembly
- Export to ADAMS/Insight



# Setup experiment

- DOE Response Surface
  - Develops interactions between all factors
- Cubic
  - Quadratic could be enough, but due to short simulation time, cubic was chosen for better results
- Latin Hypercube
- Number of Runs
  - Used a general rule of ~4x the minimum suggested by ADAMS/Insight
  - 1.7x the minimum suggested should be enough if all simulations run to completion
- Create workspace created in ADAMS/Insight but runs completed externally to avoid issues with single run failure
- After external runs have completed, the results were loaded the objectives computed.

### Design Specification

<b>Investigation Strategy</b> <ul style="list-style-type: none"> <li><input type="radio"/> Study - Perimeter</li> <li><input type="radio"/> Study - Sweep</li> <li><input type="radio"/> DOE Screening (2 Level)</li> <li><input checked="" type="radio"/> DOE Response Surface</li> <li><input type="radio"/> Variation - Monte Carlo</li> <li><input type="radio"/> Variation - Latin Hypercube</li> </ul>	<b>Model</b> <ul style="list-style-type: none"> <li><input type="radio"/> Linear</li> <li><input type="radio"/> Interactions</li> <li><input type="radio"/> Quadratic</li> <li><input checked="" type="radio"/> Cubic</li> <li><input type="radio"/> None</li> </ul>	<b>DOE Design Type</b> <ul style="list-style-type: none"> <li><input type="radio"/> Plackett Burman</li> <li><input type="radio"/> Fractional Factorial</li> <li><input type="radio"/> Full Factorial</li> <li><input type="radio"/> Box Behnken</li> <li><input type="radio"/> CCF</li> <li><input type="radio"/> D-Optimal</li> <li><input checked="" type="radio"/> Latin Hypercube</li> </ul>
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<b>Candidate Runs</b> <ul style="list-style-type: none"> <li><input checked="" type="radio"/> All</li> <li><input type="radio"/> Random</li> </ul>	<b>Number of Runs</b> <input style="width: 50px;" type="text" value="1000"/> 220 to 1000000 <b>Number of Center Points</b> <input style="width: 50px;" type="text"/> <b>Number of Candidate Runs</b> <input style="width: 50px;" type="text"/>	<b>Run Order</b> <ul style="list-style-type: none"> <li><input checked="" type="radio"/> Standard</li> <li><input type="radio"/> Random</li> <li><input type="radio"/> Ease of Adjustment</li> </ul>
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# Run simulations and load results

- Do not run analysis from ADAMS/Insight
  - Save experiment and close A/Insight
- Use
  - Command navigator → mdi → insight → build
- Rename master acf (tst.acf) to bat file
  - Change each line from
    - Command/file=tst\_xxxx.acf
  - to
    - Call adams08 acar ru-st tst\_xxxx.acf
  - This allows to run the bat file externally and the whole batch will complete even if one run do not finish
- To load analysis results
  - Command navigator → mdi → insight → load
- Return to ADAMS/Insight and load experiment

# Study the fit

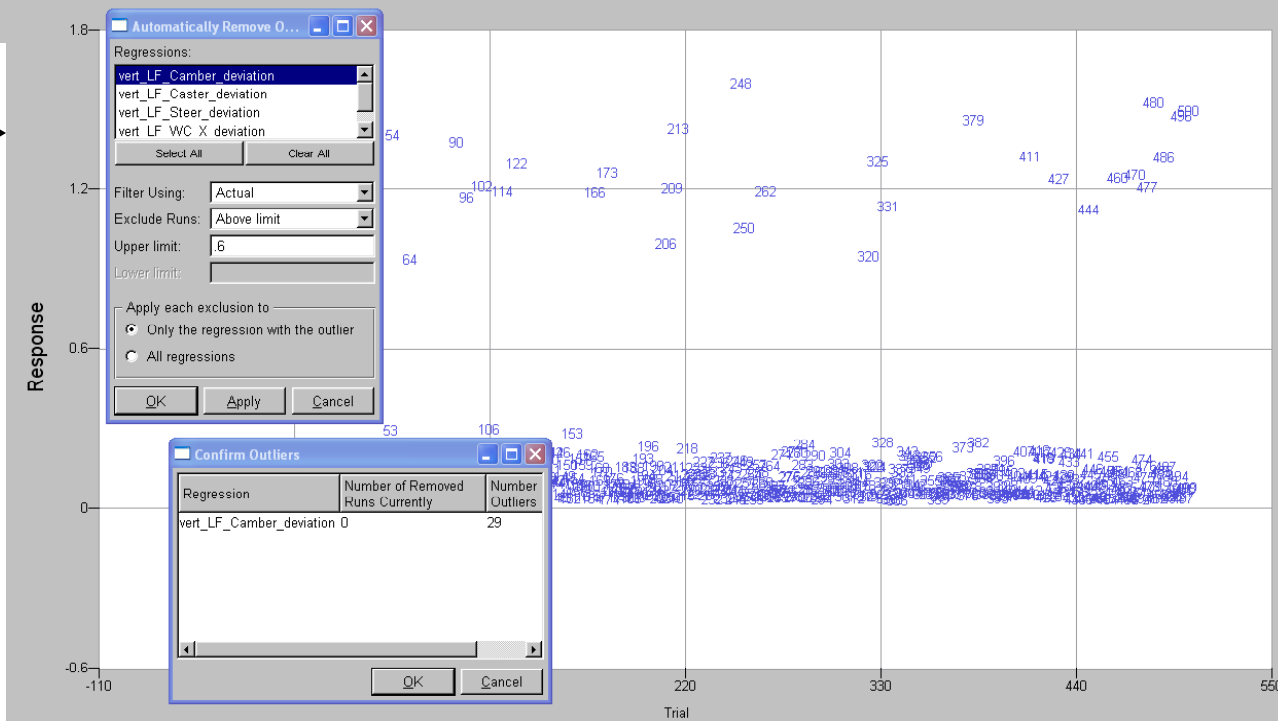
Fit for regression "vert\_LF\_Camber\_deviation"

	DOF	SS	MS	F	P
Model	230	30.3	0.132	4.14	3.99e-028
Error	269	8.58	0.0319		
Total	499	38.9			
R2	0.78	✘			
R2adj	0.591	✘			
R/V	13.5	✔			

- Without post processing the DOE has a poor fit as indicated by the fit summary.

- Automatically remove outliers above 0.6 in this case to obtain a better fit

Plot - Responses vs. Trials for regression "vert\_LF\_Camber\_deviation"



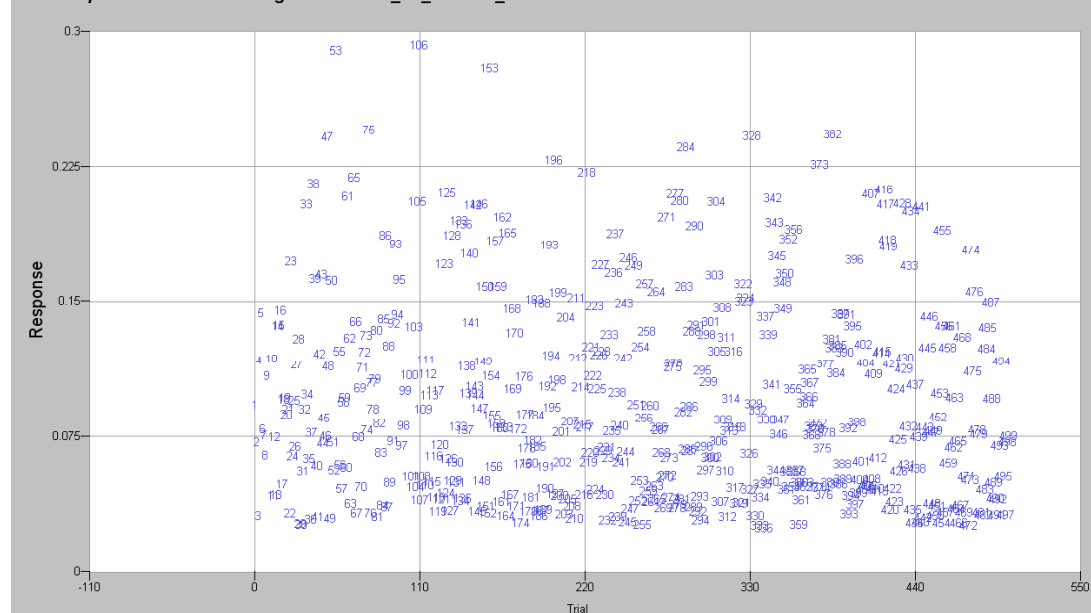
# Remove outliers

Fit for regression "vert\_LF\_Camber\_deviation"

	DOF	SS	MS	F	P
Model	230	1.38	0.00599	28.9	2.38e-108
Error	240	0.0497	0.000207		
Total	470	1.43			
R2	0.965				
R2adj	0.932				
R/V	31.2				

- Usually have an objective for last simulation time
  - Simplifies the process of eliminating runs that did not complete

Plot - Responses vs. Trials for regression "vert\_LF\_Camber\_deviation"



- DOE fit improves after outliers are removed
- This process is completed for all responses
- After this process is completed, export the Insight data to a .m file
- The m-file will be read by PME DOETool

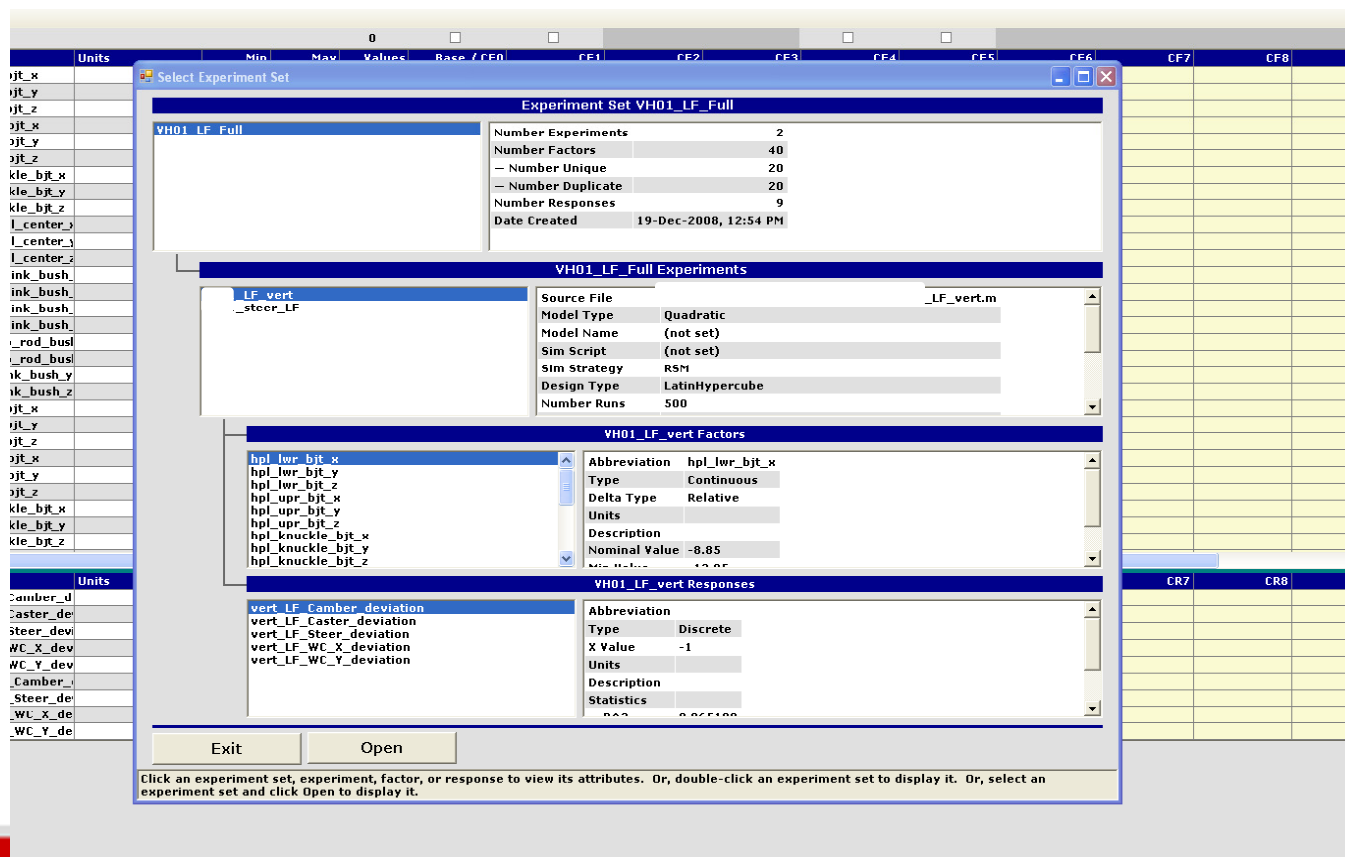
# PME DOETool®



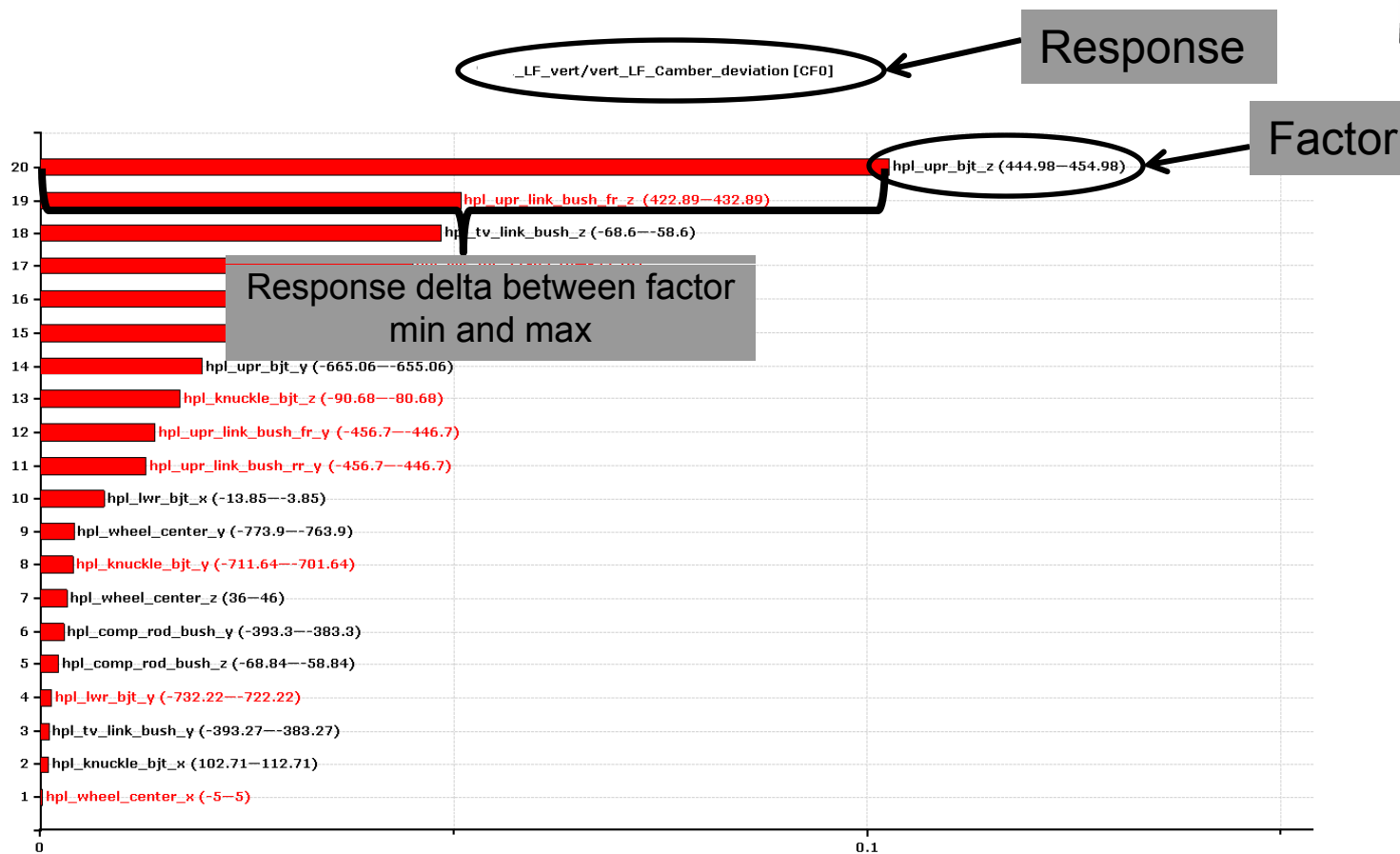
- A commercial software developed by Pratt & Miller Engineering
  - Tailor-made to post process ADAMS/Insight results
  - Simplifies the process of working with multiple experiments
  - Also adds several new type of plots to study factor contribution
    - Multiple responses vs. one factor
    - One response vs. multiple factors
  - Allows for constrained optimization across multiple experiment with overlapping factors

# Build PME DOETool<sup>®</sup> Database

- Create a new database in PME DOETool<sup>®</sup>
- Load each ADAMS/Insight experiment into the DOETool<sup>®</sup> database
- Create DOETool<sup>®</sup> “*Experiment Set*” that includes all experiments
  - Allows for optimization of factors across all the experiments

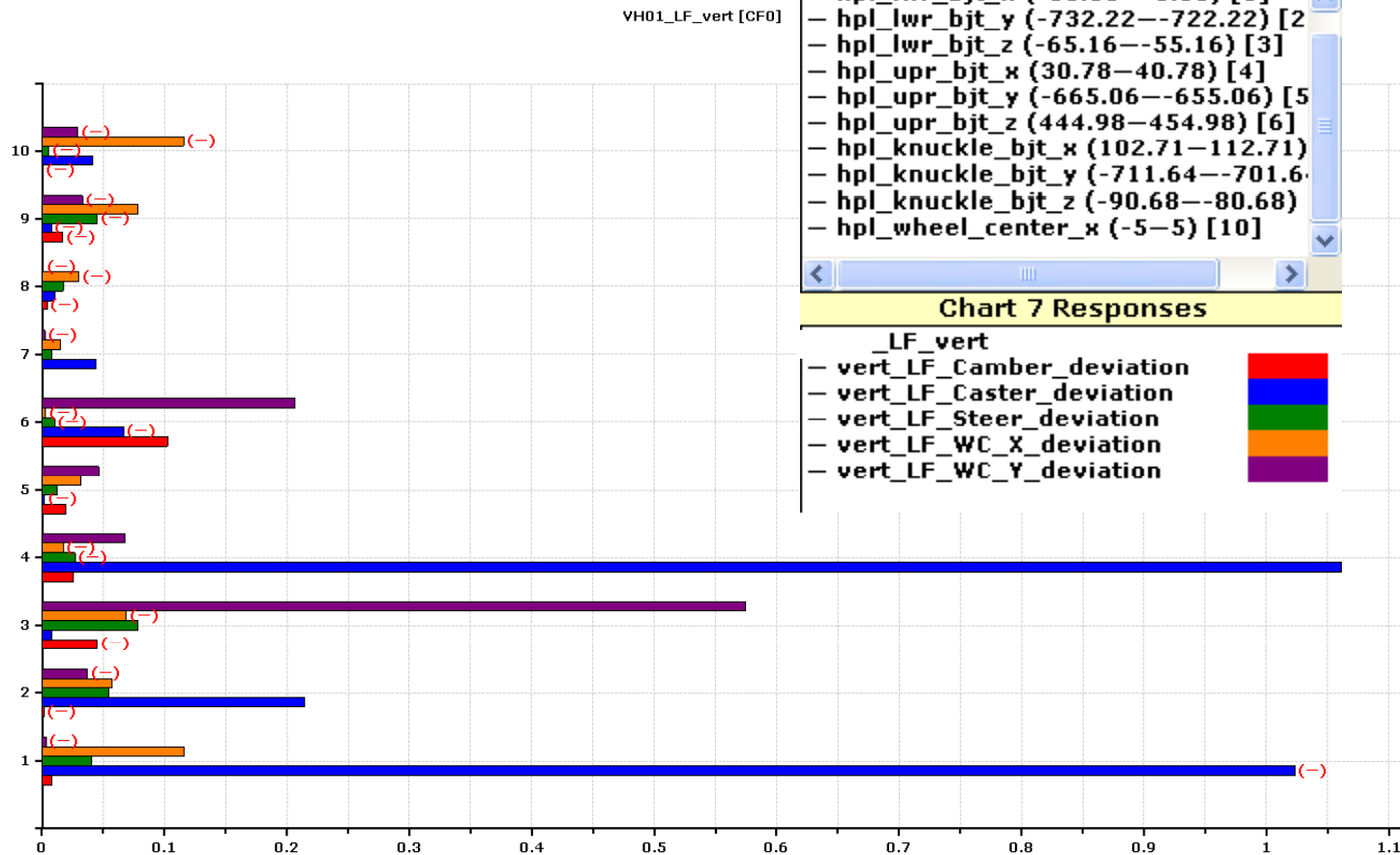


# Pareto Charts



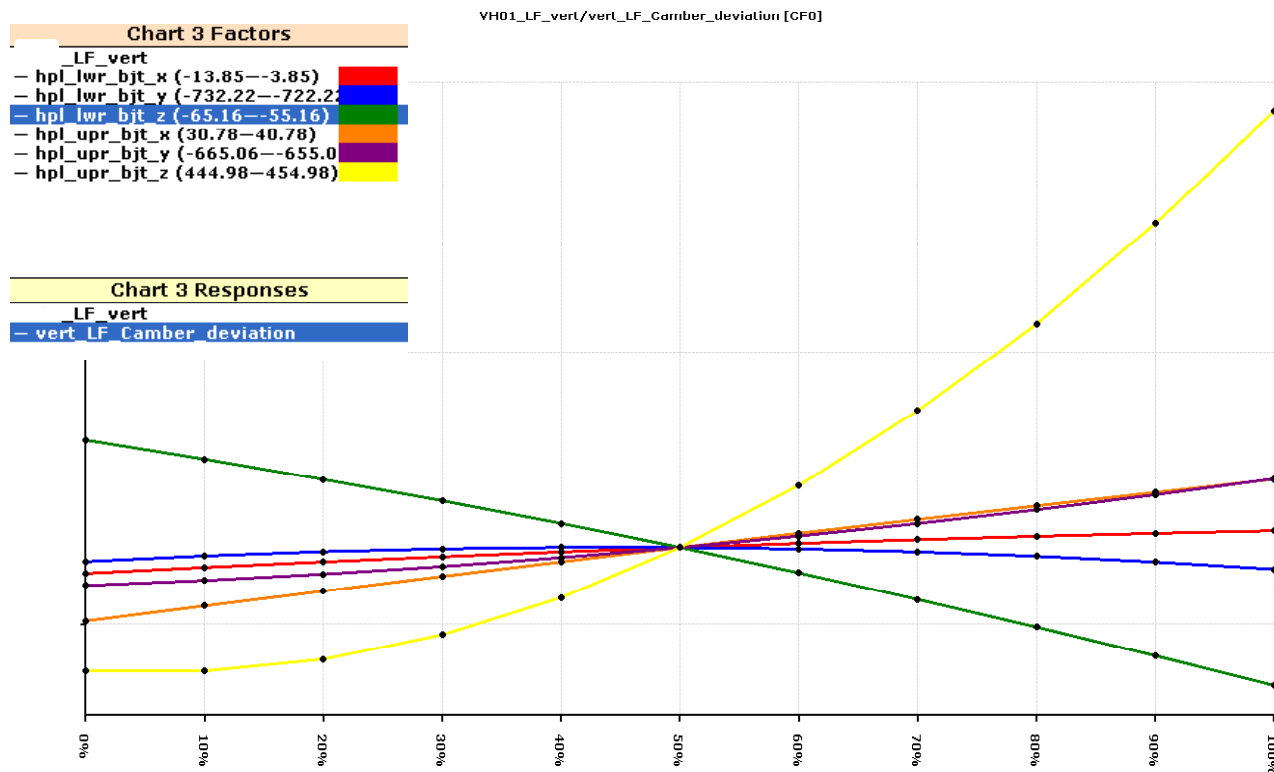
- Shows the change in response value when evaluated at the minimum and maximum of each factor
- Chart shows which factor has the most influence on the selected factor
- PME DOETool<sup>®</sup> can automatically create this Pareto chart for each response in each experiment. Gives a good 'first glance' impression of which parameters are of most importance

# Inverted Multiple Pareto Charts



- Each color bar is a response
- Each number of the y-axis is a factor
- Shows the effect of multiple factors on all the selected responses
  - While useful, it hides any non-linear response trends

# Trend – Response Charts

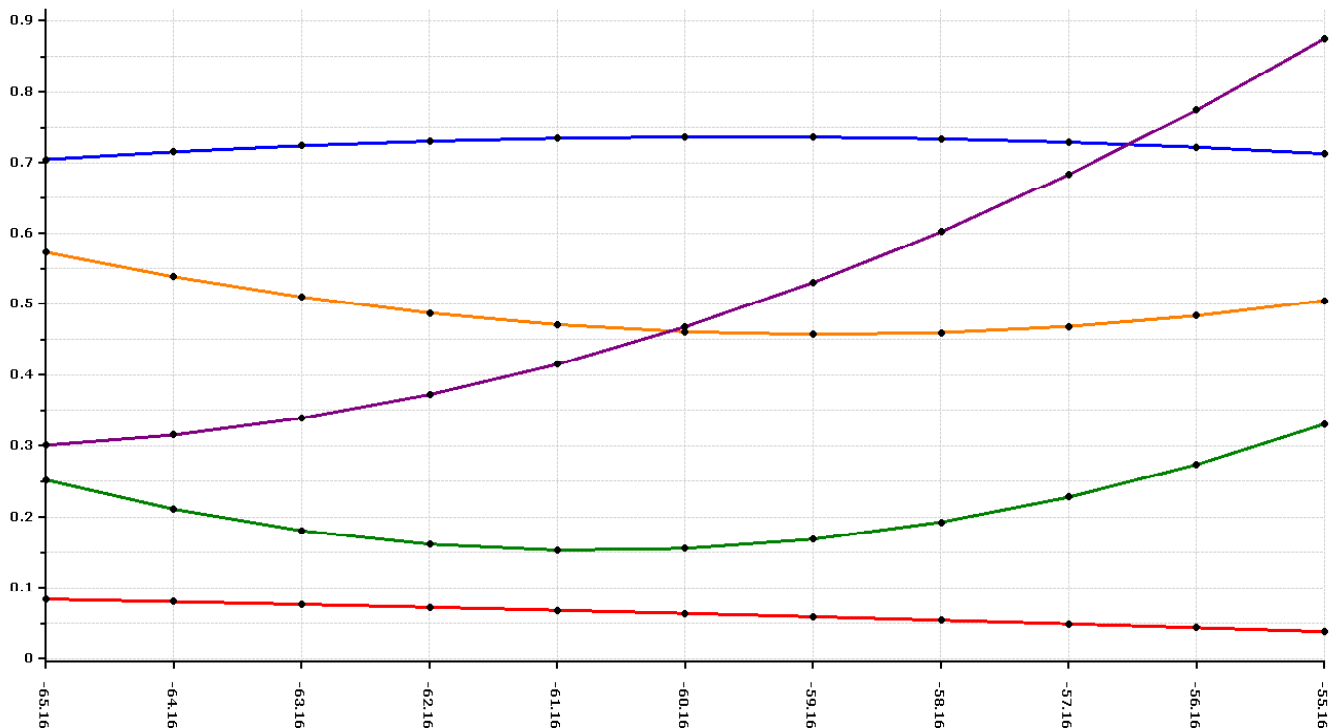


- Evaluates the selected response at 11 normalized points for each factor
  - Shows which factor truly has the highest impact along with any non-linearities in the response value



# Trend – Factor Range Charts

\_LF\_vert/hpl\_lwr\_bjt\_z(-65.16--55.16) [CF0]



**Chart 5 Factors**

- \_LF\_vert
- hpl\_lwr\_bjt\_z (-65.16--55.16)

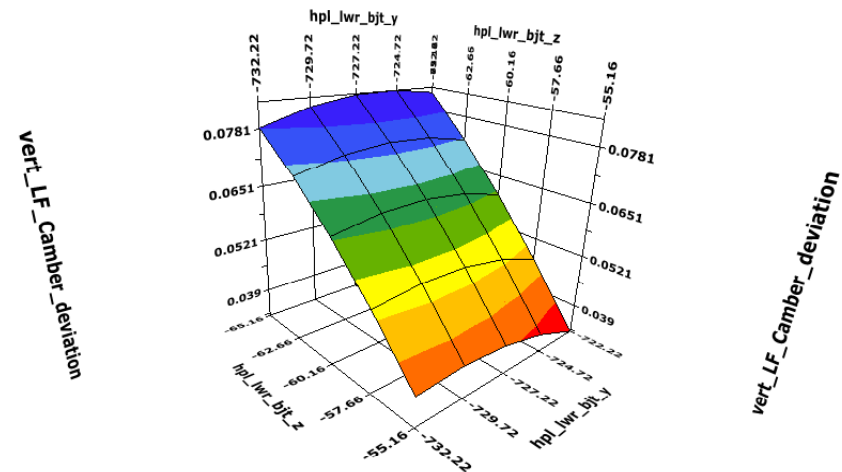
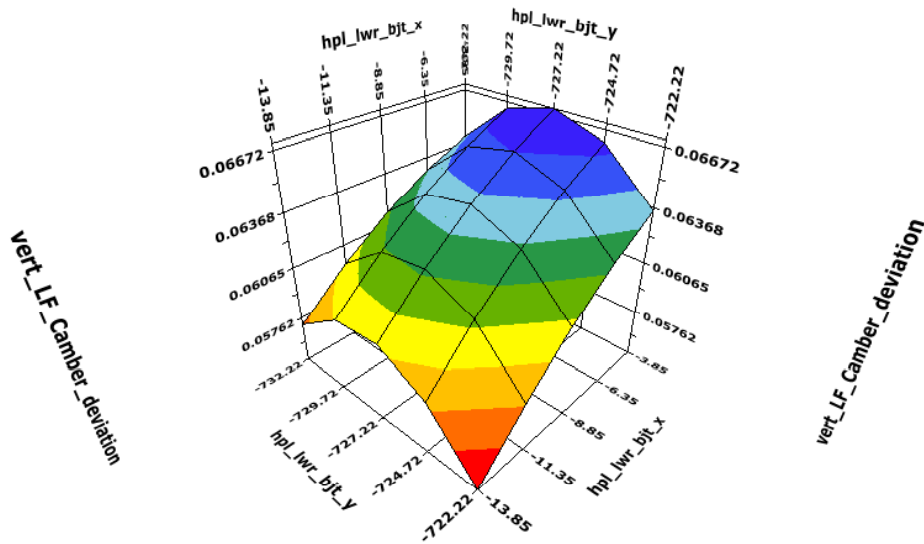
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**Chart 5 Responses**

- \_LF\_vert
- vert\_LF\_Camber\_deviation
- vert\_LF\_Caster\_deviation
- vert\_LF\_Steer\_deviation
- vert\_LF\_WC\_X\_deviation
- vert\_LF\_WC\_Y\_deviation

- This is the inverse to the ‘Trend – Response Range’ shows the trend for each response as the selected factor is varied from minimum to maximum

# Factor Interaction Surface Plots



- Each color bar is a response
- Each number of the y-axis is a factor
- Shows the effect of each selected factor on all the selected responses

# Optimization across multiple experiments



Experiment	Factor	Units	Min	Max	Include?	Opt Min	Opt Max	Base / CF0	Current	Simple Opt	Advan'd Opt	MATLAB Opt
_LF_vert	hpl_lwr_bjt_x		-13.85	-3.85	✓	-13.85	-3.85	-8.85	-8.85			
_LF_vert	hpl_lwr_bjt_y		-732.22	-722.22	✓	-7	-7	2	12			
_LF_vert	hpl_lwr_bjt_z		-65.16	-55.16	✓	-	-	6	6			
_LF_vert	hpl_upr_bjt_x		30.78	40.78	✓	-	-	8	8			
_LF_vert	hpl_upr_bjt_y		-665.06	-655.06	✓	-6	-6	6	16			
_LF_vert	hpl_upr_bjt_z		444.98	454.98	✓	4	4	8	8			
_LF_vert	hpl_knuckle_bjt_x		102.71	112.71	✓	1	1	1	1			
_LF_vert	hpl_knuckle_bjt_y		-711.64	-701.64	✓	-7	-7	4	14			
_LF_vert	hpl_knuckle_bjt_z		-90.68	-80.68	✓	-	-	8	8			
_LF_vert	hpl_wheel_center_x		-5	5	✓	-	-	0	0			
_LF_vert	hpl_wheel_center_y		-773.9	-763.9	✓	-	-	9	9			
_LF_vert	hpl_wheel_center_z		36	46	✓	-	-	1	1			
_LF_vert	hpl_upr_link_bush_fr_y		-456.7	-446.7	✓	-	-	7	7			
_LF_vert	hpl_upr_link_bush_fr_z		422.89	432.89	✓	4	4	9	19			
_LF_vert	hpl_upr_link_bush_rr_y		-456.7	-446.7	✓	-	-	7	7			
_LF_vert	hpl_upr_link_bush_rr_z		353.64	363.64	✓	3	3	4	14			
_LF_vert	hpl_comp_rod_bush_y		-393.3	-383.3	✓	-	-	3	3			
_LF_vert	hpl_comp_rod_bush_z		-68.84	-58.84	✓	-	-	4	14			
_LF_vert	hpl_tv_link_bush_y		-393.27	-383.27	✓	-3	-3	7	7			
_LF_vert	hpl_tv_link_bush_z		-68.6	-58.6	✓	-	-	6	6			

Constraint	Include?

Experiment	Response	Units	Type	Target	Weight	Subtotal	Change	Base / CR0	Current	Simple Opt	Advan'd Opt	MATLAB Opt
_LF_vert	vert_LF_Camber_deviation		Target	0	0.8	0.05	0	0.06	0.06			
_LF_vert	vert_LF_Caster_deviation		Target	0	0.9	0.66	0	0.74	0.74			
_LF_vert	vert_LF_Steer_deviation		Target	0	1	0.16	-0.02	0.16	0.16			
_LF_vert	vert_LF_WC_X_deviation		Target	0	0.75	0.35	0	0.46	0.46			
_LF_vert	vert_LF_WC_Y_deviation		Target	0	0.8	0.37	0	0.47	0.47			
_steer_LF	steer_LF_Camber_deviation		Target	0	1	0.12	0	0.12	0.12			
_steer_LF	steer_LF_Steer_deviation		Target	0	1	0.28	0	0.28	0.28			
_steer_LF	steer_LF_WC_X_deviation		Target	0	0.9	0.57	0	0.64	0.64			
_steer_LF	steer_LF_WC_Y_deviation		Target	0	1	0.34	0	0.34	0.34			

- Optimize to reduce the error between the ADAMS/Car K&C results and the measured results
- Optimum hard point locations will differ for each experiment
  - What works best for the vertical experiment may produce poor results in the steering experiment
- PME DOETool® will return a single set of hard points that represents the smallest error for all objectives across all experiments
- Responses can be weighted depending on importance to simulation
  - i.e. Wheel center movement weighted lower than bump camber and bump steer

# Update ADAMS/Car Subsystem

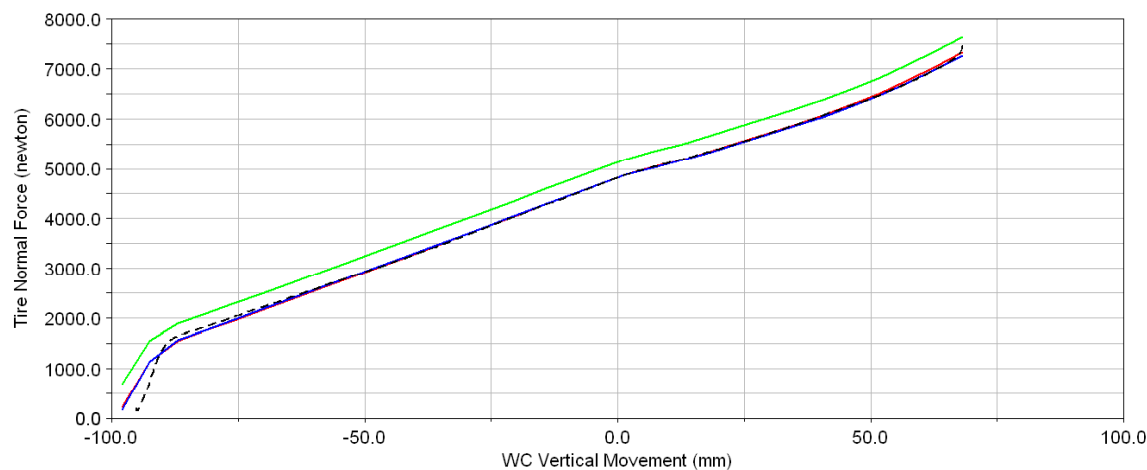
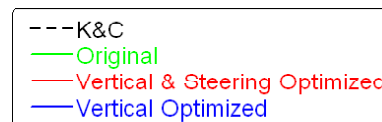
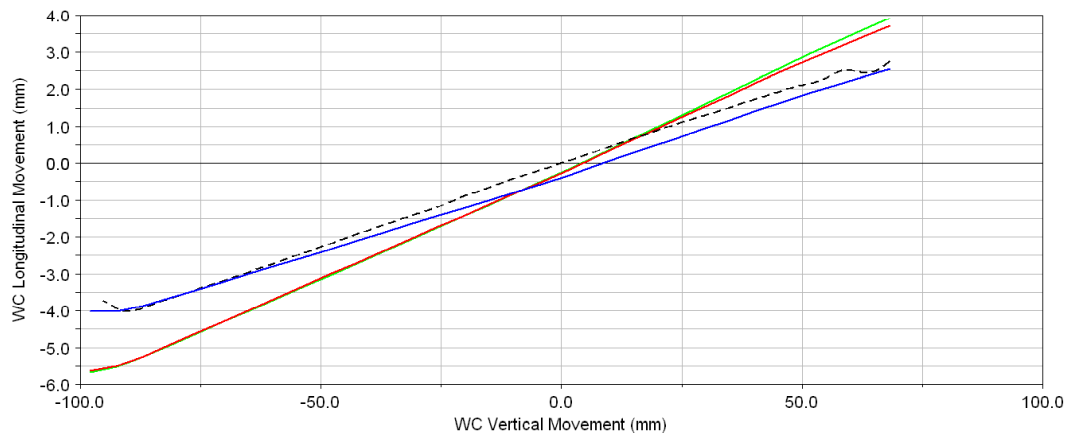
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MASS          = 'kg'
TIME          = 'sec'
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'comp_               'left/right  25            0             .84
'comp_               'left/right  25            0             .84
'comp_               'left/right  50            0             .16
'knuck               'left/right  110           0             .62
'lwr_k               'left/right  -4            0             .19
'lwr_k               'left/right  -4            0             .18
'mbr_j               'left/right  -50           0             4.6
'mbr_j               'left/right  -50           0             4.6
'mbr_j               'left/right  -50           0             4.6
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'mbr_j               'left/right  0             0             .55
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's_abs               xp           30            0             .34
's_abs               zp           -10           0             0.3
's_abs               'left/right  30            0             .34
's_abs               xp           30            0             .34
's_abs               zp           80            0             .85
'tv_li               'left/right  -4            0             3.65
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'upr_k               'left/right  30            0             .59
'upr_l               c            -90           0             3.89
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-----PART_ASSEMBLY

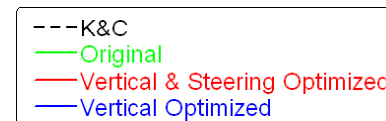
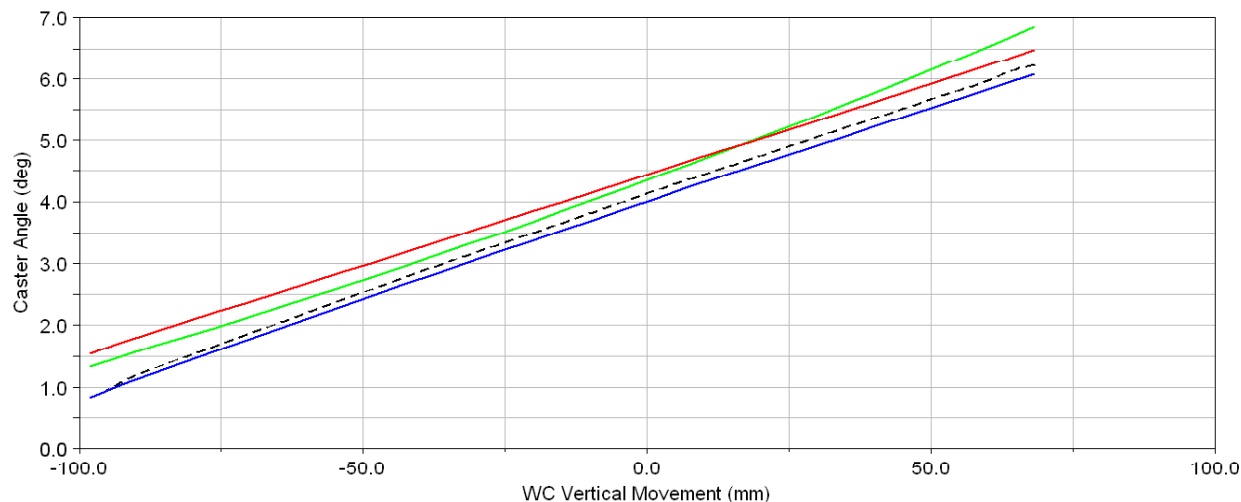
```

- Create new ADAMS/Car subsystem files with new hard points and parameters

# Compare Original Subsystem with Optimized Subsystem



# Compare Original Subsystem with Optimized Subsystem



		K&C Data		Original		Vertical Only		Both	
		Max	Min	Avg Error	Normalized Error	Avg Error	Normalized Error	Avg Error	Normalized Error
<b>Vertical</b>	Camber	1.498	-0.227	0.114	0.066	0.105	0.061	0.086	0.050
	Caster	6.206	0.942	0.266	0.050	0.159	0.030	0.333	0.063
	Steer	0.637	-0.472	0.798	0.720	0.518	0.467	0.503	0.454
	WC_X	2.731	-4.016	0.790	0.117	0.282	0.042	0.744	0.110
	WC_Y	0.359	-10.193	2.032	0.193	0.572	0.054	0.270	0.026
<b>Steer</b>	Camber	2.345	-1.828	0.041	0.010	0.197	0.047	0.137	0.033
	Steer	26.007	-23.204	0.742	0.015	0.611	0.012	0.651	0.013
	WC_X	23.308	-21.721	0.594	0.013	0.768	0.017	0.694	0.015
	WC_Y	0.155	-8.081	0.295	0.047	0.954	0.153	0.051	0.008
<b>Total Normalized Error</b>				1.231		0.884		0.773	
<b>Average Normalized Error</b>				0.137		0.098		0.086	



## Contact Details :

- For further information please contact

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