AM-VPD09-060

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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 α – Ω
  - 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

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# Example results

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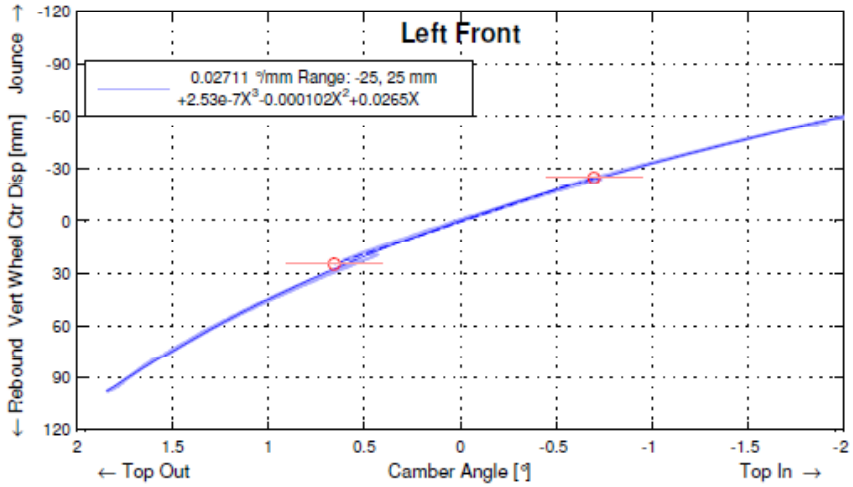


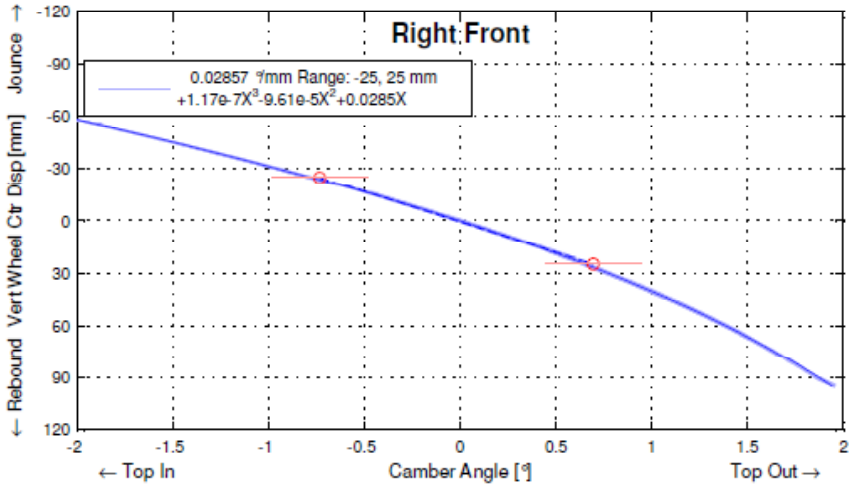


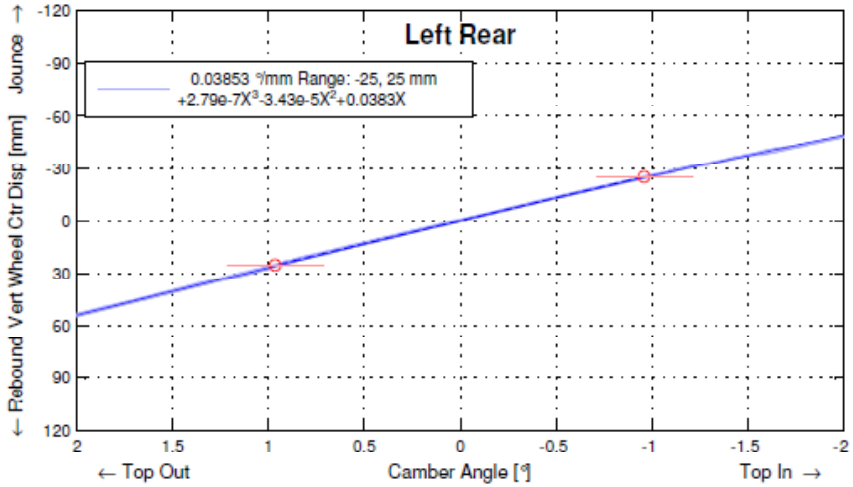


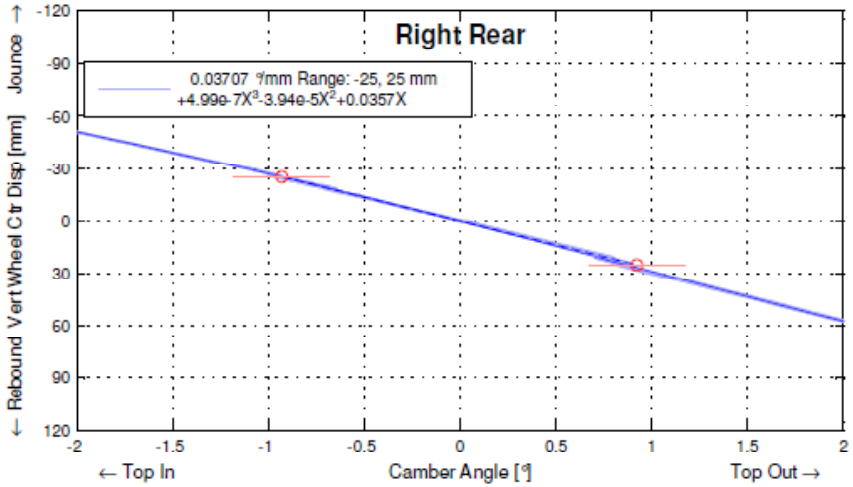

# Using Matlab, convert from K&C Raw data to filtered ADAMS splines

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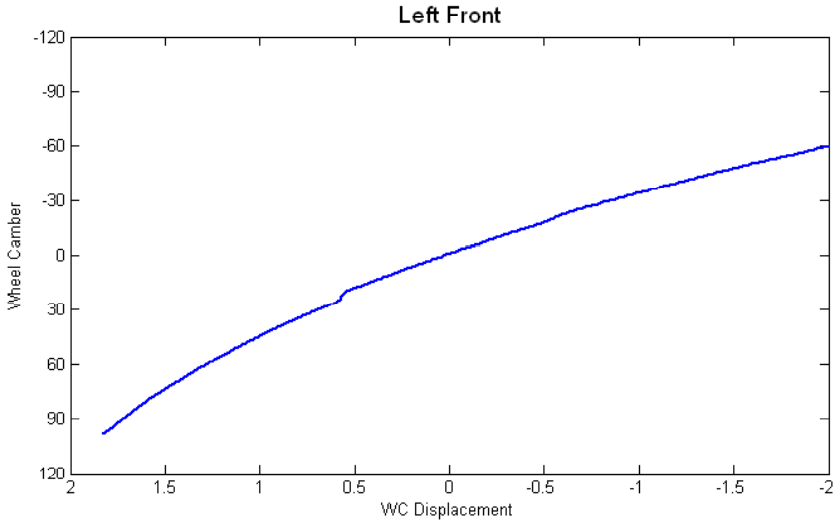


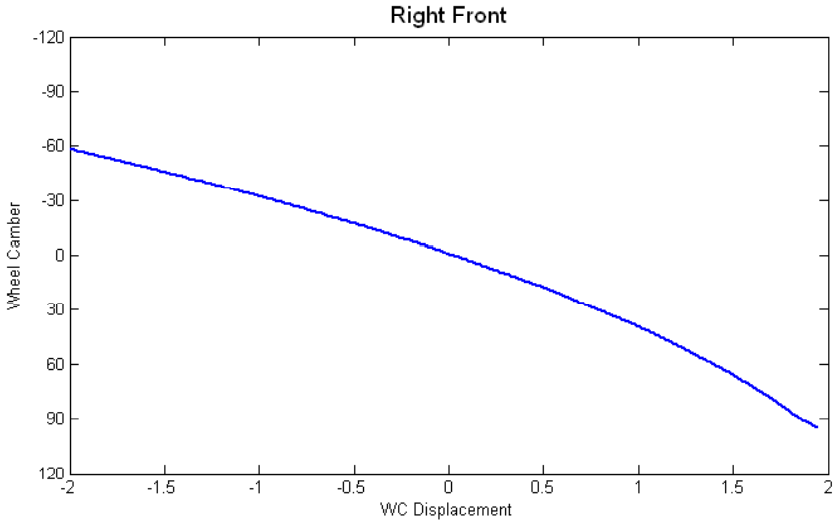


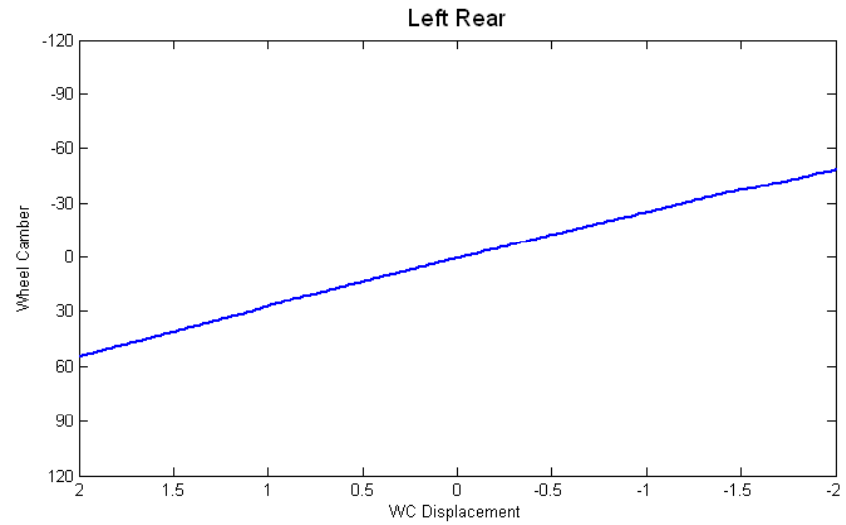


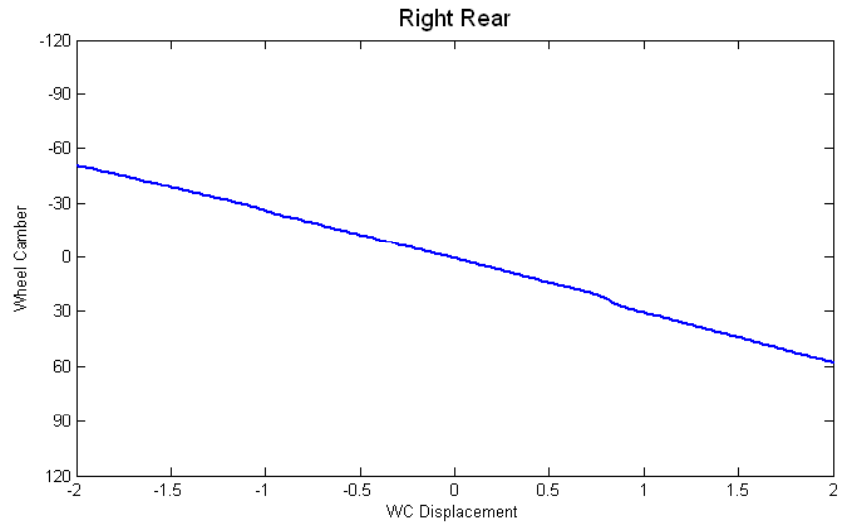

# Use Matlab scripts to write command files

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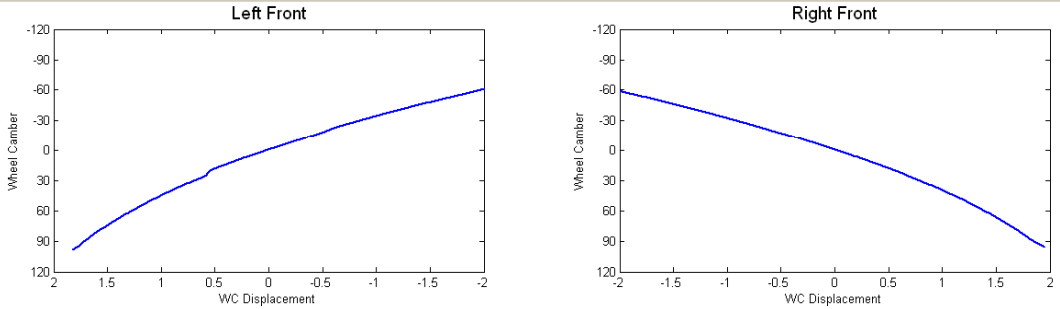
```
%condition creates the field and fills the data with zeros.
waitbar(2,h,'Filtering Data...')
for k = 1:size(chan_key,1)
    if isfield(data,chan_key(k,3))
        data_out=setfield(data_out,chan_key(k,1),chan_key(k,2),'raw_data',(getfield(data,chan_key(k,3))+chan_key(k,5)).*chan_key(k,4));
        [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(i/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');
```

ford_MSC_conf.m | ford_tab_plots.m

ures - Figure 1




```
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
y = &
1.82863,1.82859,1.82850,1.82832,1.82805,1.82763,1.82707,1.82632,1.82537,1.82421,1.82284,1.82125,1.81946,1.81746,1
```

# ADAMS Objectives

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- Created using "/View Variable and Macro"
- Sum absolute error (RMS) over simulation range
  - Use spline interpolation at output steps

```
! $analysis:t=analysis
!
!
var set var=$_self.model_name &
  obj=(eval(DB_ANCESTOR("$analysis","model")))
!
var set var=vert_LF_Camber_error_sum real=0.0
!
!
var set var=$_self.steps int=(eval(DB_COUNT("$analysis.testrig.camber_angle.left","values")))
var set var=$_self.reordered_spline real=(eval(AKIMA_SPLINE(vert_LF_desired_Camber.xs,vert_LF_desired_Camber.ys,$_self.steps)))
!
!
for variable=$_self.ii start=1 end=(eval($_Self.steps))
  var set var=$_self.i int=(eval(INT($_self.ii)))
!
  var set var=$_self.actual_value real=(eval($analysis.testrig.camber_angle.left.values[$_
  var set var=$_self.desired_value real=(eval($_self.reordered_spline.real_value[$_self.i]
!
  var set var=vert_LF_Camber_error_sum  &
    real=(eval(vert_LF_Camber_error_sum+ABS($_self.actual_value-$_self.desired_value)))
!
!
end
!
var set var=vert_LF_Camber_error_sum real=(eval(vert_LF_Camber_error_sum/$_self.steps))
!
!
var del var=(eval(DB_CHILDREN($_self,"variable")))
```

```
macro read macro_name = .vert_LF_Camber_deviation &
file = "vert_LF_Camber_macro.cmd"
!
var set var=.'    _PME_fr_susp.vert_LF_Camber_error_sum real=0.0
!
optimize objective create  &
   objective_name = (DB_DEFAULT(system_defaults, "model")//".vert_LF_Camber_deviation")  &
   variable_name = .'    _PME_fr_susp.vert_LF_Camber_error_sum  &
   macro_name = .vert_LF_Camber_deviation
!
data_element create spline &
spline_name = vert_LF_desired_Camber&
x = 0,1,2,3,4,5&
Y = 0,0,0,0,0,0
!
file command read file="vert_desired_LF_Camber_spline.cmd"
!
```

# Run ADAMS/Car Suspension Simulation

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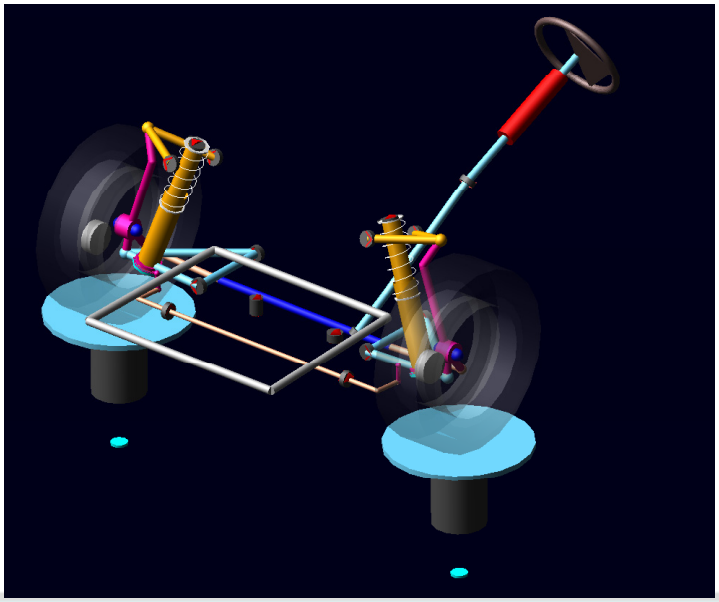
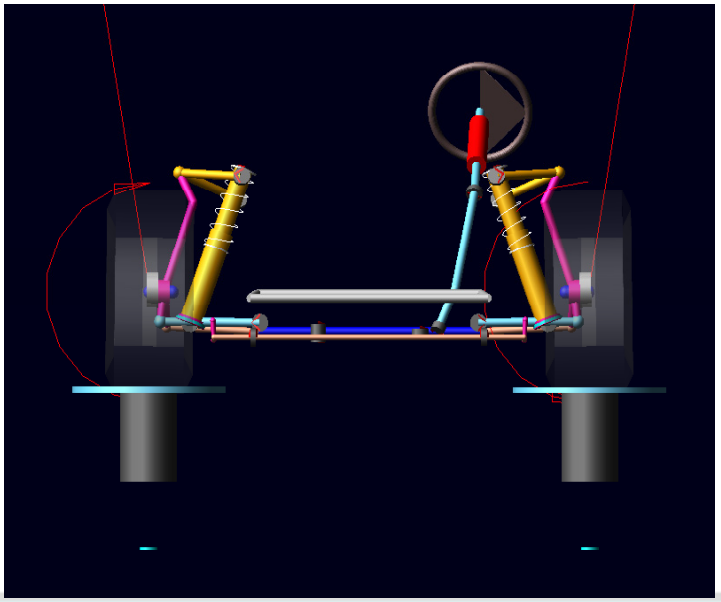
- Possible simulations:
  - Vertical wheel motion
  - Steer
  - Aligning torque
  - Lateral aiding force
  - Lateral opposing force
  - Traction force
  - Braking force
  - Roll motion
  - …
  - …

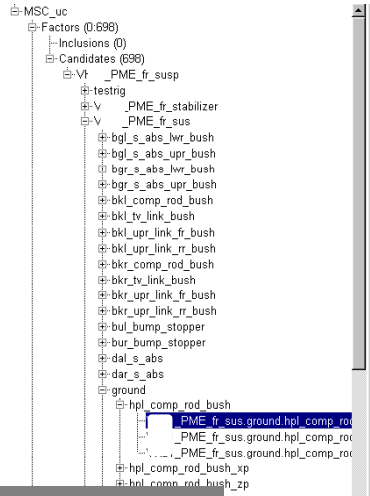
- Each simulation will result in a separate DOE experiment
- Pratt & Miller Engineering's DOETool® will be able to optimize across all the experiments

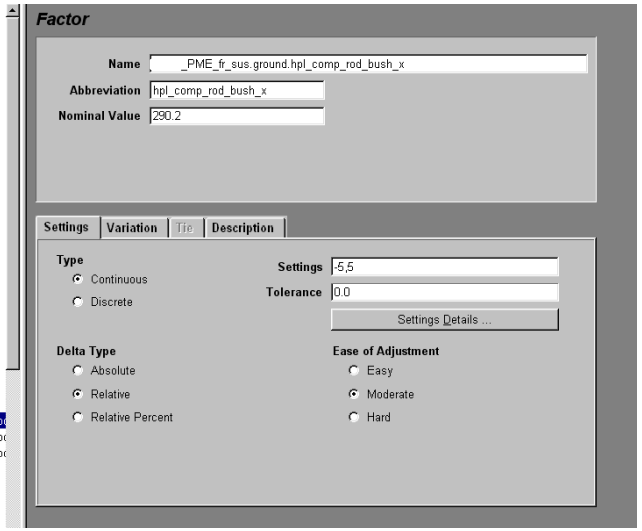


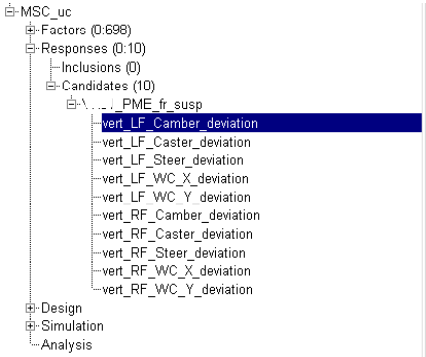


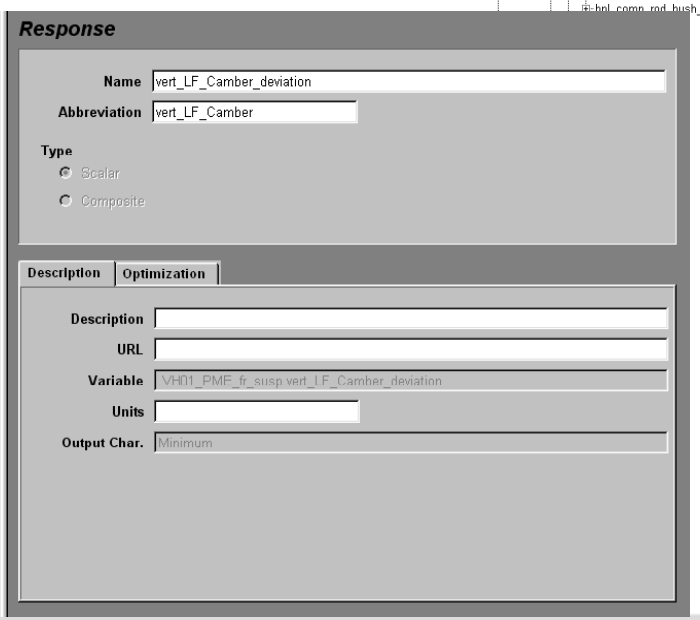
# ADAMS/Insight

- Load the assembly
- Export to ADAMS/Insight



# Setup experiment

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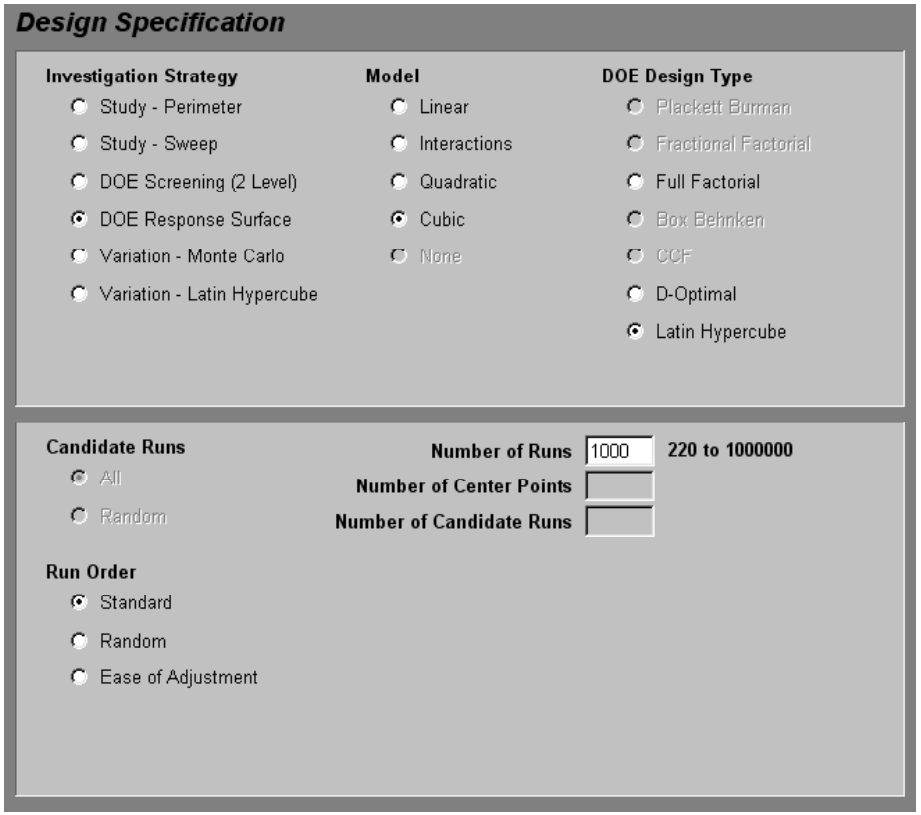
- DOE Response Surface
  - Develops interactions between all factors
- Cubic
  - Quadratic could be enough, but due to short simulation time, cubic was chosen for better results
- Latin Hypercube
- Number of Runs
  - Used a general rule of ~4x the minimum suggested by ADAMS/Insight
  - 1.7x the minimum 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.



# Run simulations and load results

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- 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

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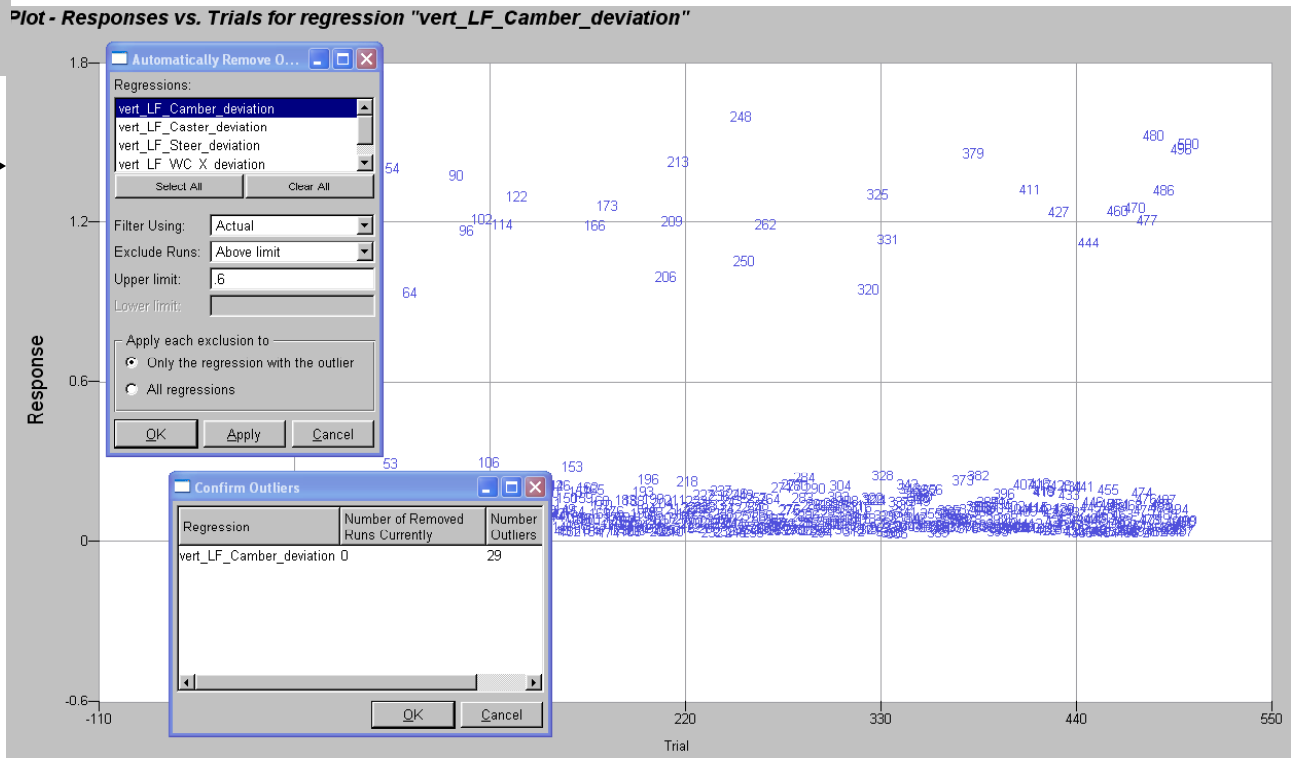
**Fit for regression "vert_LF_Camber_deviation"**

| | 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



# Remove outliers

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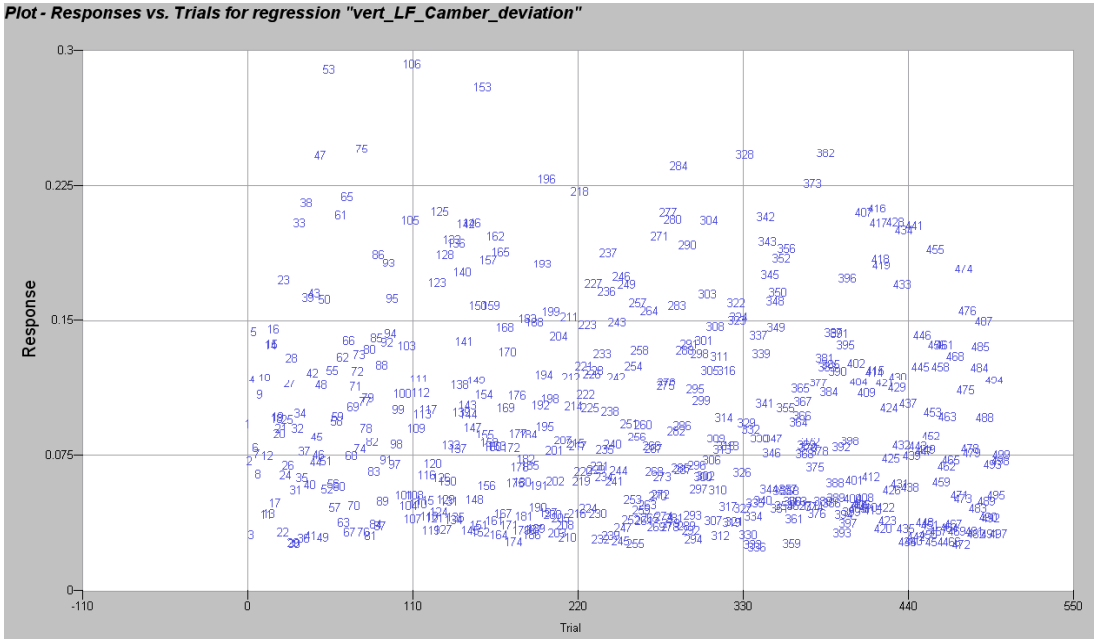
- Usually have an objective for last simulation time
  - Simplifies the process of eliminating runs that did not complete

**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 | | | | |




- 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®

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- 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® Database

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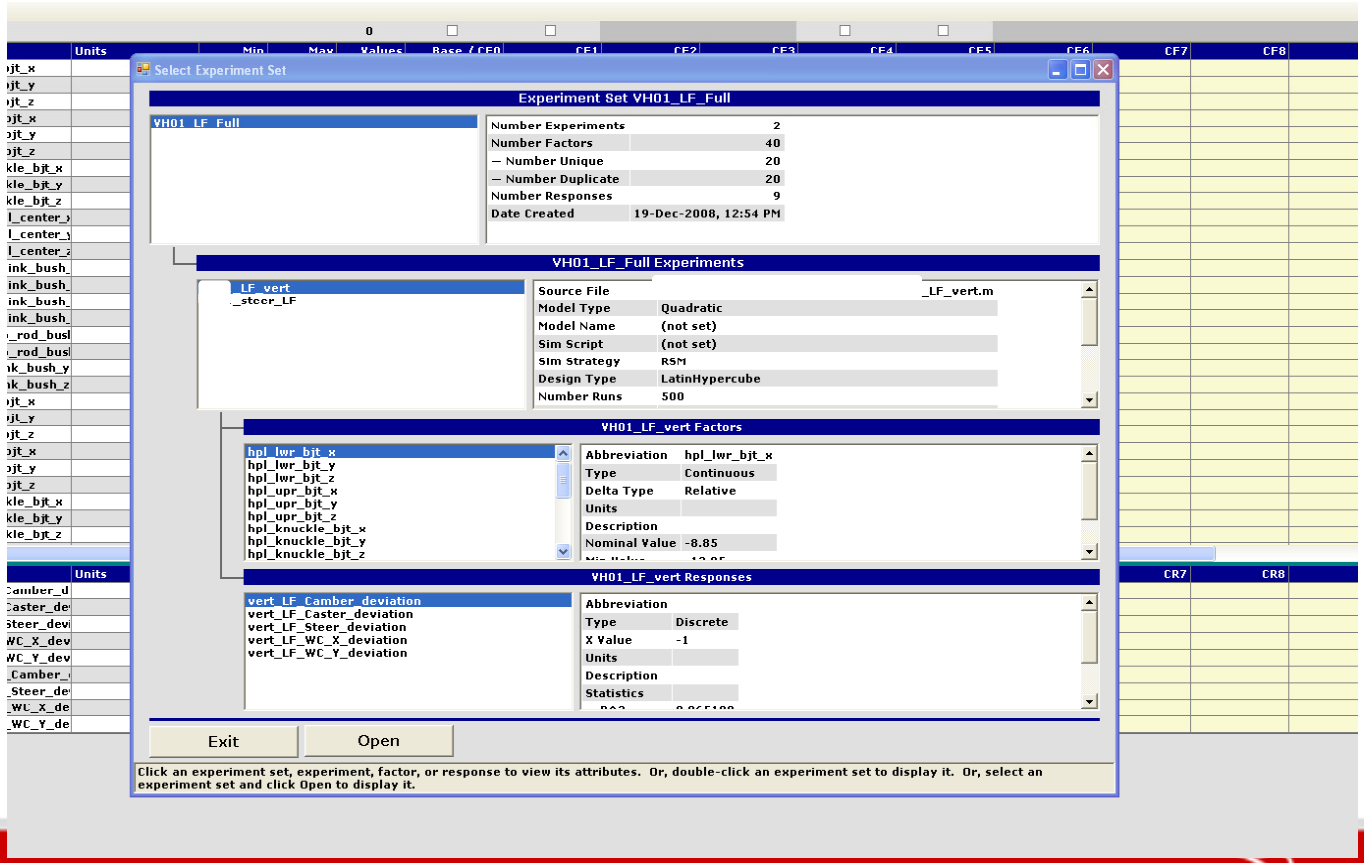
- Create a new database in PME DOETool ®
- Load each ADAMS/Insight experiment into the DOETool® database
- Create DOETool® "*Experiment Set*" that includes all experiments
  - Allows for optimization of factors across all the experiments



# Pareto Charts

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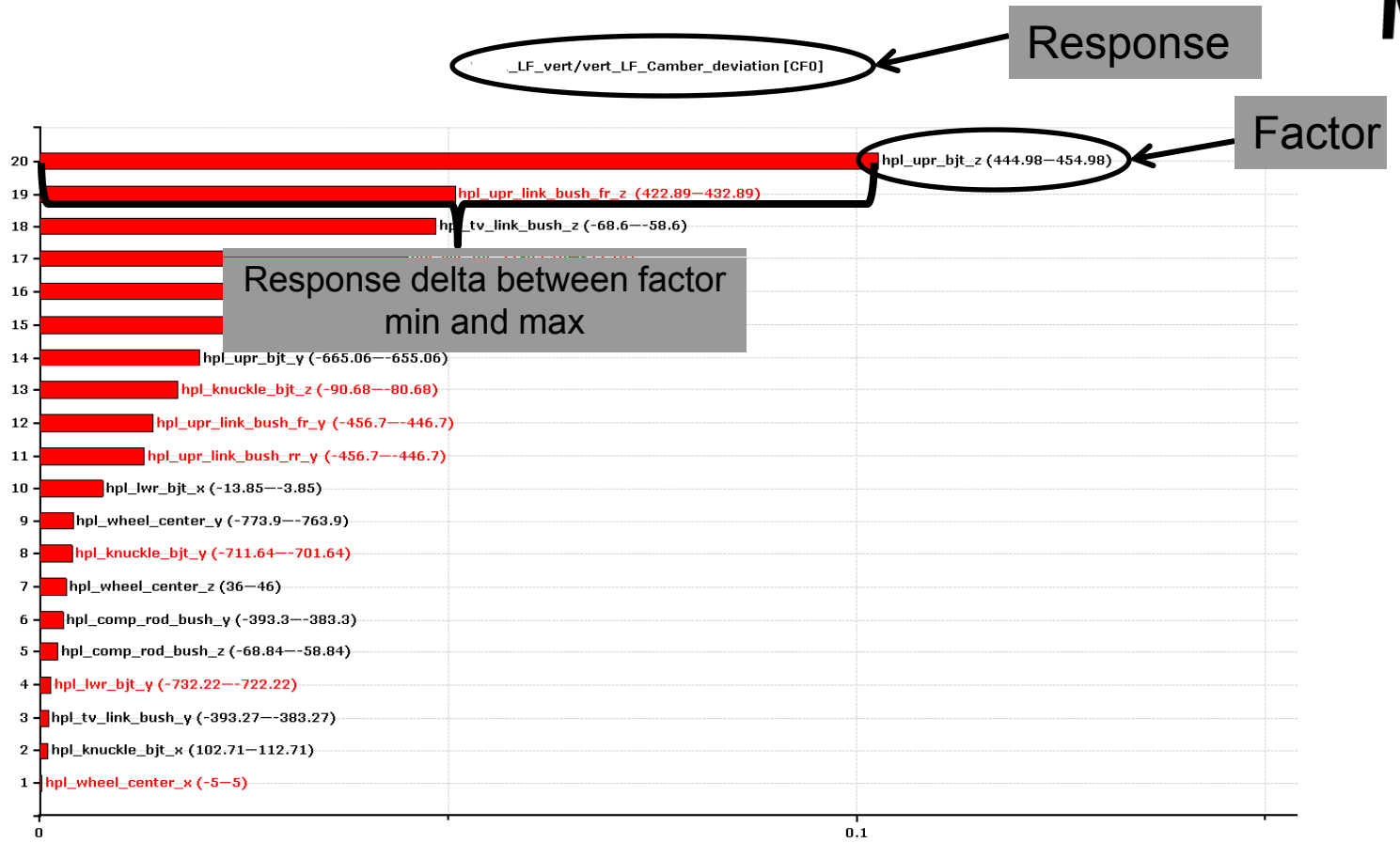
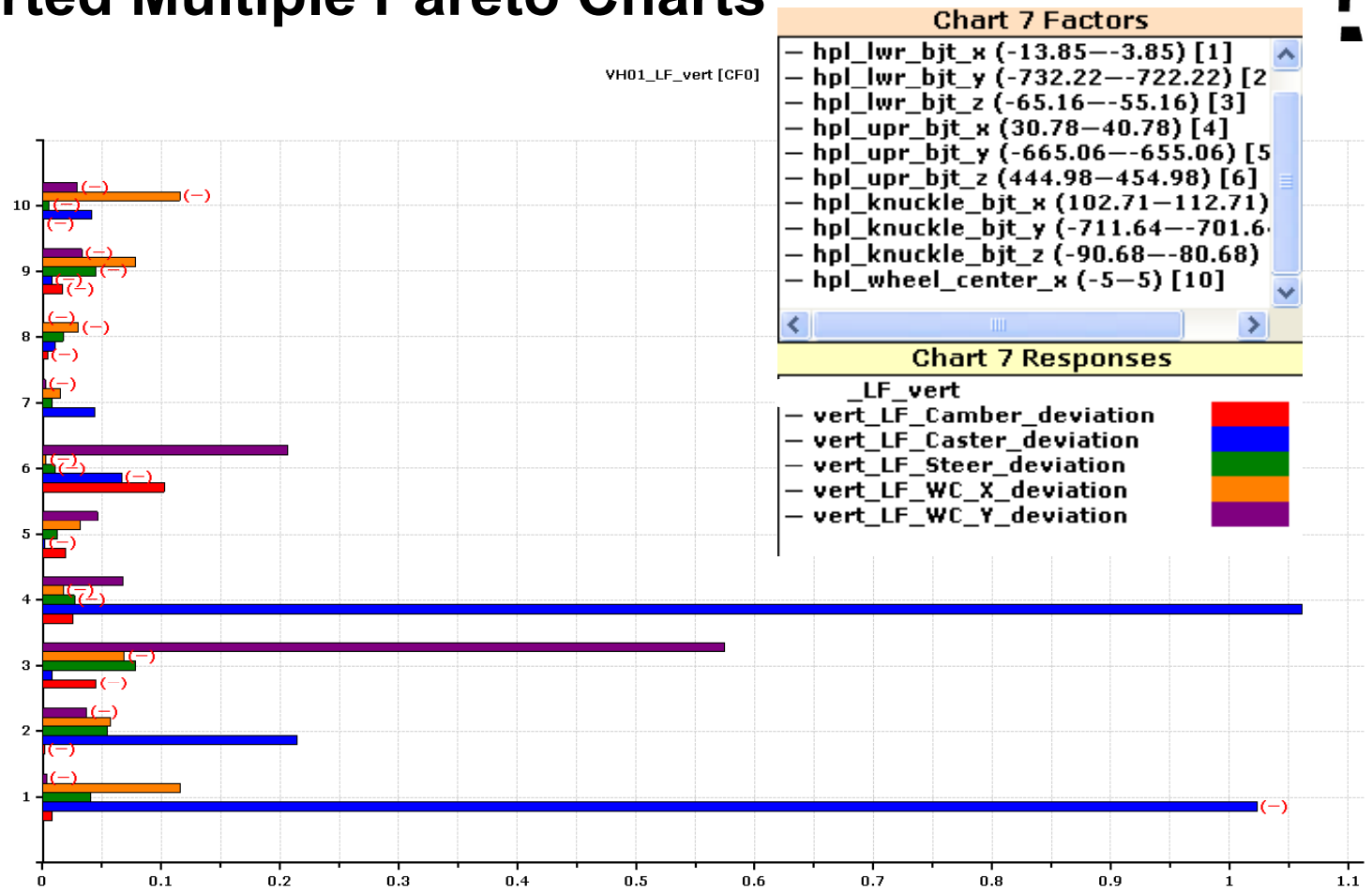


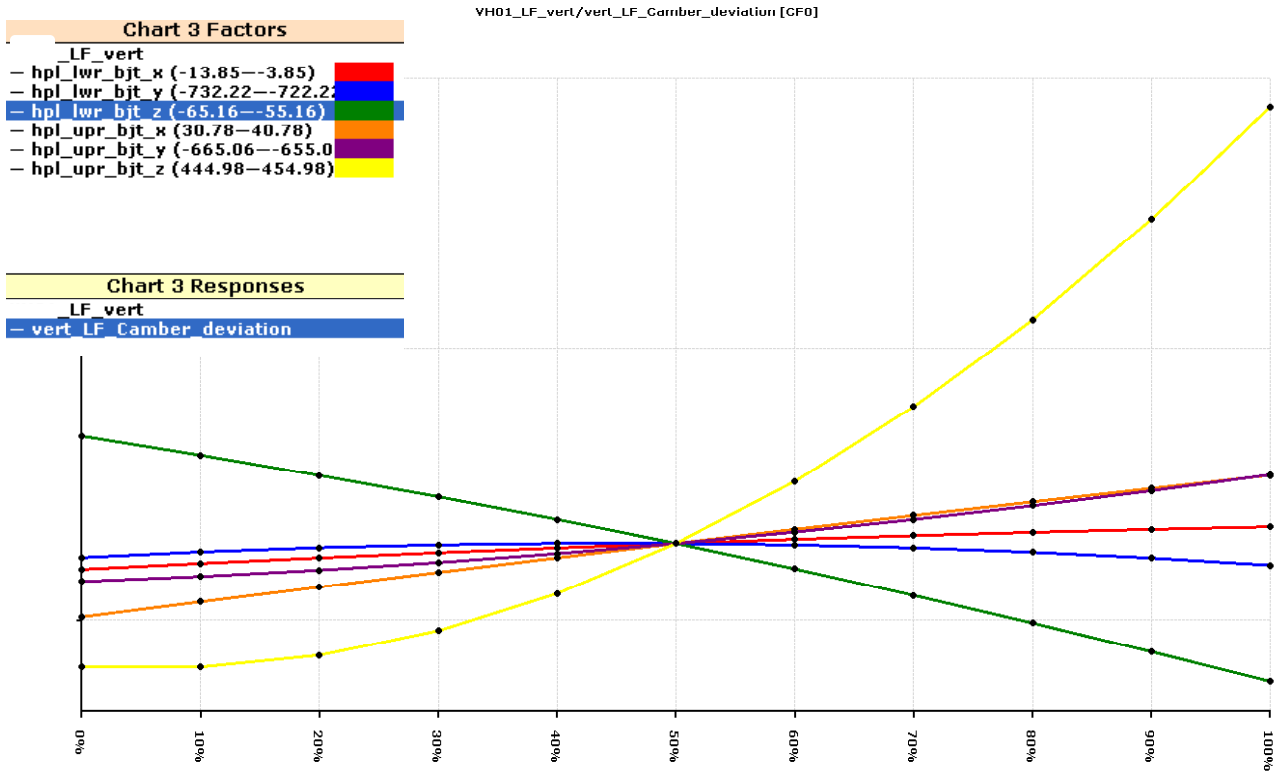

- Shows the change in response value when evaluated at the minimum and maximum of each factor
- Chart shows which factor has the most influence on the selected factor
- PME DOETool® can automatically create this Pareto chart for each response in each experiment. Gives a good ‘first glance’ impression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

# Inverted Multiple Pareto Charts



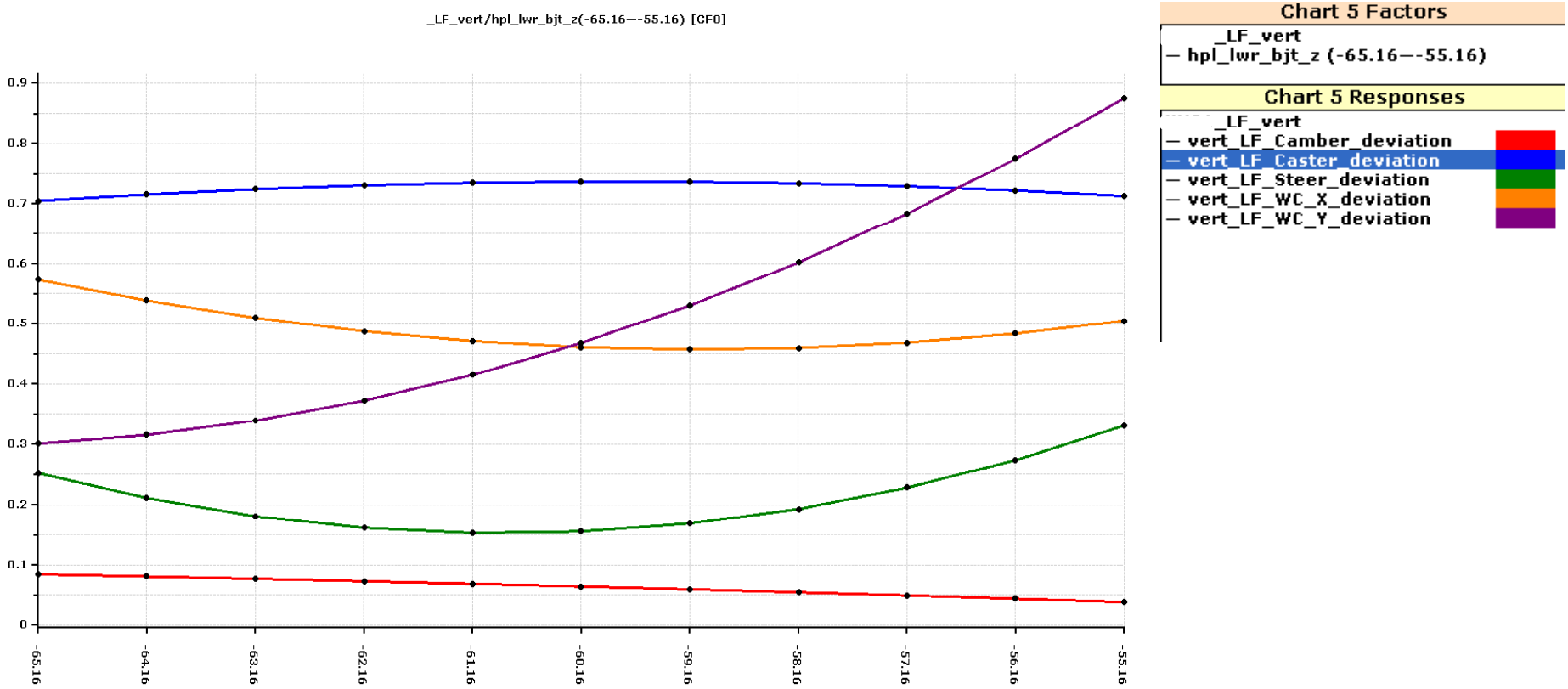

- Each color bar is a response
- Each number of the y-axis is a factor
- Shows the effect of multiple factors on all the selected responses
  - While useful, it hides any non-linear response trends

# 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




- 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

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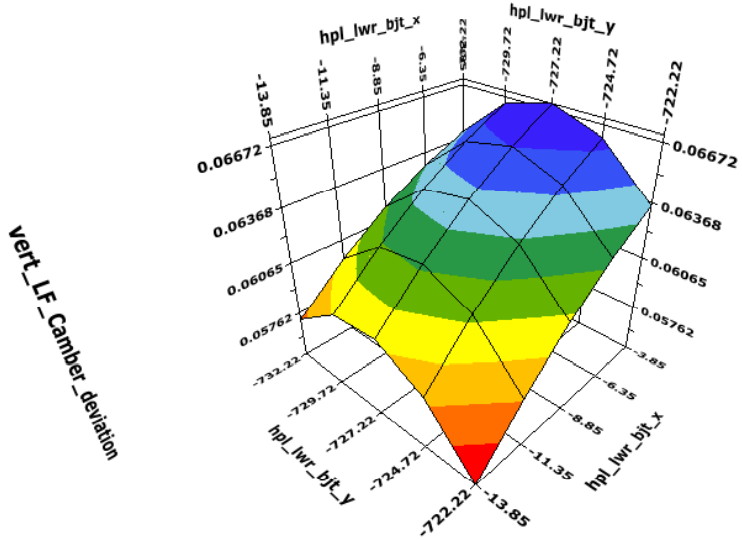


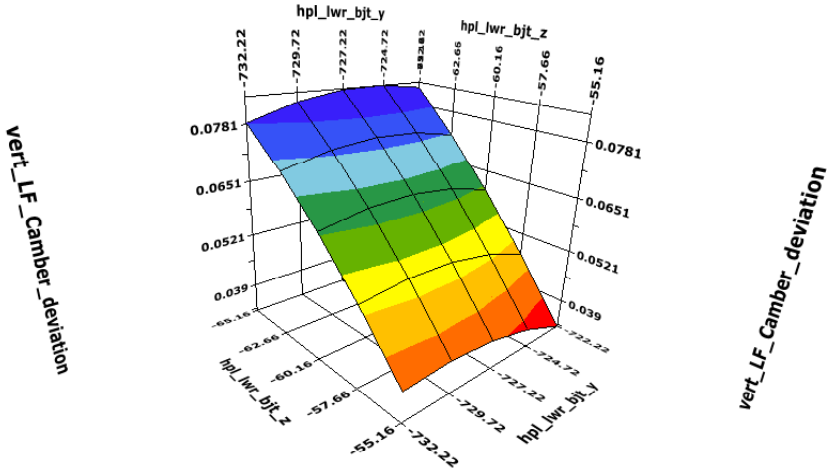


- Each color bar is a response
- Each number of the y-axis is a factor
- Shows the effect of each selected factor on all the selected responses

# Optimization across multiple experiments

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| 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 | 2 | | | |
| _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 | 06 | | | |
| _LF_vert | hpl_upr_bjt_z | | 444.98 | 454.98 | ☑ | 4 | | 8 | 08 | | | |
| _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 | 04 | | | |
| _LF_vert | hpl_knuckle_bjt_z | | -90.68 | -80.68 | ☑ | - | | 8 | 68 | | | |
| _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 | | 9 | 09 | | | |
| _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 | 04 | | | |
| _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 | 04 | | | |
| _LF_vert | hpl_tv_link_bush_y | | -393.27 | -383.27 | ☑ | -3 | -3 | 7 | 27 | | | |
| _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**
- **Reponses 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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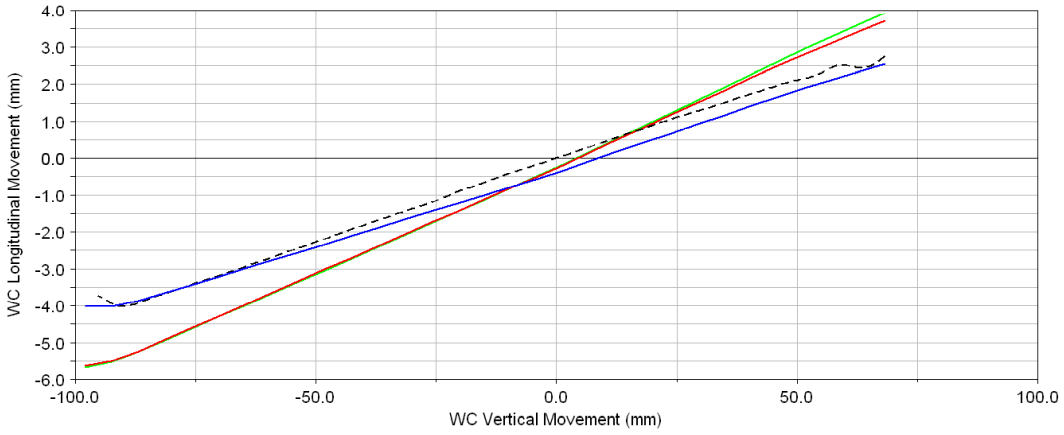
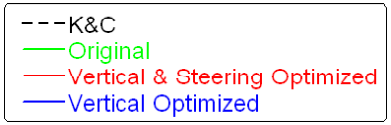
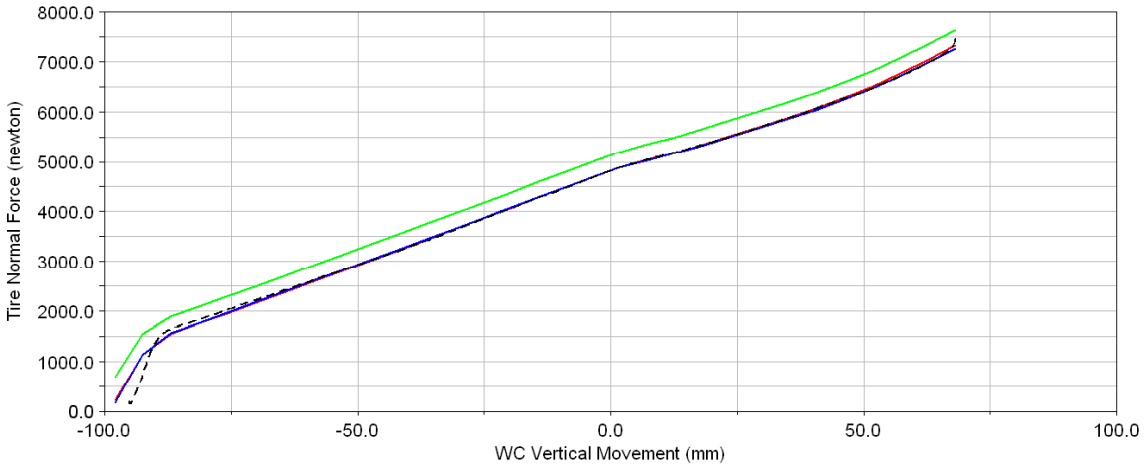
```
$----------------------------------------------------------------------MDI_HEADER
[MDI_HEADER]
 FILE_TYPE      =  'sub'
 FILE_VERSION   =  6.6
 FILE_FORMAT    =  'ASCII'
$-------------------------------------------------------------SUBSYSTEM_HEADER
[SUBSYSTEM_HEADER]
 TEMPLATE_NAME  =  '<    .>/templates.tbl/_front_suspension_sp.tpl'
 MAJOR_ROLE     =  'suspension'
 MINOR_ROLE     =  'front'
 TIMESTAMP      =  '2008/11/20,12:23:57'
$-----------------------------------------------------------------------UNITS
[UNITS]
 LENGTH  =  'mm'
 FORCE   =  'newton'
 ANGLE   =  'deg'
 MASS    =  'kg'
 TIME    =  'sec'
$---------------------------------------------------------------------HARDPOINT
[HARDPOINT]
{hardpoint_name                    symmetry         x_value     y_value     z_value}
 'origo                          '  'single     '        0                       0.0
 'comp_                          '  'left/right'      29                       .84
 'comp_             p            '  'left/right'      29                       .84
 'comp_             p            '  'left/right'      50                       .16
 'knuck                          '  'left/right'     111                       .62
 'lwr_k                          '  'left/right'      -4                       .19
 'lwr_k                          '  'left/right'      -8                       .18
 'mbr_i                          '  'left/right'     -58                      4.6
 'mbr_i                          '  'left/right'     -58                      4.6
 'mbr_i                          '  'left/right'     -58                      4.6
 'mbr_i                          '  'left/right'       7                       .55
 'mbr_i                          '  'left/right'       7                       .55
 'mbr_i                          '  'left/right'       7                       .55
 'side_                          '  'left/right'       9                      7.8
 's_abs                          '  'left/right'      -8                       .17
 's_abs             <p           '  'left/right'      35                       .34
 's_abs             zp           '  'left/right'     -18                      0.3
 's_abs                          '  'left/right'      35                       .34
 's_abs             <p           '  'left/right'      35                       .34
 's_abs             zp           '  'left/right'      80                       .85
 'tv_li                          '  'left/right'      -2                      3.65
 'tv_li                          '  'left/right'      29                       .84
 'upr_k                          '  'left/right'      40                       .99
 'upr_k                          '  'left/right'      37                       .59
 'upr_l             c            '  'left/right'     -94                      2.89
 'upr_l             c            '  'left/right'      15                      3.64
 'wheel_center                   '  'left/right'       3.                     45.99
$-----------------------------------------------------------------PART_ASSEMBLY
```

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

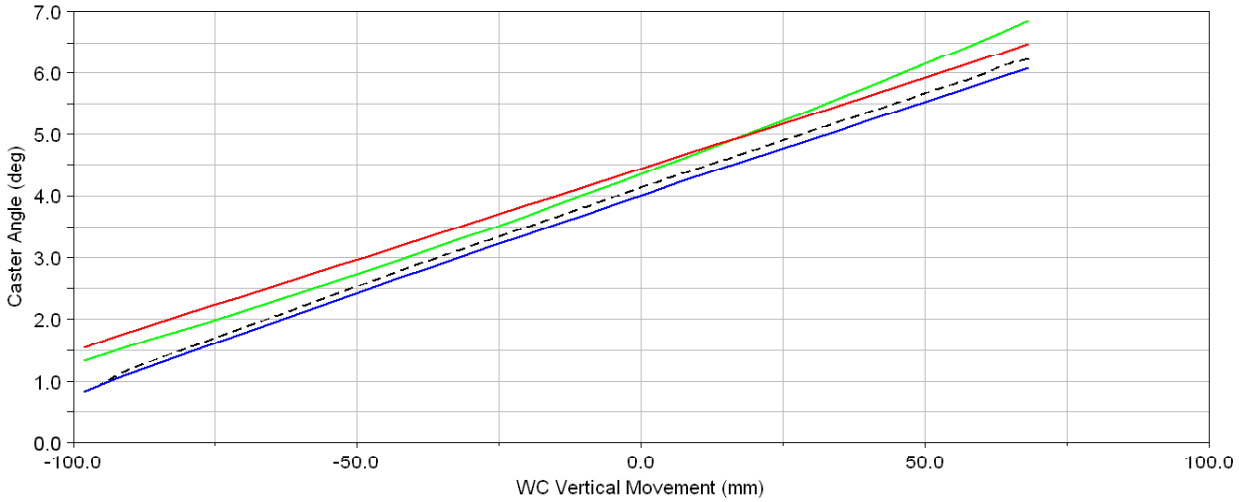
# Compare Original Subsystem with Optimized Subsystem



# 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 |
| **Vertical** | 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 |
| **Steer** | 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 | -6.081 | 0.295 | 0.047 | 0.954 | 0.153 | 0.051 | 0.008 |
| **Total Normalized Error** | | | | 1.231 | | 0.884 | | 0.773 | |
| **Average Normalized Error** | | | | 0.137 | | 0.098 | | 0.086 | |

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