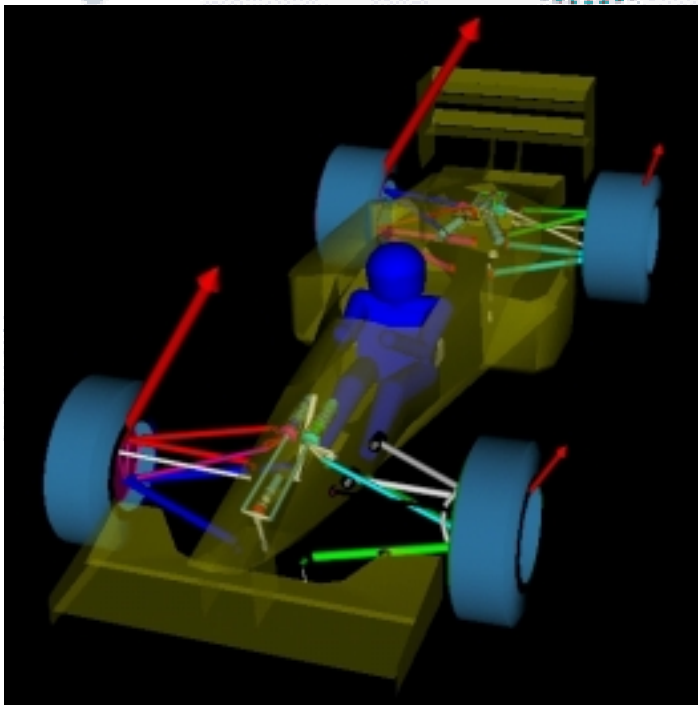




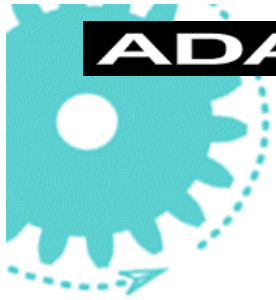
# ADAMS

**Response Surface Methodology  
(RSM) and Design of Experiments  
(DOE)**

**Applied to Racecar Vehicle  
Dynamics Simulation and  
Development**



Lynn Bishop - MDI  
David Fredriksson - MDI



## Abstract

Vehicle dynamics simulation and testing have historically proven able to produce large amounts of “static” information (data) that is very powerful and useful in the vehicle development process.

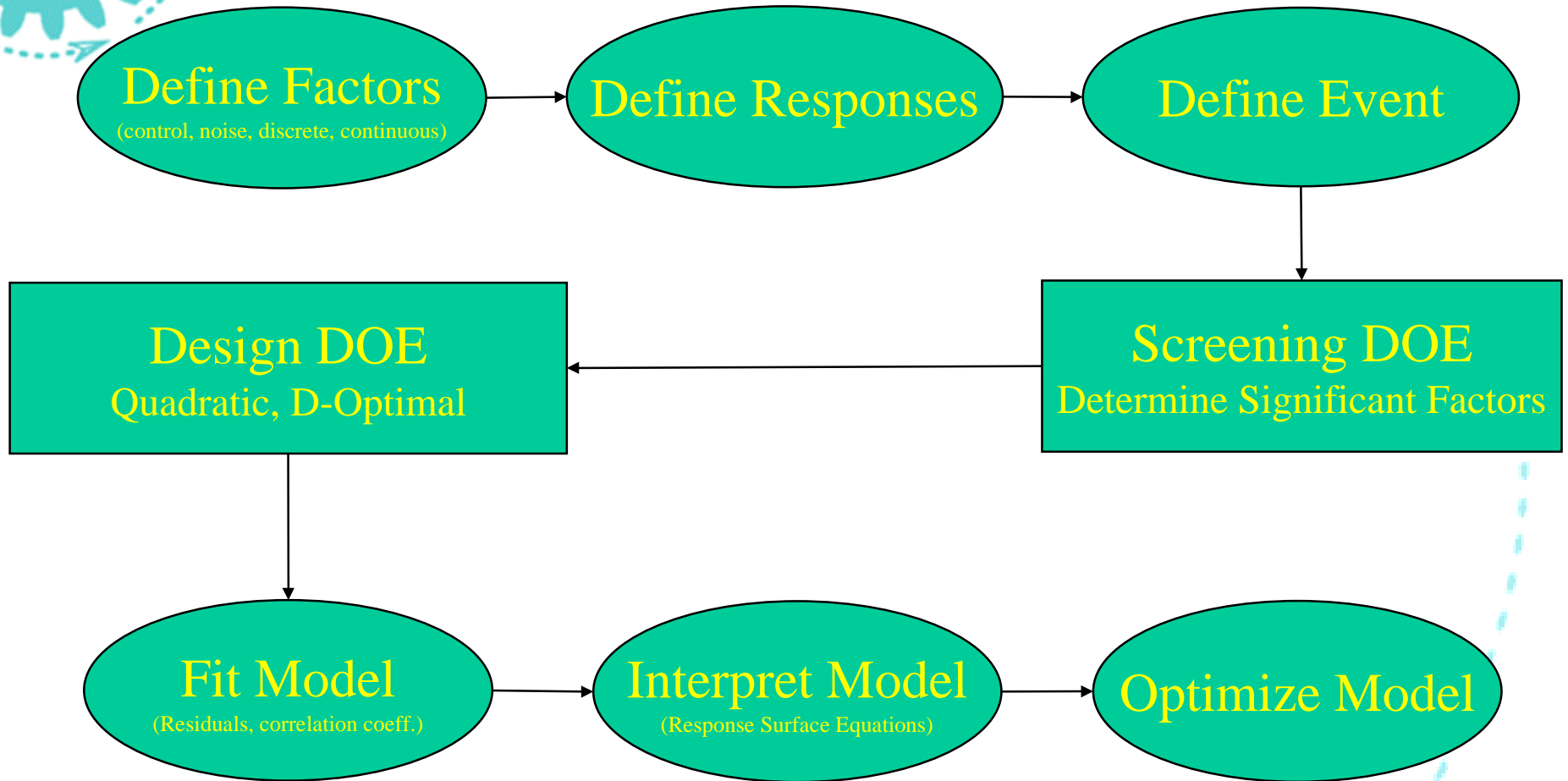
However, this data is often difficult to access in order to answer specific questions about the effects of vehicle design parameter changes on system level, vehicle dynamics and handling response.

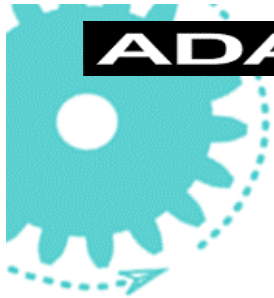
This is complicated by the fact that the information is needed in very short periods of time by a larger engineering organization outside of the simulation and testing experts



A process has been developed that combines two disciplines together with powerful and accurate computer vehicle handling simulation technology to create “live” information (data) that can be published through standard spreadsheet technology and utilized by an enterprise-wide engineering organization. This process has been proven in the most time critical environment of NASCAR, CART and Formula One racing by race engineers with little or no vehicle dynamics simulation expertise

# DOE Process

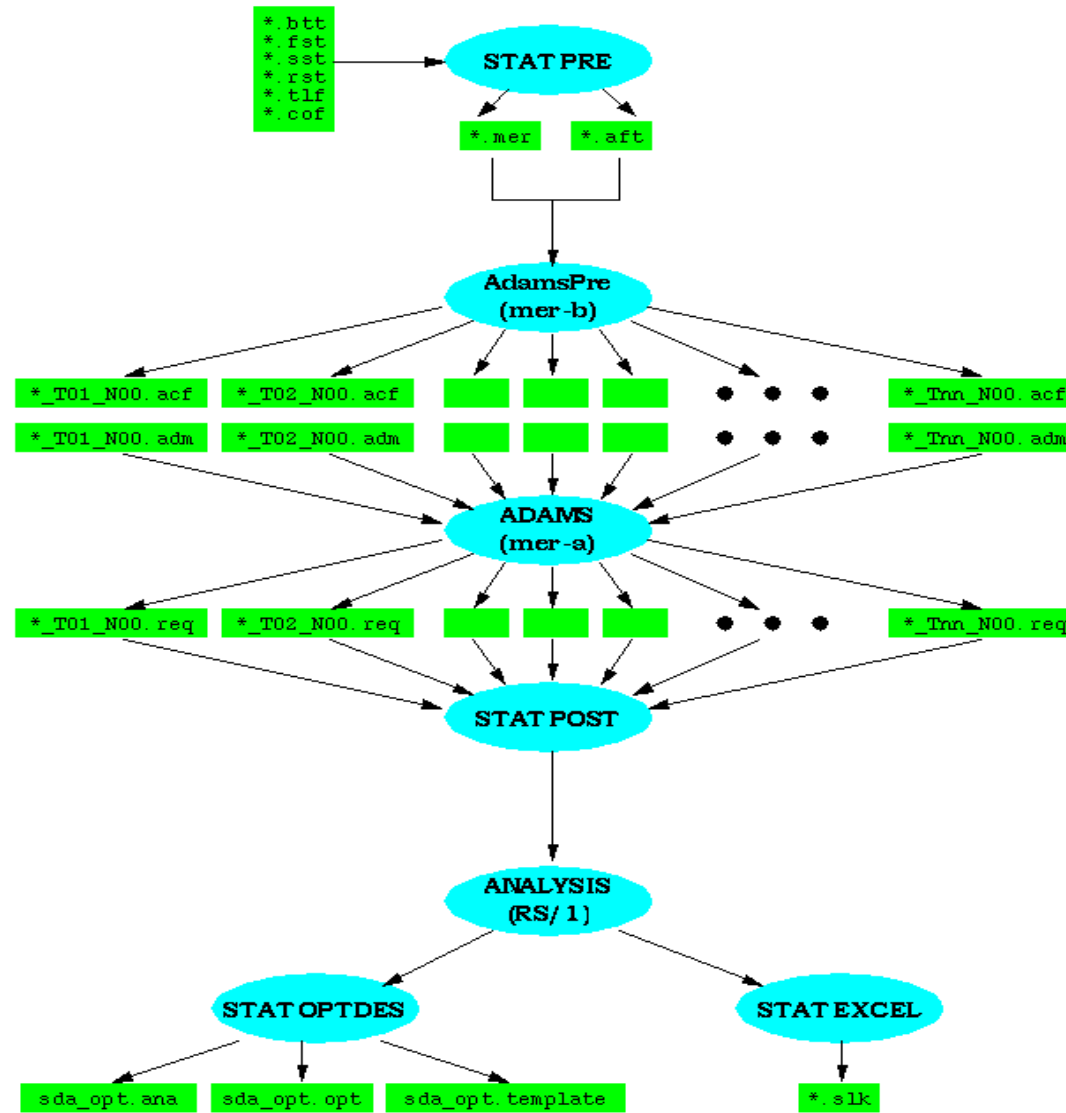


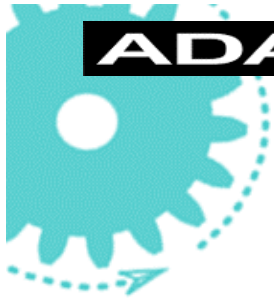


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# AutoDOE in ADAMS/RaceCar

Flow Chart of AutoDOE Files and Applications

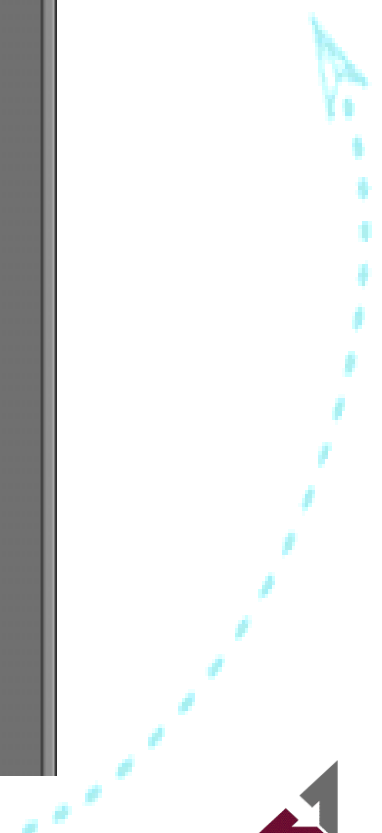




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# Factor Generation

| Master Setup                          | Chassis Setup | Damper Setup                            | Jump Stop Setup | Aerodynamic Setup | Powertrain Setup | Tire Setup |
|---------------------------------------|---------------|-----------------------------------------|-----------------|-------------------|------------------|------------|
| <b>Master Setup</b>                   |               |                                         |                 |                   |                  |            |
| <b>Front</b>                          |               |                                         |                 |                   |                  |            |
|                                       | Left          | Right                                   |                 |                   |                  |            |
| Spring Rate (lbs/in)                  | 650           | 650                                     |                 |                   |                  |            |
| Preload (lbs)                         | 1094          | 1094                                    |                 |                   |                  |            |
| Toe (deg)                             | - .25         | - .25                                   |                 |                   |                  |            |
| Camber (deg)                          | -2.25         | -2.25                                   |                 |                   |                  |            |
| Caster (deg)                          | 9             | 9                                       |                 |                   |                  |            |
| Ride Height (inches)                  | 3.100         | 3.1                                     |                 |                   |                  |            |
| Stabilizer Bar Stiffness (in-lbs/deg) | 1446          | <input type="checkbox"/> Use Beam Model |                 |                   |                  |            |
| <b>Rear</b>                           |               |                                         |                 |                   |                  |            |
| Spring Rate (lbs/in)                  | 375           | 375                                     |                 |                   |                  |            |
| Preload (lbs)                         | 725           | 725                                     |                 |                   |                  |            |
| Toe (deg)                             | .2            | .2                                      |                 |                   |                  |            |
| Camber (deg)                          | -1            | -1                                      |                 |                   |                  |            |
| Ride Height (inches)                  | 3.5           |                                         |                 |                   |                  |            |
| Stabilizer Bar Stiffness (in-lbs/deg) | 617           | <input type="checkbox"/> Use Beam Model |                 |                   |                  |            |
| Panhard Bar Height                    | 9             | 10                                      |                 |                   |                  |            |
| <b>Additional</b>                     |               |                                         |                 |                   |                  |            |
| Cross Weight (RF-LF)                  | -40           |                                         |                 |                   |                  |            |
| Gallons of Fuel                       | 15            |                                         |                 |                   |                  |            |



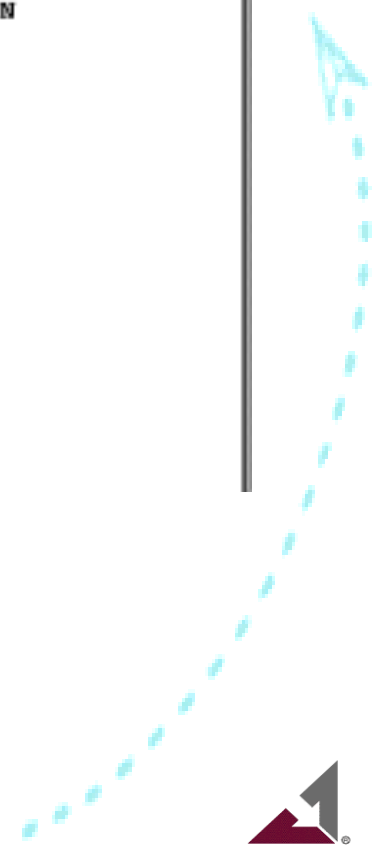


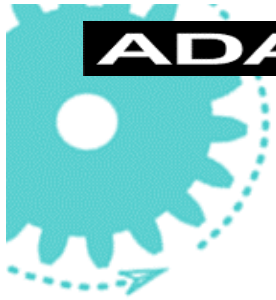
**ADAMS**

# Factor Generation

RS/1 Main Window

| 0 Factor        | 1 Abbrev     | 2 Role     | 3 Settings        | > | 1 ADD         |
|-----------------|--------------|------------|-------------------|---|---------------|
| 1 MODE          | MODE         | CONTROLLED | QUAL, RACE        |   | 2 MODIFY      |
| 2 SP_MASS_CG_X  | SP_MASS_CG_X | CONTROLLED | -5 to 1           |   | 3 COPY        |
| 3 CROSS_WT      | CROSS_WT     | CONTROLLED | -250 to 0         |   | 4 DELETE      |
| 4 L_TROD_Z      | L_TROD_Z     | CONTROLLED | -0.5 to .5        |   | > 5 DISPLAY   |
| 5 R_TROD_Z      | R_TROD_Z     | CONTROLLED | -0.5 to .5        |   | 6 CONSTRAINTS |
| 6 LEFT_CAST     | LEFT_CAST    | CONTROLLED | 2 TO 8            |   | 7 NESTING     |
| 7 RIGHT_CAST    | RIGHT_CAST   | CONTROLLED | 2 TO 8            |   | 8 NEXT        |
| 8 F_L_CAM       | F_L_CAM      | CONTROLLED | 3.0 to 5.00       |   | 9 MAIN        |
| 9 F_R_CAM       | F_R_CAM      | CONTROLLED | -3.5 to -1.5      |   |               |
| 10 LF_SP_K      | LF_SP_K      | CONTROLLED | 800 to 1300       |   |               |
| 11 RF_SP_K      | RF_SP_K      | CONTROLLED | 1600 to 2300      |   |               |
| 12 F_STA_BAR_KT | F_STA_BAR_KT | CONTROLLED | 924 to 7162       |   |               |
| 13 L_UCA        | L_UCA        | CONTROLLED | 8.75,9.0,9.25     |   |               |
| 14 R_UCA        | R_UCA        | CONTROLLED | 7.5,7.75,8.0,8.25 |   |               |
| 15 LR_SP_K      | LR_SP_K      | CONTROLLED | 325 to 425        |   |               |
| 16 RR_SP_K      | RR_SP_K      | CONTROLLED | 375 to 450        |   |               |
| 17 R_STA_BAR_KT | R_STA_BAR_KT | CONTROLLED | 0 to 373          |   |               |
| 18 L_PAN_Z      | L_PAN_Z      | CONTROLLED | 8.5 to 10.75      |   |               |
| 19 R_PAN_Z      | R_PAN_Z      | CONTROLLED | 9 to 11.25        |   |               |
| 20 L_TRKARM_Z   | L_TRKARM_Z   | CONTROLLED | 0 to 6            |   |               |
| 21 R_TRKARM_Z   | R_TRKARM_Z   | CONTROLLED | 0 to 6            |   |               |
| 22 R_L_CAM      | R_L_CAM      | CONTROLLED | 1.5 to 2          |   |               |





# Event/Response Generation

## ■ Multi-Event DOE

### ◆ SVC - Static Vehicle Characteristics

- Roll Center Heights
- Ride Frequencies
- Percent Anti-Dive/Lift/Squat

### ◆ Constant Speed Cornering with Banking

- Understeer Gradients
- Steering Sensitivity
- Roll-Couple Distribution
- Front/Rear Cornering Compliance



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# DOE Model & Design

```
RS/1 Main Window
PRS_ATLA - Experiment Specifications

0 Experimental unit      1 Run
-----
1 Non-blocking factors  MODE, SP_MASS_CG_X, CROSS_MT, L_T
2 Blocking factors
3 Maximum blocksize    ---
4 Model term type      QUADRATIC
5 Block interaction?   ---
6 Design type          D-OPTIMAL
7 Centerpoints/block   0
8 Units/block          ---
9 Number of blocks     ---
10 Number of units     500
11 Run order           STANDARD
```

- Quadratic Model for non-linear response equations
- D-Optimal Design
  - ◆ Discrete and Continuous Factors
  - ◆ Multiple Factor Levels
- 500 runs each for SVC and Constant Speed Cornering



# .MER File Generation

```
if(MODE == "QUAL"){  
    b_aero_file = "qualifying.aer";  
    lf_tire = "LS_35.tir";  
    rf_tire = "RS_55.tir";  
    lr_tire = "LS_35.tir";  
    rr_tire = "RS_55.tir";  
}else  
if(MODE == "RACE"){  
    b_aero_file = "race.aer";  
    lf_tire = "ChOLS_37.tir";  
    rf_tire = "ChORS_61.tir";  
    lr_tire = "ChOLS_37.tir";  
    rr_tire = "ChORS_61.tir";  
}
```

- Combine factors to create a single discrete factor
- Reduce size of design



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# Fit Models

```
RS/II Main Window
Least Squares Coefficients, Response %F_LT, Model DESIGN
Term          Coeff.          Std. Error      T-value
-----
1 1           60.464421       0.154345
2 MODE<1df>
3 QUAL        -0.141318       0.010776
4 RACE         0.141318       0.010776
5 -SP_MASS_C  -0.701223       0.012084
6 -CROSS_WT   0.078110       0.011820
7 -L_TROD_Z   -0.083693       0.011258
8 -R_TROD_Z   -0.156370       0.011778
9 -LEFT_CAST  0.044535       0.012211
10 -RIGHT_CAS 0.009074       0.011442
11 -F_L_CAM   -0.114595       0.011977
12 -F_R_CAM   -0.028646       0.011749
13 -LF_SP_K   -0.208394       0.011565
14 -RF_SP_K    0.732143       0.011778
15 -F_STA_BAR 2.277420       0.011645
16 L_UCA<2df>
17 8.75       0.007649       0.014778
18 9.0        0.001263       0.014796
19 9.25      -0.008912       0.013866
20 R_UCA<3df>
21 7.5        0.002709       0.017417
22 7.75      -0.025698       0.016764
23 8.0        0.020689       0.017286
24 8.25       0.002300       0.017658
25 -LR_SP_K   0.574469       0.011929
26 -RR_SP_K  -0.691295       0.011592
27 -R_STA_BAR -1.741326       0.012170
28 -L_PAN_Z   -0.871039       0.011419
29 -R_PAN_Z   -0.934234       0.011502
30 -L_TRKARM_ 0.114843       0.012348
31 -R_TRKARM_ -0.473690       0.011791
32 -R_L_CAM   -0.057317       0.012336
33 -MODE*SP_M
34 QUAL       0.014408       0.012436      1.16
35 RACE       -0.014408       0.012436     -1.16
36 -MODE*CROS
37 QUAL      -0.000316       0.012024     -0.03

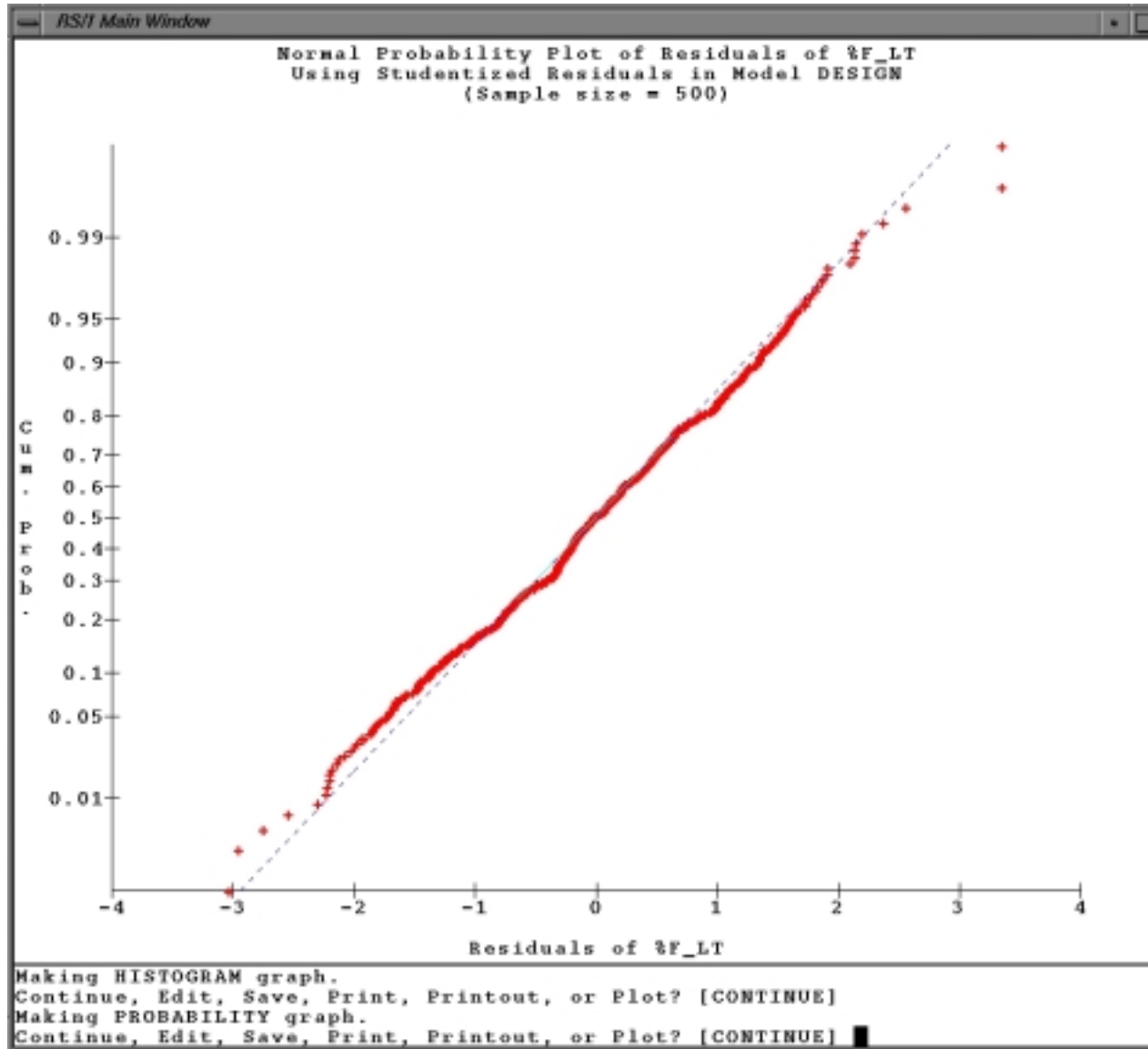
No. cases = 500      R-sq. = 0.9992      RMS Error = 0.1631
Resid. df = 159    R-sq-adj. = 0.9976      Cond. No. = 90.34
~ indicates factors are transformed.

EXPER.MULREG> [AUTOFIT]
EXPER.MULREG> [FIT]
More rows and columns to display.
MULREG.FIT> [ANOVA]
```



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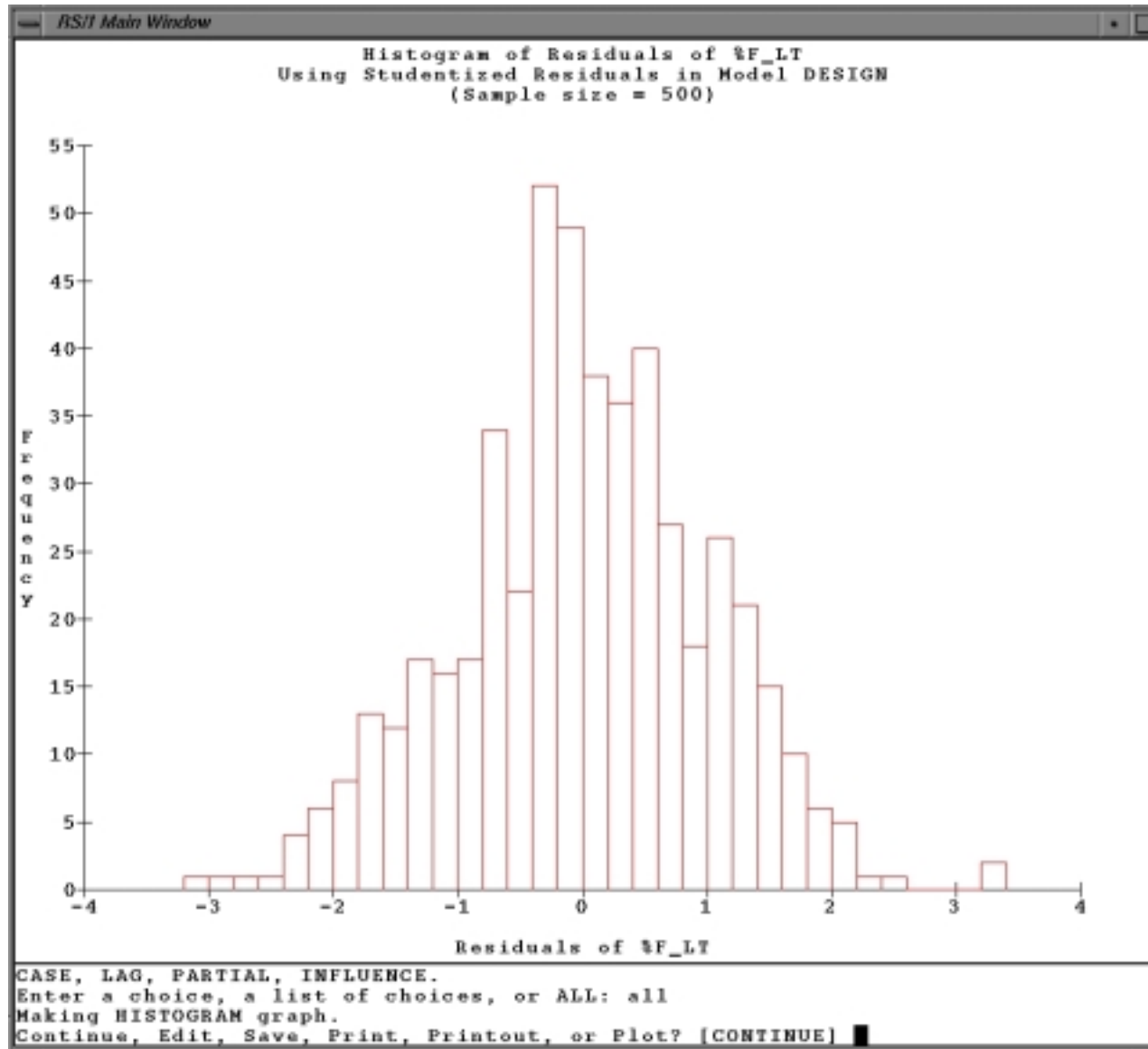
# Fit Models





**ADAMS**

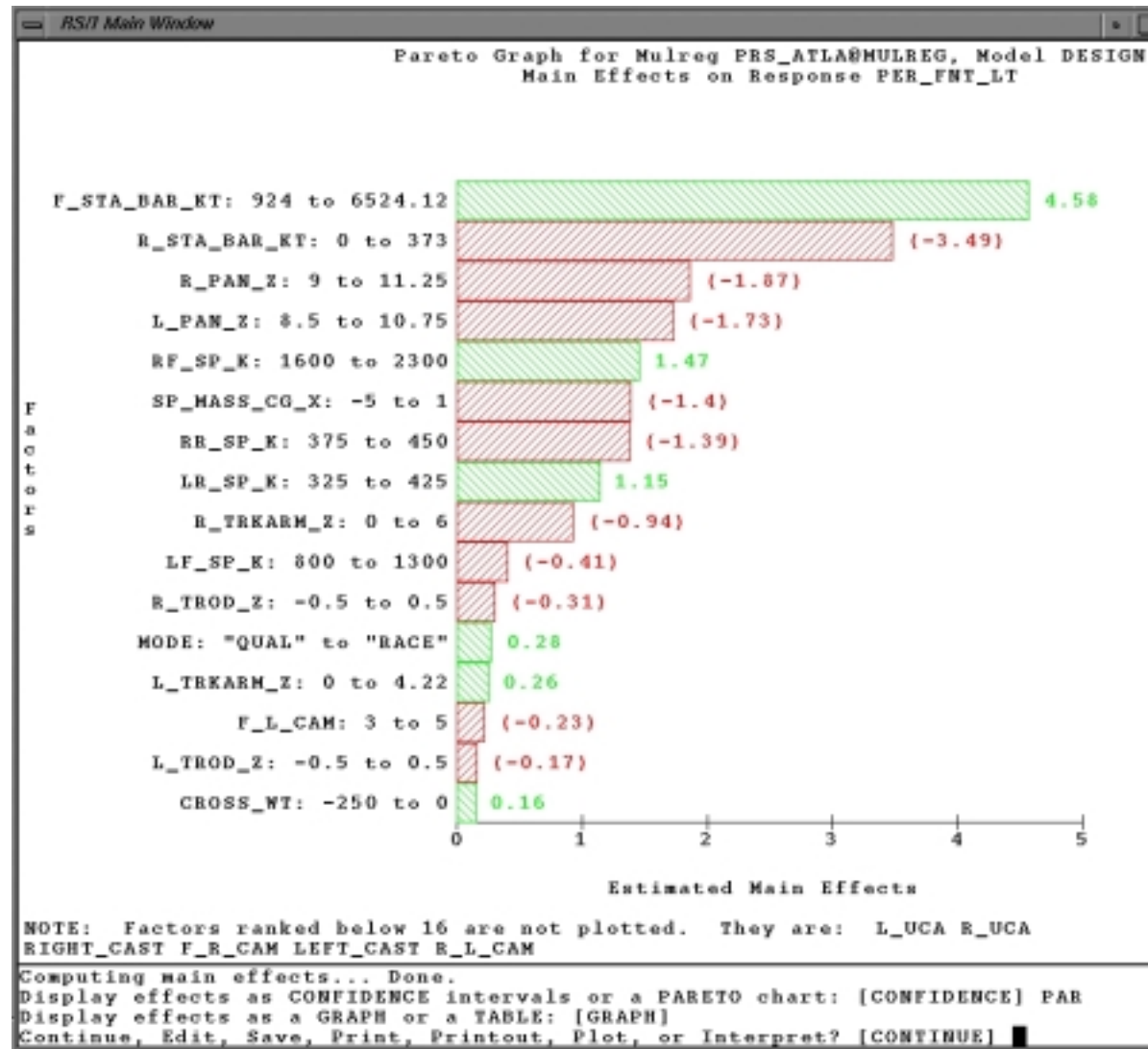
# Fit Models





**ADAMS**

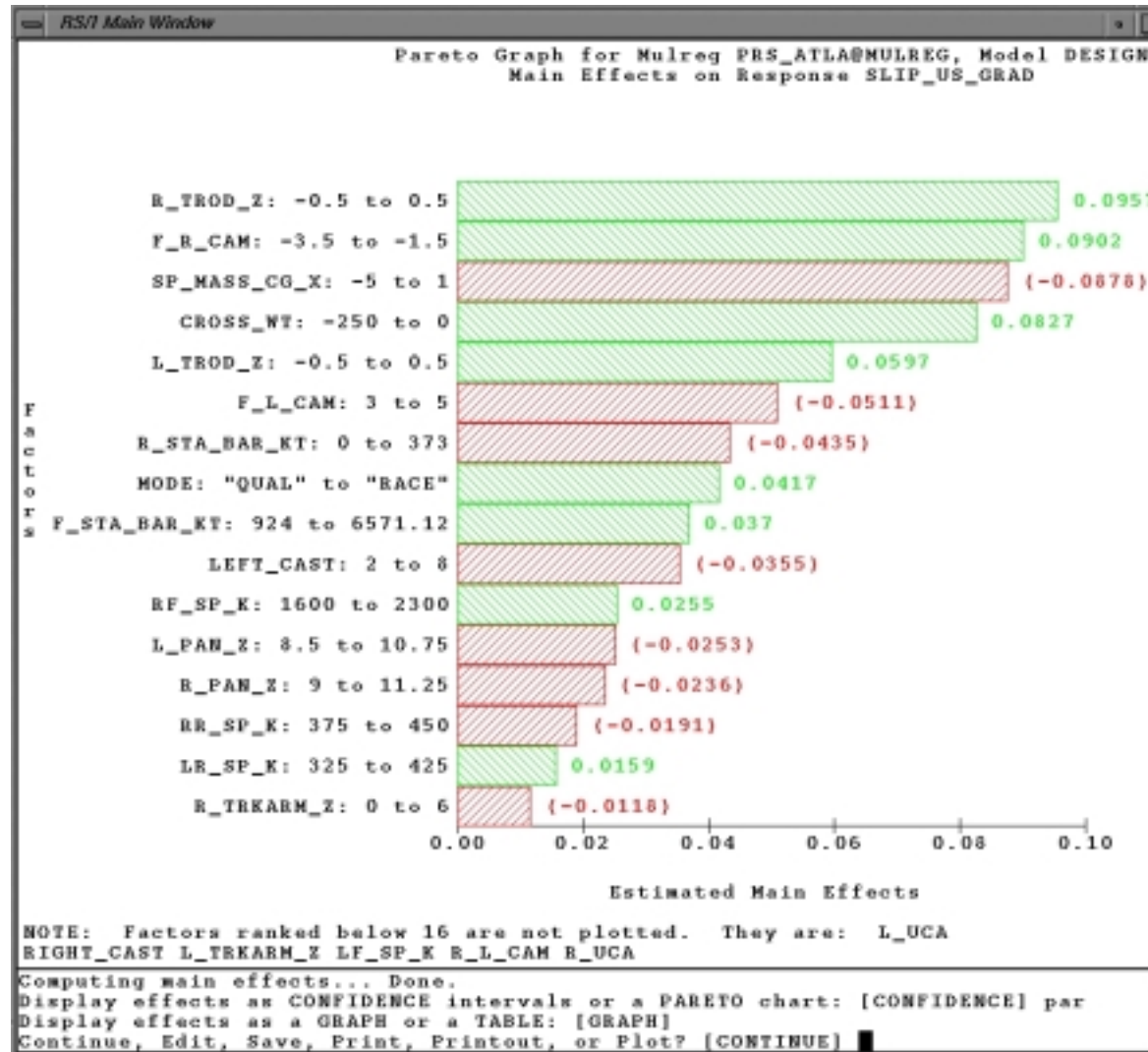
# Interpret Response Models





**ADAMS**

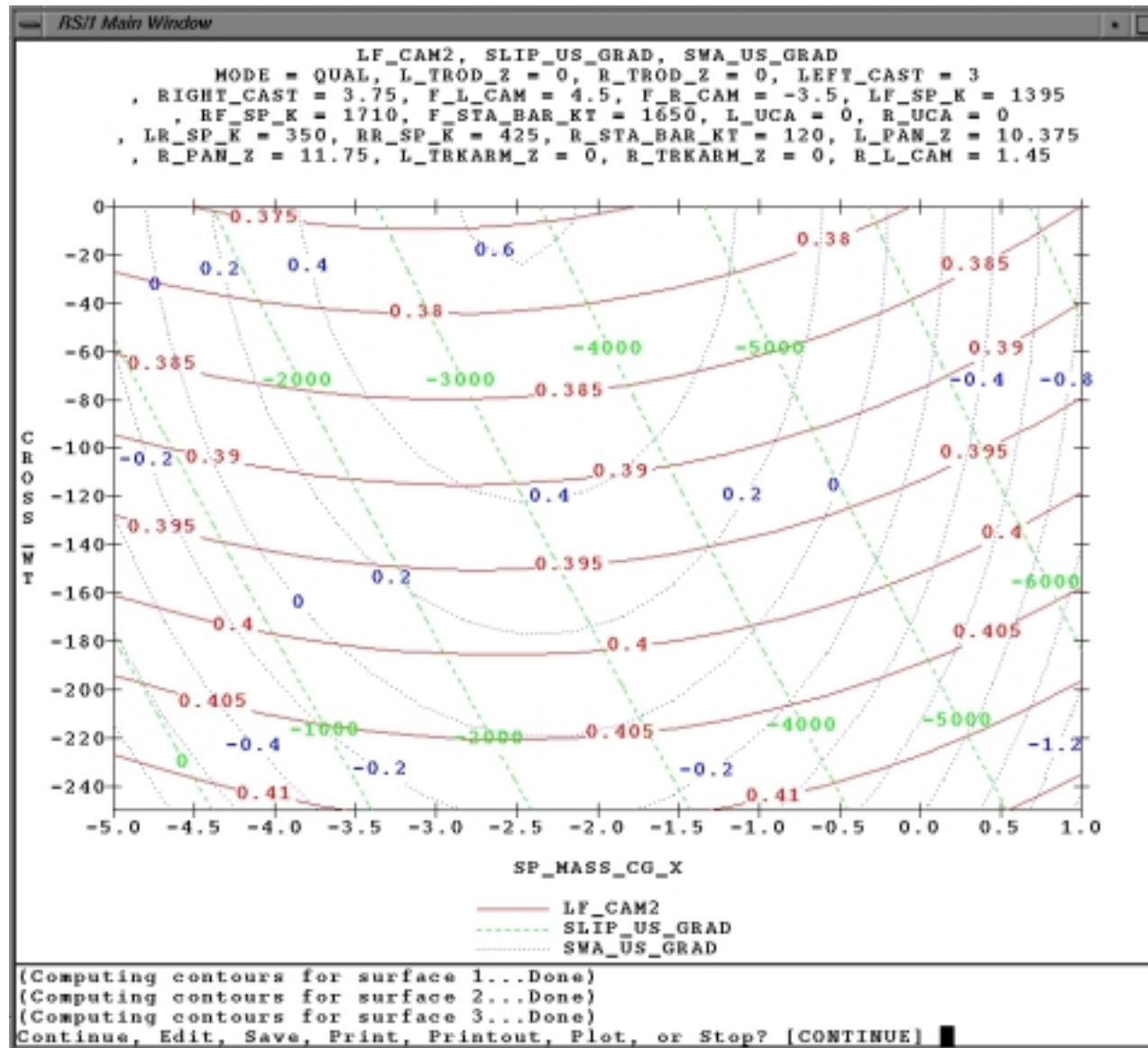
# Interpret Response Models





ADAMS

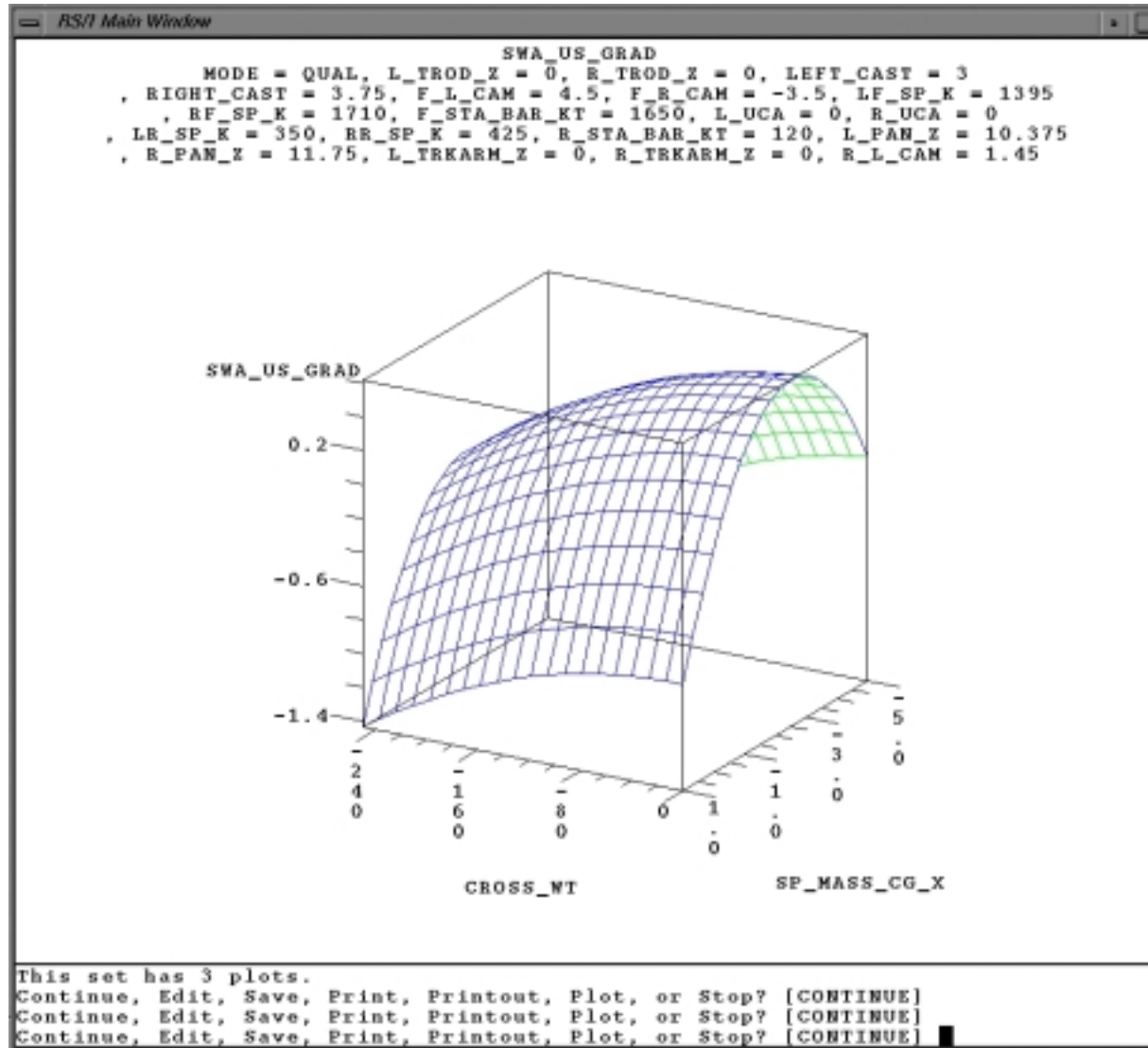
# Interpret Response Models





**ADAMS**

# Interpret Response Models





**ADAMS**

# Optimize Response Model

```
RSIT Main Window
Factor, Response or Formula      Range      Initial Setting  Optimal Value
-----
1 Factors
2 MODE                           QUAL, RACE   RACE            -0.91922
3 SP_MASS_CG_X                   -5 to 1     -2              -248.16
4 CROSS_WT                       -250 to 0   -125            0.0248
5 L_TROD_Z                       -0.5 to .5  0              0.32552
6 R_TROD_Z                       -0.5 to .5  0              3.1156
7 LEFT_CAST                      2 to 4      3              4.7427
8 RIGHT_CAST                     2.75 to 4.75 3.75           4.2473
9 F_L_CAM                        3.5 to 5.5  4.5            -4.4746
10 F_R_CAM                       -4.5 to -2.5 -3.5           1583.8
11 LF_SP_K                       1145 to 1645 1395           1898.1
12 RF_SP_K                       1510 to 1910 1710           1562.1
13 F_STA_BAR_KT                 1100 to 2200 1650           0.27368
14 L_UCA                        -0.375 to .375 0              -0.097483
15 R_UCA                        -0.375 to .375 0              331.78
16 LE_SP_K                       300 to 400  350            424.43
17 RR_SP_K                       375 to 475  425            185.11
18 R_STA_BAR_KT                 0 to 240    120            10.425
19 L_PAN_Z                      9.75 to 11  10.38          11.189
20 R_PAN_Z                      11 to 12.5  11.75
21 L_TRKARM_Z                   -1.5 to 1.5  0              0.13934
22 R_TRKARM_Z                   -1.5 to 1.5  0              -1.4065
23 R_L_CAM                      1.25 to 1.65 1.45           1.4836
24
25 Responses
26 LF_CAM2                       0.56933
27 SLIP_US_GRAD                 -3675.2
28 SWA_US_GRAD                   MIN          -8.0276

Converged to a tolerance of 0.5 after 242 steps.

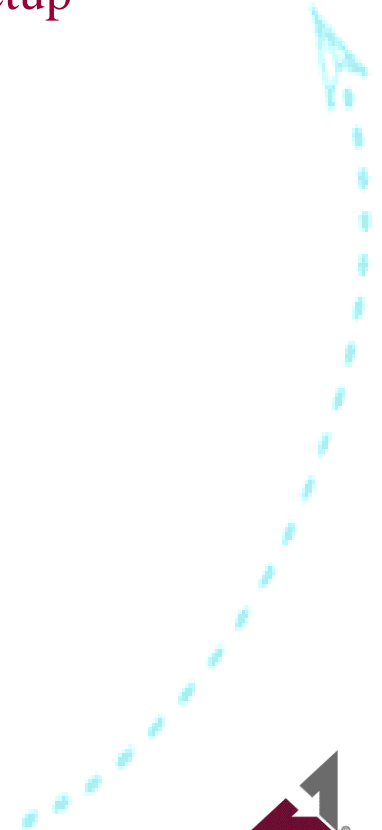
Optimizing at fixed factor setting (QUAL).
Converged to -8.02764 (tolerance = 0.5) after 208 steps.
Calculating optimal values.
INTERPRET.OPTIMIZE> [PERFORM]
```

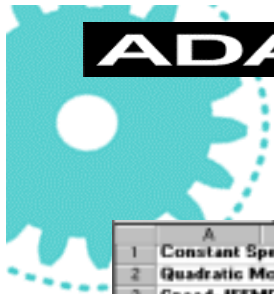


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# Response Equation Spreadsheet

- Export response surface equations to Excel
  - 32,000 lines of quadratic model terms
  - Link multi-event response equations to master setup
  
- Excel Solver functions to Optimize
  
- Session Trend Analysis and Review
  
- VBA Pareto generation





**ADAMS**

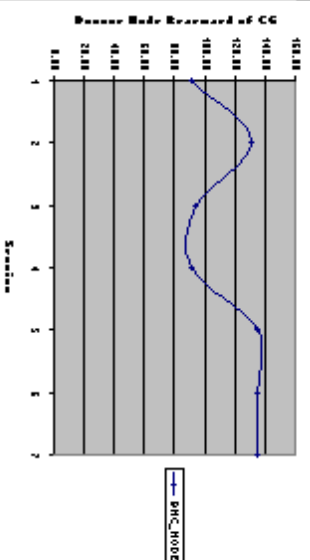
# Excel Setup Page

|                                                                                                                                            | Factor Name     | Units      | Current Setup | Session 1                          | Session 2            | Session 3 | Session 4 | Session 5 | Baseline Setup | % Change | Min               | Max   |  |
|--------------------------------------------------------------------------------------------------------------------------------------------|-----------------|------------|---------------|------------------------------------|----------------------|-----------|-----------|-----------|----------------|----------|-------------------|-------|--|
| <b>Constant Speed - Static Vehicle Characteristics DOE</b><br>Quadratic Model - RSM - D-Optimal<br>Speed: 155MPH<br>Bank Angle: 24 degrees |                 |            |               |                                    |                      |           |           |           |                |          |                   |       |  |
| <b>Chassis</b>                                                                                                                             |                 |            |               |                                    |                      |           |           |           |                |          |                   |       |  |
|                                                                                                                                            | M00E            |            | QUAL          | QUAL                               | QUAL                 | QUAL      | QUAL      | QUAL      | QUAL           | QUAL     | QUAL              | QUAL  |  |
|                                                                                                                                            | SP_MASS_CG_X    | inch       | -3.09         | -3.09                              | -3.09                | -3.09     | -3.09     | -3.09     | -3.09          | 0.0%     | -5                | 1     |  |
|                                                                                                                                            | CROSS_WT        | lbs        | -157          | -157                               | -157                 | -157      | -157      | -157      | -157           | 0.0%     | -250              | 0     |  |
| <b>Front Suspension</b>                                                                                                                    |                 |            |               |                                    |                      |           |           |           |                |          |                   |       |  |
|                                                                                                                                            | LEFT_TIE_ROD_Z  | in         | 0             | 0                                  | 0                    | 0         | 0         | 0         | 0              | NOVNO    | -0.5              | 0.5   |  |
|                                                                                                                                            | RIGHT_TIE_ROD_Z | in         | 0             | 0                                  | 0                    | 0         | 0         | 0         | 0              | NOVNO    | -0.5              | 0.5   |  |
|                                                                                                                                            | LEFT_CAST       | deg        | 2             | 2                                  | 2                    | 2         | 2         | 2         | 2              | 0.0%     | 2                 | 8     |  |
|                                                                                                                                            | RIGHT_CAST      | deg        | 3             | 3                                  | 3                    | 3         | 3         | 3         | 3              | 0.0%     | 2                 | 8     |  |
|                                                                                                                                            | LEFT_CAMB       | deg        | 4             | 4                                  | 4                    | 4         | 4         | 4         | 4              | 0.0%     | 3.25              | 4.75  |  |
|                                                                                                                                            | RIGHT_CAMB      | deg        | -4            | -4                                 | -4                   | -4        | -4        | -4        | -4             | 0.0%     | -4.5              | -2.5  |  |
|                                                                                                                                            | LF_SP_K         | lbs/in     | 1300          | 1300                               | 1300                 | 1300      | 1300      | 1300      | 1300           | 0.0%     | 700               | 1750  |  |
|                                                                                                                                            | RF_SP_K         | lbs/in     | 2070          | 2070                               | 2070                 | 2070      | 2070      | 2070      | 2070           | 0.0%     | 1500              | 2300  |  |
|                                                                                                                                            | F_STA_BAR_KT    | in-lbs/deg | 2177          | 2177                               | 2177                 | 2177      | 2177      | 2177      | 2177           | 0.0%     | 627               | 5827  |  |
|                                                                                                                                            | L_UCA           | in         | 8.75          | 8.75                               | 8.75                 | 8.75      | 8.75      | 8.75      | 8.75           | 0.0%     | 8.75,9.25         |       |  |
|                                                                                                                                            | R_UCA           | in         | 7.5           | 7.5                                | 7.5                  | 7.5       | 7.5       | 7.5       | 7.5            | 0.0%     | 7.5,7.75,8.8,9.25 |       |  |
| <b>Rear Suspension</b>                                                                                                                     |                 |            |               |                                    |                      |           |           |           |                |          |                   |       |  |
|                                                                                                                                            | LR_SP_K         | lbs/in     | 325           | 325                                | 325                  | 325       | 325       | 325       | 325            | 0.0%     | 300               | 400   |  |
|                                                                                                                                            | RR_SP_K         | lbs/in     | 375           | 375                                | 375                  | 375       | 375       | 375       | 375            | 0.0%     | 320               | 450   |  |
|                                                                                                                                            | R_STA_BAR_KT    | in-lbs/deg | 0             | 0                                  | 0                    | 0         | 0         | 0         | 0              | NOVNO    | 0                 | 240   |  |
|                                                                                                                                            | L_PAN_Z         | inches     | 8.75          | 8.75                               | 8.75                 | 8.75      | 8.75      | 8.75      | 8.75           | 0.0%     | 9                 | 11    |  |
|                                                                                                                                            | R_PAN_Z         | inches     | 9.5           | 9.5                                | 9.5                  | 9.5       | 9.5       | 9.5       | 9.5            | 0.0%     | 9.75              | 11.75 |  |
|                                                                                                                                            | L_TRKARM_Z      | inches     | 0             | 0                                  | 0                    | 0         | 0         | 0         | 0              | NOVNO    | 0                 | 6     |  |
|                                                                                                                                            | R_TRKARM_Z      | inches     | 0             | 0                                  | 0                    | 0         | 0         | 0         | 0              | NOVNO    | 0                 | 6     |  |
|                                                                                                                                            | R_L_CAM         | deg        | 1.5           | 1.5                                | 1.5                  | 1.5       | 1.5       | 1.5       | 1.5            | 0.0%     | 1.5               | 2     |  |
| <b>Corner Weights</b>                                                                                                                      |                 |            |               | <b>Toe Calculator</b>              |                      |           |           |           |                |          |                   |       |  |
|                                                                                                                                            | LEFT            | RIGHT      | CROSS:        | Inches at 10" center: <b>0.065</b> |                      |           |           |           |                |          |                   |       |  |
|                                                                                                                                            | FRONT           | 334        | 337           | FRONT:                             | Degrees: <b>0.23</b> |           |           |           |                |          |                   |       |  |
|                                                                                                                                            | REAR            | 328        | 336           | TOTAL:                             |                      |           |           |           |                |          |                   |       |  |
|                                                                                                                                            |                 |            |               | CG %:                              | -3.09                |           |           |           |                |          |                   |       |  |
|                                                                                                                                            |                 |            |               | RF-LF:                             | -157                 |           |           |           |                |          |                   |       |  |

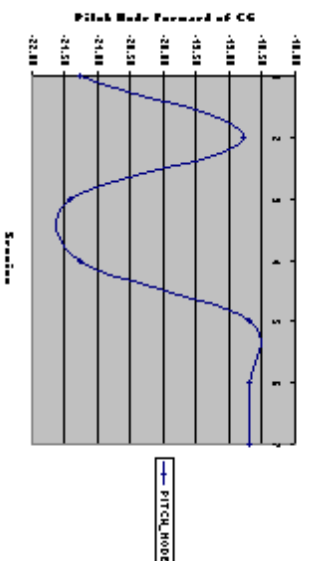
Ready



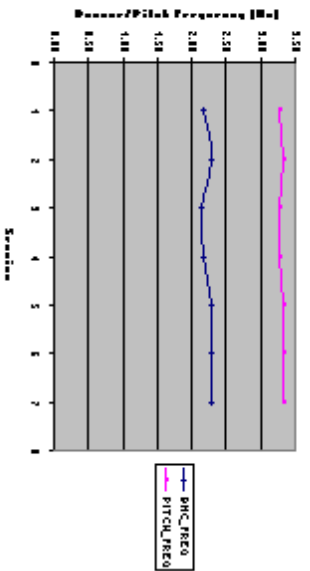
Savaria Bounce Mode Location



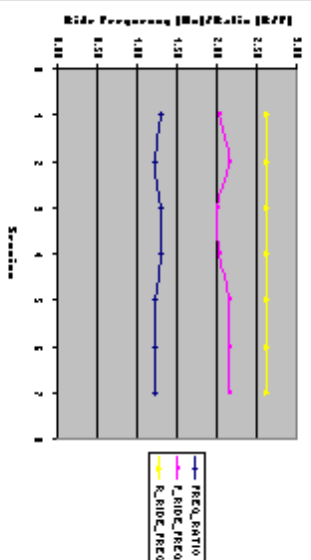
Savaria Pitch Mode Location



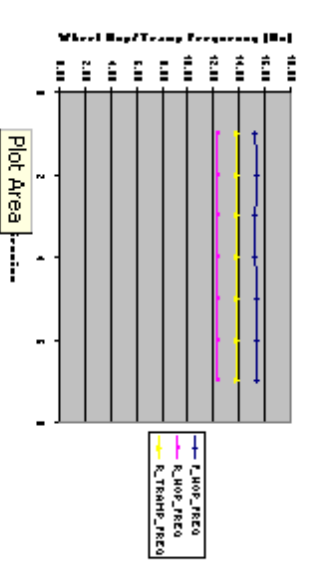
Savaria Bounce/Pitch Frequency



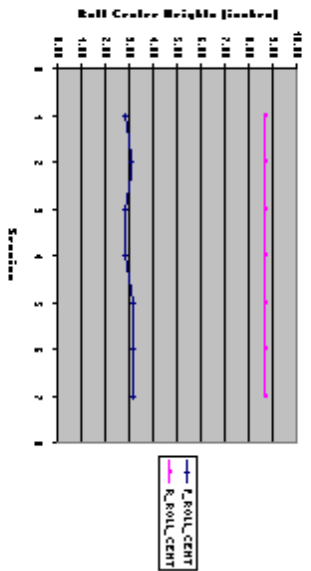
Savaria Ride Frequency/Ratio



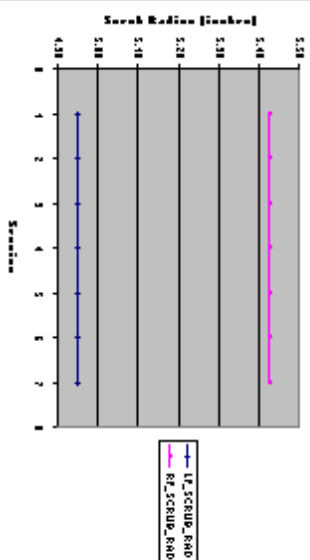
Wheel Hop/Tramp Frequency



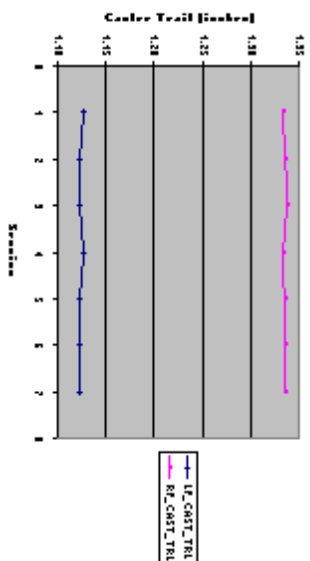
Roll Center Height



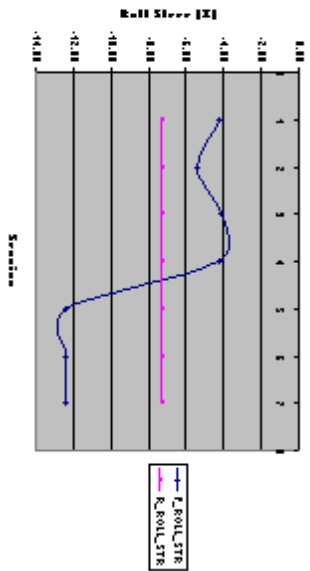
Front Scrub Radius

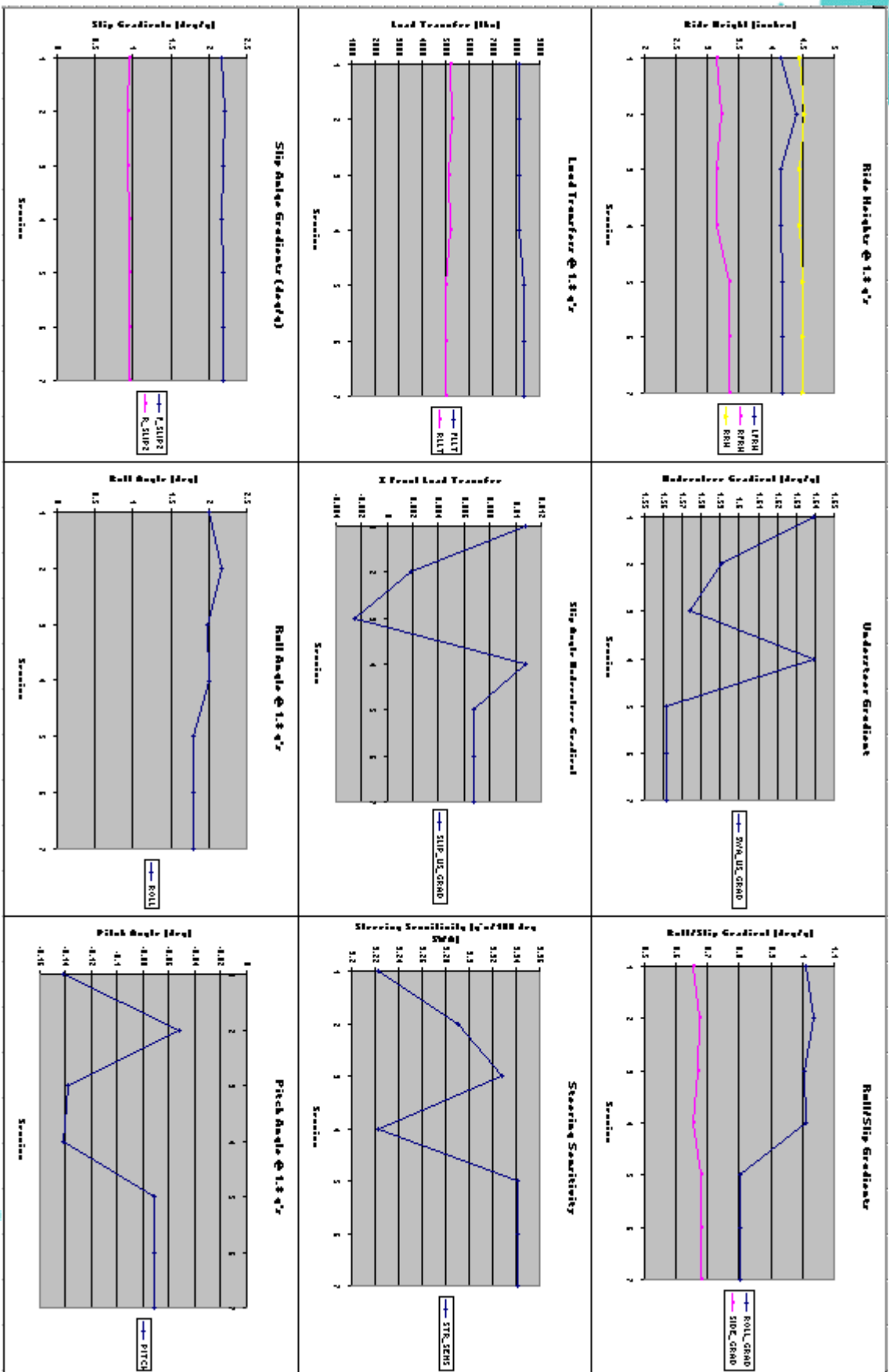


Front Corner Trail



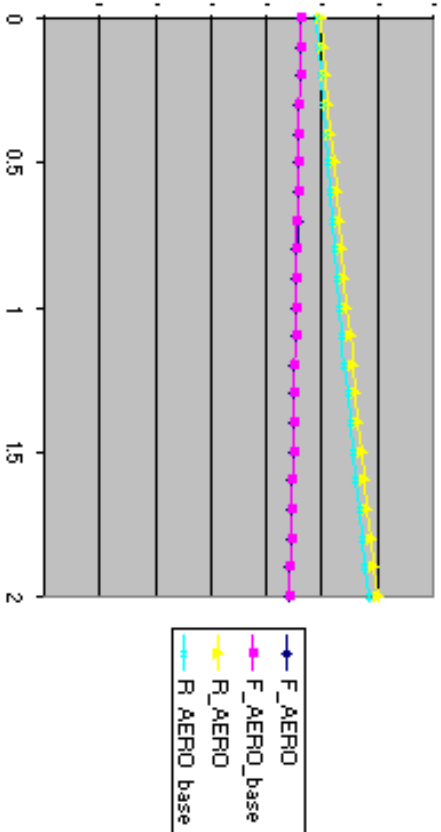
X Roll Steer



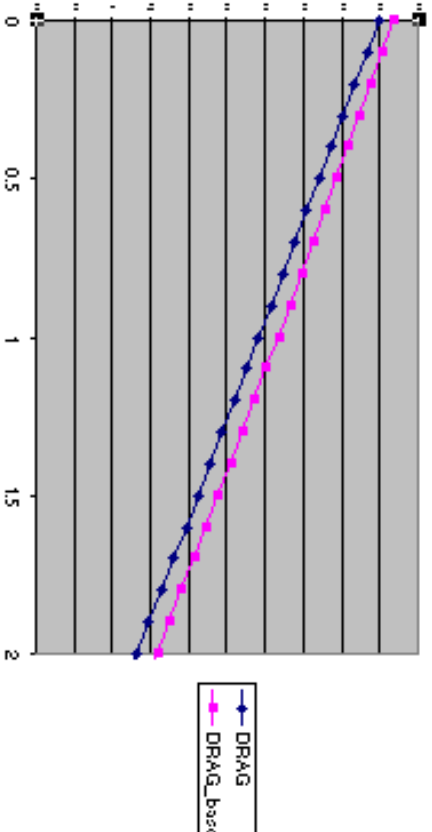




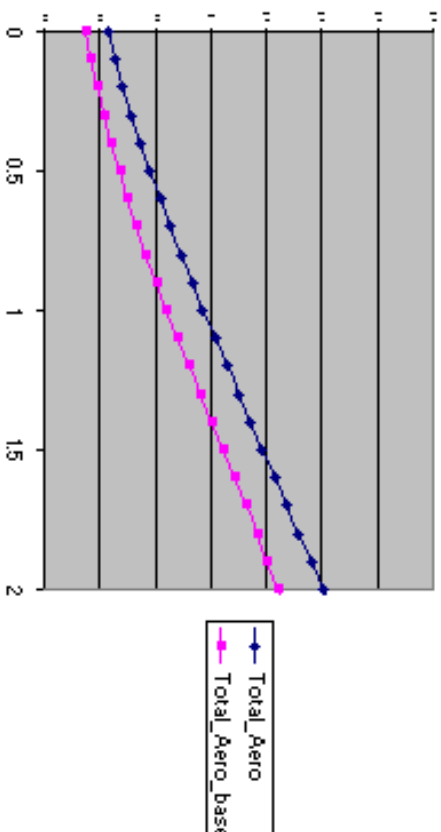
FRONT/REAR DOWNFORCE -vs- LAT. ACCEL.



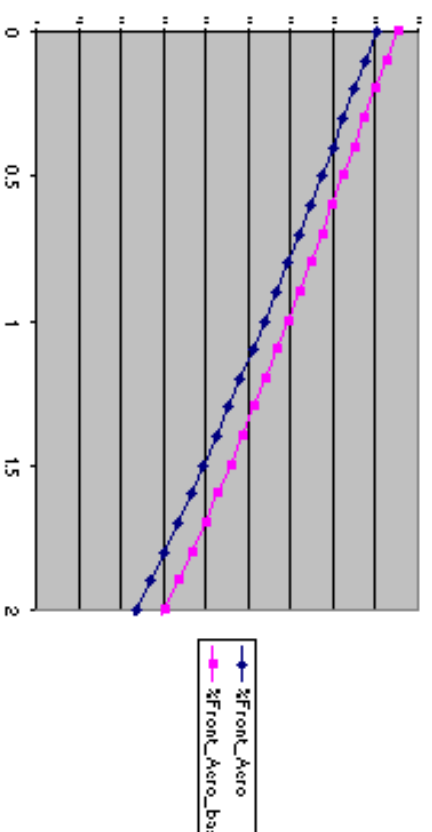
TOTAL AERO -vs- LAT. ACCEL.



TOTAL DOWNFORCE -vs- LAT. ACCEL.



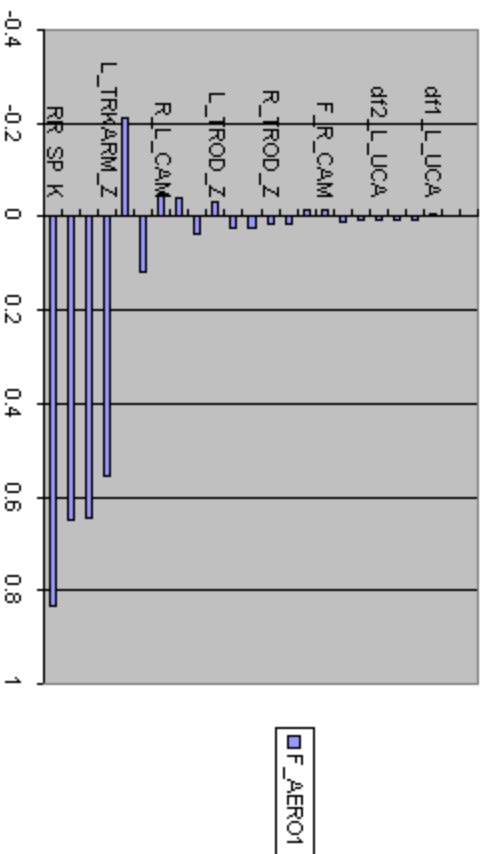
Front Aero Distribution -vs- Lat. Accel.



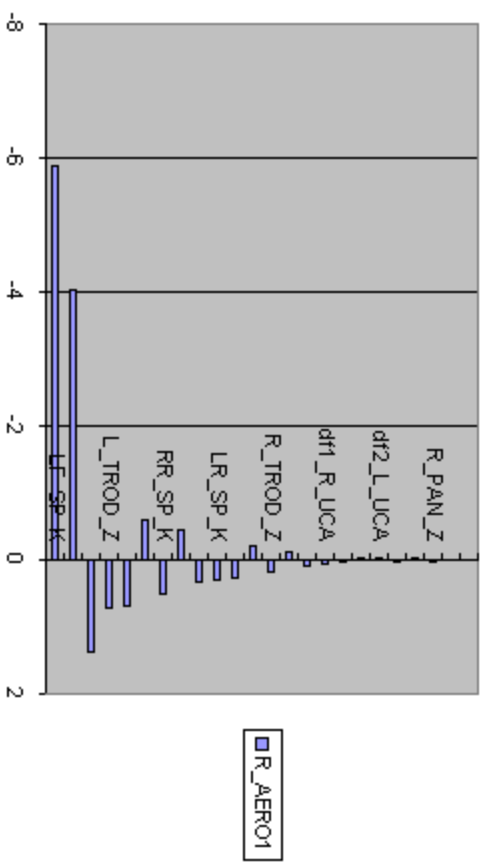


# ADAMS

F\_AERO1

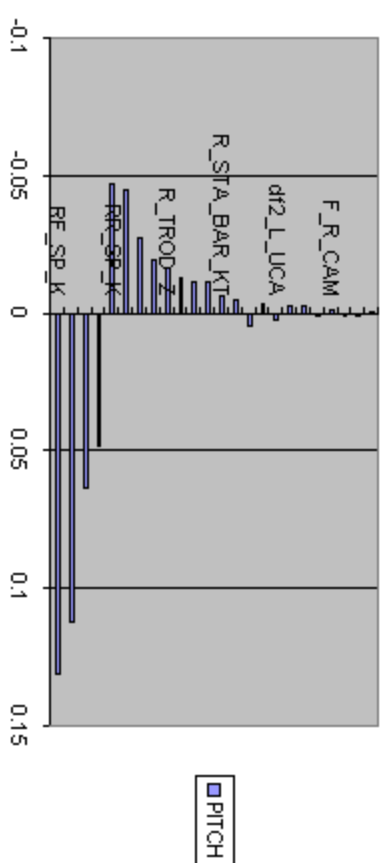
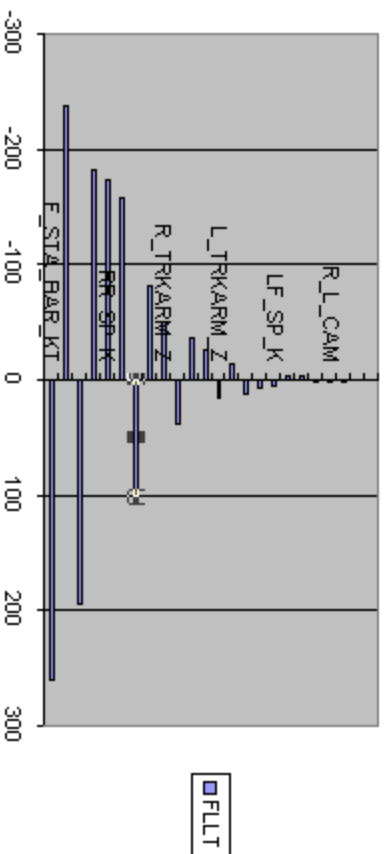


R\_AERO1



FLLT

PITCH





## Conclusions

Through the use of the ADAMS/RaceCar mechanical system simulation environment, engineers can perform Design of Experiments (DOE) on full vehicle handling models to determine vehicle response sensitivity and effects. Screening DOE's are performed to eliminate factors insignificant to vehicle response and higher order factors are investigated using RSM methodology to optimize vehicle behavior. Once the DOE is performed and Response Surface Equations are generated, the response equations are published through a standard spreadsheet environment where vehicle parameter influences and interactions can be quickly evaluated, trackside, in real-time, with the accuracy of the complex full vehicle simulation model