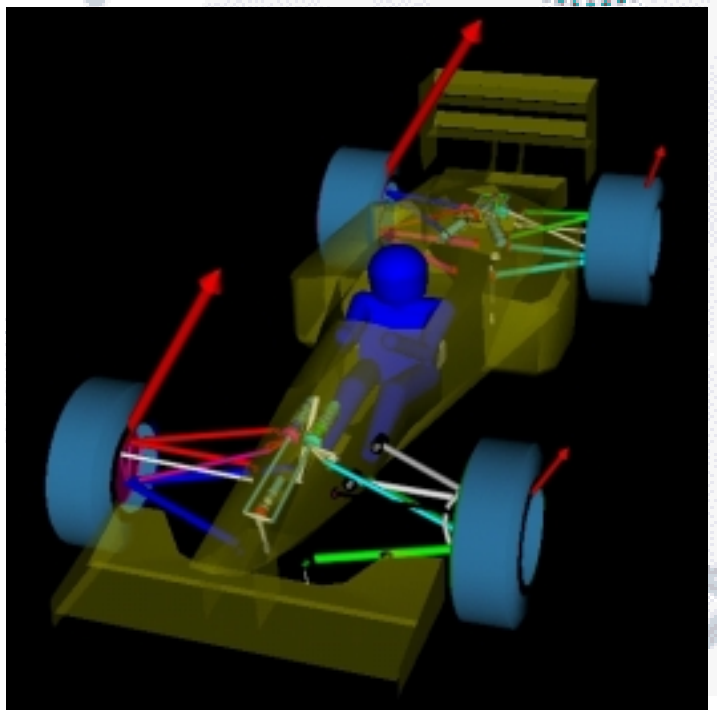
ADAMS

Response Surface Methodology (RSM) and Design of Experiments (DOE) Applied to Racecar Vehicle Dynamics Simulation and Development



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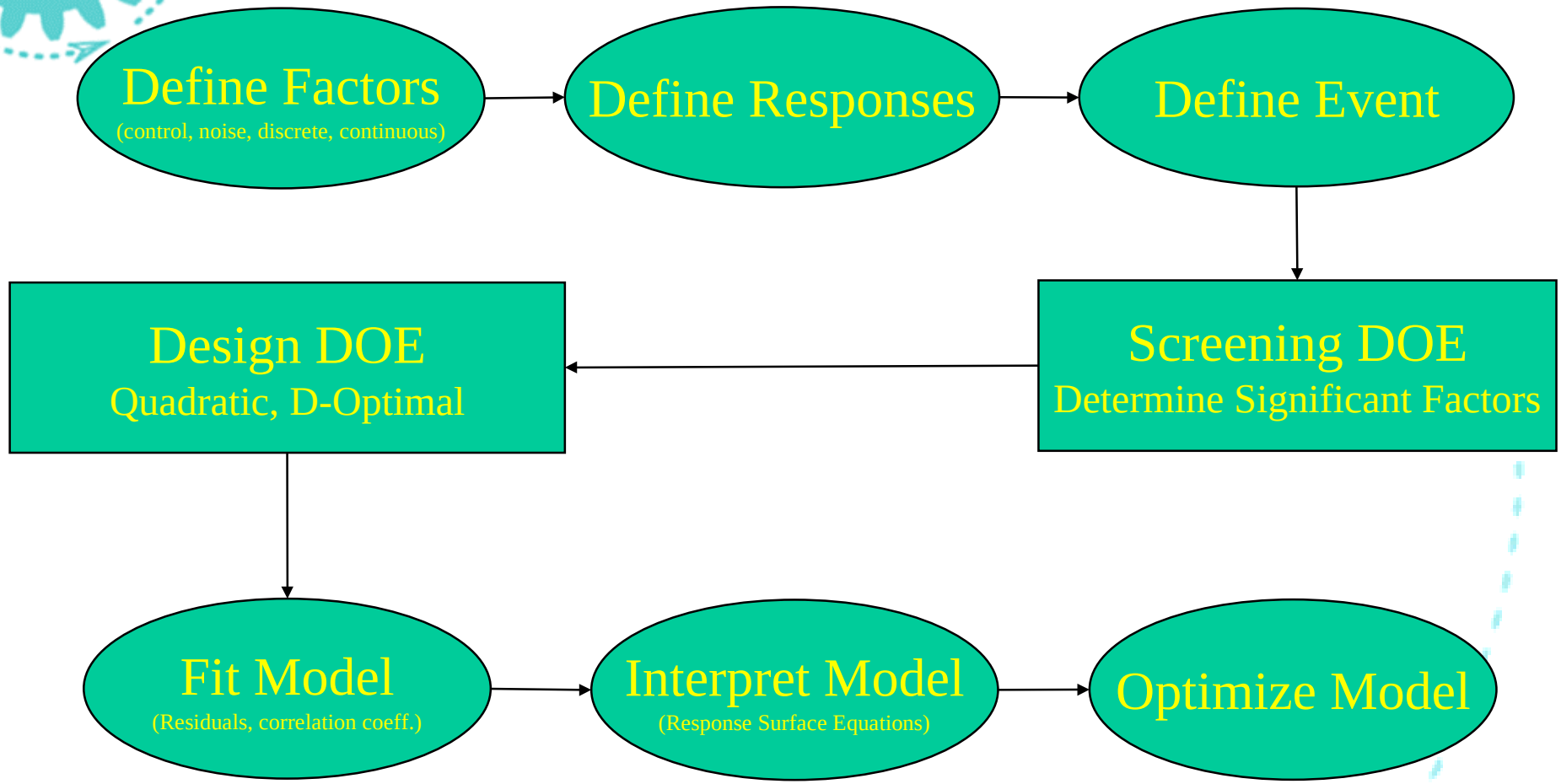
Mechanical Dynamics

Abstract

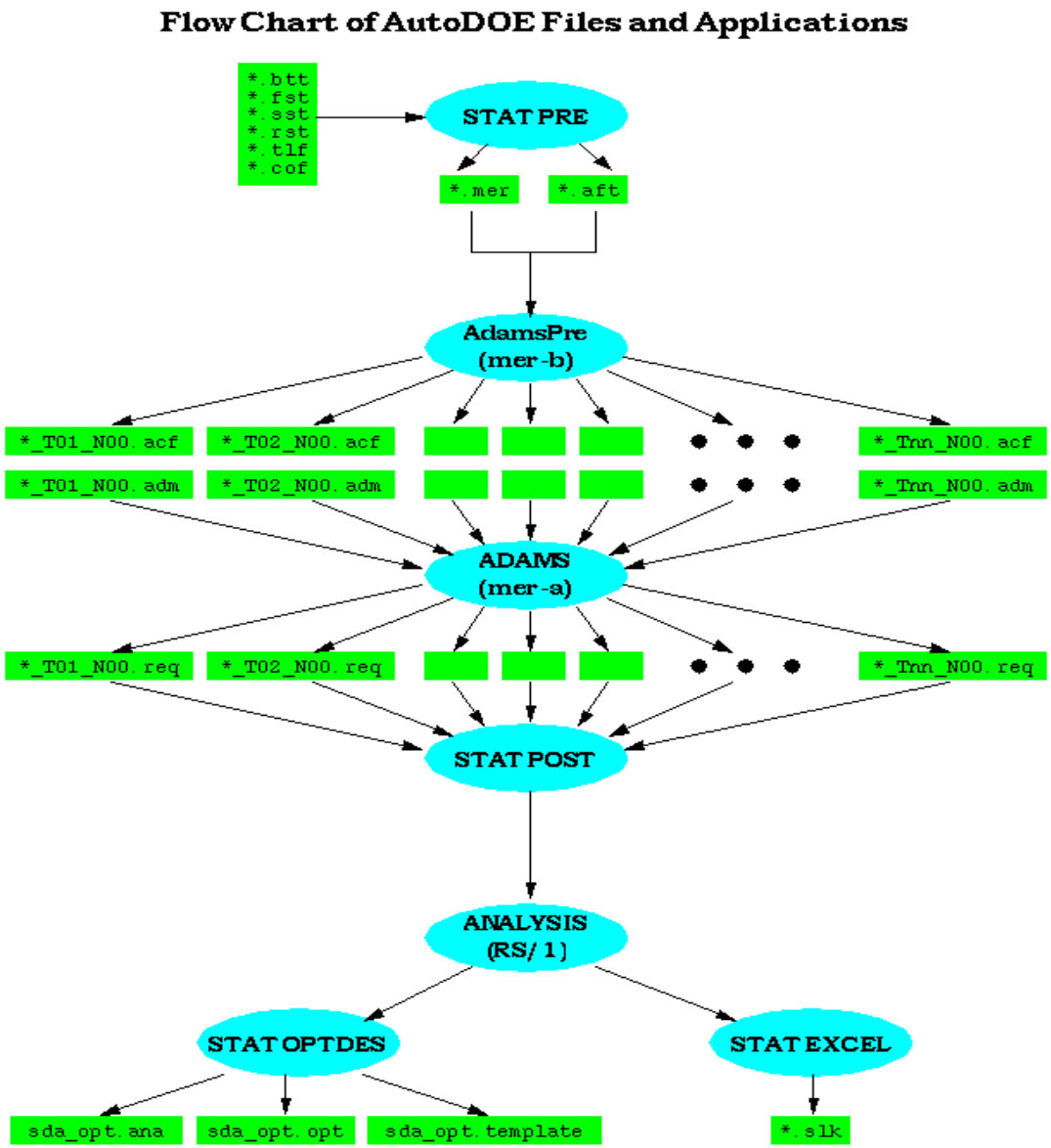
Vehicle dynamics simulation and testing have historically proven able to produce large amounts of “static” information (data) that is very powerful and useful in the vehicle development process. However, this data is often difficult to access in order to answer specific questions about the effects of 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

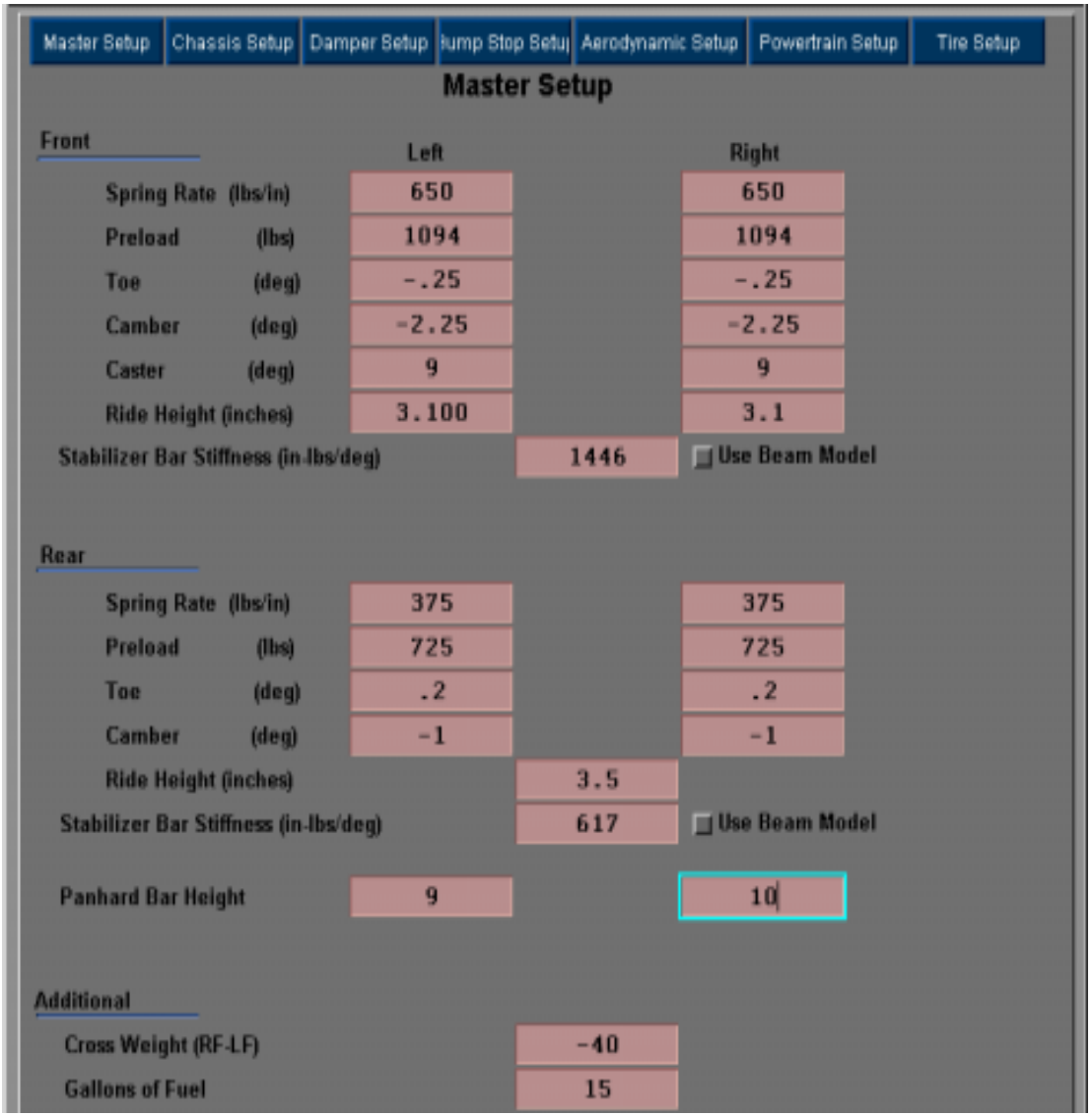

Define Factors
(control, noise, discrete, continuous)
Define Responses
Define Event
Screening DOE
Determine Significant Factors
Design DOE
Quadratic, D-Optimal
Fit Model
(Residuals, correlation coeff.)
Interpret Model
(Response Surface Equations)
Optimize Model

AutoDOE in ADAMS/RaceCar



Mechanical Dynamics

Factor Generation



Factor Generation

RSI1 Main Window

0 Factor	1 Abbrev	2 Role	3 Settings
1 MODE	MODE	CONTROLLED	QUAL, RACE
2 SP_MASS_CG_X	SP_MASS_CG_X	CONTROLLED	-5 to 1
3 CROSS_WT	CROSS_WT	CONTROLLED	-250 to 0
4 L_TROD_Z	L_TROD_Z	CONTROLLED	-0.5 to .5
5 R_TROD_Z	R_TROD_Z	CONTROLLED	-0.5 to .5
6 LEFT_CAST	LEFT_CAST	CONTROLLED	2 TO 8
7 RIGHT_CAST	RIGHT_CAST	CONTROLLED	2 TO 8
8 F_L_CAM	F_L_CAM	CONTROLLED	3.0 to 5.00
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

```
> 1 ADD
> 2 MODIFY
  3 COPY
  4 DELETE
> 5 DISPLAY
  6 CONSTRAINTS
  7 NESTING
  8 NEXT
  9 MAIN
```

Mechanical Dynamics

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

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

Mechanical Dynamics

.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

Fit Models

RSM Main Window

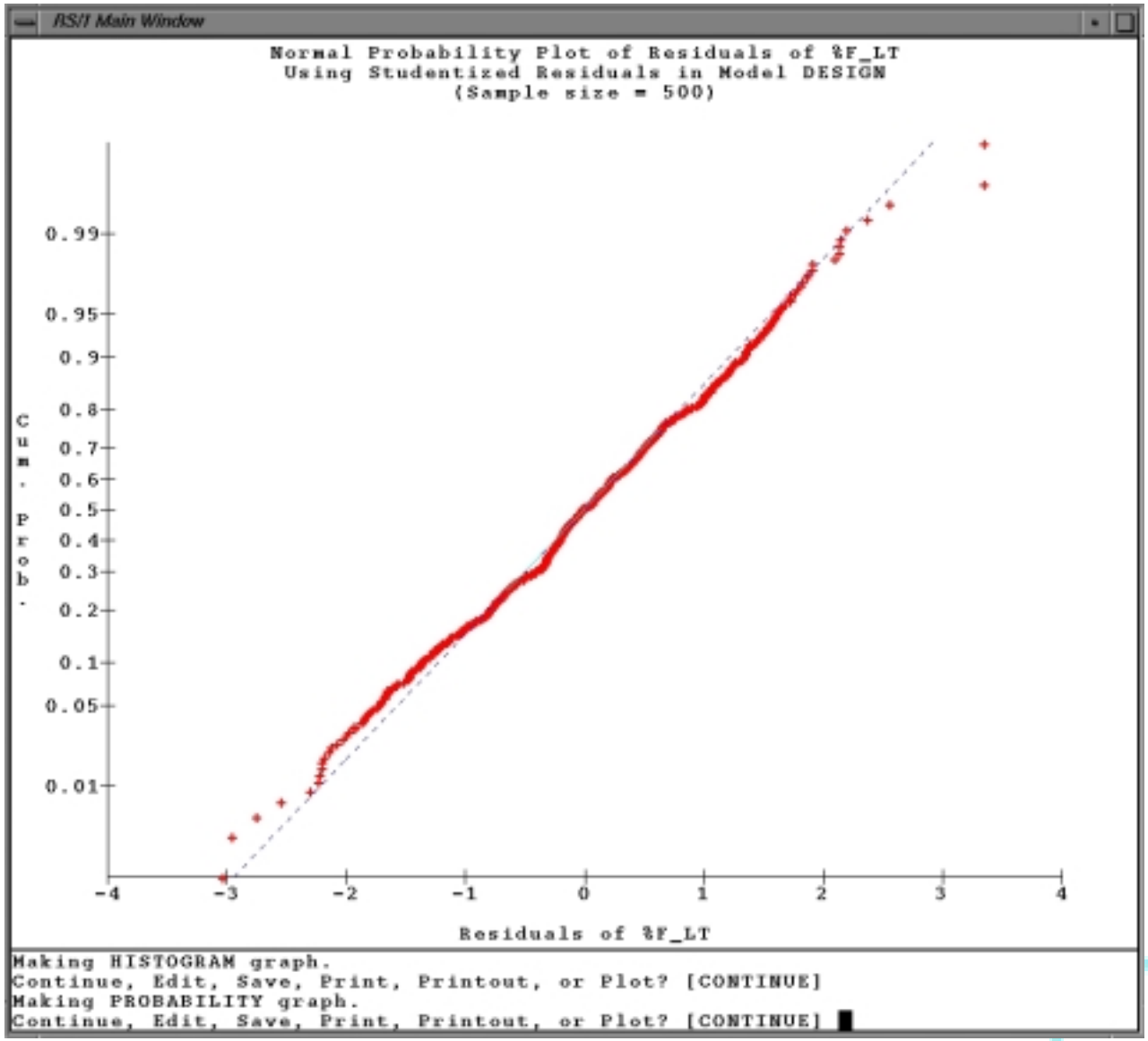
```
Least Squares Coefficients, Response %F_LT, Model DESIGN

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.
```

```
> 1 ANOVA
  2 COEFFICIENTS
> 3 RESIDUALS
> 4 GRAPHS
  5 REFINE Model
  6 CHECK Fit
  7 ACCEPT Model
> 8 RESPONSE/MODEL
  9 NEXT
```

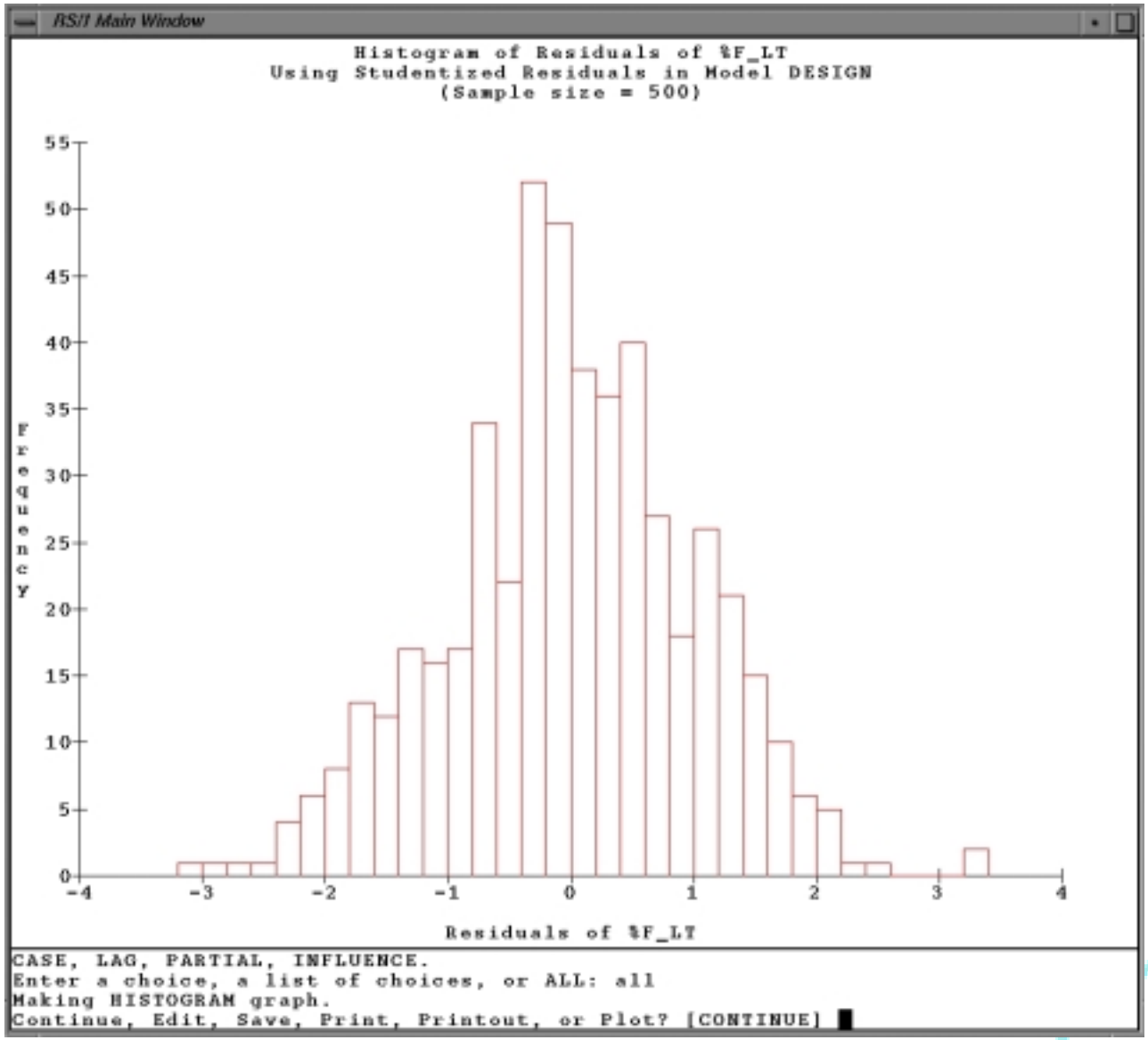
```
EXPER.MULREG> [AUTOFIT]
EXPER.MULREG> [FIT]
More rows and columns to display.
MULREG.FIT> [ANOVA]
```

Mechanical Dynamics

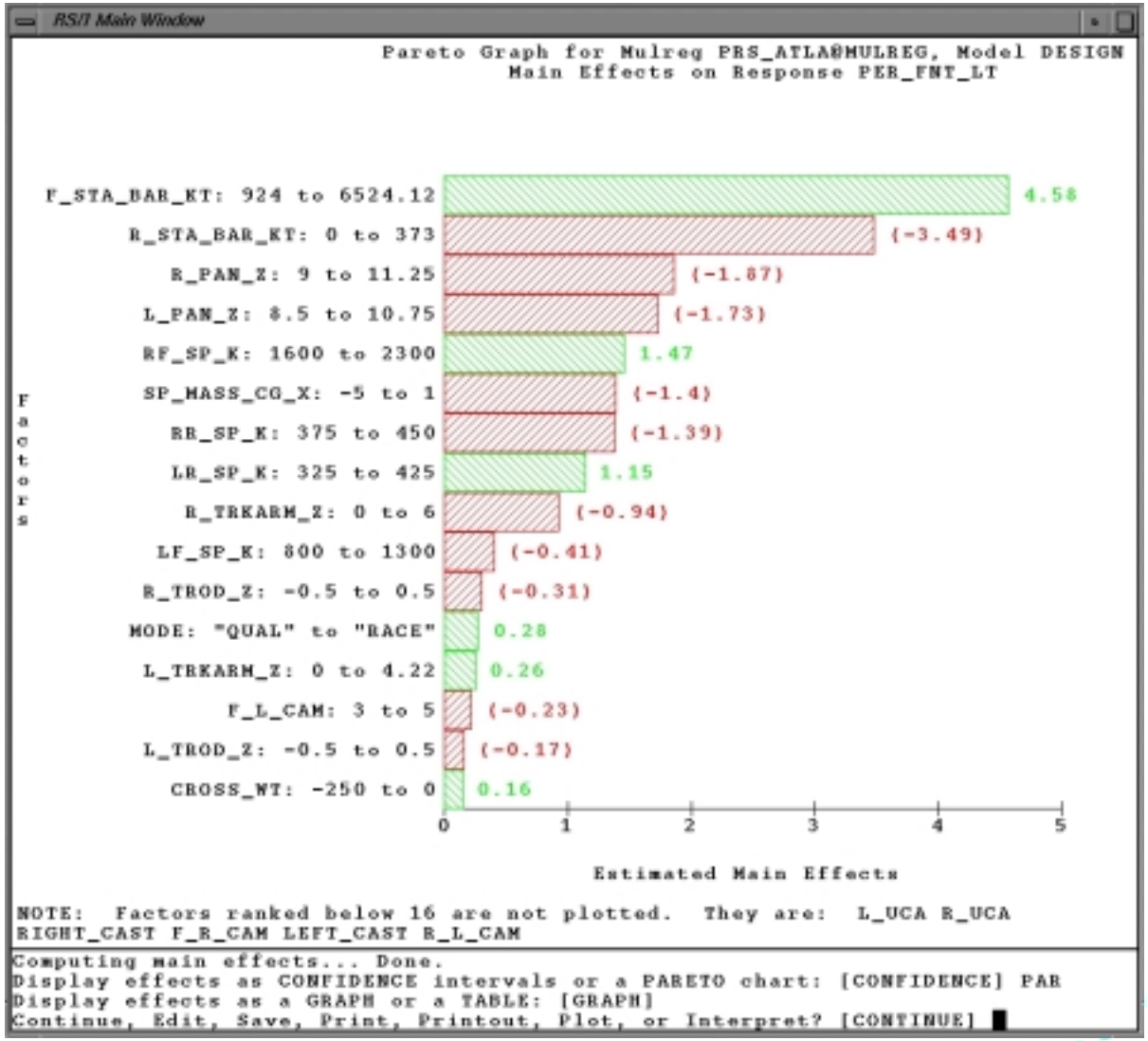
Fit Models


RS/1 Main Window
Normal Probability Plot of Residuals of %F_LT
Using Studentized Residuals in Model DESIGN
(Sample size = 500)
Cum. Prob.
0.99
0.95
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.05
0.01
-4
-3
-2
-1
0
1
2
3
4
Residuals of %F_LT
Making HISTOGRAM graph.
Continue, Edit, Save, Print, Printout, or Plot? [CONTINUE]
Making PROBABILITY graph.
Continue, Edit, Save, Print, Printout, or Plot? [CONTINUE]

Fit Models

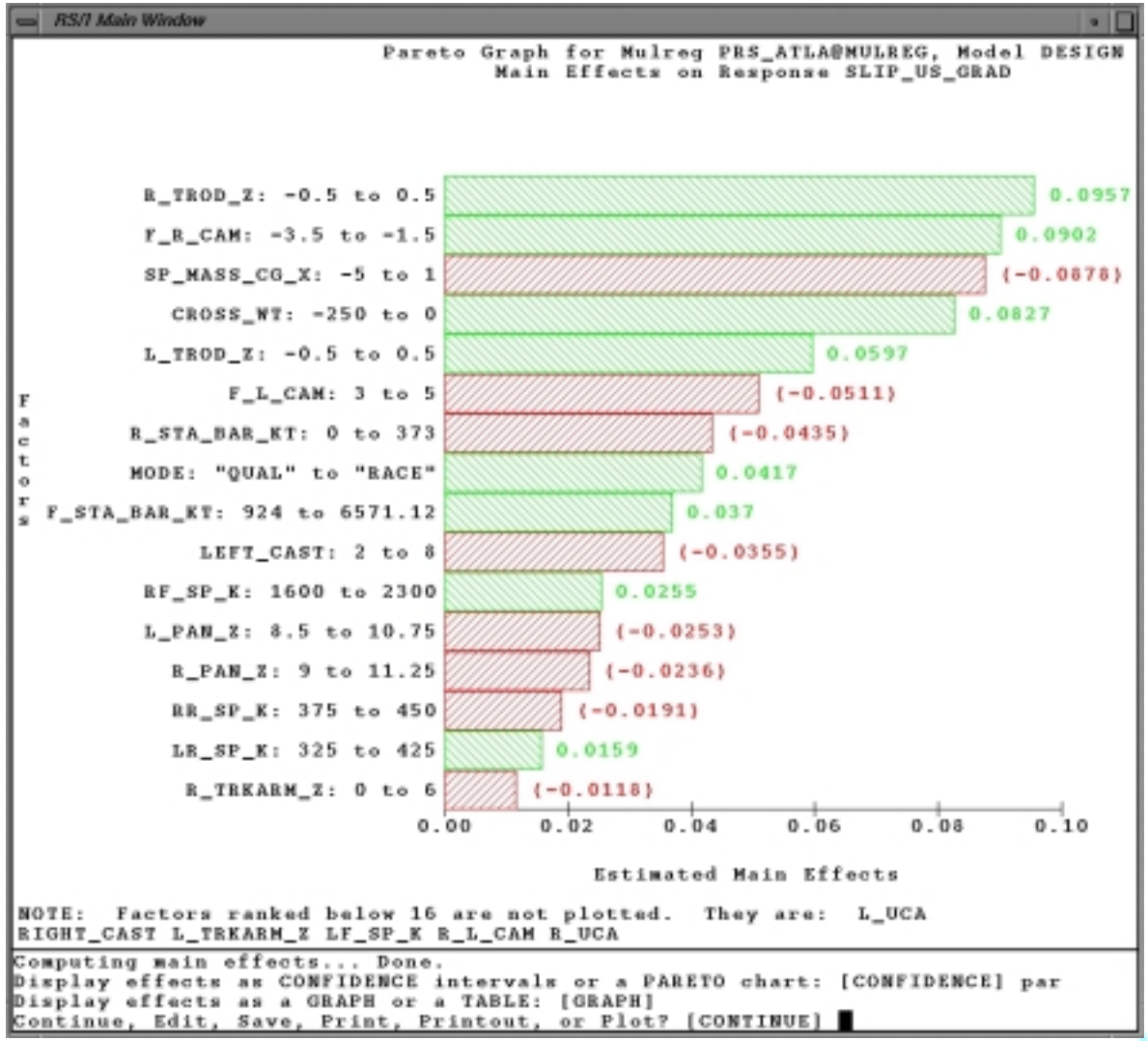

RS/1 Main Window
Histogram of Residuals of %F_LT
Using Studentized Residuals in Model DESIGN
(Sample size = 500)
Frequency
55
50
45
40
35
30
25
20
15
10
5
0
-4
-3
-2
-1
0
1
2
3
4
Residuals of %F_LT
CASE, LAG, PARTIAL, INFLUENCE.
Enter a choice, a list of choices, or ALL: all
Making HISTOGRAM graph.
Continue, Edit, Save, Print, Printout, or Plot? [CONTINUE]

Interpret Response Models

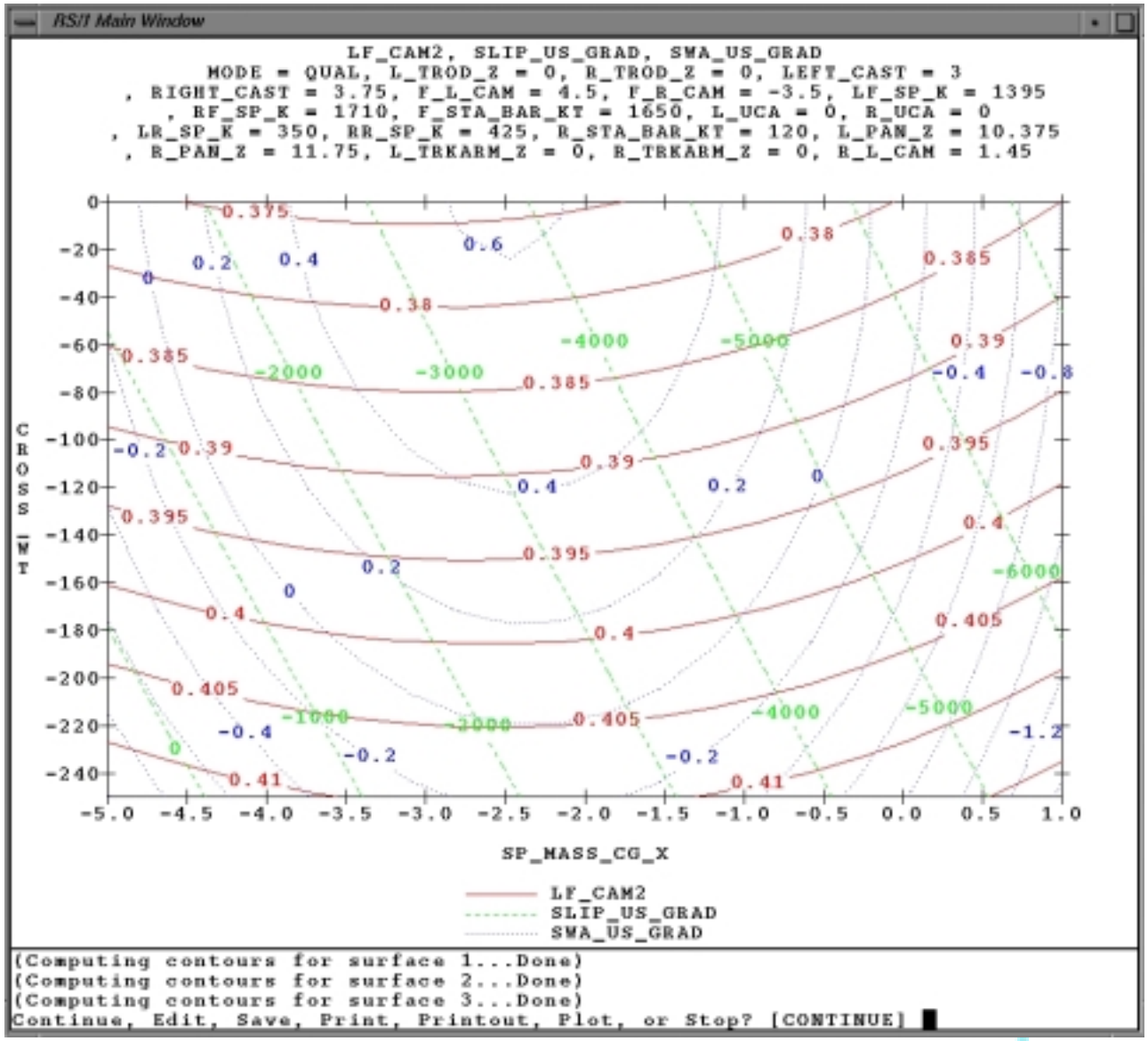


Mechanical Dynamics

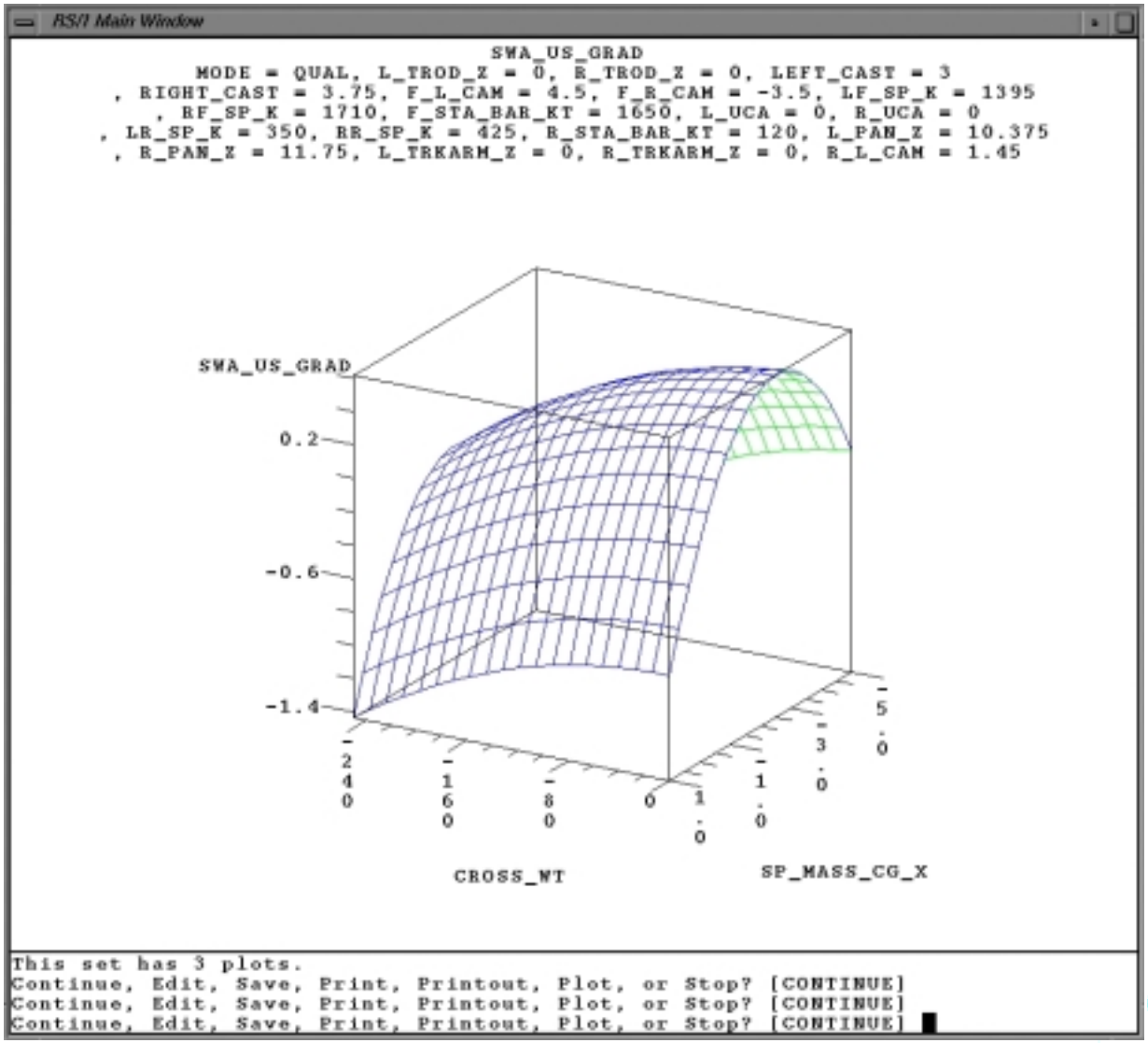
Interpret Response Models



Interpret Response Models



Interpret Response Models



Optimize Response Model

RSM Main Window

Factor, Response or Formula		Range	Initial Setting	Optimal Value
1	Factors			
2	MODE	QUAL, RACE		RACE
3	SP_MASS_CG_X	-5 to 1	-2	-0.91922
4	CROSS_WT	-250 to 0	-125	-248.16
5	L_TROD_Z	-0.5 to .5	0	0.0248
6	R_TROD_Z	-0.5 to .5	0	0.32552
7	LEFT_CAST	2 to 4	3	3.1156
8	RIGHT_CAST	2.75 to 4.75	3.75	4.7427
9	F_L_CAM	3.5 to 5.5	4.5	4.2473
10	F_R_CAM	-4.5 to -2.5	-3.5	-4.4746
11	LF_SP_K	1145 to 1645	1395	1583.8
12	RF_SP_K	1510 to 1910	1710	1898.1
13	F_STA_BAR_KT	1100 to 2200	1650	1562.1
14	L_UCA	-0.375 to .375	0	0.27368
15	R_UCA	-0.375 to .375	0	-0.097483
16	LR_SP_K	300 to 400	350	331.78
17	RR_SP_K	375 to 475	425	424.43
18	R_STA_BAR_KT	0 to 240	120	185.11
19	L_PAN_Z	9.75 to 11	10.38	10.425
20	R_PAN_Z	11 to 12.5	11.75	11.189
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

1 SELECT
2 MIN/MAX
3 FACTOR Ranges
4 CONSTRAINTS
5 INITIAL Settings
6 TOLERANCE
7 STEP Limit
8 PERFORM
> 9 STORE
10 RECALL
11 NEXT
12 MAIN

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]
```

Mechanical Dynamics

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

Excel Setup Page

Constant Speed - Static Vehicle Characteristics DOE
Quadratic Model - RSM - D-Optimal
Speed: 155MPH
Bank Angle: 24 degrees

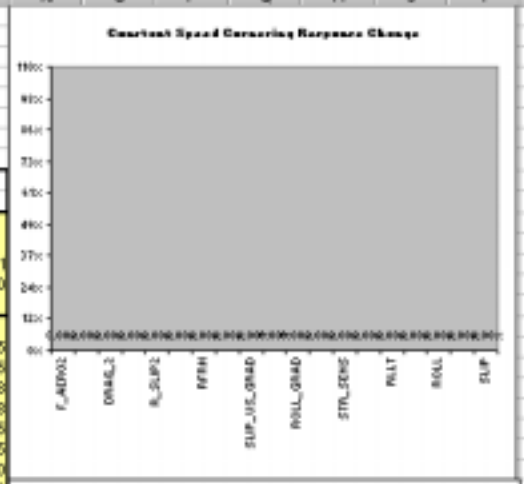
	Factor Name	Units	Current Setup	Session 1	Session 2	Session 3	Session 4	Session 5	Baseline Setup	% Change	Min	Max
Chassis												
	MODE		QUAL	QUAL	QUAL	QUAL	QUAL	QUAL	QUAL		QUAL,RACE	
	SP_MASS_CG_X	inch	-3.09	-3.09	-3.09	-3.09	-3.09	-3.09	-3.09	0.0%	-5	1
	CROSS_WT	lbs	-157	-157	-157	-157	-157	-157	-157	0.0%	-250	0
Front Suspension												
	LEFT TIE ROD Z	in	0	0	0	0	0	0	0	#DIV/0!	-0.5	0.5
	RIGHT TIE ROD Z	in	0	0	0	0	0	0	0	#DIV/0!	-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	1350
	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	5927
	L_UCA	in	8.75	8.75	8.75	8.75	8.75	8.75	8.75	0.0%	8.75,9,9.25	
	R_UCA	in	7.5	7.5	7.5	7.5	7.5	7.5	7.5	0.0%	7.5,7.75,8,8.25	
Rear Suspension												
	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	#DIV/0!	0	240
	L_PAN_Z	inches	8.75	8.75	8.75	8.75	8.75	8.75	8.75		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	#DIV/0!	0	6
	R_TRKARM_Z	inches	0	0	0	0	0	0	0	#DIV/0!	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

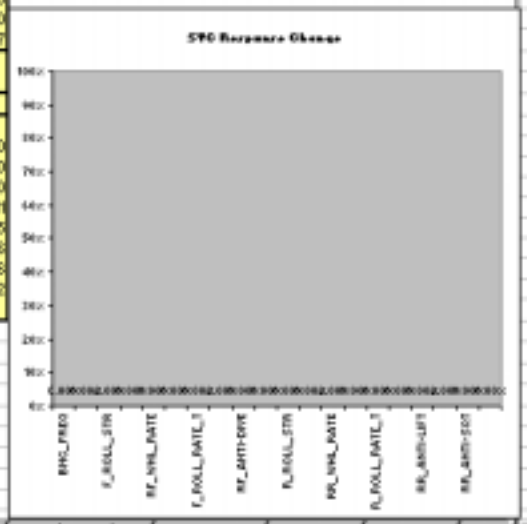
Corner Weights

	LEFT	RIGHT		
FRONT	994	937	CROSS:	48.95%
REAR	825	779	FRONT:	0.54
			TOTAL:	3395
			CG X:	-3.09
			RF-LF:	-157

Toe Calculator

Inches at 16" center:	0.065
Degrees:	0.23





cspd / svc / Setup Input / SVC Plots-1 / SVC Plots-2 / Session Metrics / Handling Metrics / Aero Forces / Cambers-Slip / SWA-SWT / Tire - Fy / Tire - Fz / CSPI

Ready

Mechanical Dynamics

ADAMS

Constant Speed - Static Vehicle Characteristics DOE
Quadratic Model - RSM - D-Optimal
Speed: 155MPH
Bank Angle: 24 degrees

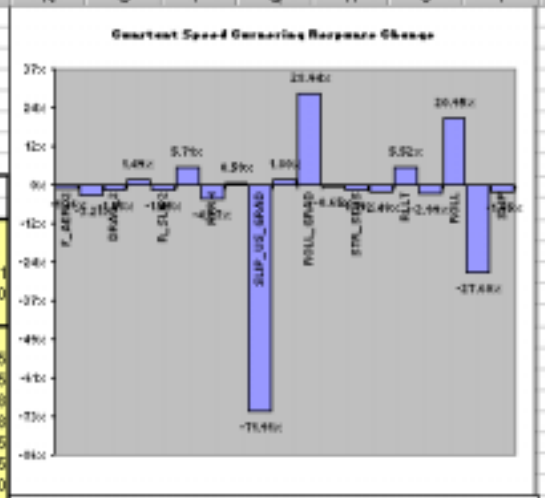
	Factor Name	Units	Current Setup	Session 1	Session 2	Session 3	Session 4	Session 5	Baseline Setup	% Change	Min	Max
Chassis												
	MODE		QUAL	QUAL	QUAL	QUAL	QUAL	QUAL	QUAL		QUAL	RACE
	SP_MASS_CG_X	inch	-3.09	-3.09	-3.09	-3.09	-3.09	-3.09	-3.09	0.0%	-5	1
	CROSS_WT	lbs	-157	-157	-157	-157	-157	-157	-157	0.0%	-250	0
Front Suspension												
	LEFT TIE ROD Z	in	0	0	0	0	0	0	0	#DIV/0!	-0.5	0.5
	RIGHT TIE ROD Z	in	0	0	0	0	0	0	0	#DIV/0!	-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	1350
	RF_SP_K	lbs/in	2070	[illegible]	[illegible]	2070	2070	2070	2070	0.0%	1500	2300
	F_STA_BAR_KT	in-lbs/deg	924	[illegible]	[illegible]	2177	2177	2177	2177	-57.6%	627	5927
	L_UCA	in	8.75	[illegible]	[illegible]	8.75	8.75	8.75	8.75	0.0%	8.75,9,9.25	
	R_UCA	in	7.5	[illegible]	[illegible]	7.5	7.5	7.5	7.5	0.0%	7.5,7.75,8,8.25	
Rear Suspension												
	LR_SP_K	lbs/in	325	[illegible]	[illegible]	325	325	325	325	0.0%	300	400
	RR_SP_K	lbs/in	375	[illegible]	[illegible]	375	375	375	375	0.0%	320	450
	R_STA_BAR_KT	in-lbs/deg	0	[illegible]	[illegible]	0	0	0	0	#DIV/0!	0	240
	L_PAN_Z	inches	8.75	8.75	8.75	8.75	8.75	8.75	8.75		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	#DIV/0!	0	6
	R_TRKARM_Z	inches	0	0	0	0	0	0	0	#DIV/0!	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

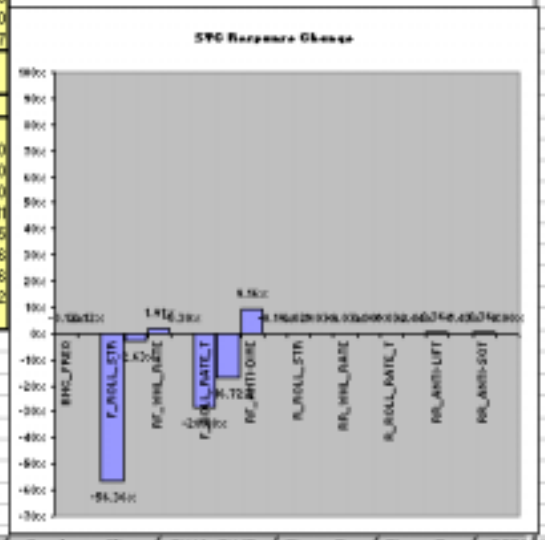
Corner Weights

	LEFT	RIGHT		
FRONT	994	632	CROSS:	48.95%
REAR	425	739	FRONT:	0.54
			TOTAL:	3395
			CG X:	-3.09
			RF-LF:	-157

Toe Calculator

Inches at 16" center:	0.065
Degrees:	0.23



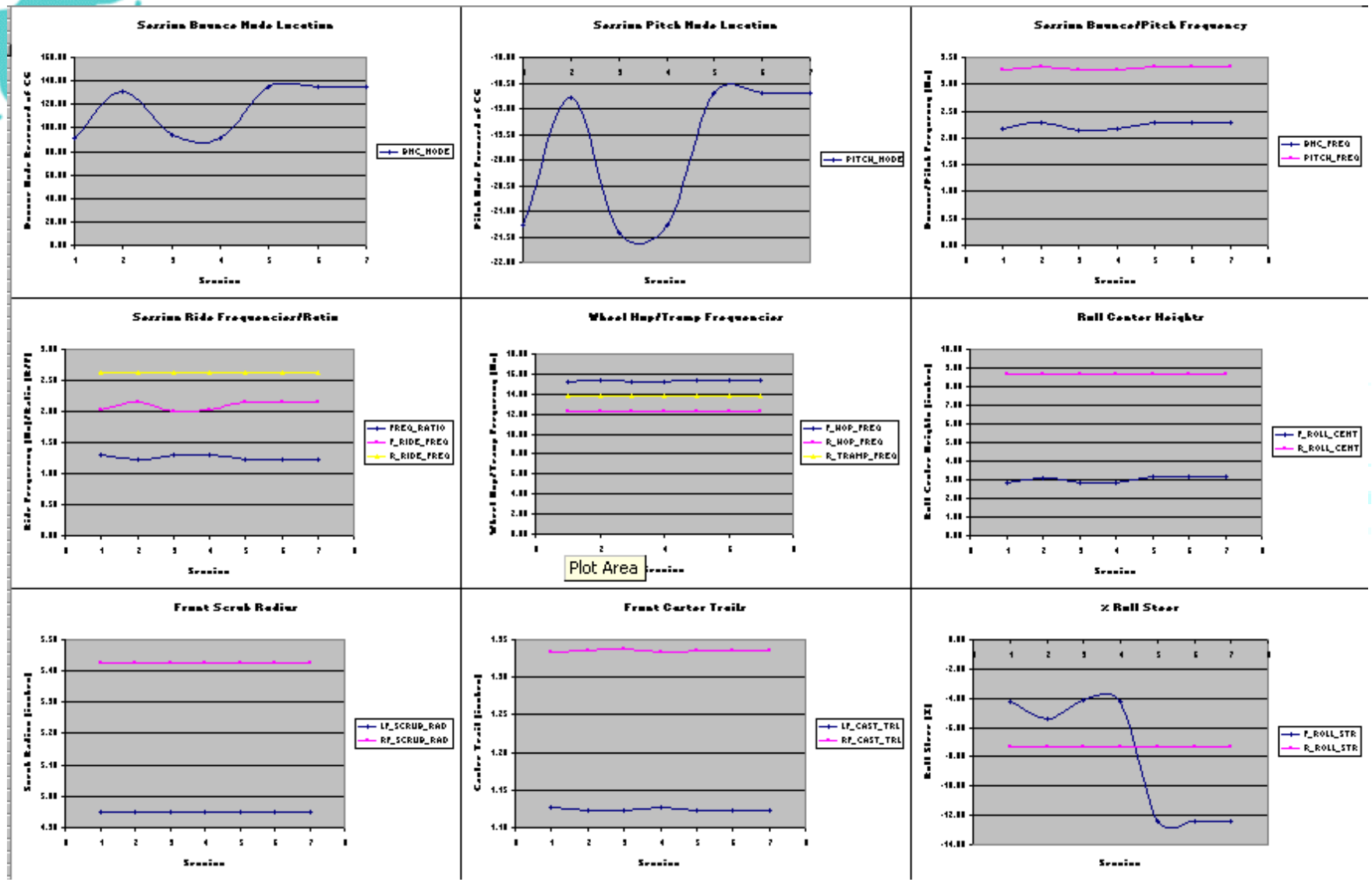


cspd / svc / Setup Input / SVC Plots-1 / SVC Plots-2 / Session Metrics / Handling Metrics / Aero Forces / Cambers-Slip / SWA-SWT / Tire - Fy / Tire - Fz / CSPI

Cell D25 commented by ncosg

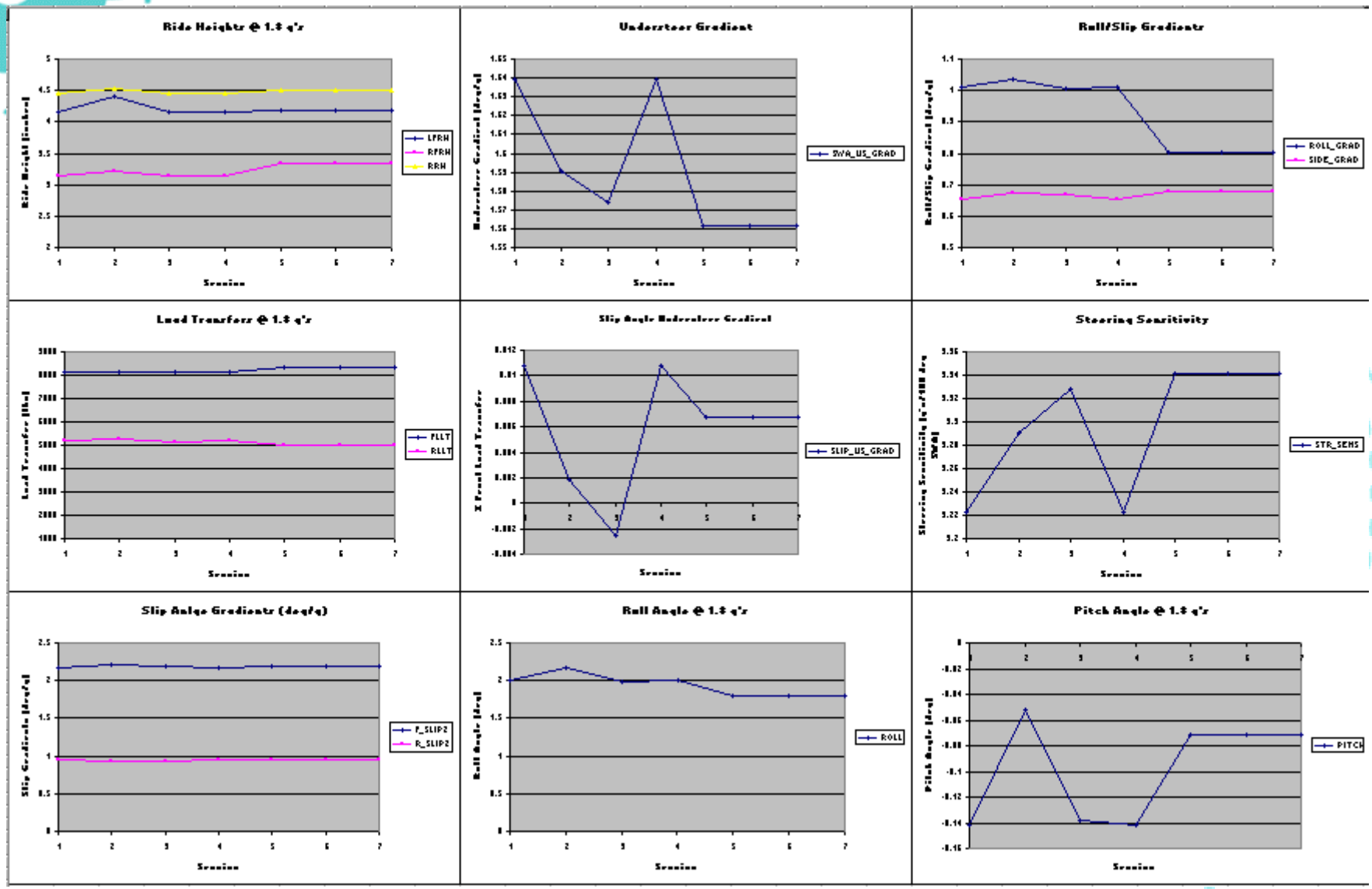
Mechanical Dynamics

ADAMS



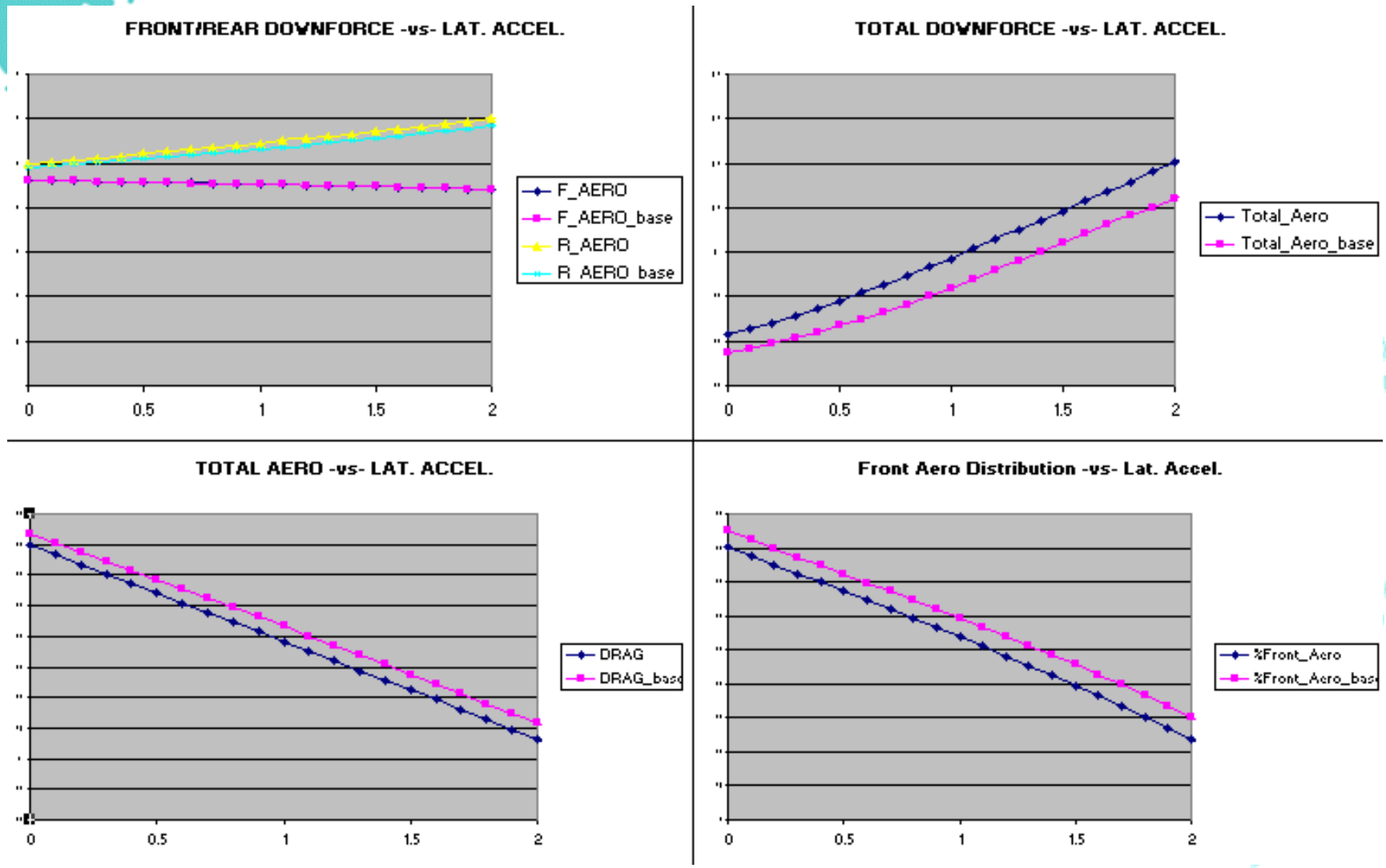
Mechanical Dynamics

ADAMS



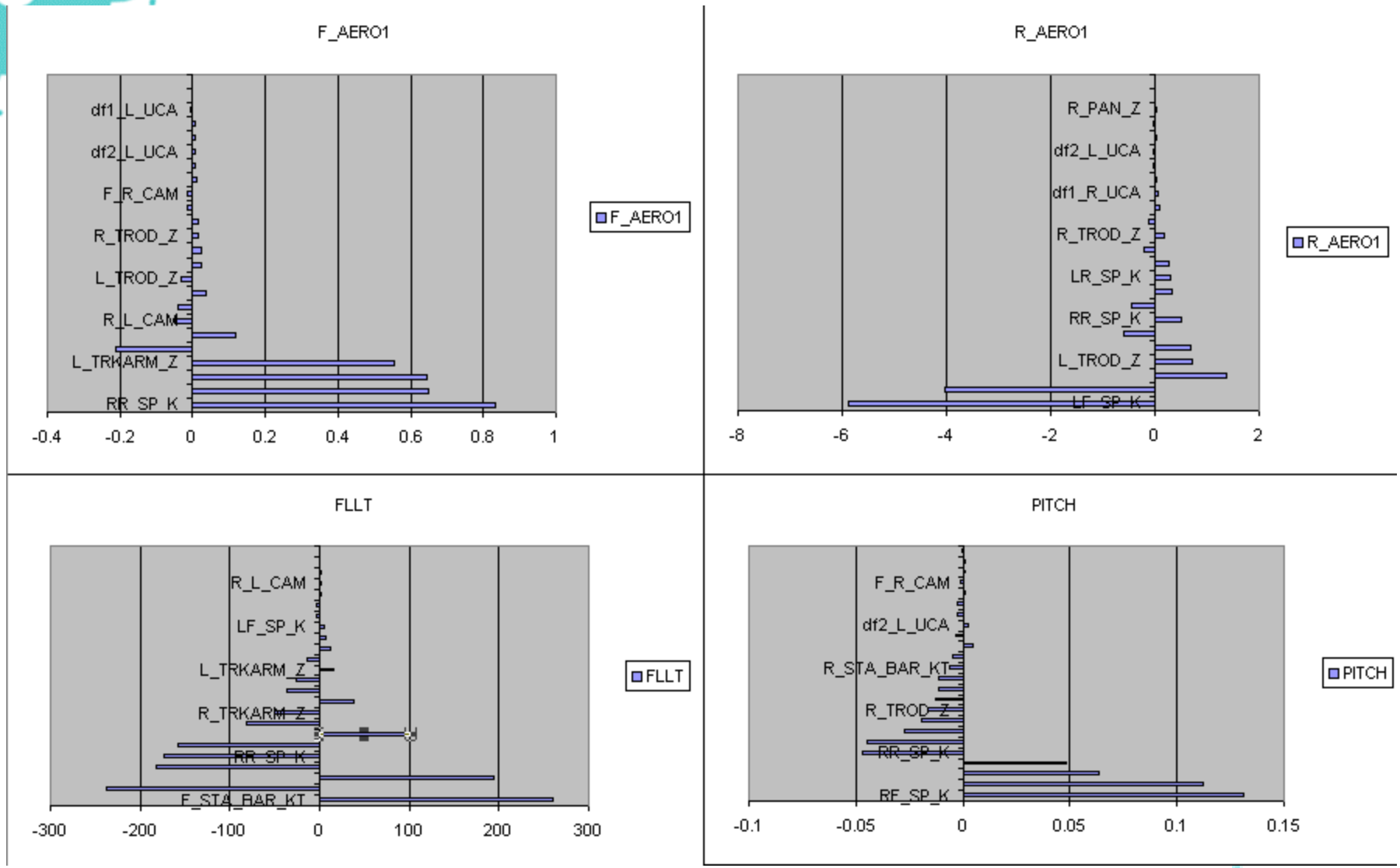
Mechanical Dynamics

ADAMS



Mechanical Dynamics

ADAMS



Mechanical Dynamics

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