THE INTEGRATION OF DESIGNED EXPERIMENTS AND ADAMS

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ABSTRACT

Traditional engineering processes depend on manufacturing to build quality into a product. Additionally, product development often involves several design-build-test iterations. Competitive pressures, however, demand that customer satisfaction be influenced in the conceptual stage of product design and new products be brought to market more quickly. To meet these demands, simulation and analysis must be used to direct a system to an improved or even optimal state versus merely a functional one. The integration of Design of Experiments (DOE) with ADAMS creates a powerful combination of tools for rapid and thorough investigation of a specified design space, identification of the optimal system configuration, and illustration of the effects of system changes on a given output.

The attached presentation demonstrates this approach for two suspension system applications: the reduction of body pitch acceleration associated with the phenomena called "freeway hop", and the reduction of vertical loads into a suspension's front shock tower due to a severe pothole road event.

THE DOE PROCESS

The design of experiments process illustrated in this presentation consists of the following steps:

- Specify the experimental output variable(s);
- Decide which factors and levels are to be used in the experiment;
- Develop the mathematical model (ADAMS model);
- Plan the experiment;
- Run the experiment and record the observations (ADAMS simulations);
- Analyze the data;
- Make conclusions.

DOE vs. OFAT

The traditional way to address the "freeway hop" problem illustrated in the presentation is by conducting one-factor-at-a-time (OFAT) experiment. This strategy, however, assumes that a system is merely the sum of its parts, and interactions are unimportant. For example, a suspension ride engineer may choose the optimal spring first, then tune the damper, then the bushings, and the mounts. Once all the individual components are established, and additional time is available, damper tuning is often changed since interactions *are* important. Nevertheless, many combinations of components (factors) are never examined and large areas of the design space are ignored. However, OFAT experimentation creates the illusion of requiring fewer iterations to reach an optimum, fooling the uninformed engineer. The informed engineer, as mentioned above, may continue to vary factors even after an optimum appears to have been reached. While this approach may result in a solution identical to the one found by DOE, the process is not as efficient and engineers gain considerably less insight into the system (many of the results from DOE are not readily available using OFAT).

OFAT experimentation also relies heavily on the expertise of individuals. Referring again to the ride problem illustrated in the presentation, an experienced ride engineer might be able to quickly identify the best solution based on years of experience. There are, however, many potential pitfalls if an organization relies on the expertise of a few individuals: people move to new assignments, or eventually retire; qualitative knowledge is not easily retained or passed on; etc. In addition, major design changes can cause systems to behave unlike past concepts, sometimes stifling the experts. Designed experimentation with an ADAMS model, or another math-based system representation, minimizes the dependence on past experience.

CONCLUSIONS

The examples illustrated in this presentation are two-level experiments exploring a single response of the systems. Revolutionary changes to system design will occur when this technique is used to explore multiple responses, since design involves compromise among various system outputs. When this hurdle is cleared, multi-level experiments will illustrate the interior of the design space and totally illuminate the effect and interaction functions.

Results from one system can not necessarily be generalized to similar systems. The complexities of some systems demand that each be evaluated and optimized independently.

While ADAMS models can be used to predict specified system responses of interest, DOE can be applied to intelligently explore an entire design space of many factors. The effects on the system for a given design change become readily apparent, and problem situations can be avoided or quickly corrected. Clearly, intelligently applying this methodology to analytic exploration forms a powerful combination capable of drastically improving both the design process and the final products.

For more information, please refer to the paper **SAE 930264**: "Improving the Suspension Design Process by Integrating Multibody System Analysis and Design of Experiments", Mark F. Lamps and Edward C. Ekert.

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TECHNOLOGY WORLDWIDE

THE INTEGRATION OF DESIGNED EXPERIMENTS AND ADAMS

Ed Ekert

1994 ADAMS USER CONFERENCE

DELCO CHASSIS TECHNOLOGY WORLDWIDE

PRESENTATION OBJECTIVES

- INTRODUCE DELCO CHASSIS
- CONVEY IMPORTANCE OF LEVERAGING CUSTOMER SATISFACTION EARLY IN PRODUCT DEVELOPMENT
- INTRODUCE THE DOE PROCESS
- REVIEW EXAMPLES OF DOE AND ADAMS:
  - VEHICLE FREEWAY HOP PHENOMENA
  - SEVERE VEHICLE SUSPENSION FORCES
- CONCLUDE WITH LESSONS, RECOMMENDATIONS, AND FUTURE DIRECTION

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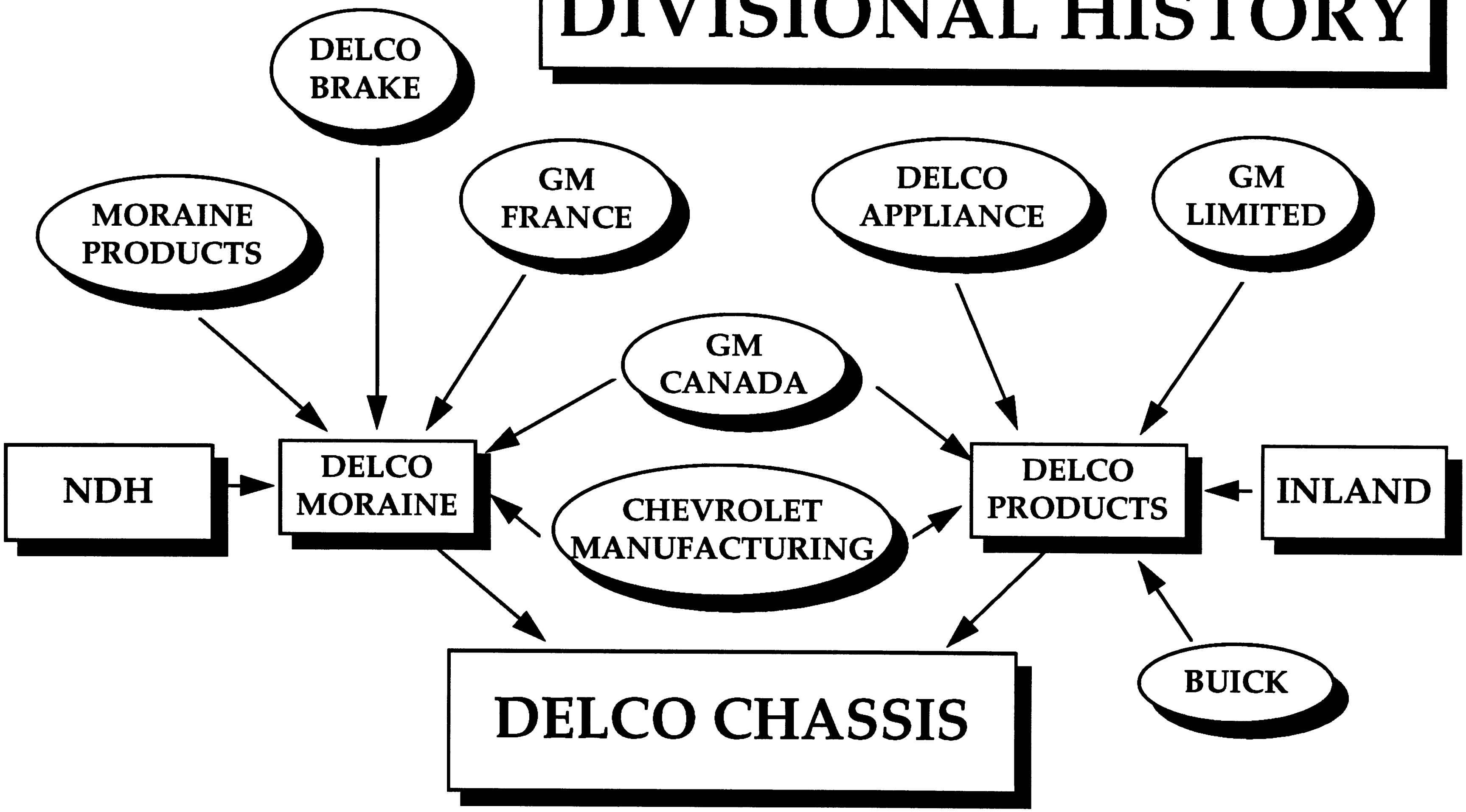
DIVISIONAL HISTORY



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SYSTEMS AND COMPONENTS MANUFACTURED

- **BRAKING SYSTEMS:**
  - APPLY SYSTEMS: BOOSTERS, MASTER CYLINDERS, ABS & TCS MODULATORS, SENSORS, CONTROLLERS
  - WHEEL SYSTEMS: ROTORS, CALIPERS, PADS, WHEEL BEARINGS, KNUCKLES, DRUMS, SHOES
- **SUSPENSION SYSTEMS:**
  - PASSIVE: SHOCKS AND STRUTS, COILS SPRINGS, COMPOSITE LEAF SPRINGS, MOUNTS, CONTROL ARMS, BALL JOINTS, SUSPENSION LINKS
  - CONTROLLED: AUTOMATIC LEVELING, ADAPTIVE, AND REAL TIME SYSTEMS

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1994 STATISTICS

21,000 EMPLOYEES (WORLDWIDE)
- 3,500 SALARIED
- 17,500 HOURLY

16 MILLION SQ. FT. FLOOR SPACE
12 PLANTS IN NORTH AMERICA
6 PLANTS OUTSIDE N.A.

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TECHNOLOGY WORLDWIDE

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LOCATIONS

WARREN, MICHIGAN
FLINT, MICHIGAN
LIVONIA, MICHIGAN
BRIGHTON, MICHIGAN
SAGINAW ,MICHIGAN

SANDUSKY, OHIO
DAYTON, OHIO

KETTERING, OHIO
VANDALIA, OHIO
ELIZABETHTOWN, KENTUCKY

CHIHUAHUA, MEXICO
GUADALAJARA, MEXICO

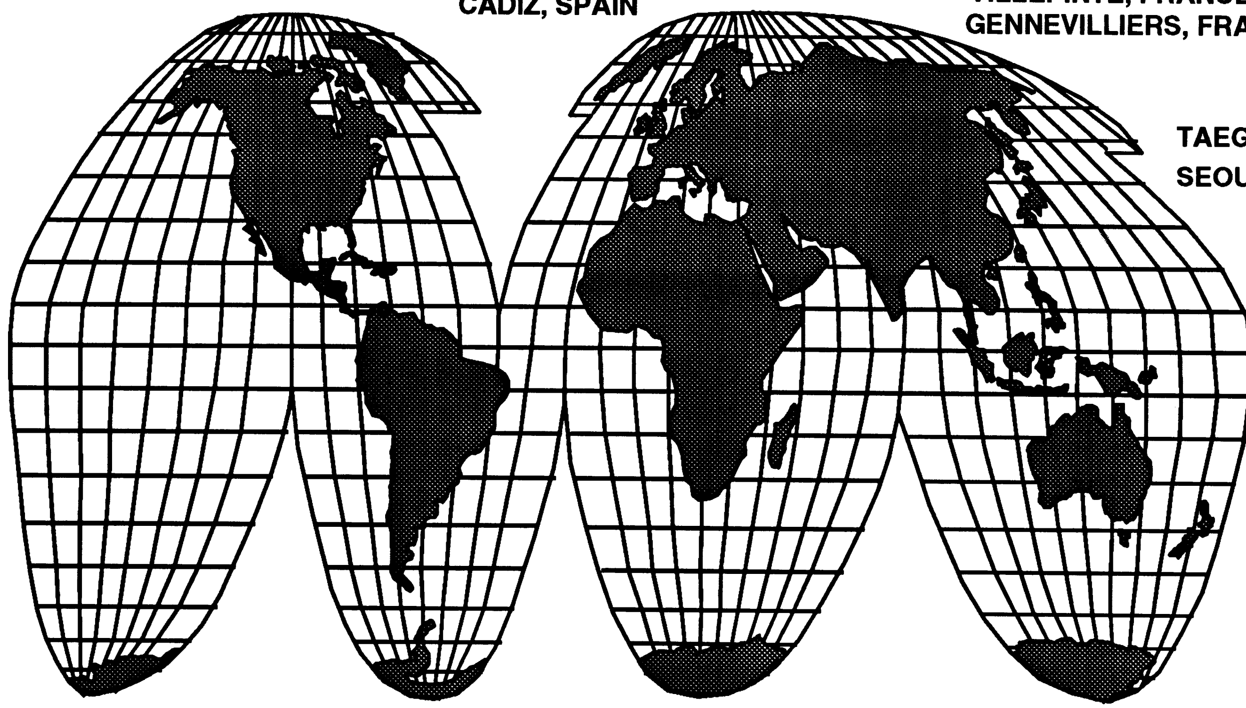
OSHAWA, ONTARIO
ST. CATHERINES, ONTARIO

PUERTO REAL, SPAIN
CADIZ, SPAIN

DUNSTABLE, ENGLAND
RUESSELSHEIM, GERMANY

ANDE, FRANCE
VILLEPINTE, FRANCE
GENNEVILLIERS, FRANCE

TAEGU, KOREA
SEOUL, KOREA



THE USE OF ADAMS AT DELCO

- IN USE SINCE 1983
- ABOUT 10 ENGINEERS USING ADAMS
- CURRENTLY RUNNING ON HP735 ENGINEERING WORKSTATIONS
- USE ADAMS/Solver, ADAMS/View, ADAMS/Linear

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THE USE OF ADAMS AT DELCO

- PRELIMINARY CONCEPT DEVELOPMENT:
  - SUSPENSION KINEMATICS AND PACKAGING USING UG/Mechanisms (INCLUDES ADAMS/Kinematic)
  - VEHICLE DYNAMICS
  - SUSPENSION LOADS ANALYSIS
- DESIGN REFINEMENT:
  - VEHICLE DYNAMICS
  - SUSPENSION LOADS ANALYSIS

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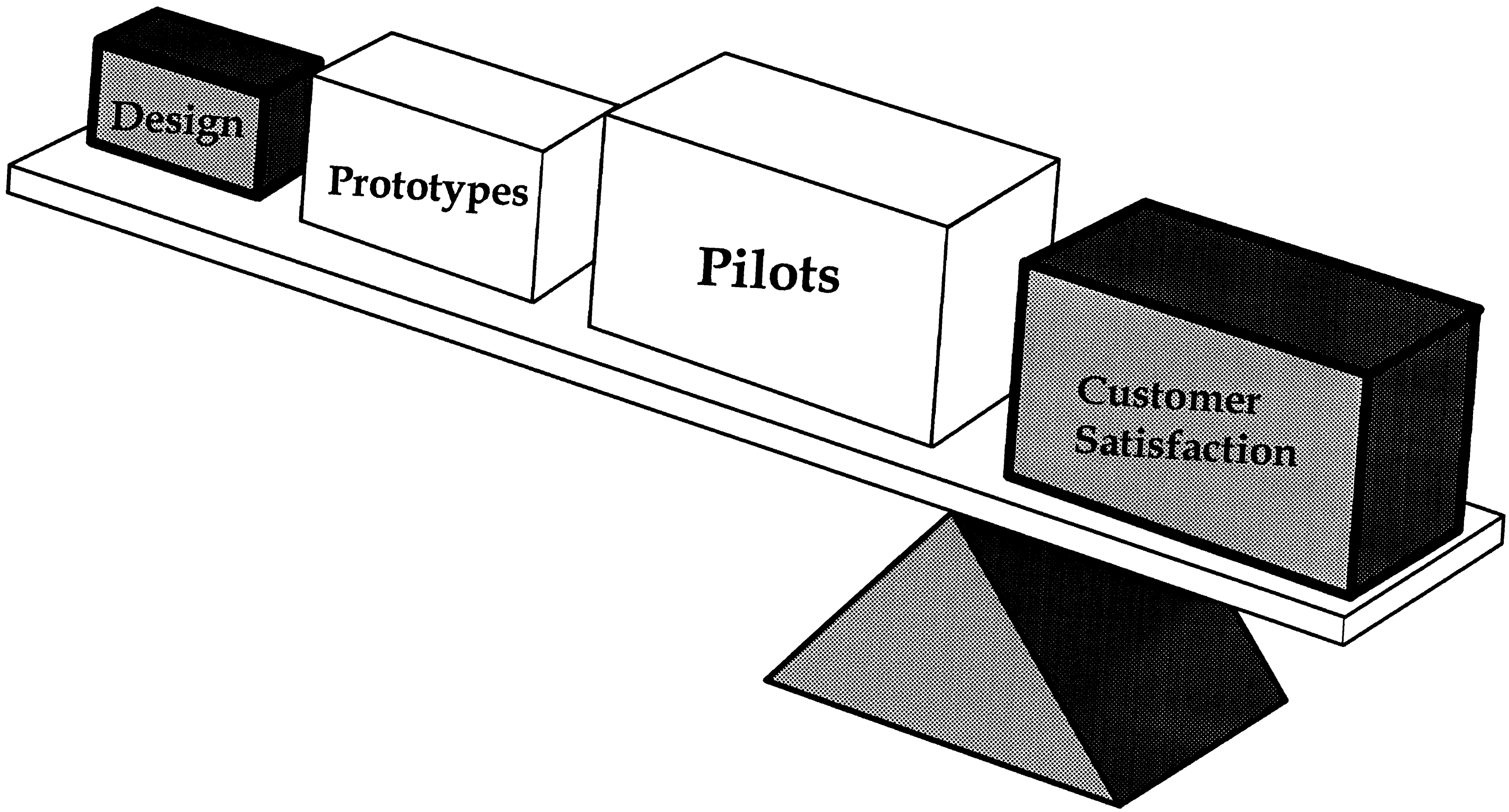
LEVERAGING CUSTOMER SATISFACTION



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EXPLORE THE DESIGN SPACE

COMPLEX SYSTEM RESPONSE FUNCTIONS DEMAND FULL EXPLORATION OF THE POSSIBLE DESIGN SPACE

DESIGNED EXPERIMENTS:

- ❖ **DETECT RELATIONSHIPS AMONG FACTORS**
- ❖ **DEVELOP MODELS**
- ❖ **PREDICT SYSTEM BEHAVIOR**
- ❖ **CONFIRM OR DENY HYPOTHESES**

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THE DOE PROCESS

- SPECIFY THE EXPERIMENTAL OUTPUT VARIABLE(S)
- DECIDE WHICH FACTORS AND LEVELS ARE TO BE USED IN THE EXPERIMENT
- DEVELOP THE MATHEMATICAL MODEL (ADAMS MODEL)
- PLAN THE EXPERIMENT
- RUN THE EXPERIMENT AND RECORD THE OBSERVATIONS (ADAMS SIMULATIONS)
- ANALYZE THE DATA
- MAKE CONCLUSIONS

EXAMPLE 1: VEHICLE FREEWAY HOP PHENOMENA

- **PROBLEM:**
  - EXCESSIVE VEHICLE PITCHING IS AN UNDESIRABLE RIDE MOTION
  - REDISTRIBUTION OF MASS NOT FEASIBLE
- **ENGINEERING TASK:**
  - CHANGE SUSPENSION PARAMETERS TO MINIMIZE PITCHING MOTION WITHOUT COMPROMISING OTHER SUSPENSION FUNCTIONS

EXAMPLE 1: VEHICLE FREEWAY HOP PHENOMENA

- OUTPUT VARIABLE:
  - BODY PEAK-TO-PEAK PITCH ACCELERATION
- FACTORS AND LEVELS:
  - FULL-FACTORIAL EXPERIMENT
  - FOUR FACTORS, TWO LEVELS FOR EACH FACTOR

FACTOR	SYMBOL	BASE VALUE	LOW VALUE	HIGH VALUE
FRONT COMPRESSION DAMPING	FC	100%	55%	146%
FRONT EXTENSION DAMPING	FE	100%	56%	143%
REAR COMPRESSION DAMPING	RC	100%	55%	145%
REAR EXTENSION DAMPING	RE	100%	59%	141%

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EXAMPLE 1: VEHICLE FREEWAY HOP PHENOMENA

- MATHEMATICAL MODEL:
  - ADAMS ONE-HALF CAR MODEL
  - 6 dof
  - SINUSOIDALLY DISPLACE THE TIRE GROUND CONTACT PATCH AT 3 Hz
- PLANNING THE EXPERIMENT:
  - FOUR-FACTOR, TWO-LEVELS, FULL-FACTORIAL REQUIRES 2^4 (OR 16) OBSERVATIONS
- RUNNING THE EXPERIMENT:
  - USE ADAMS CONTROL FILE TO RUN ALL OBSERVATIONS
  - USE REQSUB TO RECORD OUTPUT FOR EACH OBSERVATION

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EXAMPLE 1: VEHICLE FREEWAY HOP PHENOMENA

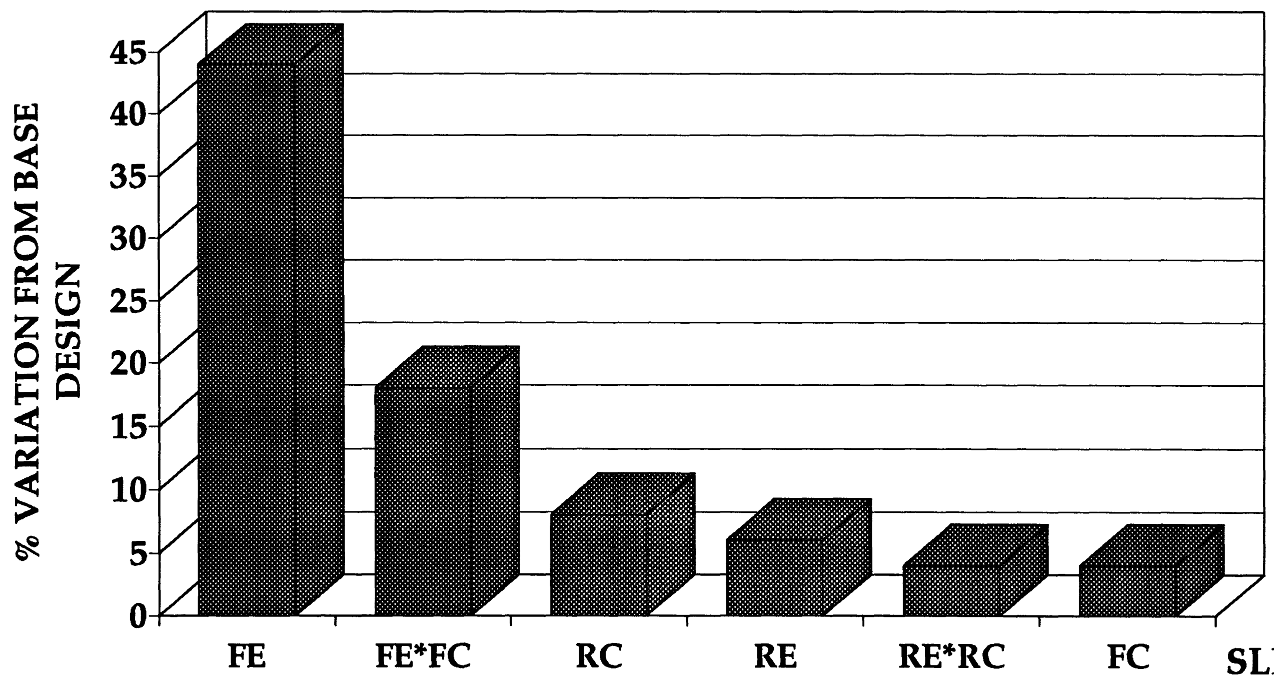
ADAMS .acf FILE:

```
deact/sfo,range=200,216
save/system,file=doe.init
reload/system,file=doe.init,out=doe01
activ/sfo,id=201
req/101,fu=user(4,199,110,3,1.,1.95,01,1)
string/1,st=doe01
sim/statics
sim/dyn,end=2.0,steps=200
reload/system,file=doe.init,out=doe02
activ/sfo,id=202
req/101,fu=user(4,199,110,3,1.,1.95,02,1)
string/1,st=doe02
sim/statics
sim/dyn,end=2.0,steps=200
.
.
.
```

EXAMPLE 1: VEHICLE FREEWAY HOP PHENOMENA

- ❖ **ANALYZING THE DATA:**
  - DETERMINE THE MAGNITUDE OF THE VARIOUS SOURCES OF VARIATION USING YATE'S ALGORITHM

SOURCES OF VARIATION



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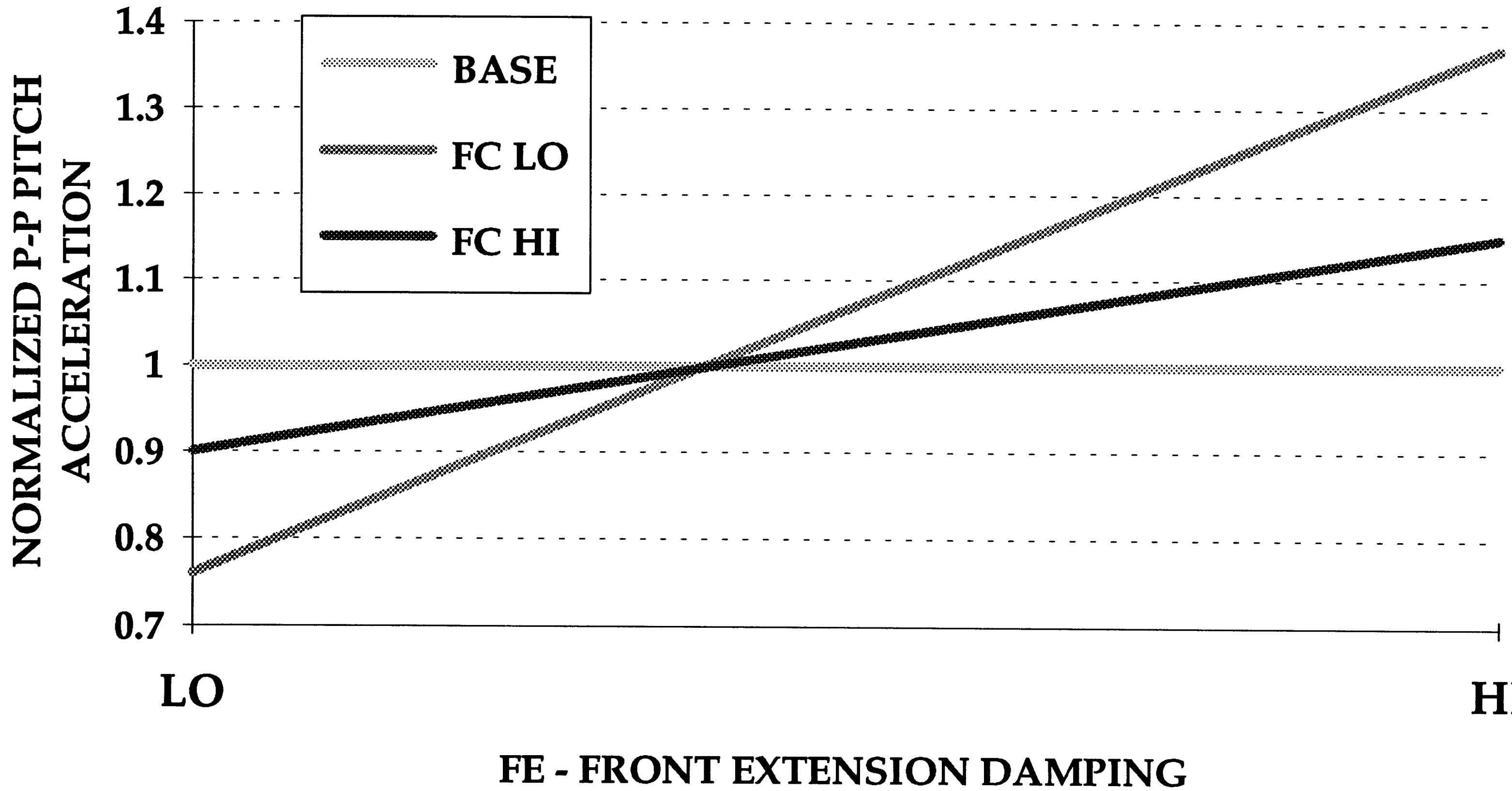
EXAMPLE 1:
VEHICLE FREEWAY HOP PHENOMENA

INTERACTION OF FACTORS . . .



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EXAMPLE 2:
SEVERE VEHICLE SUSPENSION FORCES

- PROBLEM:
  - HIGH FORCES ARE GENERATED WHEN A VEHICLE ENCOUNTERS A POTHOLE
  - SUSPENSION AND BODY PARTS MUST HAVE SUFFICIENT STRENGTH TO WITHSTAND SUCH FORCES
- ENGINEERING TASK:
  - SELECT THE PROPER COMBINATION OF COMPONENTS TO MINIMIZE THE PEAK FORCES WITHOUT COMPROMISING OTHER SUSPENSION FUNCTIONS

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EXAMPLE 2: SEVERE VEHICLE SUSPENSION FORCES

- **OUTPUT VARIABLE:**
  - PEAK TOWER FORCE DURING SEVERE POTHOLE EVENT
- **FACTORS AND LEVELS:**
  - FULL-FACTORIAL EXPERIMENT
  - FIVE FACTORS, TWO LEVELS FOR EACH FACTOR

FACTOR	SYMBOL	BASE VALUE	LOW VALUE	HIGH VALUE
JOUNCE BUMPER LENGTH	JBL	Base	- 3 mm	+ 3 mm
JOUNCE BUMPER STIFFNESS	JBS	100%	70%	130%
COMPRESSION DAMPING	CD	100%	70%	130%
TRIM HEIGHT	TRMHT	Base	- 5 mm	+ 5 mm
SPRING RATE	SPRT	100%	75%	125%

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EXAMPLE 2:
SEVERE VEHICLE SUSPENSION FORCES

- **MATHEMATICAL MODEL:**
  - ADAMS QUARTER-CAR MODEL
  - 17 dof
- **PLANNING THE EXPERIMENT:**
  - FIVE-FACTOR, TWO-LEVELS, FULL-FACTORIAL REQUIRES 2^5 (OR 32) OBSERVATIONS
- **RUNNING THE EXPERIMENT:**
  - USE ADAMS CONTROL FILE TO RUN ALL OBSERVATIONS
  - USE REQSUB TO RECORD PEAK FORCE FOR EACH OBSERVATION

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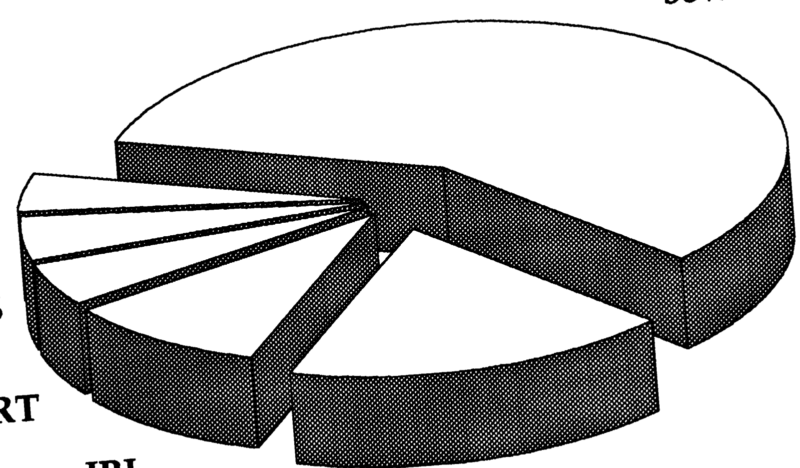
EXAMPLE 2: SEVERE VEHICLE SUSPENSION FORCES

- ❖ **ANALYZING THE DATA:**
  - PERFORM ANALYSIS OF VARIANCE (ANOVA) ON PEAK FORCE DATA FROM OBSERVATIONS

VARIATION CONTRIBUTION RATIOS:



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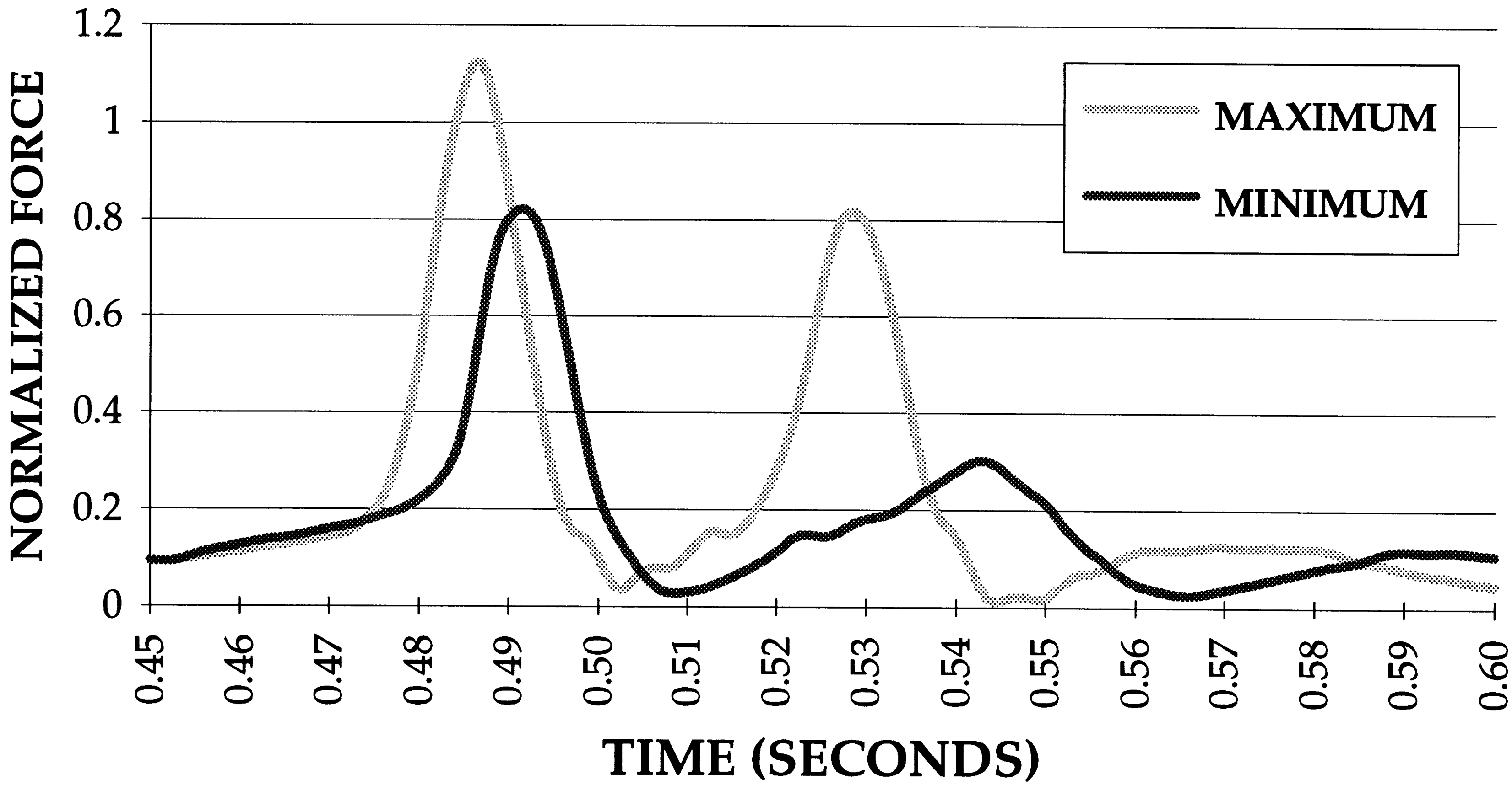
EXAMPLE 2: SEVERE VEHICLE SUSPENSION FORCES

SUSPENSION TOWER FORCE TRACES



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ADAMS & DOE vs CONVENTIONAL ANALYSIS

ADAMS & DOE	CONVENTIONAL ANALYSIS
FACTORS VARIED SIMULTANEOUSLY	OFAT OR HAPHAZARD VARIATION
INTERACTIONS BETWEEN FACTORS EXPOSED	INTERACTIONS CONFOUNDED
OPTIMIZED DESIGN THROUGH LOGICAL EXPERIMENTATION	MORE RESOURCES REQUIRED TO REACH OPTIMUM
REDUCES DEPENDENCE ON PAST EXPERIENCE	RELIES ON EXPERTISE

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RESPONSES . . .

- ONE RESPONSE CREATES STRAIGHTFORWARD SYSTEM OPTIMIZATION

BUT . . .

- DESIGN INVOLVES COMPROMISE AMONG VARIOUS OUTPUTS TO ACHIEVE CUSTOMER SATISFACTION

OBJECTIVE FUNCTIONS BALANCE MULTIPLE RESPONSES FACILITATING EVALUATION

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CONCLUSIONS

- THE COMBINATION OF ADAMS & DOE CREATES A POWERFUL TOOL FOR EFFICIENT GATHERING AND COMMUNICATION OF SYSTEM INFORMATION
- THE RESULTS OF ONE SYSTEM ARE NOT UNIVERSAL, THUS THESE TECHNIQUES SHOULD BE INTEGRATED INTO THE PRODUCT DEVELOPMENT PROCESS
- GREAT IMPACT ON CUSTOMER SATISFACTION WILL BE REALIZED WHEN THIS PROCESS IS USED TO COMPREHEND ALL FUNCTIONS OF A SYSTEM