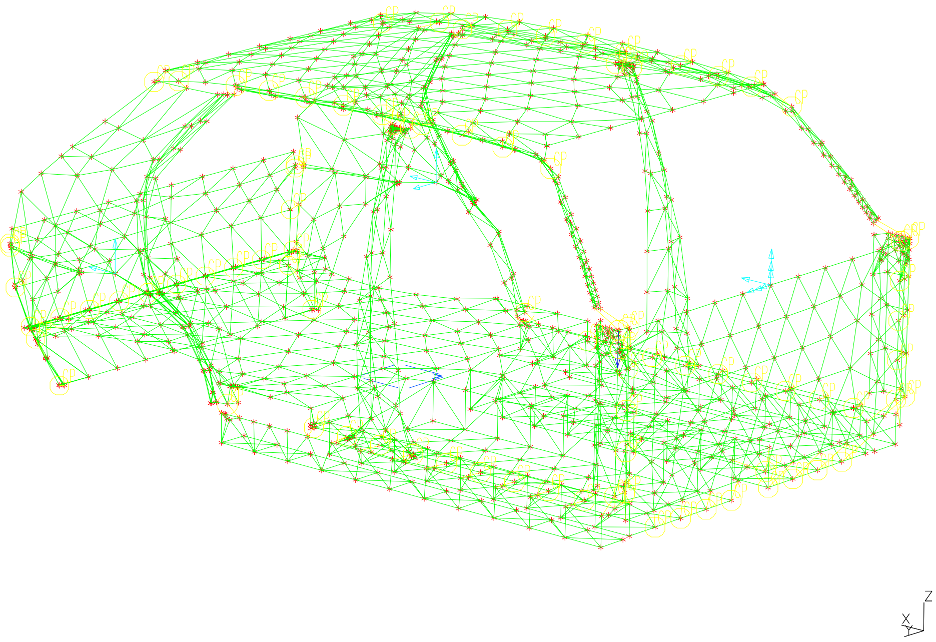
Project Report

Preliminary Vehicle Structure Design with Imprecise Information

June–September 1997



presented at VW Wolfsburg
9 September 1997

Erik K. Antonsson, Ph.D.
Michael J. Scott
Engineering Design Research Laboratory
California Institute of Technology
1200 E. California Blvd.
Pasadena, CA 91125
U.S.A.
(626) 395-3790 telephone
(626) 568-4963 FAX
`erik@design.caltech.edu`

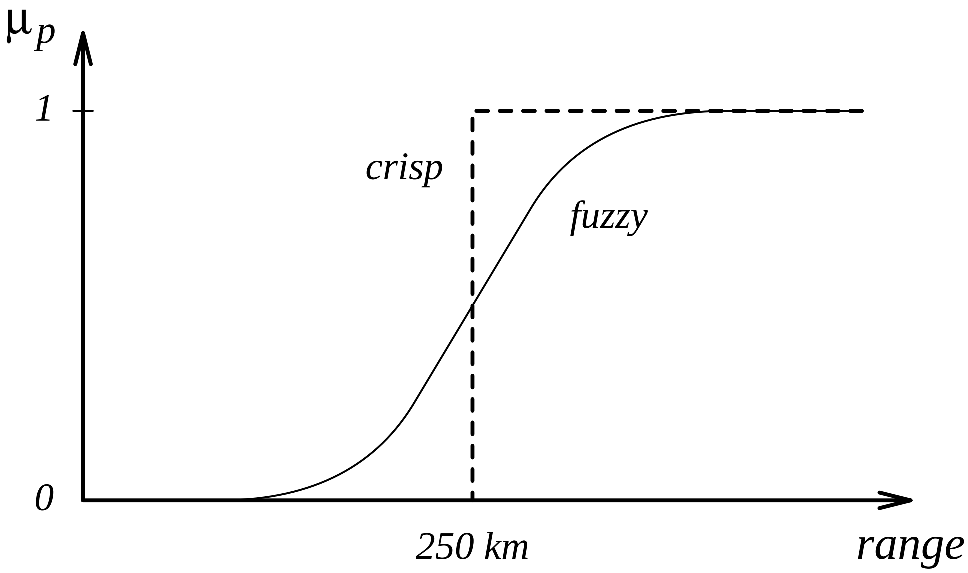


Figure 1: Example imprecise specification.

1 Imprecision

This report presents work done at the Engineering Design Research Laboratory of the California Institute of Technology to demonstrate the incorporation of imprecise information in vehicle structure design. The need to include imprecision in engineering design can be illustrated by a simple example. Figure 1 shows a specification for one performance variable (p_j). As specifications are commonly written, $p_j \geq 250$ km would be represented by the dashed line (the sharp-edged rectangular step), where $\mu_p = 1$ in the acceptable region. However, this crisp specification (or requirement) indicates that two different designs, one with $d_j = 250 - \epsilon$ and $d_j = 250 + \epsilon$ would have completely different acceptabilities, no matter how small ϵ becomes. Thus two designs, indistinguishably different in d_j (as $\epsilon \rightarrow 0$), have completely different preferences: one is completely acceptable and one is unacceptable. This situation makes no sense.

Alternatively, the solid line shown in Figure 1 indicates a smooth transition of acceptability of performances from unacceptable ($\mu_p = 0$) to acceptable ($\mu_p = 1$), and thus reflects a more realistic specification. The range over which the transition from unacceptable performance to most desired performance takes place will depend on the particular design problem, and may be more or less steep, and smooth or faceted.

The attached paper provides a more detailed introduction to this and other as-

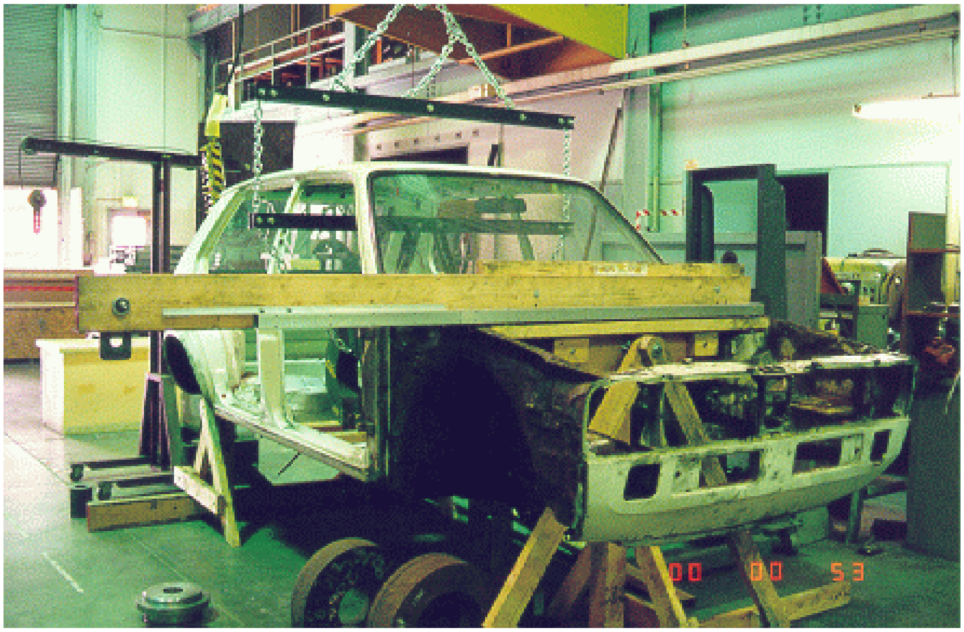


Figure 2: 1980 VW Rabbit in stiffness testing

pects of imprecision in engineering design.

2 Analysis of the 1980 4-Door Rabbit

Drawings for a recent Polo had been provided for the demonstration project, but it was decided that more information about the vehicle structure would provide a more effective demonstration of the method. To this end a 1980 VW Rabbit (see Figure 2) was acquired. The vehicle was stripped to the structural body-in-white, and torsional and bending stiffnesses were measured. The intact body-in-white was found to have a torsional stiffness of approximately 4900 N-m/degree and a bending stiffness of approximately 2500 N/mm. Tables of data from some of the load tests are shown in the Appendix. In addition, geometric data were gathered and used to create a solid model (using SDRC I-DEAS — see Figure 3). The solid model and the structural stiffness information together were used to create a finite element model (see Figure 4), which was solved using MSC Nastran.

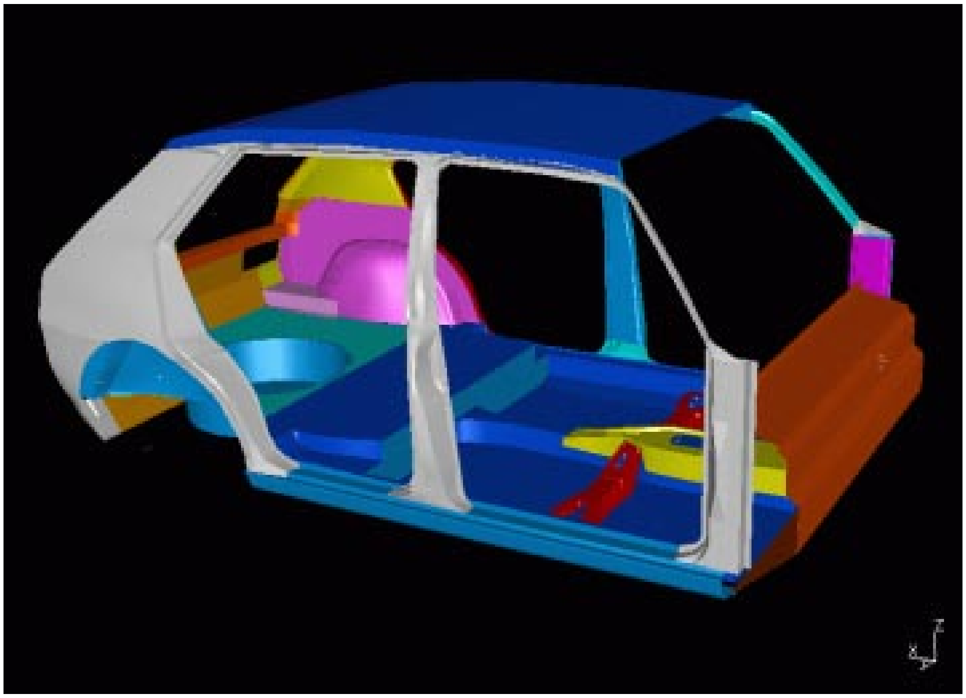


Figure 3: Geometric model of VW Rabbit in SDRC I-DEAS

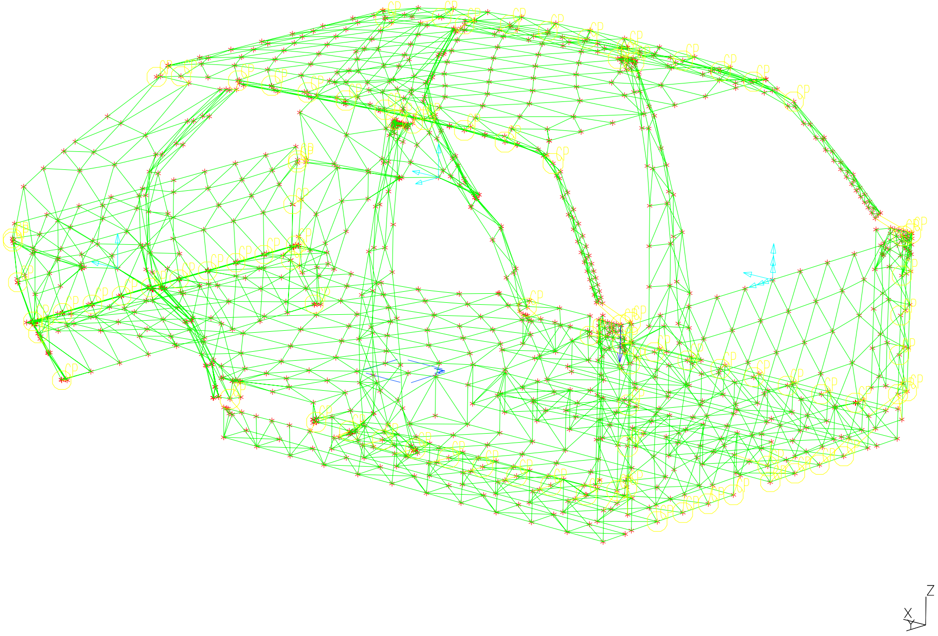


Figure 4: Finite element model of VW Rabbit

The finite element model was parameterized with five design variables:

1. A-pillar thickness (mm)
2. B-pillar thickness (mm)
3. floor pan thickness (mm)
4. floor rail thickness (mm)
5. B-pillar location (mm aft of a nominal point chosen by stylists)

and the performance was assessed with three measures:

1. Bending stiffness (N/mm)
2. Torsional stiffness (N-m/$\deg$)
3. Weight (kg)

The calculation of both stiffness for a single design point takes about a minute on a Sun Ultra1-170MHz workstation; the calculation of weight is of negligible cost. This analysis model was used as the basis for the inclusion of imprecise information.

3 Including Imprecise Information

While standard optimization methods could be used to attempt to determine the highest achievable bending stiffness, the highest achievable torsional stiffness, or the lowest achievable weight for this analysis model, such an optimization would not tell the designer which designs are the most promising. On the one hand, there is a necessary trade-off between the stiffnesses and the weight; it is impossible to maximize both simultaneously. On the other hand, there is other (imprecise) information to consider when making the decision, such as manufacturing and styling concerns.

For bending stiffness, torsional stiffness, and weight, the imprecise performance requirements are specified with a linear interpolation between two points. For bending stiffness, for example, the customer (or manager) is asked to specify the lowest stiffness that would be acceptable, and this point is given a preference of 0 (or $\mu = 0$). He also gives the stiffness that is so good that nothing much is gained by increasing it, and this point has a preference of $\mu = 1$. The two questions can be asked, “What is the lowest performance you can live with? What performance

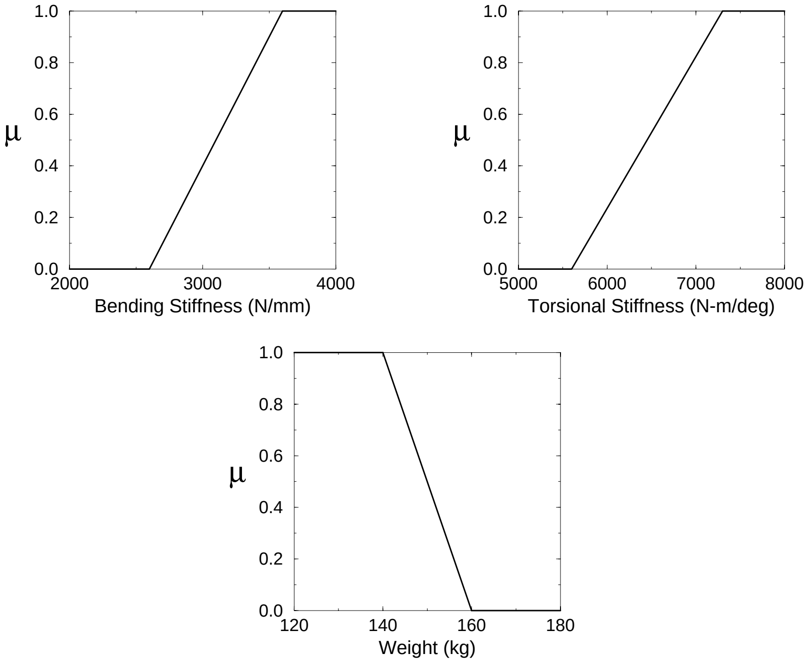


Figure 5: Imprecise performance requirements

would you most like?" Figure 5 shows the imprecise requirements on stiffness and weight.

To include requirements on manufacturing, availability, style, and other things which are not calculated in the finite element analysis, *designer preferences* are specified on the design variables. As with the imprecise performance requirements, they range from $\mu = 0$ at the unacceptable limit to $\mu = 1$ at the most preferred. A preference is defined on each of the five design variables, as shown in Figure 6:

1. The sheet steel for stamping the A-pillar is only available in certain increments, so this plot is discrete rather than continuous. The manufacturing engineer has a higher preference for thinner sheets, since they are easier to form.

2. The B-pillar thickness is continuous and more complicated than the linear performance preferences. (The method can handle any shape preference a person has the patience to specify.) This preference does *not* indicate that the B-pillar might be 1.113 or 1.114 mm thick; it means that the designer knows that the finite element model is simplified, and that a high number for B-pillar thickness means that more reinforcing features will need to be added to the B-pillar. The designer would like to keep the B-pillar as simple as possible.

3. The floor pan thickness is preferred thicker by the designer for ease of attachments and for durability.

4. The floor rail thickness preference is an example of a sourcing preference; it states that some thicknesses are more easily obtained than others.

5. The preference for B-pillar location comes from the stylists, who are looking for a particular "look" for this year's model. It has been specified differently from the other design preferences, using α-*cuts*, so that the stylists have given a range of perfectly acceptable values, a range of barely acceptable values, and a range of values that fall in the middle. This method for specifying preferences can have computational advantages.

In addition to these preferences, each attribute is assigned a weight indicating its relative importance, and the way in which attributes trade-off against each other must also be specified. In this test example, it was determined that bending and torsional stiffness traded-off in a non-compensating manner — the lowest performer is maximized. Together they traded-off with weight in a compensating manner, so that high performance on stiffness could partly make up for low performance on weight, and vice versa. The designer preferences all traded-off in a compensating manner as well.

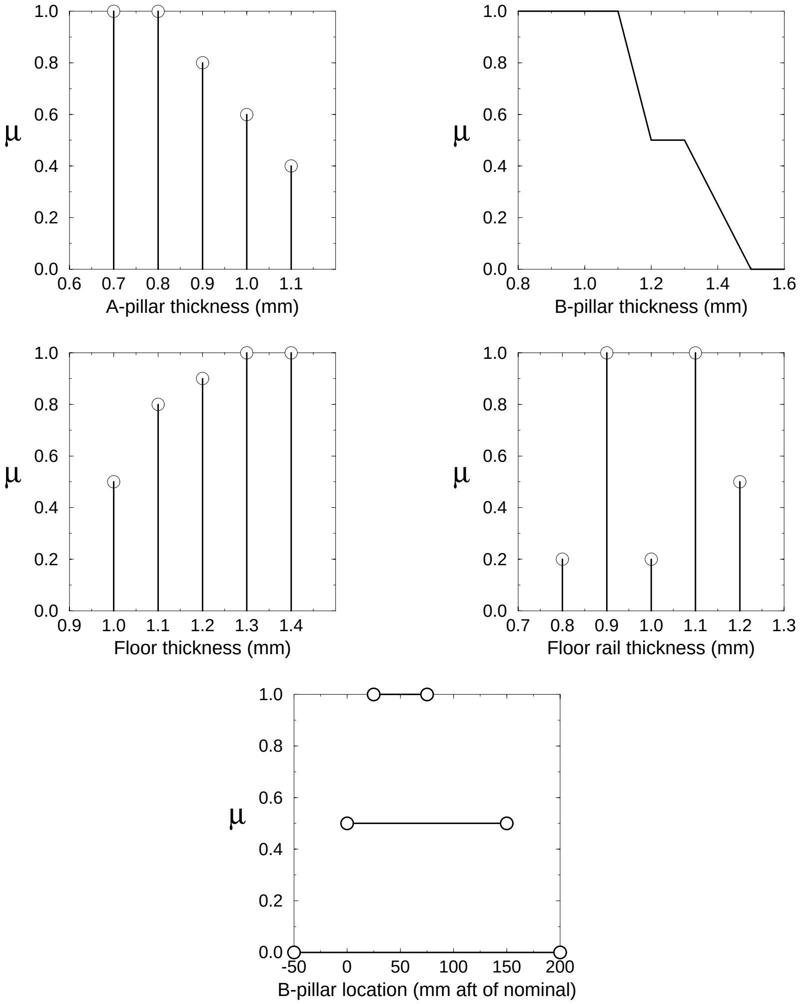


Figure 6: Designer preferences

4 Results

The design problem, including all imprecise information, was solved in two different ways. First, in order to demonstrate the method, the finite element analysis was run 3125 times to provide a coarse but complete check of the entire design space. Naturally, this exhaustive evaluation of points in the design space would not be performed on a real design problem. It was performed here for comparison purposes because it was computationally tractable. An approach that utilized Design of Experiments (DOE) reached substantially similar conclusions in only 21 runs (or approximately 20 minutes).

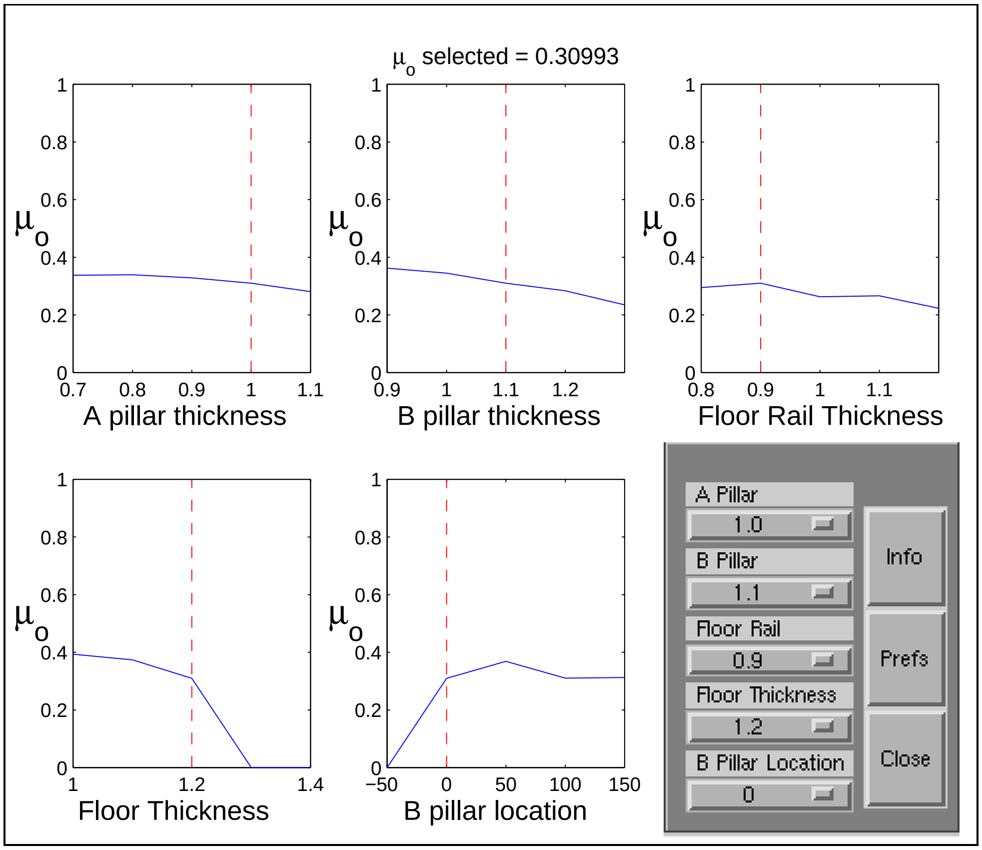
Once the imprecision calculations are performed, the results are presented in the form of a total combined preference μ_o, which varies with each of the five design variables. Although it is impossible to display all five dimensions varying at once, a tool was written that uses the commercial package Matlab to display results interactively. Using the tool, the designer can see the change in preference that would occur by varying each design variable independently from a chosen beginning point. The designer can of course change the beginning point. Results can be seen on five separate plots in two dimensions (see Figures 7 and 8) or three dimensions (see Figure 9).

5 Conclusions

The incorporation of imprecision in engineering design, particularly engineering design, is an important problem. A project that demonstrates a method for including imprecise information in design has been presented here. The method allows for the imprecise specification of requirements, and for the inclusion of information from manufacturing engineers, design engineers, stylists, managers, and others in the engineering analysis. In addition, the method addresses the problem of how to pick a “best” design when there are many competing attributes by which to evalute the design. A more detailed introduction to some of the underlying theory is presented in the attached paper.

Acknowledgements

The authors would like express their appreciation to Zee Khoo and Juan Nuño for their many hours of work load-testing the Rabbit and building the solid model, and to Mike Gerfen, manager of Caltech’s Central Engineering Shop, for his generous help in procuring space and equipment.



A Pillar 1.0

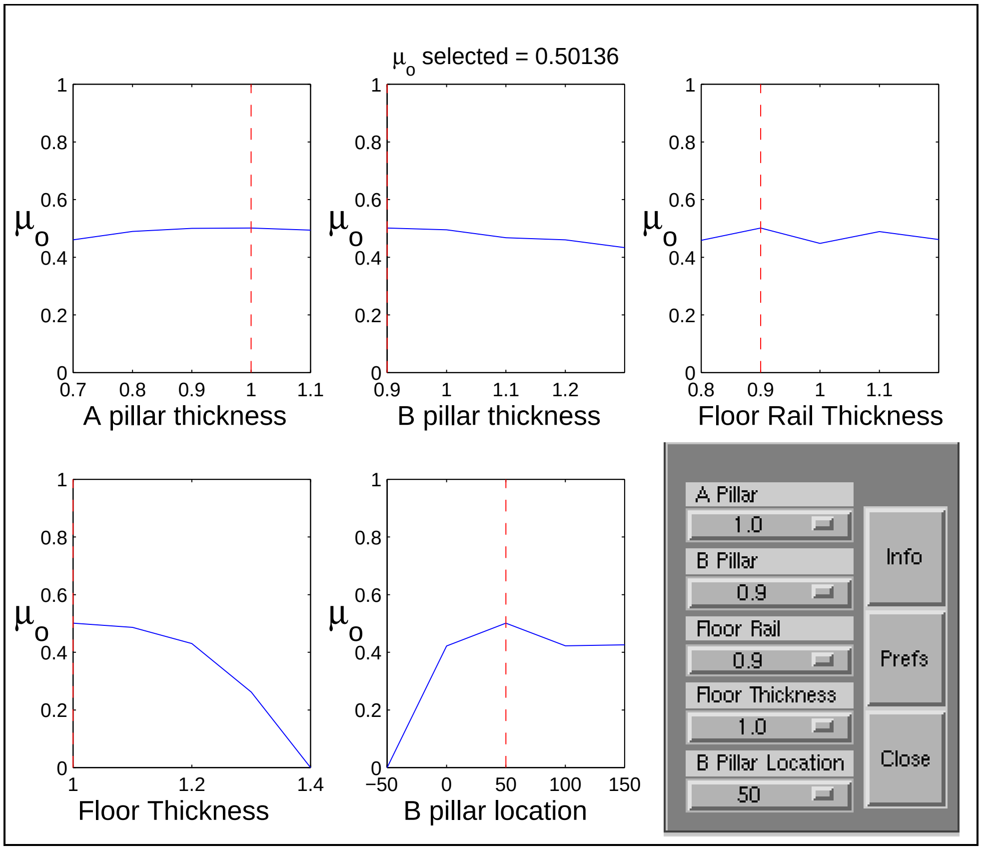
B Pillar 1.1

Floor Rail 0.9

Floor Thickness 1.2

B Pillar Location 0

Figure 7: Graphical User Interface for Preference Display



μ_o selected = 0.50136

A Pillar: 1.0

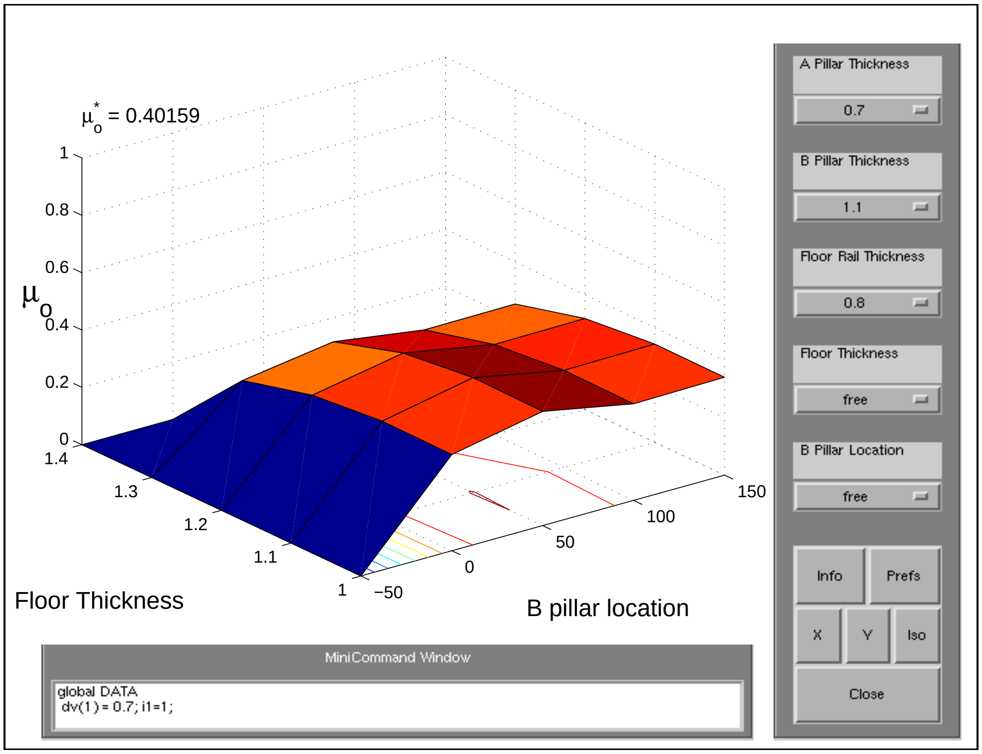
B Pillar: 0.9

Floor Rail: 0.9

Floor Thickness: 1.0

B Pillar Location: 50

Figure 8: Graphical User Interface for Preference Display



A Pillar Thickness
0.7

B Pillar Thickness
1.1

Floor Rail Thickness
0.8

Floor Thickness
free

B Pillar Location
free

```
global DATA
 dv(1) = 0.7; i1=1;
```

Figure 9: 3-D Graphical User Interface for Preference Display

This material is based upon work supported, in part, by the National Science Foundation under NSF Grant Number DMI-9523232. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the sponsors.

Appendix

RABBIT CHASSIS PERFORMANCE TEST

TORSIONAL STIFFNESS TEST (WINDSHIELD AND REAR HATCH INTACT)

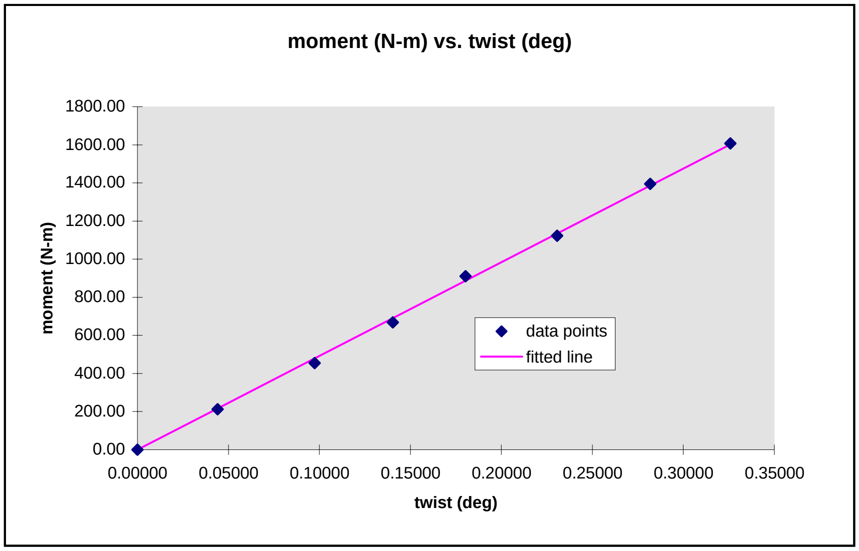
TEST DATE : July 11
indicator radius : 1.42 m (56 in)
moment arm : 1.65 m (65 in)

weight (lbf)	deflection (0.001 in)
0	0
29	43
62	95
91	137
124	176
153	225
190	275
219	318

load (N)	moment (N-m)	deflection (mm)	twist (deg)
0.00	0.00	0.00	0.00000
128.99	212.84	1.09	0.04407
275.78	455.03	2.41	0.09736
404.77	667.87	3.48	0.14041
551.55	910.06	4.47	0.18038
680.54	1122.90	5.72	0.23060
845.12	1394.45	6.99	0.28184
974.11	1607.28	8.08	0.32591

y = mx + c
slope : 4960.74 N-m/deg
y - intercept : -10.16 N-m

y = mx + 0
slope : 4917.04 N-m/deg



RABBIT CHASSIS PERFORMANCE TEST

BENDING STIFFNESS TEST (REAR HATCH AND WINDSHIELD INTACT)

TEST DATE : July 16

deflection (in)	load (lbf)
0	0
0.004	64
0.007	124
0.013	188
0.031	450
0.036	514
0.046	638

deflection (mm)	load (N)
0.00000	0.00
0.10160	284.67
0.17780	551.55
0.33020	836.22
0.78740	2001.60
0.91440	2286.27
1.16840	2837.82

y = mx + c
slope : 2424.16 N/mm
y - intercept : 51.79 N

y = mx + 0
slope : 2484.80 N/mm