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16. Abstract

A round-robin center of gravity height measurement study was conducted to assess current practice in the measurement of the vertical position of the center of gravity (c.g.) of light truck-type vehicles. The study was performed by UMTRI for the Motor Vehicle Manufacturers Association. Chrysler, Ford, General Motors, and the National Highway Traffic Safety Administration participated. The primary objectives were (i) to determine to what extent the differing experimental procedures currently used by the participating laboratories result in significant differences in the measured vertical position of the center of mass of light truck-type vehicles, and (ii) to gain insight into the physical causes of such differences. The results of the program showed (i) there were significant differences between the c.g. height measurement results obtained by different laboratories, (ii) repeatability of results within the individual laboratories was generally good, and (iii) close examination of the individual procedures tended to explain the differences in results between laboratories, thus providing the expectation that variability in this regard could be significantly reduced.

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Center of Gravity Height: A Round-Robin Measurement Program

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The University of Michigan
Transportation Research Institute

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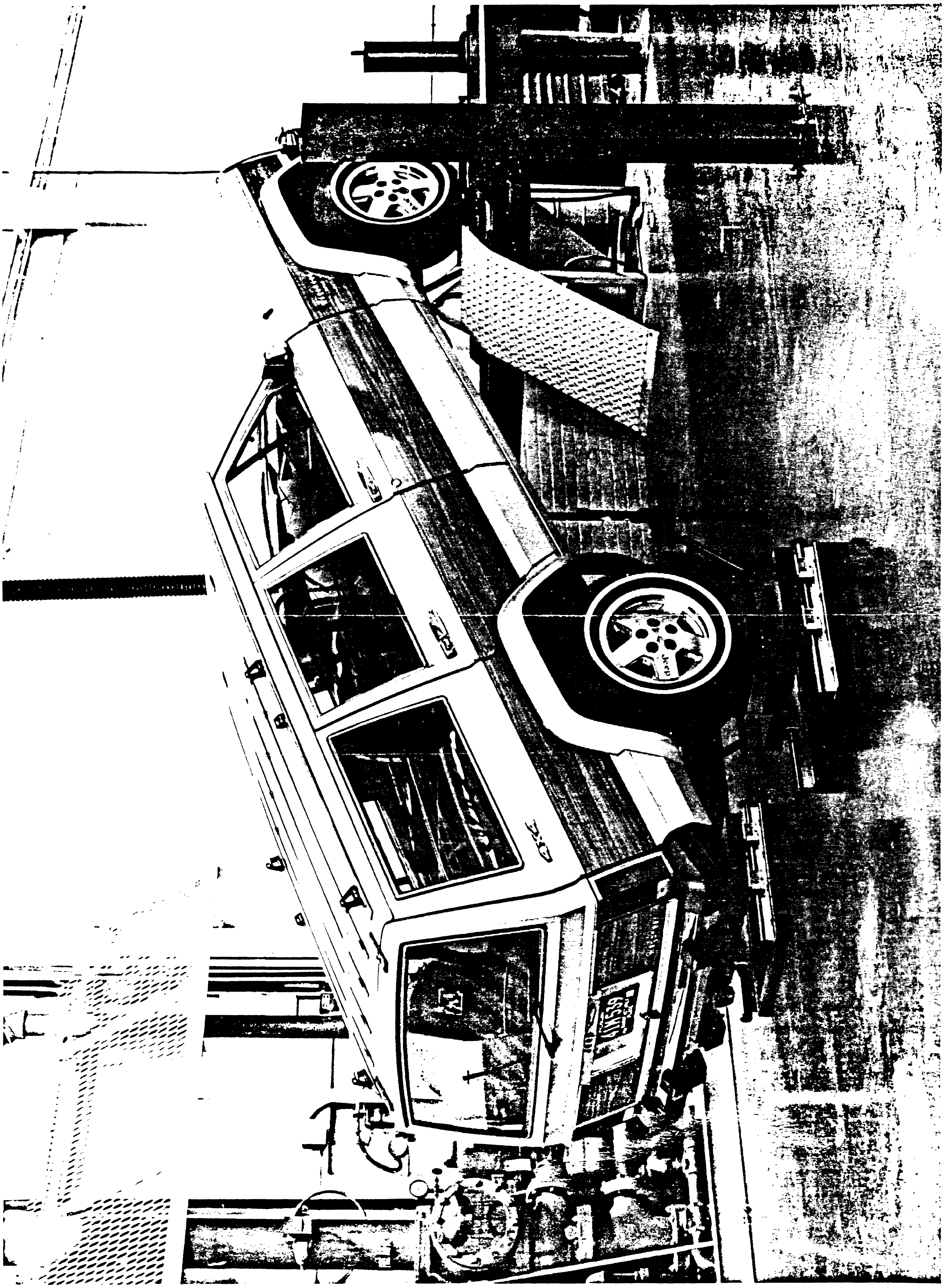

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Summary

The Round-Robin Center of Gravity Height Measurement Study was conducted to assess current practice in the measurement of the vertical position of the center of gravity (c.g.) of light truck-type vehicles. The study was performed by UMTRI for the Motor Vehicle Manufacturers Association (MVMA). The primary objectives of this study were (i) to determine to what extent the differing experimental procedures *currently* (i.e., prior to the study) used by the participating laboratories result in significant differences in the measured vertical position of the center of mass of light truck-type vehicles, and (ii) to gain insight into the physical causes of such differences. The results of the program showed (i) there were significant differences between the c.g. height measurement results obtained by different laboratories, (ii) repeatability of results within the individual laboratories was generally good, and (iii) close examination of the individual procedures tended to explain the differences in results between laboratories, thus providing the expectation that variability in this regard could be significantly reduced.

The laboratories participating in the study were those of Chrysler Corporation (Chrysler), Ford Motor Company (Ford), General Motors Corporation (GM), and the National Highway Traffic Safety Administration of the US Department of Transportation (NHTSA). Certain reference measurements were also made at UMTRI's laboratory, although UMTRI did not measure c.g. heights.

Three vehicles plus a reference, or calibration, "buck" were used as measurement subjects. The vehicles were a Chrysler mini-van, a full-sized Ford pickup truck, and a GM sport/utility vehicle. GM also provided the reference buck. This buck was seen as a reference sample of known quantity by which the absolute accuracy of the test procedures could be judged.

Prior to the actual measurement program, UMTRI personnel visited each of the four participating laboratories for the purpose of (i) gaining an understanding of the measurement procedures, and (ii) obtaining reference data to provide a statistical basis for planning the measurement program.

The measurement program was structured such that each of the participating laboratories measured the c.g. height of the test vehicles and reported their results to UMTRI. The laboratories measured each of the real vehicles four times, and the buck, three times. Repeat measurements were interspersed according to a specific order determined by UMTRI. The vehicles were delivered as a group to each laboratory, and each laboratory conducted all of its measurements in one, congruent time period. At the start of the program and after the measurement program at each laboratory, reference

measurements of wheel loads and ride height were made at the UMTRI laboratory. These were intended to detect any changes in the relevant properties of the vehicles over the three-and-one-half-month period of the measurement program.

The reference measurements made by UMTRI indicated that the properties of the vehicles were very stable over the period of the program. Repeatability within the individual laboratories was very good. When expressed as the coefficient of variation (standard deviation of the c.g. height divided by the average, and expressed as a percentage), the results were: NHTSA, 0.24%; GM, 0.27%; Ford, 0.57%; and Chrysler, 3.22%. The corresponding standard deviations ranged from 0.062 inch to 0.786 inch. Due to the relatively good repeatability of the individual laboratories, all of the differences between the laboratories are highly significant, with only a few exceptions. As would be expected, the individual laboratories generally found significant differences between the average c.g. heights of the four vehicles. The primary exception to this involved the Chrysler measurements. Because these measurements were somewhat more variable, the differences between vehicles as measured by Chrysler, and the differences between Chrysler measurements and those of the other laboratories, were generally not statistically significant, even though the magnitudes of these differences were sometimes relatively large.

Analysis of the c.g. height measurements showed that there were significant differences in the c.g. height as measured at the four laboratories. In the worst case, the GM Sport/Utility vehicle, the average c.g. height ranged from 24.3 inches (Chrysler) to 27.9 inches (Ford). Average measured c.g. heights are summarized in the table below for each laboratory and vehicle.

Average C.G. Height By Laboratory and Vehicle, inches above ground					
	Laboratory				
Vehicle	NHTSA	GM	Ford	Chrysler	Average
Ford Pickup	27.22	26.25	27.70	26.18	26.84
GM Sport/Utility	26.37	25.54	27.86	24.30	26.02
Chrysler Mini-van	25.28	24.78	25.91	24.38	25.09
GM Buck	23.88	24.11	25.04	22.93	23.99
Average	25.81	25.24	26.73	24.55	25.58

Neglecting to account properly for small, compliant motions of the vehicle and the facility is a primary source of error in determining the vertical position of the center of gravity of vehicles. Very small horizontal motions of the c.g. which occur during the measurement process may lead to errors in the predicted vertical position unless the proper compensation is included in the data reduction process. Generally, the error in vertical position is several times the magnitude of the neglected horizontal motion. (For one laboratory's procedure, the resulting error was on the order of two hundred times the magnitude of horizontal motions.) With one exception, the differences in the results obtained by the four participating laboratories appeared to be explained by this mechanism and the extent to which the individual procedures restricted and/or accounted for horizontal motions.

In general, this study highlights the fact that c.g. height determination is not at all a simple matter. Subtle error sources abound, and different measurement procedures, each undertaken with great care, can produce significantly different results. Nevertheless, the results of the several participating laboratories showed better agreement than might have been expected. Perhaps more importantly, the observed relationship between the results of the several laboratories suggests that, with appropriate improvements put in place, the participating laboratories would be expected to obtain results quite similar to each other.

TABLE OF CONTENTS

1. Introduction

The Round-Robin C.G. Height Measurement Study was conducted to assess current practice in the measurement of the vertical position of the center of gravity (c.g.) of light truck-type vehicles. This study was performed by UMTRI for the Motor Vehicle Manufacturers Association (MVMA).

The primary objectives of this study were (i) to determine to what extent the differing experimental procedures *currently* (i.e., prior to the study) used by the participating laboratories result in significant differences in the measured vertical position of the center of mass of light truck-type vehicles, and (ii) to gain insight into the physical causes of such differences. Concurrently, the study also examined the variability of measurement procedures within the individual laboratories, and tried to make some reasonable estimate of the absolute accuracy being obtained in making these measurements.

The laboratories participating in the study were those of Chrysler Corporation (Chrysler), Ford Motor Company (Ford), General Motors Corporation (GM), and the National Highway Traffic Safety Administration of the US Department of Transportation (NHTSA). Certain reference measurements were also made at UMTRI's laboratory, although UMTRI did not measure c.g. heights.

Three vehicles plus a reference, or calibration, "buck" were used as measurement subjects. The vehicles were a Chrysler mini-van, a full-sized Ford pickup truck, and a GM sport/utility vehicle. GM also provided the reference buck which is shown in Figure 1. The frame of the buck was a simple weldment made up of rectangular steel tube and a large ballast weight. Two solid axles with wheels and tires are bolt rigidly (no suspension) to the underside of the frame and additional solid steel ballast weights are bolted to the topside of the frame. The c.g. position of the buck had been determined, by calculation, with what was believed to be a high degree of precision. Thus, the buck was seen as a reference sample of known quantity by which the absolute accuracy of the test procedures could be judged.

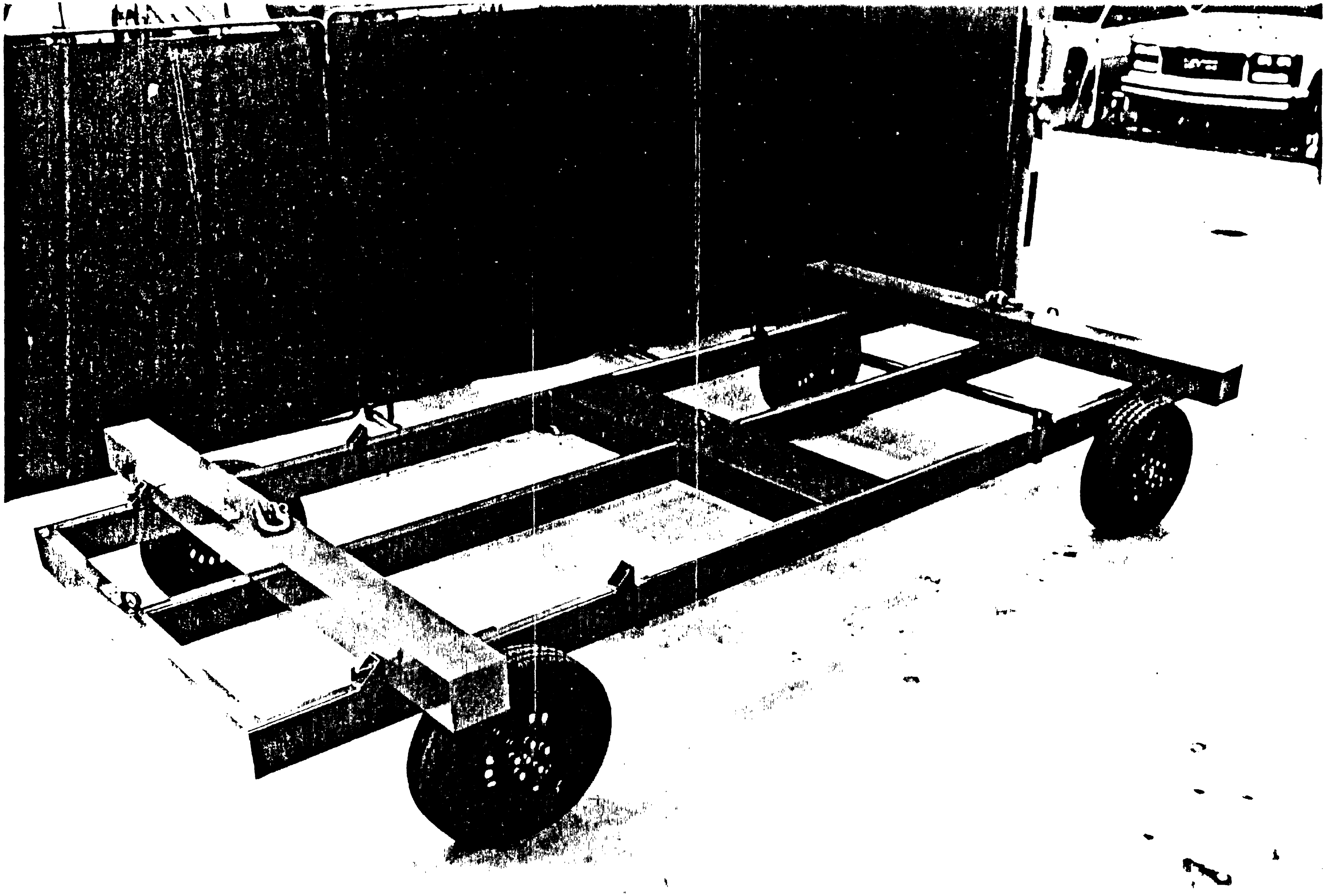

Figure 1. A photograph of the reference buck provided by General Motors.

2. Methodology

Test Site Visits

Prior to the start of the actual measurement program, UMTRI personnel visited each of the four participating laboratories for the purpose of (i) gaining an understanding of the measurement procedures, and (ii) obtaining reference data to provide a statistical basis for planning the measurement program.

During the site visits, UMTRI personnel were able to observe the measurement procedures used by each of the laboratories. Laboratory personnel were questioned regarding many details of equipment and instrumentation, procedures, and data reduction. The information and insights gained in this process served two purposes. First, the precautionary purpose of ensuring that the test plan to be developed would not be incompatible with any specific detail of the laboratories' test procedures. Second, it was hoped that the insights gained would provided a basis for a physical explanation of the variability in c.g. height measurements among the laboratories. Section 4. will describe how this second purpose was largely fulfilled.

During the site visits, each of the laboratories was asked to supply data from previous measurement programs which would indicate the repeatability of its procedure. Each laboratory had previously conducted repeated tests of at least one vehicle, and was able to provide the requested data. UMTRI used these data to formulate the statistical design of the experiment.

The Measurement Program

The measurement program was conceived to have a general structure in which the participating laboratories would measure the c.g. height of the test vehicles and report their results to UMTRI. Each laboratory would be requested to measure each vehicle a specified number of times in order to yield statistically significant results. For economy, all test vehicles would be delivered as a group to a single laboratory, and the laboratory would perform all of its measurements. Then the vehicles would be moved to another laboratory. At the start of the program and after the measurement program at each laboratory, the vehicles would be transported to UMTRI for a series of reference measurements intended to detect any changes in the relevant properties of the vehicles over the period of the study.

It was the intent of the program to determine the variability and accuracy of measurement procedures as *currently* practiced. Therefore, it was UMTRI's intent to provide a minimum of instructions to the participating laboratories, other than for them to use their "normal procedures." On the other hand, it was necessary that each of the several laboratories measure "the same" vehicles. Thus, it was determined that UMTRI would provide instructions as to the proper "settings" for all "user-variable" properties of the vehicle.

The instructions to the participants identified the proper test configurations of the three real vehicles as follows:

i) All fluid levels full.
ii) Tire pressures adjusted to within ±0.5 psi of the manufacturer's recommendation for the lightly loaded condition, as per the door frame placard.
iii) Adjustable seating positioned as follows.
   a) All seats with fore/aft adjustment shall be positioned full aft.
   b) All seats with vertical adjustment shall be positioned full down.
   c) All seats with back rake angle adjustment shall be positioned with the back in the most forward, standard use condition.
   d) All seats which may be folded or tilted for 'storage' or for enhancing cargo space shall be configured for normal passenger seating use, except in cases where seats are automatically retracted or re-configured when not in use.
iv) No driver, passenger, or any other additional loads beyond curb condition shall be installed in the vehicle.

The GM buck was to be measured in the configuration it was in when delivered, with the additional stipulation that tire pressures were to be set to 34.8 ±0.5 psi.

Since the measurements in this program were intended to characterize the individual sample vehicles, and were not intended to be representative of the vehicle model, participants were instructed to treat each vehicle as if it were an unknown quantity; that is, as if they had no knowledge of "design intent," etc. Otherwise, participants were asked to observe any vehicle configuration or pretest procedures which were normal to their methods, as long as they did not conflict with those prescribed above.

The experiment was designed as a two-way analysis of variance, with the vehicles and laboratories as the independent variables, each having four levels. The only parameter to specify is the number of repeat observations to be made on each vehicle. The analysis of variance test of significance basically compares the variability across laboratories and across vehicles with the inherent repeatability of the experiment. The power of the test is increased with more replications. If the repeatability of the test can be estimated, then the number of replications can be specified such that a difference of a given magnitude, say between vehicles or between laboratories, will be statistically significant at a specified level. The information available on the repeatability of c.g. height measurements was used to specify the number of replications.

The information on repeatability had been gathered prior to this project by the participating laboratories for their own purposes. Typically, these data were collected for the purpose of characterizing the accuracy of the instrumentation and test facility. Consequently, the replications were often made without removing the vehicle from the test fixture. Also, some laboratories follow a practice of censoring outliers, so that only the most consistent observations are retained. This practice overstates the accuracy of the procedure. In order to facilitate comparisons between laboratories for the purposes of this project, it was necessary that a replication include all of the various adjustments and procedures that are associated with bringing a previously unmeasured vehicle into the laboratory. There was not a lot of information on the repeatability of the measurement when the vehicle was removed from the test facility for each replication.

The best source seemed to be a 1988 SAE paper by Garrott, Monk, and Chrstos[1] that reports a standard deviation of 0.17 inches for 6 measurements on a 1986 Buick Electra. The vehicle is reported to have been removed to a storage area for 1-2 weeks between each measurement. Other tabulated data provided by NHTSA showed the standard deviation ranging from 0.042 to 0.83 inches. The standard deviation of the tests observed during the site visit was 0.98 inches.

GM provided an internal file memo from 1971 showing a standard deviation of 0.16 inches based on 6 replications with a Firebird. Again, these tests were specifically intended to address the repeatability of the entire measurement procedure. The memo stated that the vehicle was removed for each test. A later internal memo (1977) describing the GM buck and the calibration of the tilt table reported the systematic error as 0.1 inch or less with a repeatability of 0.05 inch. No mention was made of removing the buck between observations. Although some of the data showed much better repeatability, the standard deviation was assumed to be 0.17 inches for purposes of the sample size calculation in order to be on the safe side.

The nominal design specification chosen for this experiment was for a 0.5 inch difference (between vehicles or laboratories) to be statistically significant at the 95% level. With the assumed standard deviation, this proved to be a rather easy design specification to meet. With 3 replications, a difference of 0.4 inches would be significant at the 95% level, and with 4 replications, a difference of 0.3 inches would be significant. Given the expense of assembling and transporting four vehicles to each of four laboratories, four replications were recommended for each of the actual vehicles. On the expectation that the buck would be less variable, only three replications were recommended for the buck.

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[1]W. Riley Garrott, Michael W. Monk, and Jeffrey P. Chrstos. *Vehicle Inertial Parameters--Measured Values and Approximations.* Warrendale, PA: Society of Automotive Engineers. Paper No. 881767. October 1988.

An equally important assumption for the statistical tests of significance is that the observations be independent. From a practical point of view, this is largely an effort to eliminate systematic errors due to unknown or uncontrolled sources. Many such errors tend to be associated with time during the course of the experiment. A calibration or transducer shifts part way through the experiment. Some part of the apparatus is bent. Amplifiers heat up over the course of the experiment. The shift may end and different personnel finish the tests. While most laboratories take precautions to eliminate or control the examples of systematic error given, the point is that one is inviting systematic error to creep in if, for example, the three replications of the buck are always done first and the pickup truck is always tested last. Specifying a random sequence for the tests is a standard experimental design technique to convert systematic errors to random errors, thus satisfying the assumption of independence.

Based on these considerations, the following test sequence was specified. Each of the replications was treated as blocks to be conducted sequentially. This means that the first replication for each vehicle should be completed before going on to the second replication of any vehicle. Within each replication, the order in which each of the four vehicles was to be measured was randomized. The resulting test sequence is that shown in Figure 2. Each laboratory was required to follow the same test sequence exactly.

When performing repeat measurements on a given vehicle, the participants were requested to repeat as much of the entire measurement process as was reasonably practical. At a minimum, they were to:

i) Remove the vehicle from the measurement facility.
ii) Remove any and all temporary reference marks which they had applied to the vehicle and/or the facility.
iii) Move, remove, or otherwise "undo" any adjustable elements of the facility whose positioning was established by the particulars of the test vehicle.
iv) Redo any and all preliminary measurements of the vehicle including weights and geometric measurements.
v) Recalculate any and all facility set-up parameters.
vi) Repeat the primary measurement process.
vii) Complete an additional data reporting form.

The participating laboratories were requested to determine the total mass and the longitudinal and vertical position of the center of gravity of the total mass of the three vehicles and the GM calibration buck. They were also requested to report several reference geometric measurements of the vehicle. A sample of the Test Data Reporting Form appears in Figure 3.

Test Sequence Schedule for the MVMA Round-Robin Center of Gravity Measurement Program

Test Number	Test Vehicle	Replication Number
1	Ford Pickup	1
2	GM Buck	1
3	GM Sport/Utility	1
4	Chrysler Mini-van	1
5	GM Buck	2
6	GM Sport/Utility	2
7	Chrysler Mini-van	2
8	Ford Pickup	2
9	Chrysler Mini-van	3
10	GM Sport/Utility	3
11	Ford Pickup	3
12	GM Buck	3
13	Ford Pickup	4
14	GM Sport/Utility	4
15	Chrysler Mini-van	4

Figure 2. The testing sequence schedule followed by each of the participating laboratories.

Test Data Reporting Form
for the MVMA
Round-Robin CG Measurement Program

Test No.___________ Date:______________________
Time:______________________
Test Vehicle:__________ Trial No.:_________________
Laboratory : ___________ Contact Person:
Vehicle wheel base:_________________❑inches or ❑mm

Wheel loads:
Left front:_____________________❑pounds or ❑kilograms
Right front:____________________❑pounds or ❑kilograms
Left rear:______________________❑pounds or ❑kilograms
Right rear:_____________________❑pounds or ❑kilograms

Spindle height above ground:
Left front:________________________❑inches or ❑mm
Right front:_______________________❑inches or ❑mm
Left rear:_________________________❑inches or ❑mm
Right rear:________________________❑inches or ❑mm

Sprung mass reference* heights above ground:
Left front:________________________❑inches or ❑mm
Right front:_______________________❑inches or ❑mm
Left rear:_________________________❑inches or ❑mm
Right rear:________________________❑inches or ❑mm

Center of Gravity Position:
Forward of rear axle center line:______❑inches or ❑mm
Above ground:_____________________❑inches or ❑mm

Figure 3. The test data reporting form.

Figure 3 shows that the measures requested in addition to c.g. height were: wheel base, the individual wheel loads, the spindle heights, the height of four sprung mass reference points, and the for/aft position of the c.g.

UMTRI provided the four sprung mass reference points. On the real vehicles, a paper sticker with a cross hatch marker was located on the fender above each wheel. On the buck, a similar marker was placed on the side of the frame near each wheel. In each case, the vertical position of these reference points was chosen arbitrarily.

The purpose of requesting these measures from the individual laboratories was to provide physical measures which might explain differences in c.g. height results. Most important among the measures was the sprung mass reference height. It was presupposed that some variations in the results obtained by different laboratories might well derive from different vehicle ride heights. The straightforward measurement of the sprung mass reference height was seen as a means of monitoring ride height condition during testing. Spindle height measures were requested for essentially the same reason. All of the other measures were known (from the site visits) to be measures taken routinely by all laboratories. These were requested for completeness and in the knowledge that they did not represent an additional burden.

As indicated previously, UMTRI also made measurements of the test vehicles. UMTRI did *not* measure c.g. position, but did perform all of the reference measures. UMTRI made these measurements at the outset of the measurement program, and then following the measurements of each laboratory. The purpose of this was, of course, to monitor the condition of the test vehicles throughout the program. It was a concern that some property of the vehicle (ride height, for example) might "truly" change over the period of the program. If this were the case, it would be necessary to track such changes in order to properly interpret the data.

UMTRI took what could well be called "excessive care" in conducting these reference measures in order to insure a high degree of repeatability over an extended period of time. Prior to each measurement, UMTRI configured the vehicles according to the same rules provided to the participants, with the additional stipulation that the vehicles were kept indoors and at room temperature for a minimum of twelve hours immediately prior to measurement. Lacking a precision flat surface, or bed plate, contact patch patterns for each vehicle were marked out on the shop floor, and the measurements were always made with the vehicle in the indicated position (± about .5 inch at each wheel). Four Toledo balance scales, one per wheel (simultaneously), were used for measuring wheel weights. The same scale was always used at each wheel positions, and the scale positions on the floor were carefully repeated.

The geometric measures (wheelbase, spindle heights, and ride heights) were all made with each of the vehicle's tires resting on an air bearing (also carefully located on the floor). The purpose, of course, was to insure that there were no constraining forces to the tires and suspensions other than vertical load, thus enhancing repeatability. Wheelbase was measured using a long, bar divider. Steering was adjusted until wheelbase was the same on the right and left sides, then the measurement was taken. Spindle heights and sprung mass reference heights were measured using a machinist's height gauge referenced to the upper surface of the air bearings.

Care was taken to minimize variability in reference height measurements due to suspension friction. For example, the procedure to measure front reference heights was as follows: With the vehicle resting on the air bearings, the front suspension was compressed by bearing down on the front bumper and releasing it very slowly. The front reference heights were then checked. Then, this procedure was repeated whatever number of times was required to achieve a "steady state" minimum of the reference height measures. A similar procedure involving lifting on the bumper was conducted to determine the upper limit of positions of the front reference marks. The reported reference height was the average of the upper and lower limits thus determined. A similar procedure was used to determine rear reference heights.

Logistical matters associated with scheduling and delivery of vehicles to the various laboratories were handled by MVMA through Mr. Craig Winn of Chrysler Corporation. The timing of the testing conducted by the various participants, including UMTRI, is indicated in Figure 4.

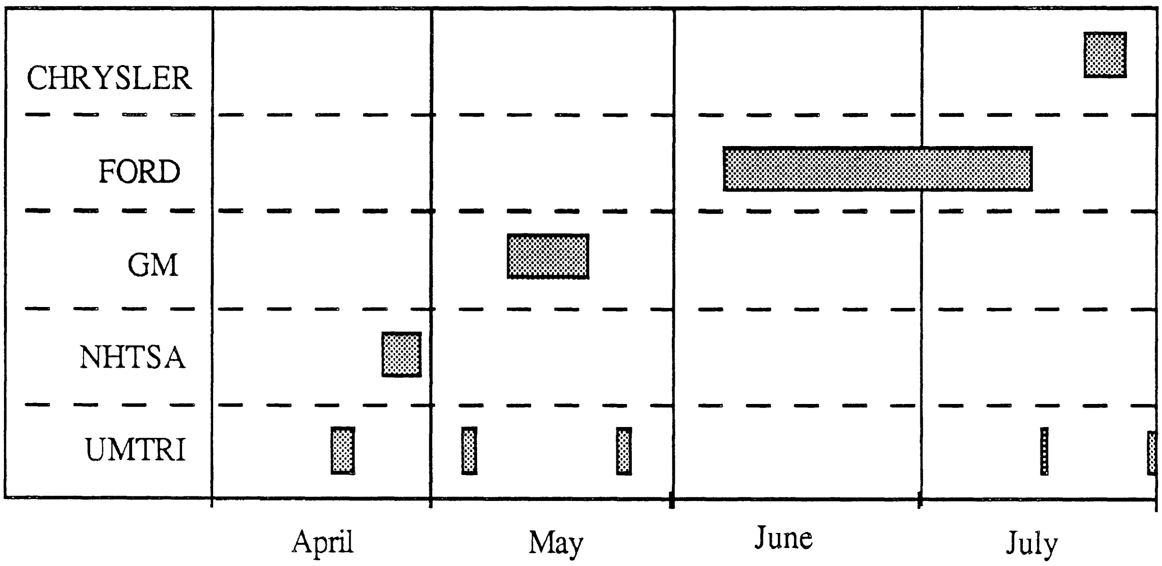


Figure 4. The actual schedule of the testing program.

3. Results

As a preface to the presentation of results, it should be noted that the UMTRI reference measurements indicate that the properties of the subject vehicles remained constant over the period of the measurement program. Figures 5, 6, and 7 review the results of the reference measurements of wheel loads, spindle heights, and sprung mass height made by each laboratory on the mini-van test vehicle. Similar data for each of the vehicles are provided in the Appendix, but the data shown here were typical.

On each graph, the five sets of UMTRI measures, spread out over the several months of the testing program, are shown interspersed among the four trials of each of the participants. Referring first to Figure 5, the measure shown is the average of the four wheel loads. The scatter in the five UMTRI repeats is slightly greater than that of the four measurements by Ford, GM, or NHTSA, and slightly less than that of the Chrysler measurements. Nonetheless, the UMTRI measurements would indicate that the average wheel load of this vehicle varied less than four pounds (or less than 0.5% of the average value) over the period of the program.

Figure 6 presents the weighted averages of the reference spindle height measurements. In the averaging process, each spindle height is weighted according to the load born by its wheel. The purpose is to produce a single measure that is closely related to the vertical

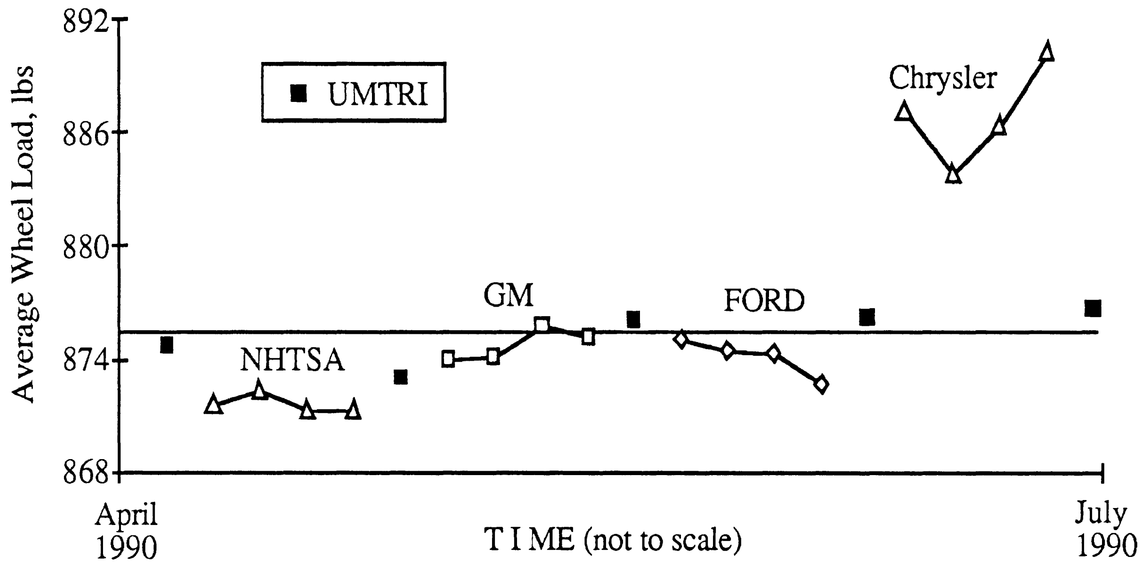


Figure 5. The averages of the measured wheel loads of the Chrysler mini-van.

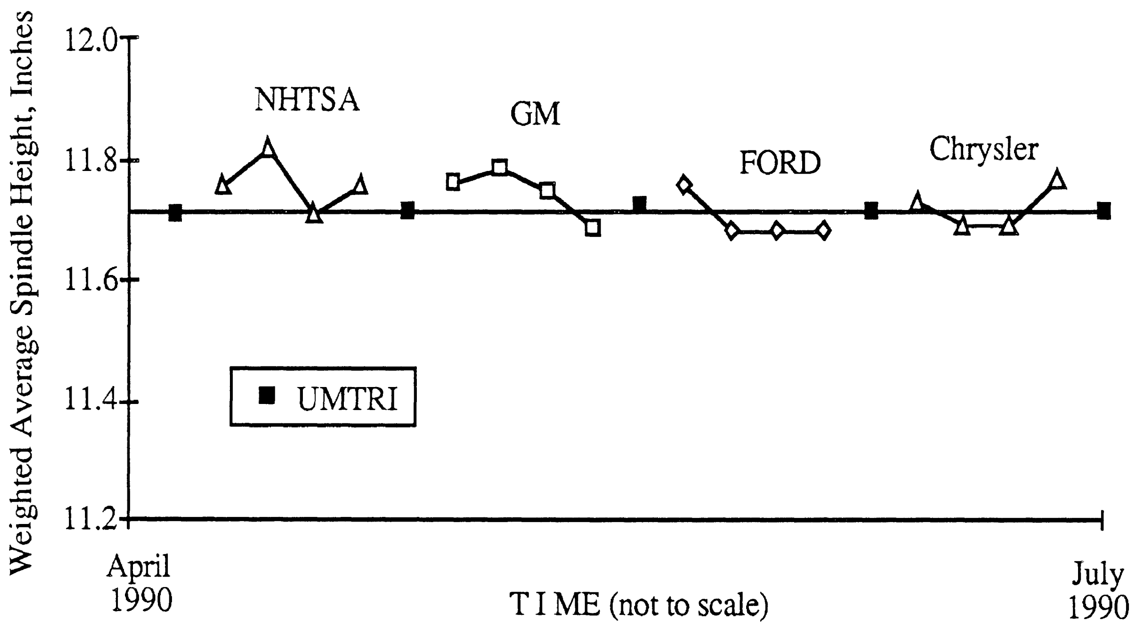


Figure 6. The weighted averages of the measured spindle heights of the mini-van.

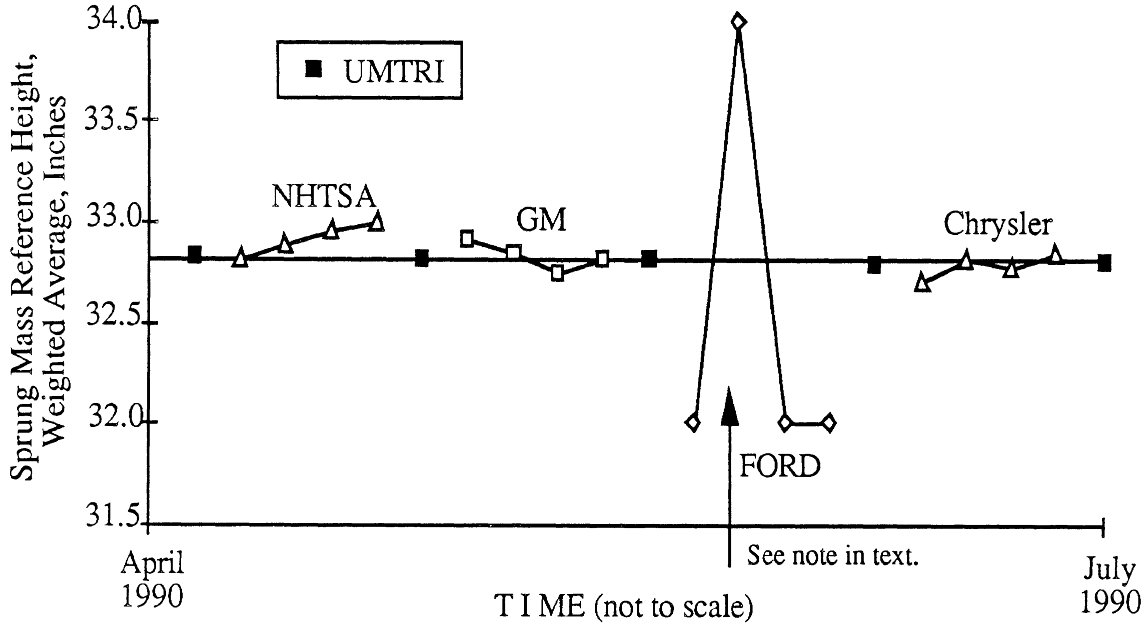


Figure 7. The weighted averages of the measured reference height of the mini-van.

motion of the c.g. of the vehicle. Probably because of the use of air bearings, UMTRI's measures show less scatter than any individual laboratory. UMTRI's values range from 11.707 to 11.725 inches, indicating that this property was very stable over the course of the program.

Data for the most important measure, the weighted average of the sprung mass reference heights, are presented in Figure 7. Weighting is, again, according to wheel load. UMTRI's measures range from 32.79 to 32.83 inches, showing that this property was also very consistent over the entire project period. (Note that the erratic nature of the Ford data for this measure is a result of misinterpretation of intent. Ford measured and reported the position of its own reference marks rather than those of UMTRI. Since they made new reference marks for each trial, at essentially arbitrary locations, their results show much more scatter. The Ford data is included simply for completeness, but is not relevant to the point made here.)

The average measured c.g. heights are shown in the upper portion of Figure 8 for each vehicle and laboratory. Ninety-five percent confidence intervals of the averages are indicated by the bars in the four smaller graphs below. In comparing any two averages, it would be correct to say that if the intervals shown overlap, the averages are not significantly different.

The most significant finding shown in this figure is the pervasiveness of differences between laboratories. Nearly all of the differences in the measured c.g. heights from one laboratory to another are highly significant. The most notable exception is that GM and NHTSA got essentially the same measurement for the GM buck, 24.1 and 23.9 inches respectively. This exception is notable because the buck is much closer to a "rigid body" than any actual vehicle. The other exceptions involve the Chrysler measurements. Because the variability of the Chrysler measurements was somewhat higher, their confidence intervals overlap those of the other three laboratories for the mini-van and the buck. The c.g. height of the pickup truck measured by Chrysler is significantly lower than the Ford and NHTSA measurements of that vehicle, but not the GM measurements. The Chrysler measurement of the sport/utility vehicle is significantly lower than that measurement by all the other laboratories.

A second characteristic to observe from Figure 8 is that the differences between laboratories are fairly consistent, or systematic. The Ford measurements are always the highest, followed in order by NHTSA, GM, and Chrysler, with only a couple of exceptions. The most notable exception here is the sport/utility vehicle. Apparently this vehicle posed special problems. Ford measured a higher c.g. position for the sport/utility vehicle than for the pickup, when it appears it should have been lower. And Chrysler measure a c.g. position for the sport/utility vehicle which was lower than that for the mini-van, when it appears it should have been higher. This resulted in the sport/utility vehicle

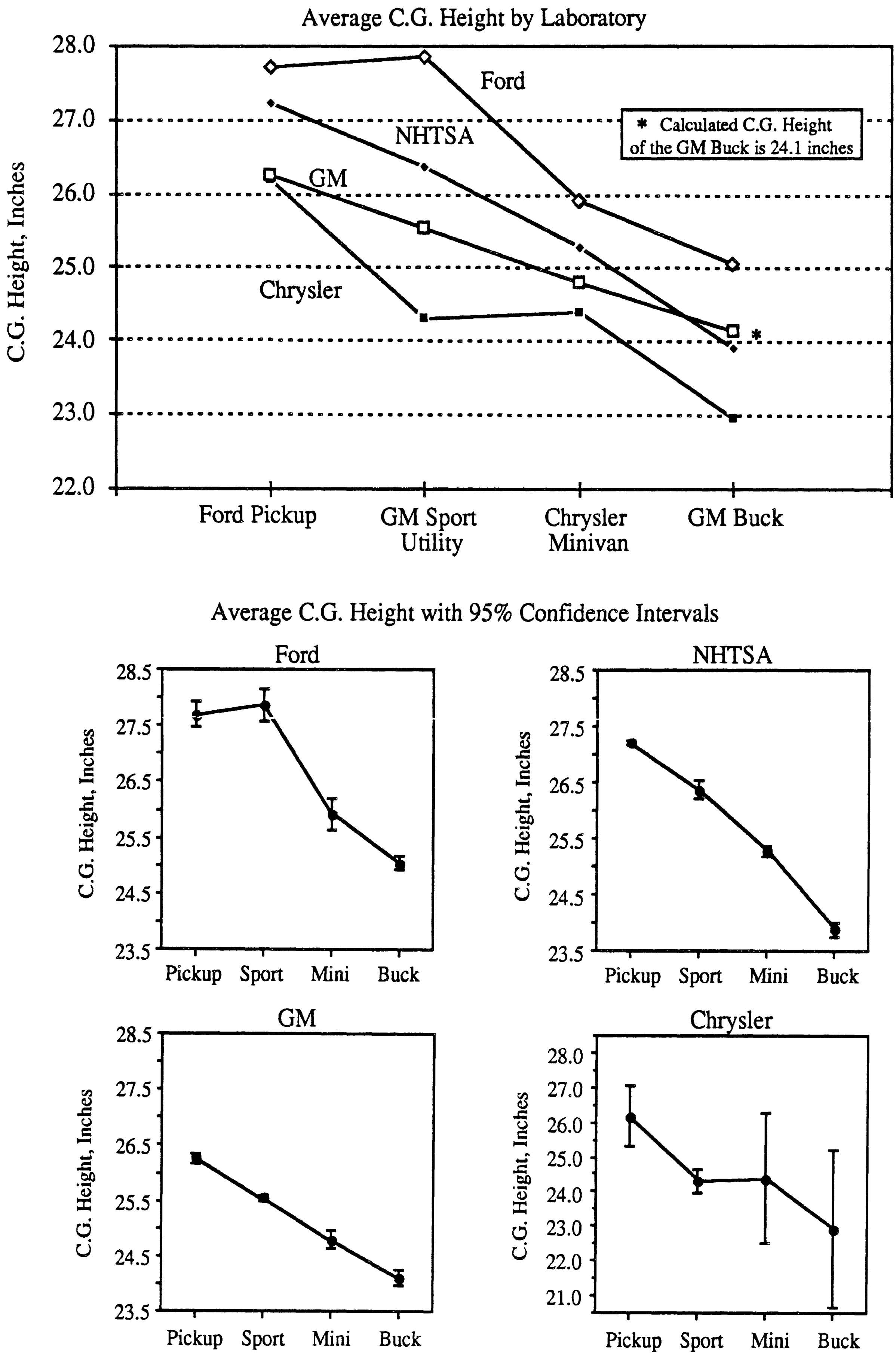


Figure 8. Center of gravity height measurement results for the four test vehicles presented by laboratory.

producing the greatest spread in average c.g. height measured for a single vehicle, namely, from 24.3 to 27.9 inches.

A final observation from Figure 8 is that the individual laboratories generally were able to discriminate between the c.g. heights of the four vehicles. Typically, the vehicle-to-vehicle differences for a given laboratory were statistically significant with just a few exceptions. Ford did not discriminate between the pickup truck and the sport utility vehicle, while these were the only two vehicles that were significantly different in the Chrysler measurements. This result implies that some additional, non-random errors crept into the Ford and Chrysler measurement of the sport/utility vehicle beyond the more pervasive systematic differences observed between laboratories.

Tabular results are presented in Tables 1 through 6. Table 1 repeats the average c.g. values illustrated in Figure 8. The calculated standard deviation of the observed c.g. heights is shown in Table 2 by vehicle and laboratory. The first thing to notice in Table 2 is the difference in repeatability among the laboratories. GM and NHTSA are the lowest, with Chrysler the highest. No consistent or significant trends are observed in the variations in repeatability from vehicle to vehicle. The marginal values shown in Table 2 need some explanation. The bottom row of Table 2 shows pooled standard deviations. The pooled standard deviation is based on a weighted average of the standard deviation calculated for each vehicle (weighted by the degrees of freedom, n-1). The pooled standard deviation is the best estimate of the repeatability of each laboratory. Differences in the average c.g. height from vehicle to vehicle are *not* reflected in the pooled standard deviation. The last column of Table 2, labelled "Across Laboratories" shows the standard deviation in c.g. height of each vehicle when the measurements from all four laboratories are combined. In other words, the laboratory to laboratory differences *are* reflected in the standard deviation shown in the last column of Table 2. The entry in the bottom row of the last column is a pooled standard deviation, like the rest of the entries in the last row. Thus, vehicle to vehicle differences are not included.

The pooled standard deviation across laboratories from Table 2 is approximately 1 inch. This figure estimates the standard deviation of the measured c.g. height of a given vehicle based on the observed variations from laboratory to laboratory. There is no way to know if the variability across the four laboratories in this experiment is representative of the variability among other laboratories. If anything, the participating laboratories might be considered among the best. Based on this figure, an approximate 95% confidence interval on a single c.g. height measurement from an arbitrary laboratory would range plus and minus 2 inches.

Repeatability is often expressed as a coefficient of variation, calculated as the standard deviation as a percent of the average value. Coefficients of variation are shown in Table 3

Table 1. Average C.G. Height, inches above ground

Vehicle	Laboratory NHTSA	GM	Ford	Chrysler	Average
Ford Pickup	27.22	26.25	27.70	26.18	26.84
GM Sport/Utility	26.37	25.54	27.86	24.30	26.02
Chrysler Mini-van	25.28	24.78	25.91	24.38	25.09
GM Buck	23.88	24.11	25.04	22.93	23.99
Average	25.81	25.24	26.73	24.55	25.58

Table 2. Standard Deviation of the Observations, inches

Vehicle	Laboratory NHTSA	GM	Ford	Chrysler	Across Laboratories
Ford Pickup	0.019	0.059	0.154	0.55	0.72
GM Sport/Utility	0.099	0.038	0.171	0.216	1.34
Chrysler Mini-van	0.050	0.099	0.176	1.173	0.80
GM Buck	0.049	0.060	0.050	0.902	0.87
Pooled	0.062	0.068	0.153	0.786	0.969

Table 3. Coefficient of Variation

Vehicle	Laboratory NHTSA	GM	Ford	Chrysler	Across Laboratories
Ford Pickup	0.07%	0.22%	0.56%	2.10%	2.67%
GM Sport/Utility	0.37%	0.15%	0.61%	0.89%	5.16%
Chrysler Mini-van	0.20%	0.40%	0.68%	4.81%	3.17%
GM Buck	0.21%	0.25%	0.20%	3.93%	3.63%
Pooled	0.24%	0.27%	0.57%	3.20%	3.79%

by vehicle and laboratory. Overall, the repeatability was very good with three of the four laboratories showing coefficients of variation well under 1%. Even the highest was only a little over 3%. The pooled coefficient of variation across laboratories is less than 4%.

The 95% confidence intervals shown in Figure 8 are calculated as the average c.g. height plus and minus the half interval. Table 4 shows the calculated half intervals for the average c.g. height and Table 5 shows the resulting upper and lower bounds for the 95% confidence intervals by vehicle and laboratory.

Table 4. Half of the 95% Confidence Interval, inches

Vehicle	Laboratory NHTSA	GM	Ford	Chrysler
Ford Pickup	0.030	0.094	0.245	0.875
GM Sport/Utility	0.157	0.060	0.272	0.344
Chrysler Mini-van	0.080	0.158	0.280	1.866
GM Buck	0.123	0.149	0.125	2.241
Pooled	0.035	0.039	0.087	0.447

Table 5. 95% Confidence Intervals for the Average, inches

Vehicle	Laboratory NHTSA		GM		Ford		Chrysler	
	HI	LO	HI	LO	HI	LO	HI	LO
Ford Pickup	27.25	27.19	26.34	26.16	27.94	27.46	27.05	25.30
GM Sport/Utility	26.52	26.21	25.60	25.48	28.13	27.59	24.64	23.96
Chrysler Mini-van	25.35	25.20	24.94	24.63	26.19	25.63	26.24	22.51
GM Buck	24.01	23.76	24.26	23.96	25.16	24.91	25.17	20.69
Average	25.84	25.77	25.28	25.20	26.82	26.65	24.99	24.10

Table 6. Analysis of Variance

Source	Sum of Squares	Degrees of Freedom	Mean Square	F-Ratio	P
Laboratory	38.46	3	12.82	48.00	0.000
Vehicle	62.53	3	20.84	78.05	0.000
Error	14.15	53	0.267		

The repeated measurements for each vehicle are also plotted in the Figures A9 and A10 in the Appendix. The repeatability within each laboratory, and the spread among the laboratories is evident from these figures. A tabulation of the observed c.g. heights from the original data sheets is also included in Table A1 in the Appendix.

A basic assumption of the analysis of variance is that the inherent repeatability is the same for each vehicle and each laboratory. Table 2 shows that this is not the case for the laboratories. The consequence of this situation is that the within variance is dominated by cells with poor repeatability, and the power of the test of significance is reduced. Despite this problem, the analysis of variance, shown in Table 6, indicates that the differences in both vehicles and laboratories are highly significant.

Based on these results, the problem is not repeatability, that is, random errors. Rather, the systematic, or bias, errors between the laboratories dominate. The variation in the reference measurements taken by each laboratory and UMTRI are small in comparison to the variation in measured c.g. heights across laboratories. Thus, changes in the vehicles are not responsible for the laboratory to laboratory differences. Presumedly there are differences in the way each laboratory measures c.g. height that are responsible for these differences. Possible explanations are presented in the Discussion that follows.

4. Discussion

The observations made by UMTRI during the site visits served to explain some of the differences between the results of the several participants. As a preface to a review of the procedures of the participating laboratories, a brief discussion of perhaps the most important source of error in c.g. height measurement follows.

An Important Source of Error in C.G. Height Measurement

This discussion is intended to addresses an underlying conceptual difficulty with c.g. height measurement which results in distinctly orderly errors that tend to make predictions of c.g. height too high. It does not cover the "usual" sources of experimental error, i.e., measurement inaccuracy resulting from instrument limitations, and other sources of "random" error.

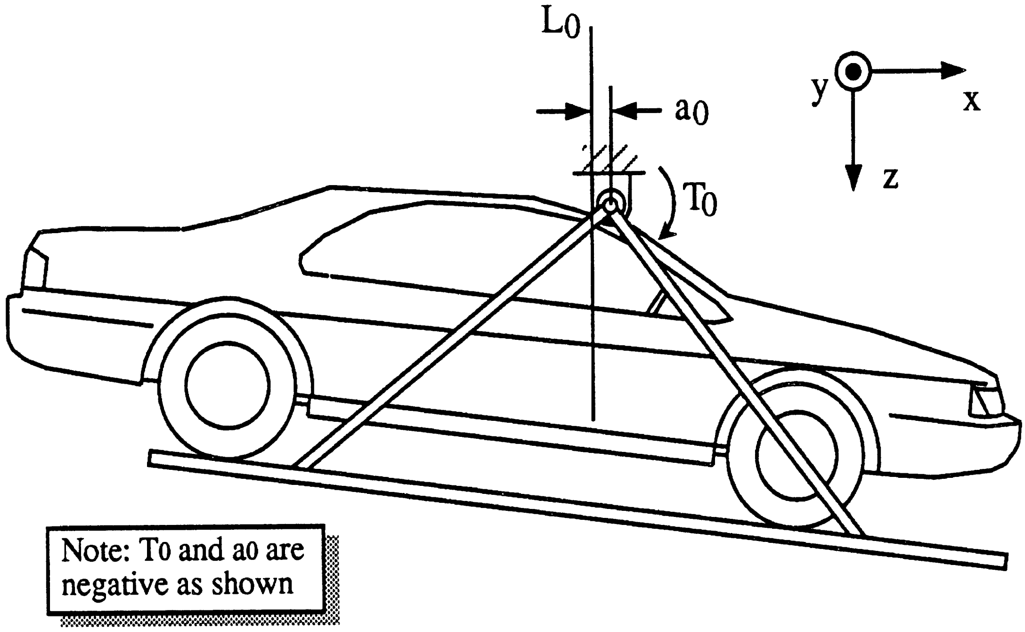
Figure 9 provides a schematic diagram of one approach to determining c.g. position. The vehicle is mounted on a pendulum swing which rotates in pitch about a lateral axis. The pivot axis is above the c.g. so that the system is stable.[2] For the purpose of this discussion, we will ignore the influence of the mass of the facility structure, and consider only the mass of the test vehicle. The weight of the vehicle is assumed to be W. The reference axis system is a right hand system with positive x-direction being forward, positive y-direction to the right, and positive z-direction vertical. This axis system is fixed in inertial space, not in the vehicle or the swing.

A method for using this arrangement to determine c.g. position is as follows:

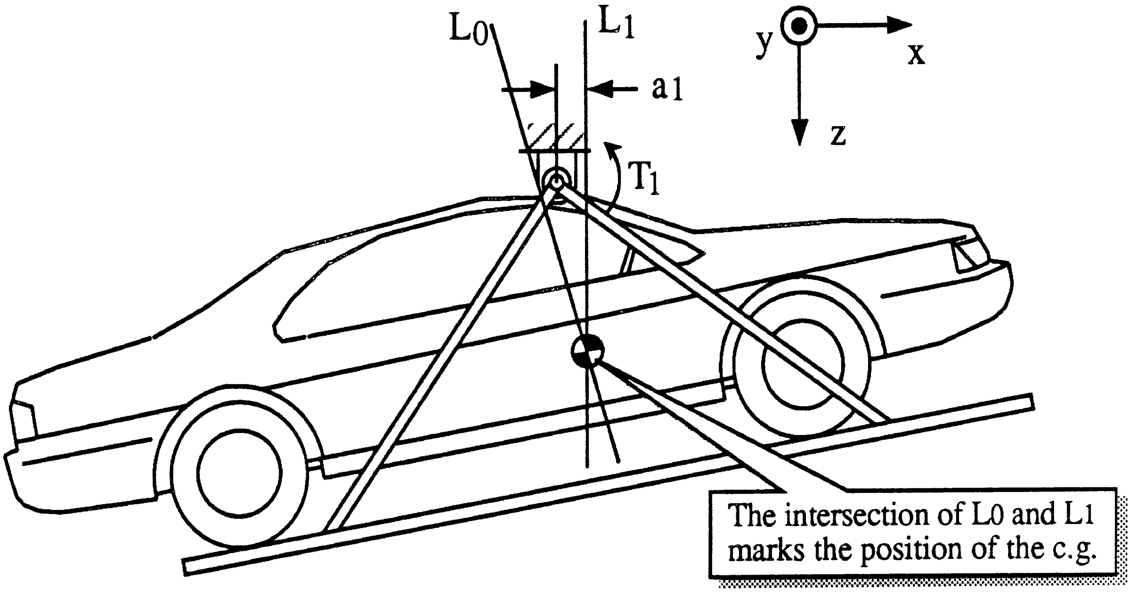
i) A torque of T_0 is applied to the system in the y direction. T_0 must be small enough to allow the system to attain a static, steady state response. Indeed, a very convenient, small torque which is often used is $T_0 = 0$. The system is allowed to come to steady state. From the need for static moment balance about the y axis, it is known that the c.g. of the vehicle must lie on a vertical line (L_0) located the distance a_0 from the pivot axis, where $a_0 = T_0 / W$. See Figure 9.a.

ii) A torque of T_1 is then applied to the system in the y direction. T_1 must also be small enough to allow the system to attain a static, steady state

2 Two of the four participating laboratories actually used this general arrangement. The points which will be made here, however, are applicable to virtually all "static-tilt" procedures for determining c.g. position.



a. With the torque T_0 applied



b. With the torque T_1 applied

Figure 9. A schematic diagram of a c.g. height measurement procedure

response. Again, the system is allowed to come to steady state. Now the c.g. of the vehicle must lie on a vertical line (L_1) located the distance a_1 from the pivot axis, where $a_1 = T_1 / W$. See Figure 9.b.

iii) The point at which the lines L_1 and L_0 intersect indicates the position of the c.g.

Of course, analysis can produce mathematical expressions which predict the "intersection point" without the actual need to "draw" the lines. This generally requires measuring the angular position of the system in pitch at the two steady state conditions (θ_0 and θ_1), as well as measuring the two applied torques. But the "graphical method" presented here is the equivalent of such calculations, and can help provide insight into a most important error source in such procedures.

The method just described depends on an important, implicit assumption for its validity —namely, that the system (swing and vehicle) is a rigid body, and that, therefore, motion of the c.g. relative to the pivot axis derives exclusively from rotation about the pivot axis. Unfortunately, this assumption is generally invalid. Motion of the c.g. resulting from the compliant response of the system as it rotates with respect to gravity is nearly always appreciable, and may produce significant errors if not considered.

Figure 10 illustrates the error (ε) in c.g. height measurement which results when such motion of the vehicle relative to the pitch pivot is not considered. The figure suggests that, as a result of compliances in the facility or in the vehicle restraint, the actual position of the vehicle c.g. shifted "downhill" a distance Δ when the system was tilted through the angle ($\theta_1 - \theta_0$). Thus, the position of the c.g. on the facility is not constant during the experiment. Note, however, that the c.g. did, indeed, lie on line L_0, *but only when T_0 was applied*, and the c.g. did lie on line L_1, *but only when T_1 was applied.* If the motion Δ is ignored, the position of the c.g. is predicted at the intersection of L_1 and L_0. If, however, the horizontal motion of the c.g. is considered, the actual position(s) of the c.g. is seen to fall a distance ε below this intersection. From the geometry of the figure, and when θ_0 is small, it can be seen that:

$$\varepsilon \approx \Delta / \tan(\theta_1 - \theta_0) \qquad (1)$$

Note that ε will be very sensitive to Δ if the tangent of ($\theta_1 - \theta_0$) is small. For example, if ($\theta_1 - \theta_0$) $\approx$ 6 degrees, then $\varepsilon \approx (10 * \Delta)$. Small motions of the c.g. in the horizontal plane of the vehicle can produce large errors in predicted vertical position. Intuitively, this seems reasonable since, when pitch angle is small, the horizontal position of the c.g. has a first order influence on the pitch moment balance, while the vertical position of the c.g. (in a vehicle reference axis system) has only a second order influence.

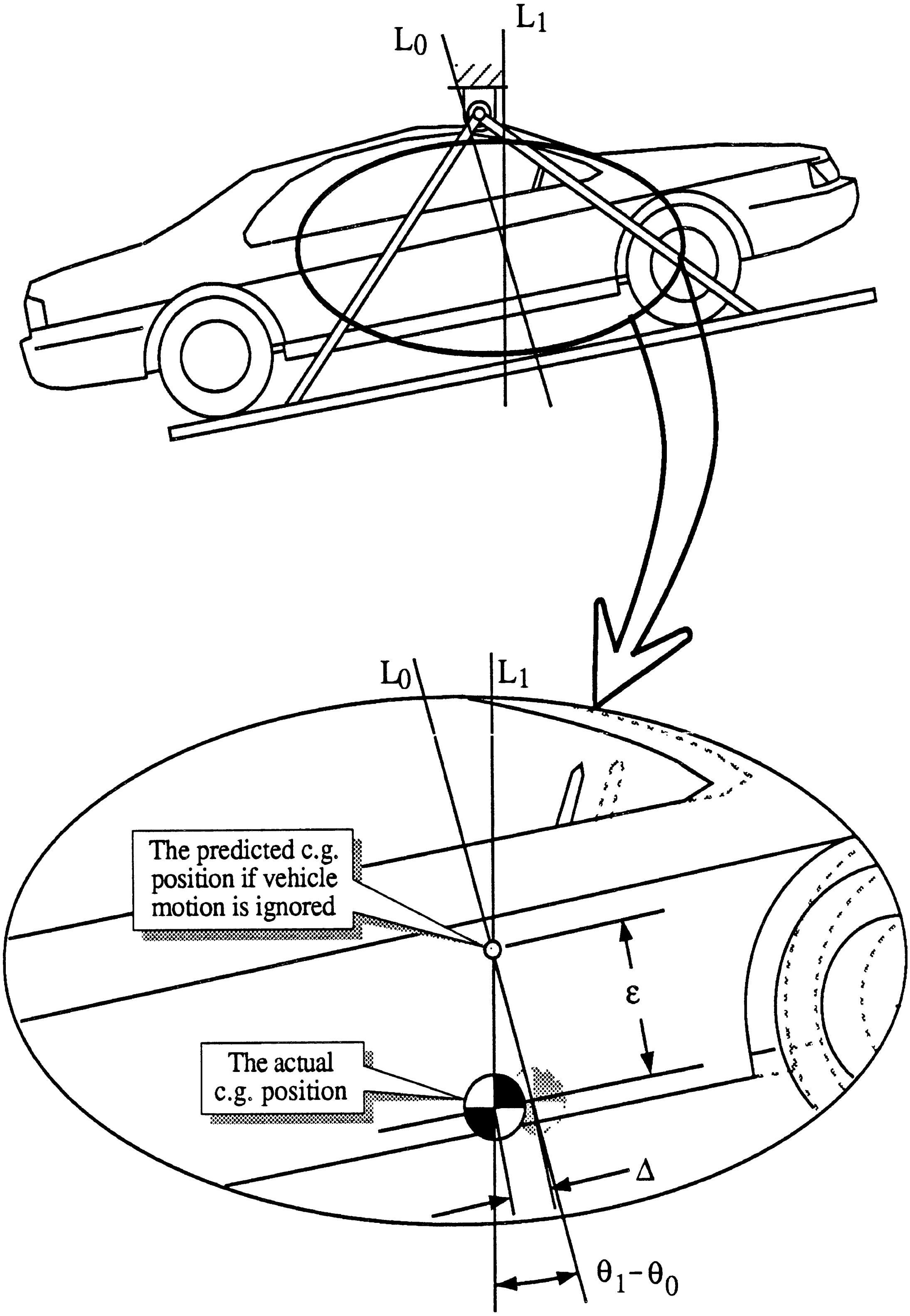


Figure 10. The error in the prediction of c.g. height which may result when the horizontal movement of the vehicle is not considered.

Also note that this error mechanism virtually always causes the predicted position of the c.g. to be higher than the actual position. Compliances virtually always allow the c.g. to shift "downhill" as shown in Figure 10, not "uphill." This polarity of motion always causes a prediction that is too high.

The error mechanism discussed here also implies a conceptual limitation to the very notion of "*the*" c.g. position. Until this point, the discussion has dealt with errors which may result when "the vehicle" moves on the facility with respect to the pivot axis. There has been another implicit "rigid body" assumption made —this time, that the vehicle itself is rigid. But, of course, it is not. The body, the drive train, and the suspensions are all interconnected with compliant rubber bushings (to say nothing of the motions of liquids within the vehicle). The relative motions of these parts which make up "the vehicle" imply an internal motion of the vehicle c.g. (Note that the tire-to-ground contact points are the de facto reference for this "internal motion" of the c.g., but even these are likely to move relative to one another.) This motion may be small, but as we have seen, *it* constitutes the first order effect, while the experiment seeks to decipher the second order effect. That is, we have seen that small horizontal motions of the c.g. beget large errors in predicted c.g. height.

To put the issue of required accuracy of c.g. height in context, consider that c.g. height is not *the answer* which is generally sought. Rather, c.g. height is usually but one vehicle-descriptive parameter intended for use in an analysis that contains several other important parameters. Usually, the significance of c.g. height in the analysis is to aid in the prediction of the distribution of vertical load among the tires during the imposition of accelerations parallel to the ground. (For example, in roll stability analyses, c.g. height is used to help predict the lateral acceleration which is just large enough to cause that particularly interesting situation in which all the vertical tire loads on one side of the vehicle drop to zero.) It is useful to keep in mind that, if such an analysis does not include (i) the small motions of the c.g. in the horizontal plane which result from the internal compliances considered here, or (ii) similar small changes in lateral positions of the tires, then there is little reason to demand a high level of accuracy in representing the vertical position of the c.g. In summary, it is not, then, generally useful to pursue a level of accuracy in determining c.g. height which exceeds the inaccuracy implied by a limited knowledge of the horizontal position of the c.g. The appropriate relationship is roughly indicated by equation (1) if ε represents the accuracy of the c.g. height, Δ is interpreted as the level of accuracy to which the horizontal position of the c.g. is known, and $(\theta_1 - \theta_0)$ is the roll angle of interest for the analysis at hand (which is always rather small at, or prior to, wheel lift).

Measurement Procedures Used by the Participants

UMTRI personnel visited each of the four participating laboratories at the outset of the project. On each visit, we were able to observe a demonstration of the facilities and procedures used to determine c.g. height. One purpose of these visits was to gain insights into the procedures which might explain differences observed in the measurement results of the laboratories. In large part, this goal was realized.

A brief review of the relevant observations made at each laboratory will be presented, followed by a discussion of how these observations might explain specific differences observed in the measurement results of the laboratories in the program. The intention is to first provide a discussion based solely on observation and engineering judgement, as "unbiased" as possible by the additional information provided by comparing the results of the several laboratories. Then these individual observations will be compared and reconciled with the actual results.

The reader will find that the following material focuses on procedural details specific to the individual techniques used by the laboratories, and not on "standard" issues of experimental practice such as instrumentation calibration, etc. That is because we are particularly interested in seeking out orderly error sources which produce an absolute bias in the results of repeated measurements, rather than in identifying random error sources which would produce scatter about the correct results.

NHTSA Site Visit

The first visit was made to the NHTSA facility at the Transportation Research Center of Ohio on February 23, 1990.

The NHTSA facility, shown in Figure 11, can be used to measure moments of inertia in roll, pitch, and yaw, as well as c.g. height. The facility is a pendulum swing whose main member is in the form of a wide, shallow "U" with the pivot axis bearings located at the top of the upright arms. At the center of the base of the U is mounted a turntable assembly which includes two wheel ramps, one each for the left and right track of the vehicle. In the figure, this assembly is shown in a position such that rotation of the pendulum swing results in pitch rotation of the vehicle. C.g. height and pitch inertia measurements are made with the facility in this configuration. The ramp assembly may be rotated 90 degrees about the vertical axis so that swing rotation produces roll motion of the vehicle. Roll inertia is measured in this configuration. Finally, the turntable assembly is fitted with mechanical springs such that, with the pendulum motion constrained, the turntable and vehicle can oscillate about a vertical axis in order to make yaw moment of inertia measurements.

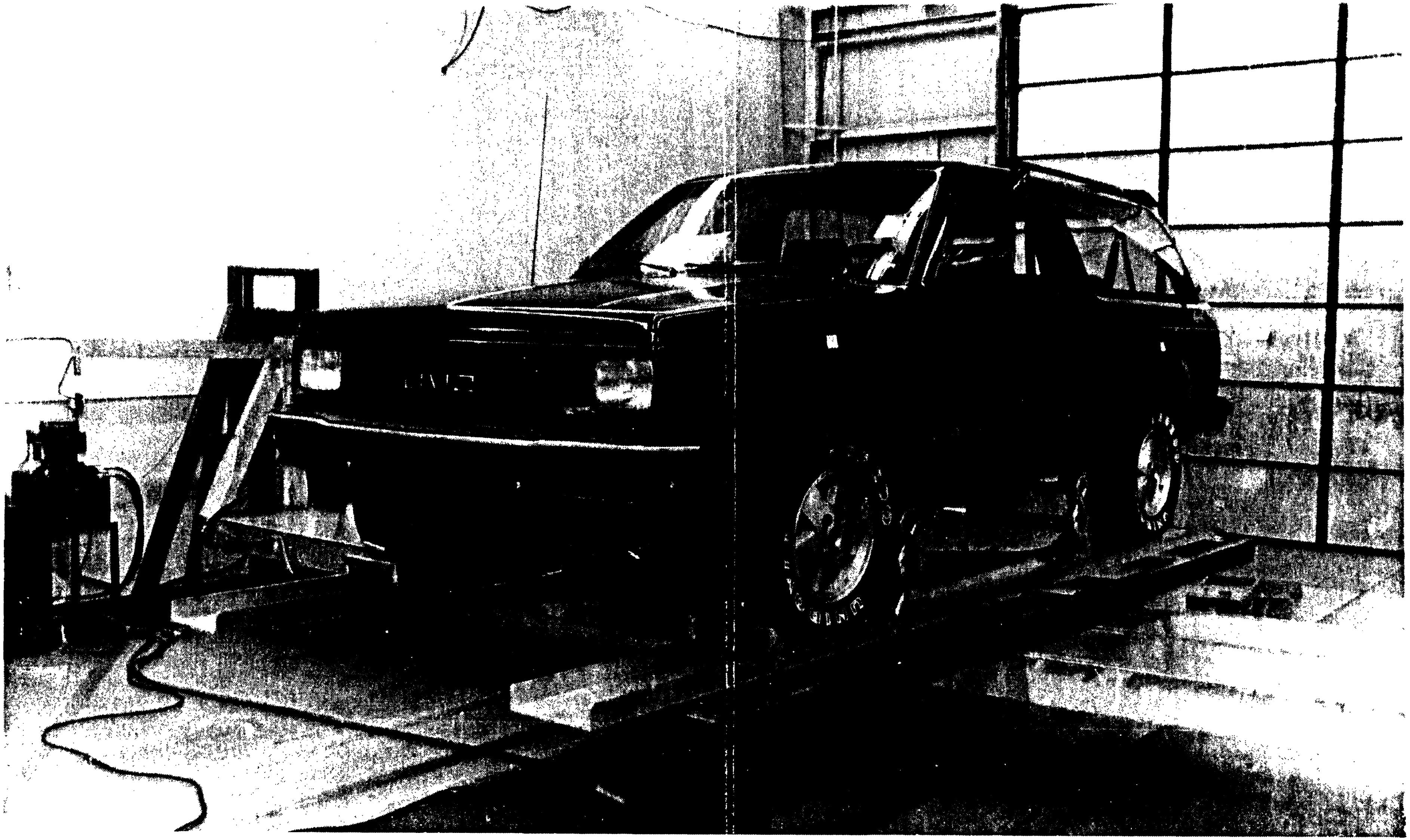


Figure 11. The facility used by NHTSA for determining c.g. height.

C.g. measurements are made with the facility configured as a pitch plane pendulum. The remaining discussion will be concerned only with the vehicle facility in that configuration. The upright members of the main structure are fitted with "moment arms" in the immediate vicinity of the pivot axis bearings. Each upright has two arms, one extending forward and one rearward. The arms on the right-hand upright are visible in Figure 11. To apply torque to the system, dead weights are hung from precisely located points on the moment arms. Weights are distributed evenly between the left- and right-hand moment arms. The resulting inclination is measured by an electronic inclinometer (with 1 minute resolution) mounted near the bearing on the right-hand upright. A string potentiometer is used to measure longitudinal motion of the vehicle during testing. Data taken electronically (inclination and longitudinal motion) are triggered by an operator pushing a button. His timing is based on observing inclinometer readout and waiting for quiescence. Twelve seconds of data are taken at 100 hz.

The facility is recognized to be rather flexible. The wheel track support ramps are known to deflect significantly under the changing loads which occur when the facility is tilted. In recognition of this, the data reduction process includes an empirically derived "model" intended to compensate for motions of the vehicle and facility structure which are not transduced. The transduced motion of the vehicle, as indicated by the output of the string potentiometer, is also considered in the data reduction process.

Wheel weights and reference geometric measures were made prior to mounting the vehicle on the facility. For this demonstration, a 50-percentile male dummy had been installed in the driver's position. (No dummy was used in the program measurements.) The vehicle was driven onto the facility and its for/aft position adjusted to obtain a pitch attitude within ± 1/3 degree of level. The vehicle was constrained fore/aft with wheel chocks which "captured" the front wheels. Then a set of four scissors jacks were "touched up" to the body, nominally at the four corners of the passenger compartment. However, there was no subsequent effort to tie down the vehicle to the jacks. An additional longitudinal constraint was provided through a pair of light nylon straps which were attached between the vehicle undercarriage and the facility. The straps ran nominally fore/aft and were tensed in opposition. The string potentiometer body was mounted to the main member of the pendulum under the vehicle. The string extended forward to the front suspension area and was attached with a simple clamp to a frame member.

The left and right bearings were lifted simultaneously with hydraulic cylinders and then set down on prepared blocks. (The horizontal quality of the pivot axis could not be confirmed.) The first data set was taken with no torquing weights applied. Subsequently, measurements were made with 100 and then 200 pounds applied for forward (front down) tilt. The zero condition was repeated and then tests with 100, and 200 lbs for rearward tilt were done. Finally, the zero condition was repeated. (In all cases the weights quoted are totals with half applied to the left-hand moment arm and half applied to the right-hand arm.) The absolute value of the angles achieved in this process were nominally 0, 4, and 8 degrees.

Data reduction was accomplished by a computer program which included the compensation calculations for the flexibility of the structure, as well as the transduced motion of the vehicle.

Our observation of the facility and procedures suggest three primary areas of concern. These are indicated below.

i) The rigidity of vehicle constraint could be improved. While the sprung mass is constrained from moving downward, it was not constrained from moving upward. The chassis was observed to lift from at least one jack during testing. Binding the vehicle down tightly on the four jacks would likely yield a more rigid longitudinal constraint, also.

ii) The compliance of the facility itself is a real concern. The importance of this compliance is clearly recognized by the operators and reflected in the substantial compensating calculations. If all compliances are adequately handled by the data reduction process, then there is no problem. Whether this compensation is complete would always seem to be a concern. Attention seemed to be focused on the beam deflection of the ramps. Torsional deflection of the main member appeared to be a real possibility also. And, since the yaw motion turntable was constrained by centering springs, a lateral offset of the vehicle c.g. may induce unrecognized motions of the vehicle c.g.

iii) The location of the potentiometer sensing vehicle longitudinal motion could be improved. This sensor was mounted well below the c.g. and was offset from the longitudinal centerline of the vehicle. Thus, yaw and pitch motions of the vehicle could induce data signals not representative of the translational motion of the vehicle c.g. The string was also attached to a sub-frame member, separated from the more massive elements of the vehicle by compliant bushings. Finally, the potentiometer body was mounted at a point on the facility which might, itself, be deflecting relative to the pivot axis.

Chrysler Site Visit

The second site visited was the Chrysler/Jeep facility on Plymouth Road in Detroit. This visit took place on March 2, 1990.

Chrysler does not use a special purpose facility for c.g. measurement; rather, they perform a relatively ad hoc experiment in which the vehicle is tilted through a large pitch angle by raising one end with a garage lift. Figure 12 shows a test in progress. Four specialized wheel load scales are used to monitor each of the four wheel loads. Each scale uses a Lebow strain gauge load cell as the measuring element. A top plate mounted on the cell includes constraints to prevent wheel motion relative to the cell. Two scales are located on the garage lift so that one end of the vehicle can be raised. The other two scales are placed on linear bearings on the shop floor so that they can move longitudinally as required when the vehicle is raised to large pitch angles.

Pitch angle is determined by measuring the lift height (with a tape measure) and knowing the wheelbase of the vehicle. A new addition to the procedure is an electronic inclinometer (30 sec resolution) affixed to the roof of the vehicle. As of the time of the site visit, the signal from this instrument was recorded and used as a check, but was not used for calculation. Software changes to come will alter this situation.

Prior to testing, the vehicle fuel tank was filled and the desired loading condition established. (Since this was a demonstration for our benefit, the vehicle was empty and simply in a condition established by previous testing requirements.) Body reference height was determined by measuring the height of the wheel fender lips. The four spindle heights were also measured and recorded.

With the vehicle at the measured ride height, the stroke positions of the shocks were marked. The shocks were removed, their oil drained, and the rod welded to the body at the established stroke position. The shocks were then reinstalled as suspension "blocks." (Shock modification and installation had been accomplished prior to our arrival.)

The vehicle was then mounted onto the wheel load scale and linear bearing arrangement. The vehicle was parked in this manner with the brakes released and the transmission in neutral. (No check to insure that the wheels turned freely on their spindles was evident. Also, no check of the parallelism of the axis of motion of the left-hand and right-hand linear bearings was evident. The bearings were noticeably misaligned at one point in the demonstration.)

In the demonstration, data collection was started with the vehicle quiescent and in the level position and continued though lift, a 10-second pause at the maximum pitch angle, the descent, and another short quiescent period in the level condition. The data were then displayed on the computer screen. Wheel loads to be used in the calculation were selected "by eye" from graphical displays. Values were taken only from the level and maximum positions, not from the transient portion.

Normal procedure was said to include two lifts to the maximum angle allowed by vehicle and suspension geometry. This would typically be in the 20-30 degree range. We observed two trials with front wheels lifted and two with the vehicle position reversed so that rear wheels were lifted.

Figure 12. A c.g. height measurement test in progress at the Chrysler laboratory.

Some of the wheel load time histories taken looked strange in that they had distinct discontinuities. In one case, it was determined that the wheel scale structure interfered with the rear lift spring at full lift. These tests were repeated with less lift. Similar, but less severe qualities in earlier runs were not accounted for. However, the four successful trials gave repeatable results within about 1/4 inch.

The data reduction procedure assumes that the axle spindle is the tilt pivot. That is, the basic calculation determines c.g. height in reference to the spindle. Separate calculations are made by summing moments about the rear spindle and about the front spindle and the results are averaged.

Our observations of the Chrysler methodology prompts comments on three topics.

The most serious shortcoming of this procedure would appear to be the failure to observe and account for motion of the vehicle c.g. relative to the pitch pivot. The wheel spindles are used as the pitch pivot, about which moments are summed in the data reduction process. In fact, the front and rear spindle axes are each used, since the data reduction process includes two separate calculations, one for moments about the front spindles, and one for moments about the rear spindles. Vehicle suspensions usually have significant compliance in the longitudinal direction, however, and the longitudinal loading (in the vehicle axis system) of the test vehicle suspensions is quite significant during this test procedure. One can expect that the relative motion of the c.g. with respect to the pitch pivot is also significant, but it is not monitored or considered in the data reduction process.

Our second concern is that there may be other significant sources of pitch moment acting on the vehicle which are not considered in the analysis. Figure 13 shows a simple schematic freebody diagram of the forces and moments in play during the experiment. We have included the possibility of a longitudinal force and an axial moment at each spindle. Using the geometry and nomenclature of the figure, static analysis yields two expressions for h_S, the height of the c.g. above the plane of the spindles. One expression comes from summing moments about spindle A, and one from moments about spindle B. These expressions are:

From moments about A:

$$h_S = \frac{1}{\tan\theta}\left[a - \frac{F_{Z2}}{W}\,wb\right] + \frac{F_X}{W}\,wb + \frac{M}{W}\,\frac{1}{\sin\theta} \tag{2}$$

From moments about B:

$$h_S = -\frac{1}{\tan\theta}\left[b - \frac{F_{Z1}}{W}\,wb\right] + \frac{F_X}{W}\,wb + \frac{M}{W}\,\frac{1}{\sin\theta} \tag{3}$$

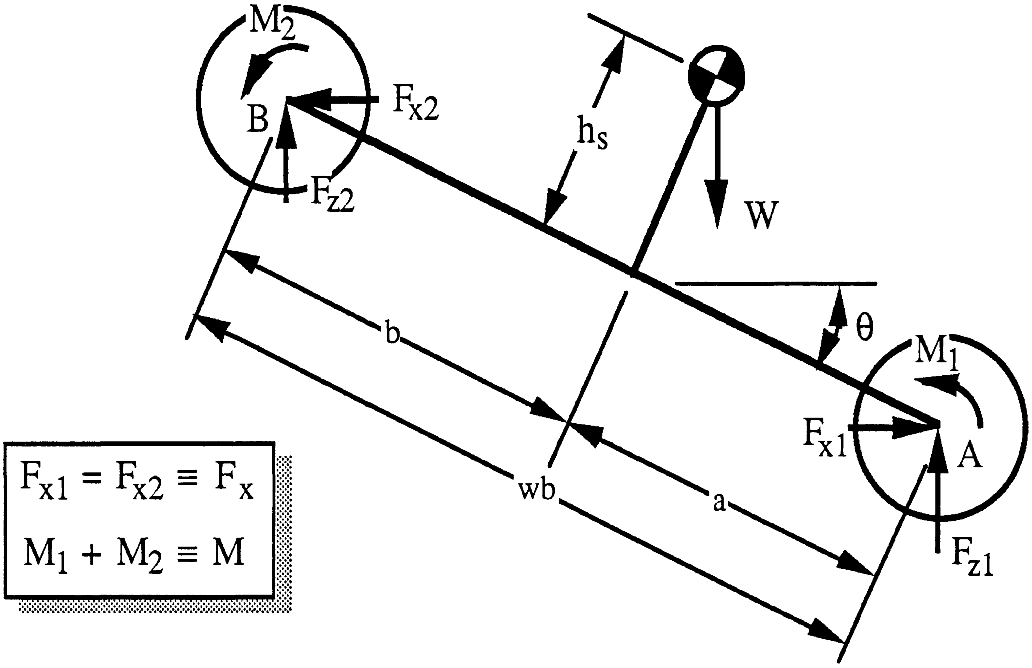


Figure 13. A schematic freebody diagram of the measurement procedure used by Chrysler.

Equation 2 and equation 3 each independently yield the following expressions for the partial derivatives of h_s with respect to F_x and M.

$$\frac{\partial h_s}{\partial F_x} = \frac{wb}{W} \tag{4}$$

$$\frac{\partial h_s}{\partial M} = \frac{1}{W \sin\theta} \tag{5}$$

Equations 4 and 5 indicate the obvious — that failure to include significant spindle moments or longitudinal forces at the spindles influences the calculated c.g. height — and the not-so-obvious — that averaging results from the two methods of data reduction does not tend to cancel these error sources.

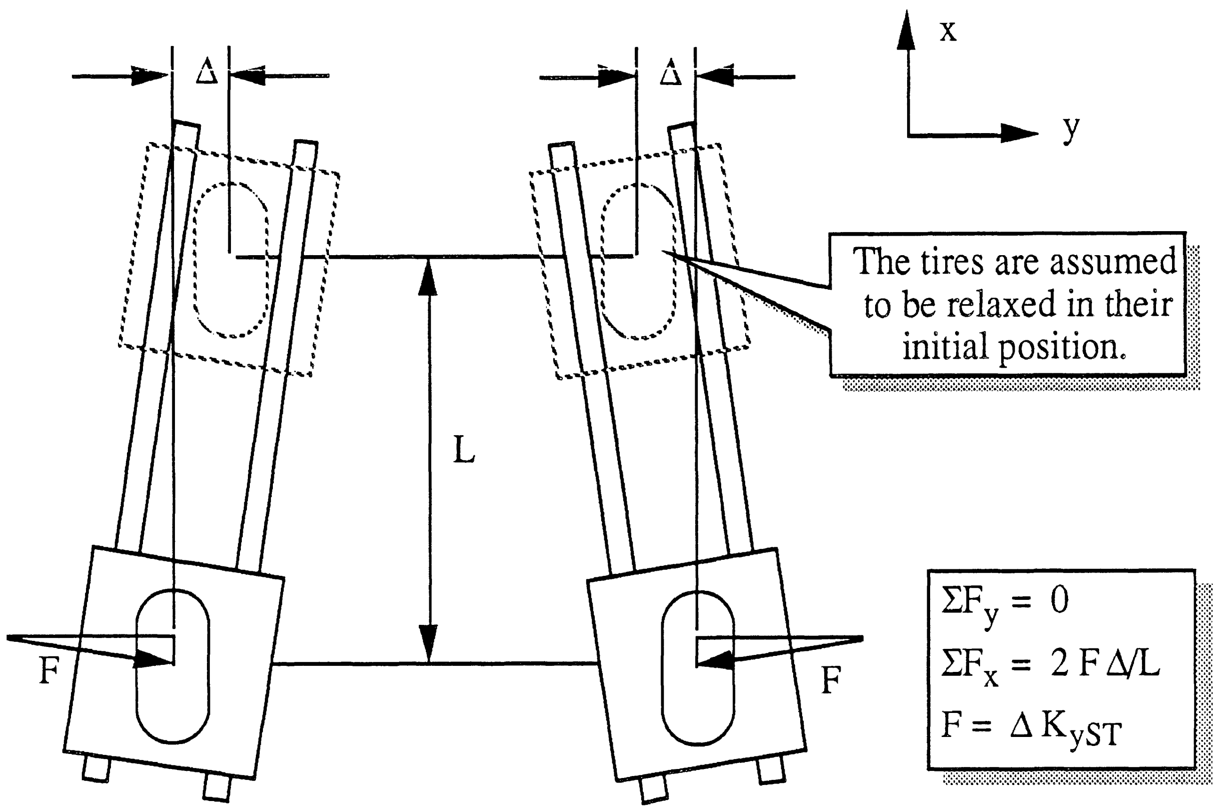
Applying approximate parameters for the vehicles ($W \approx 4000$ lb., $wb \approx 120$ in.) and the procedure ($\theta \approx 25°$) to equations 3 and 4 yields:

$$\frac{\partial h_s}{\partial F_x} = 3 \times 10^{-2} \tag{6}$$

$$\frac{\partial h_s}{\partial M} = 6 \times 10^{-4} \tag{7}$$

These results indicate that c.g. height errors of roughly one inch could result from (i) longitudinal forces at the left and right spindles totaling roughly 30 pounds, or (ii) spindle moments at all four spindles totaling 1670 in-lb (equivalent to about 140 lb tangential force at the tire circumference). The latter suggests that typical brake drag and/or bearing and drive train drags should produce little error. The former, when combined with the potential for misalignment of the linear bearing pads used in the experiment, may well produce noticeable error.

Figure 14 shows a schematic diagram of the linear bearings in the plan view. The tires and bearings are depicted to be at the top of the figure when the vehicle is at its initial, level condition. After the vehicle is tilted, the tires and bearings have moved to the lower position in the figure. Assuming that the tires were relaxed laterally in the initial condition, they would be deflected laterally in the final condition, and would produced forces (F) proportional to the standing tire lateral spring rate (K_{yST}). Those forces would be oriented perpendicular to the bearing axes and, therefore, would have a combined longitudinal component (ΣF_x). Note that, assuming the tires were relaxed initially, ΣF_x would always be in the direction opposed to motion, regardless of the polarity of bearing misalignment.



(Forces shown are those applied to the tires.)

Figure 14. Forces resulting from misalignment of the linear bearings.

Our rather casual observations suggest the possibility of misalignment perhaps as large as $\Delta = 0.5$ inches over a distance L = 10 inches. Assuming a representative K_{yST} of 500 lb/in., this would produce ΣF_x of 25 lb. or a potential error in vertical c.g. prediction in the regime of 1 inch. Since ΣF_x is always positive, but the analysis assumes ΣF_x is zero, the ΣF_x "error" is negative. Since the partial derivative of equation 6 is positive, the error implied in c.g. height prediction is negative. That is, the error source hypothesized here implies a predicted c.g. height which is too low.

Finally, the ad hoc nature of the Chrysler procedure would obviously lead to the expectation that the results from this laboratory would show greater variability than those from the other participating labs. The decision not to bear the expense of a specialized facility is essentially equivalent to a decision to tolerate a lower level of "optimization" in experimental accuracy. (For example, wheel load measurement is a relatively inaccurate means of measuring the external torque applied to the vehicle— differential wheel loads between the level and full displacement positions are on the order of 10% of the nominal wheel load value.) This is of relatively little consequence from the point of view taken herein where attention is focused more on orderly error sources than on random sources.

GM Site Visit

The third site visit was to the GM facility at the Milford Proving Ground. This visit took place on March 9, 1990.

GM uses a tilt platform which rotates in roll to measure c.g. height. The facility is illustrated in Figure 15. The platform is a very stout weldment structure composed primarily of steel I-beam. The roll pivot is located an inch or so below "ground," and is nominally aligned beneath the longitudinal centerline of the vehicle. The section height of the I-beams used for construction is on the order of 10-12 inches . An I-beam runs longitudinally under each track with an inverted steel channel on top to act as a "ramp." Cross members at the front and rear of the table are made of the same I-beam and mount the pillow blocks that form the pivot axis. The facility is definitely a very stout structure which appears to be practically rigid.

A "load beam" extends to the side at mid wheelbase and provides the means for measuring external torque applied to the structure. Since the pivot lies below the system c.g., the system is unstable. Vertical load applied to the load beam stabilizes the system and is measured with a balance scale with a resolution of 1/4 kg. A mechanism employing a pivot pin and horizontal planar bearing ensures that the effective moment arm of the applied load is accurately known and that the force is truly vertical. The mechanism includes a means for adding "blocks" between the scale and arm, thus changing the tilt angle of the facility. (All blocks are kept on the scale, whether in use as spacers or not. In this way, the weight of the blocks in use does not influence the relative scale readings.)

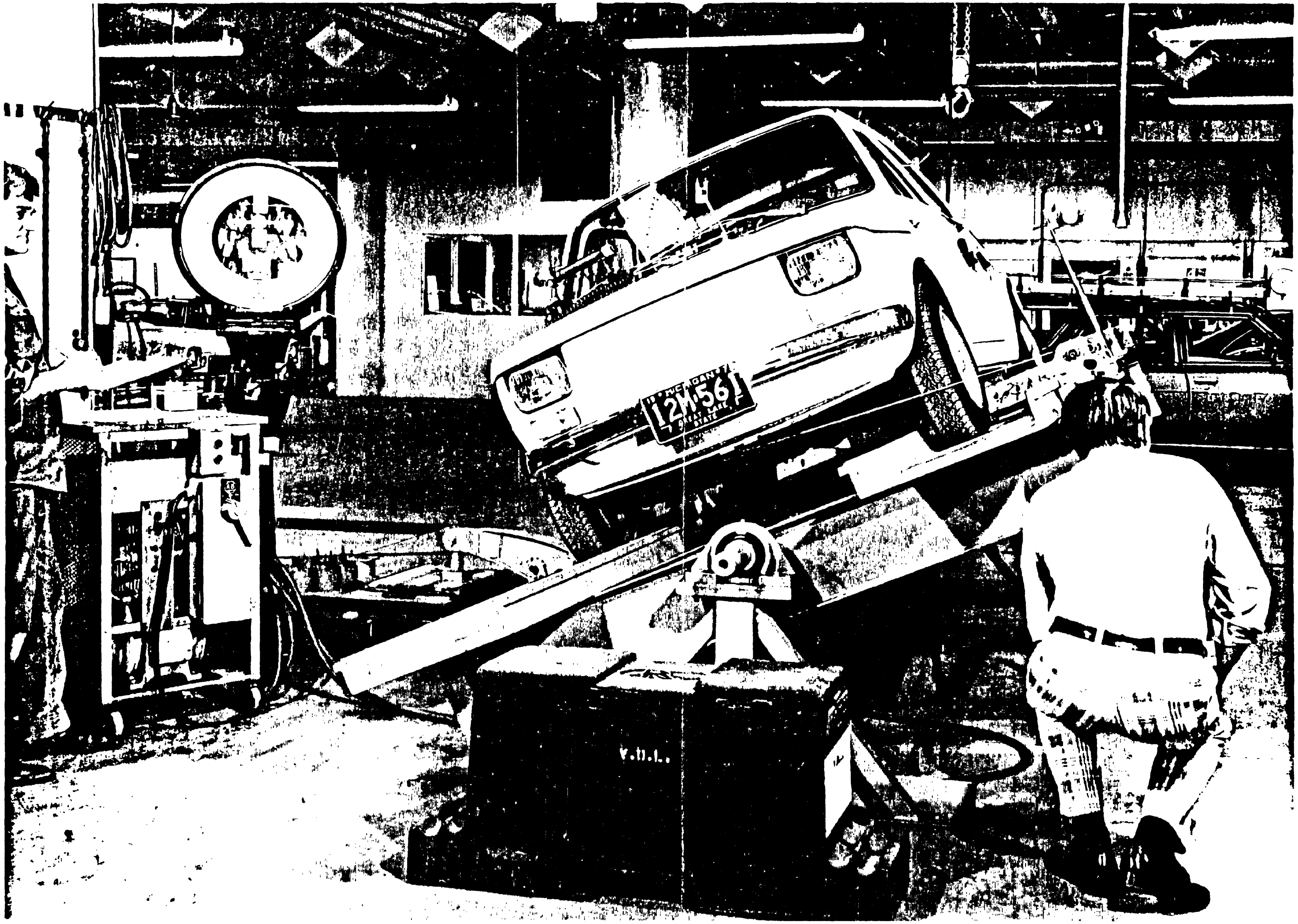


Figure 15. The facility used by General Motors for determining c.g. height.

When installing blocks, the facility is lifted by an hydraulic cylinder beneath the table. The cylinder clevis has a large lash and the system is equipped with limit switches at both ends. Lights operated by the switches show that the clevis pin is in the lash when measurements are actually recorded.

Tilt angle is measured with a bubble inclinometer mounted on the side of the table. The device has a resolution of one minute. Lateral motion of the vehicle relative to the table structure is measured with a machinist's digital indicator. The indicator is mounted on a vertical rod beside the vehicle and bears against a front door panel. It is located with the intention of it being on a nearly vertical surface. Resolution is .01 mm. All data was taken "by hand."

For this demonstration the vehicle was set up in "official curb" condition, i.e., i) all fluids full, ii) all seats in full back position , iii) tire pressures set to placard numbers ±0.5 psi., and iv) no driver or passengers represented.

Prior to installing the vehicle on the table, it was driven "a couple of blocks" to a scale facility equipped with four individual, "in ground" wheel scales. (The accuracy of the system is believed to be such that the whole car weight may be off as much as 50-60 lb.) The vehicle was weighed and then driven back to the test bay.

Trim height was determined with the vehicle parked on the shop floor. The procedure includes the following steps. i) Depress the front bumper and release very slowly. Repeat three times. ii) Measure front wheel fender height above the spindle axis. If the fender profile makes this difficult, apply tape and pencil line to serve as a reference. iii) Repeat i and ii but lift bumper. iv) Average the hi and low results for each fender. v) Repeat the procedure at rear.

The spindle heights were also measured before the vehicle was lifted onto the facility using a specialized crane device.

The vehicle was securely tied down on the facility at the measured trim height condition. To do this, four post jacks were located under the vehicle. Their location was partly established by the recognized need to get good purchase on the c.g, and partly by the under-vehicle profile. Stout wire rope was attached to the underbody near the jacks and, with the aid of small hand winches, used to load the vehicle down onto the jacks securely. Two lateral wire rope constraints were also used. One was located in front of the front axle and one behind the rear axle. These are seen primarily as safety items. The tie down system probably provides the primary lateral constraint.

(The preceding portions of the procedure were described and/or demonstrated using other vehicles. The actual test vehicle was secured on the facility prior to our arrival.)

The facility was then tilted to full displacement (about 26 degrees) and all clearances were checked. A check for excessive lateral motion was also made. Lateral motion was said to typically be less than 2 mm.

The table was returned to zero tilt and the dial gauge and inclinometer were "zeroed." Then the table was moved to full tilt displacement and the first measurements were made. Seven more measurements were made at tilt angles spaced approximately evenly down to about 9 degrees.

The recorded data were typed into a PC by the technician for analysis. In essence, a best linear fit to the eight data points is provided as an initial answer. Deviations of the individual points are given in terms of percentage. The maximum allowed deviation is 0.5%. One point may be discarded and the calculation repeated. If the allowable deviation is still exceeded, the test would be repeated.

These observations suggest that the greatest potential for error in the GM procedure lies in the potential inaccuracy of the vehicle weight. Errors of 50-60 pounds may be in the range of 2% of smaller vehicles. Since the table weight is relatively high and the pivot axis is below "ground," analysis would likely show the sensitivity of c.g. height error to errors in vehicle weight to be somewhat greater than unity. In principle, some improvement might also be gained by locating the lateral displacement transducer closer to the longitudinal and vertical position of the c.g. But the potential for improvement here is small since the displacement is small at relatively large tilt angles (< 2mm at ≈ 26 degrees). It seems likely that the GM procedure yields results which are virtually correct within the conceptual limits of considering the vehicle as a single, rigid body.

Ford Site Visit

The final site visit was to the Ford laboratory in Dearborn, Michigan. This visit took place on March 12, 1990.

The Ford facility, shown in Figure 16, is a "swing" used for measurement of c.g. position and all three moments of inertia. The swing is not a permanent installation; rather a temporary facility setup on a precision bed plate. C.g. measurement is done with the swing configured for pitch inclination. The swing consists of a rectangular (in the plan view) frame made of approximately eight-inch aluminum I-beam. This frame is about 20 feet by 8 feet, and it surrounds the vehicle at roughly "belt line" height. The end rail is removed to drive the vehicle into place on the bed plate. The vehicle rests on its tires on two "cross members" which are U-shaped in the fore-aft view. These attach to the underside of the side rails and run laterally beneath the vehicle. Knife blade bearing fixtures attach to the upper surface of the side rails. The vehicle is constrained

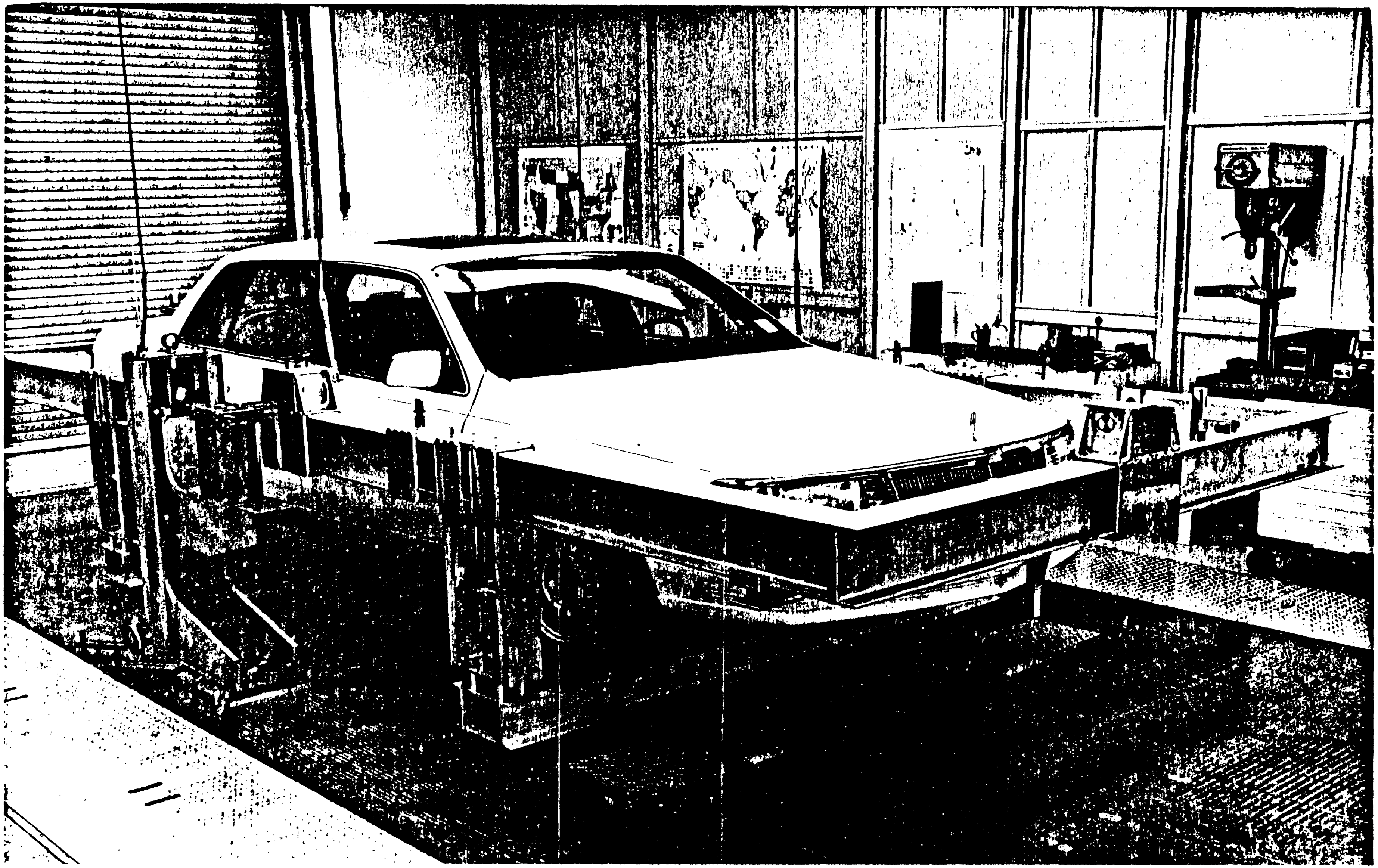


Figure 16. The facility used by Ford for determining c.g. height.

longitudinally with two additional cross rails placed tightly against the front and rear bumper.

The swing is lifted by jacking devices which include the knife blade. Torque is applied with the application of precision dead weights to the front and the rear end rails at positions know precisely with respect to the pivot axis. Pitch deflection is determined by measuring the vertical motion of this same reference point. There is no measurement of longitudinal motion, and there is no vertical constraint of the vehicle. Pitch displacement is on the order of only 1/4 degree. The small displacement and the resulting small load transfer is said to eliminate the need for vertical constraint— suspension friction is believed to provide sufficient constraint for the small load changes.

Measurements are generally made with the vehicle at curb condition —full fluids, no passengers. The vehicle is weighed on a scale facility at a nearby location. Individual wheel weights are measured, and the process is repeated with the vehicle position reversed as a check on the four individual wheel weights. The vehicle is returned to the measurement facility and tire pressures are checked and set prior to making a set of preliminary geometric measurements. (Weighing had been completed prior to our arrival.)

The vehicle was aligned on a dimensional measurement facility bed plate to ±0.06 inch using transit and referencing (in this case) the frame rails near the front and rear. The left- and right-side wheel bases were "balanced" (by steering) using a bar divider referencing the front and rear spindle machining centers. Then the wheelbase was measured on the right side using the facility's transit device. The overall length of the vehicle was measured with the transit system. The vertical position of the four wheel spindles and the left and right door sills were measured. Sill heights were measured at fore and aft end on both sides. Vertical reference marks were made on each of the four fenders. To do this, tape was applied to the fender and a height gage used to apply a mark at 30 inches above the bed plate surface. The transients were used to locate a vertical cross hatch directly above the spindle center. Front and rear tracks were measured with a tape measure.

With the wheel weights and dimensional data in hand, a computer program was used to produce setup parameters. The program identifies the proper longitudinal positions of the axle cross rails and the knife blade fixtures. These parameters are calculated such that i) the vehicle is geometrically centered in the swing and ii) the blades are at the longitudinal position of the combined vehicle/facility c.g.

Three sides of the main frame were assembled and sitting on jack stands on the plate when the vehicle was rolled into place. The rear cross member was then put in place. The vehicle was jacked up and the axle support cross members were accurately located on the side rails using the bar divider. Wheel pads were accurately located laterally on the cross members according to the measured tracks. A system of air bearings allowed the frame to be located accurately under the vehicle before lowering it onto the wheel pads. The front and rear constraint members were then installed loosely.

The blade fixtures were attached to side rails accurately. Jack assemblies, including the pivot axis blade, were moved into place on air bearings and located quite accurately. Left and right side blades were aligned to be co-linear, probably within 0.01 inch.

The whole system was lifted, and the left and right side blade heights were measured and balanced to 0.001 inch.

The vehicle was rolled fore and aft to make the facility level. That is, the right side wheel pad surfaces were at equal heights. The vehicle was then constrained tightly with the front and rear bumper restraint members. All four wheel pad heights and all four fender marks were measured using a height gauge.

The reference/weight fixtures were installed on the front and rear cross members. The height of the reference point was set with a height gauge to be at the same height as the blades.

Four "tilts" were then done— two with weights at the front and two with weights at the rear. Weights of 1.41 and 2.41 pounds were used. The vertical position of the reference points was measured with a height gauge. The largest displacements were on the order of 0.5 inches, or about 0.25 degrees of pitch.

Data reduction was done by computer program and yielded results from the four trials within 0.06 inches. The average of the two 1.41 lb trials was used as the answer. It was said these runs would produce the better results since they would involve smaller tire and suspension deflections.

These observations suggest that the most serious fault with the Ford procedure is the lack of attention to the longitudinal motion of the vehicle. The very small pitch motions used do not negate the need for measuring this motion and including its influence in the data reduction process. Small pitch motions certainly mean that the longitudinal motion of the vehicle are similarly small, but equation 1 (presented earlier) reveals that, for small angles, the sensitivity of measurement error to longitudinal motion is inversely proportional to the amount of tilt motion. For the Ford procedure, where tilt motions are on the order of 0.25 degrees, equation 1 indicates that $\varepsilon \approx 230\,\Delta$. Thus even very small motions can not be ignored. For example, a longitudinal movement of the vehicle of only 0.001 inch which is not considered would produce a c.g. height measurement error of about 0.23 inches.

Measurement Results in Light of the Site Visit Observations

The measurement results most germane to this discussion were presented previously in Figure 8. These data are repeated here, for convenience, in Figure 17. Our interpretation of the results shown in the figure, in light of the observations made during the site visits, is as follows.

Based solely on the site visit data, our general expectation would have been that the c.g. height values produced at the GM labs would have been the lowest, and probably the most accurate of the four sets of measurements. This expectation comes from our observations that (i) motion of the vehicle relative to the pivot axis is generally the most powerful, non-random error source, (ii) this error source causes predictions of c.g. position which are too high, and (iii) GM operates the stiffest facility, uses the stiffest vehicle constraints, and accounts for measured vehicle motion in the data reduction process. After the GM results, our expectation would be that the NHTSA results would be higher, the Ford results would be higher still, and the Chrysler results would be highest. NHTSA's facility is rather flexible, and while the effort to account for vehicle motions is admirable, it might well be incomplete. Also, the transduced vehicle motion is probably less than the actual c.g. motion. The Ford facility is fairly stiff, but the small vehicle motions are ignored. And finally, the Chrysler procedure ignores the motion of the vehicle c.g. relative to the spindle axes, which serve as the pivot, and are probably rather compliant. Our expectation would be that the other recognized source of error in the Chrysler procedure —misalignment of the linear bearings— would not overcome the error due to pivot motion.

Figure 17 tends to support all these expectations with the exception of the Chrysler results. We tend to believe that we have simply "missed something" in the Chrysler method that also tends to produce low predictions. It continues to seem unlikely that the error deriving from bearing misalignment could, by itself, overcome the error due to c.g. motion relative to the pivot. Something else is probably involved. We have noted that the weight data reported by Chrysler was consistently high by a small percentage, but recalculation using corrected weight data (by Chrysler) did not produce significant changes in the results. We must also point out that variations in the measured reference heights at the several labs do not tend to explain or account for the variations seen in Figure 17.

Putting aside the Chrysler results, the remainder of Figure 17 is as expected. The notion that the GM results are "correct" is enhanced by the GM prediction of the c.g. height of the buck. This result is right on our expectations based on c.g. height of the buck calculated from the known weights and geometry of its individual parts.

So as not to overstate the importance of results for measurement of the buck, we also note that the NHTSA result for the buck is nearly as accurate as the GM result. However,

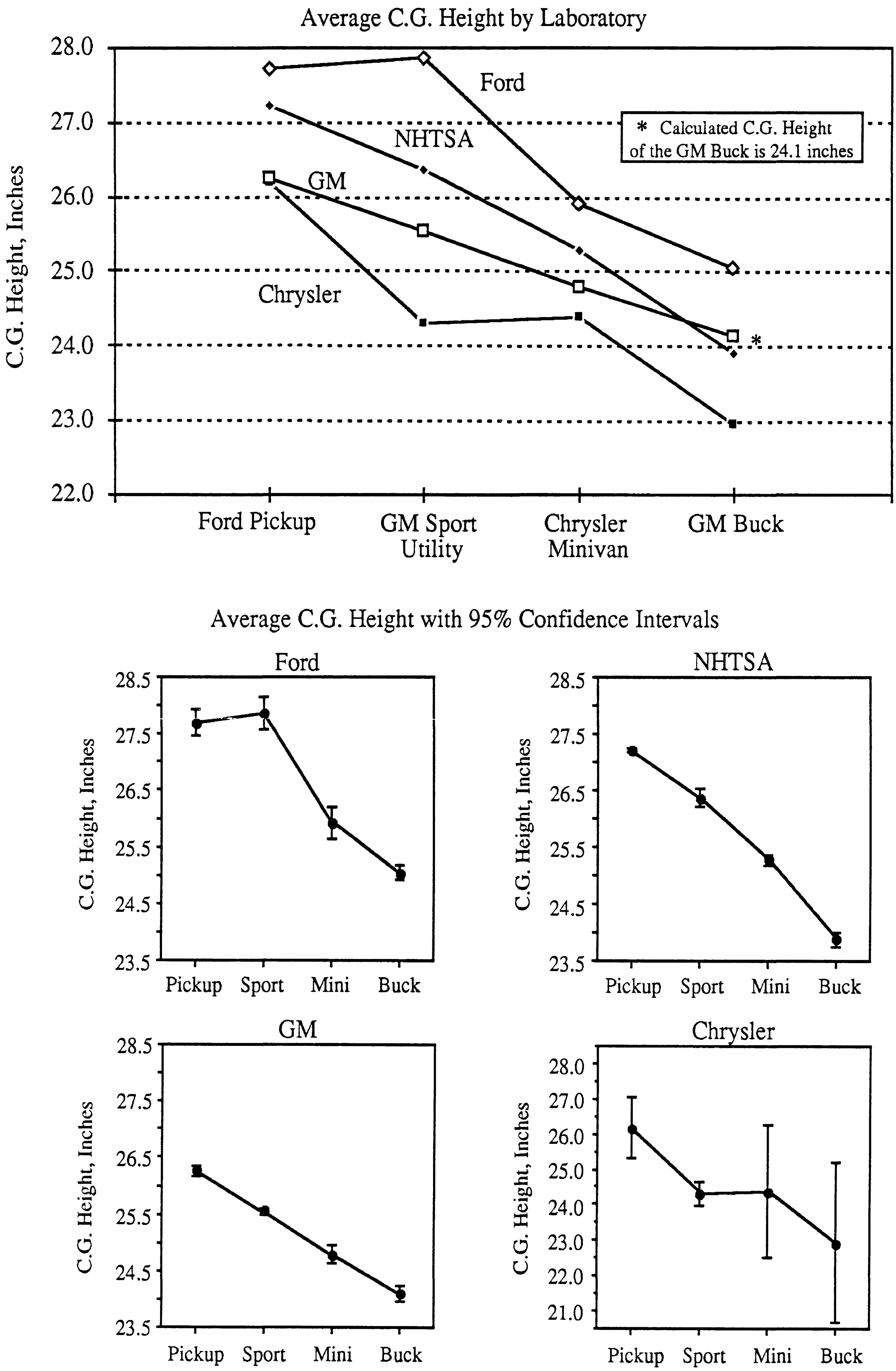


Figure 17. Center of gravity height measurement results for the four test vehicles presented by laboratory. (A repeat of Figure 8.)

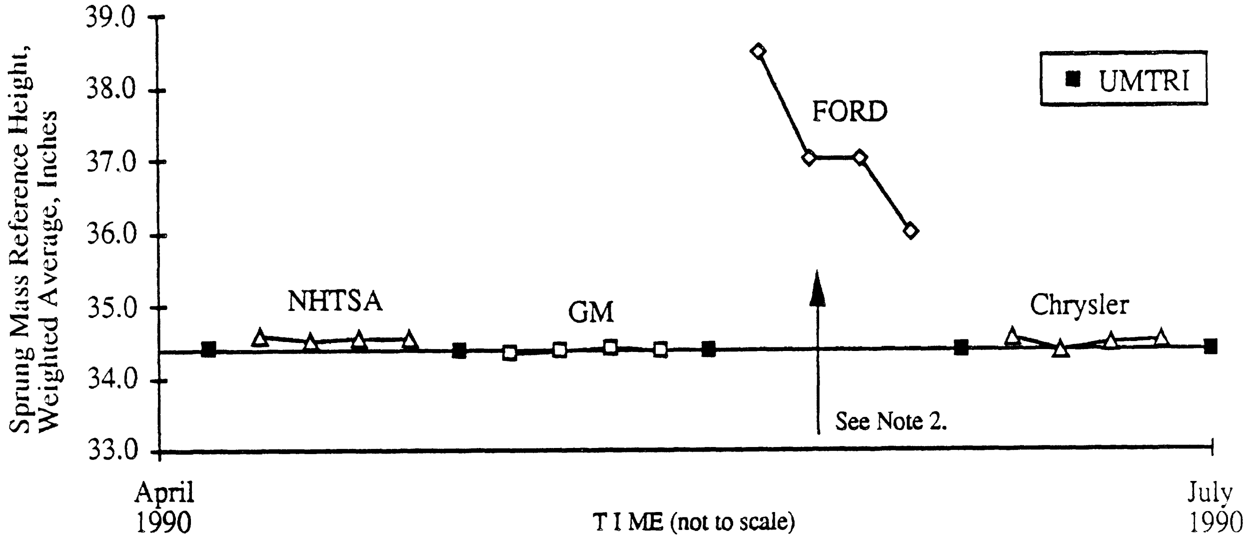
these two labs get significantly different results for all other vehicles. The conclusion must be that the ability to accurately determine the c.g. height of the buck is just that, and does not necessarily imply the ability to accurately determine the c.g. height of a real vehicle. Real vehicles have a whole set of compliances that do not exist in the buck and may contribute to errors in the measurement of vehicles.

We also point out, with some emphasis, that "correct" must be interpreted within the inherent limits of considering the whole vehicle as one, rigid body. In fact, the "real" c.g. height of the real test vehicles is probably lower than the GM measurements. During the GM procedures, as well as during all the others, we can be certain that the drive train, for example, moved on its flexible mounts and shifted "downhill." Other masses on other compliant mounts also shifted. These motions surely produced a translation of the composite c.g. of the vehicle. Thus, the measured c.g. height should be viewed as an "equivalent" c.g. height. It is "equivalent," in that it is the c.g. height of the imagined rigid vehicle, which would result in the same load transfer response to horizontal acceleration (lateral in the case of GM, and longitudinal in the case of the other labs) as the real vehicle would exhibit.

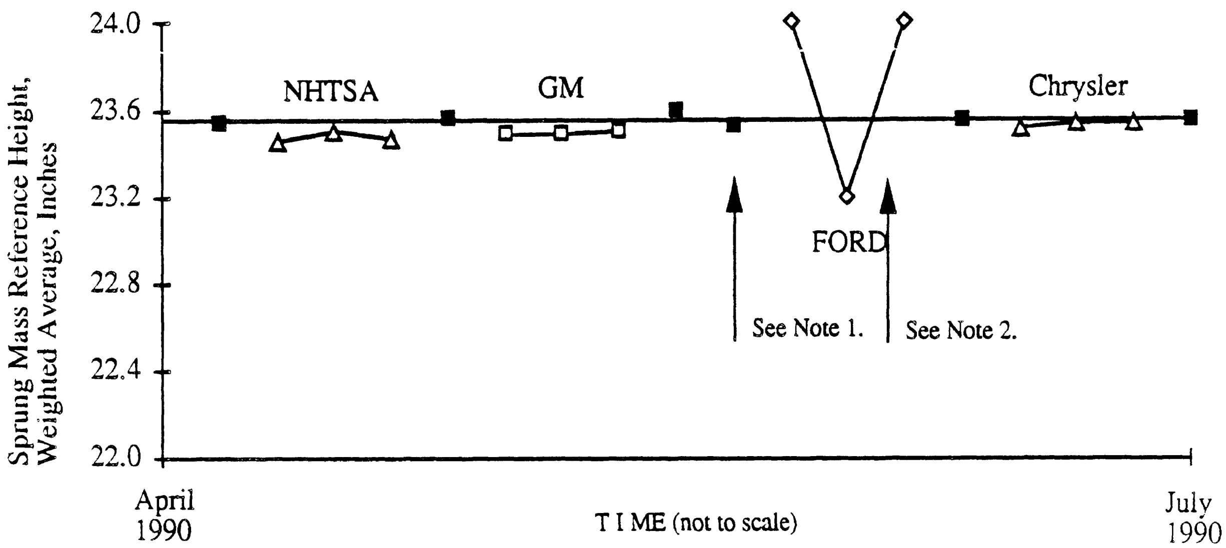
In general, this discussion should highlight the fact that c.g. height determination is not at all a simple matter. Subtle error sources abound, and different measurement procedures, each undertaken with great care, can produce significantly different results. Nevertheless, the results of Figure 17 show better agreement between laboratories than might be expected. Perhaps more importantly, this discussion, and the observed relationship between the results of the several laboratories suggest that, were appropriate improvements put in place, the participating laboratories might be expected to obtain very similar results.

APPENDIX

Ford Pickup



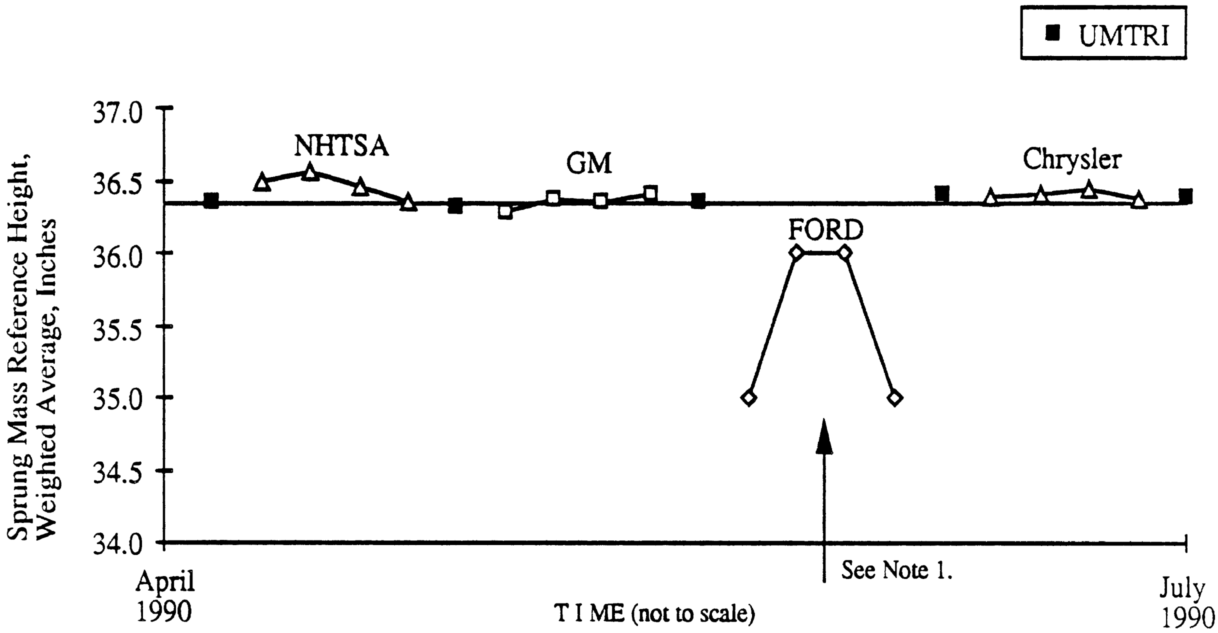
G.M. Buck



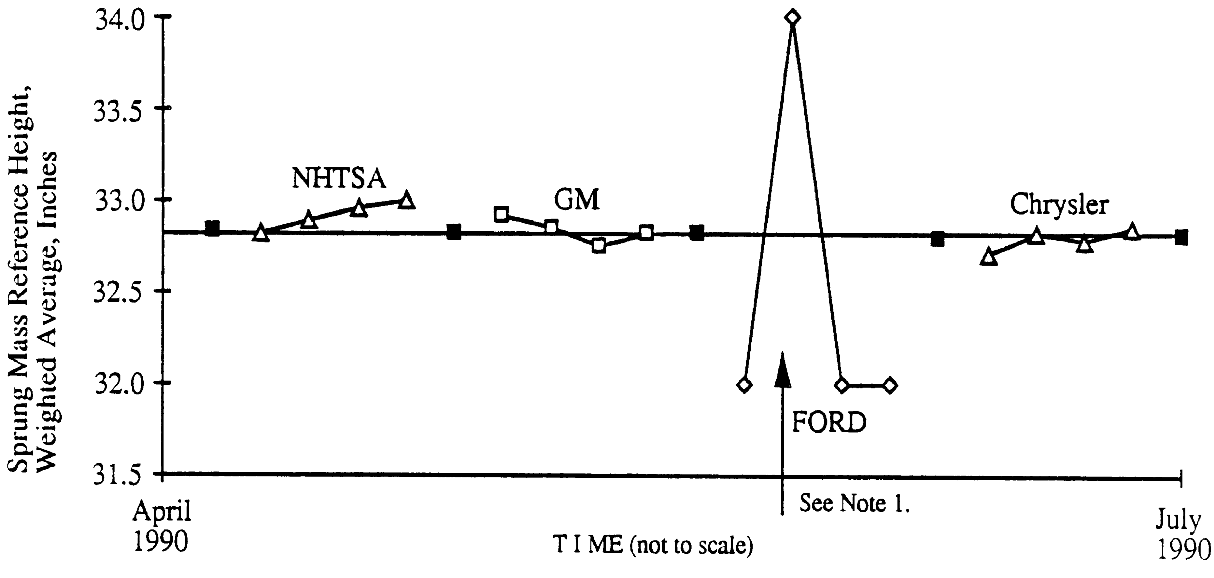
Notes:
1. UMTRI measurements for the third test of the Buck were retaken because of obvious errors in the reference height measurement.
2. The erratic nature of the Ford data for this measure is a result of misinterpretation of intent. Ford measured and reported the position of their own reference marks rather than those of UMTRI. These marks were different for each repeat measurement.

Figure A1. Review of Sprung Mass Reference Height for the Ford Pickup and the GM Buck.

GM Sport Utility



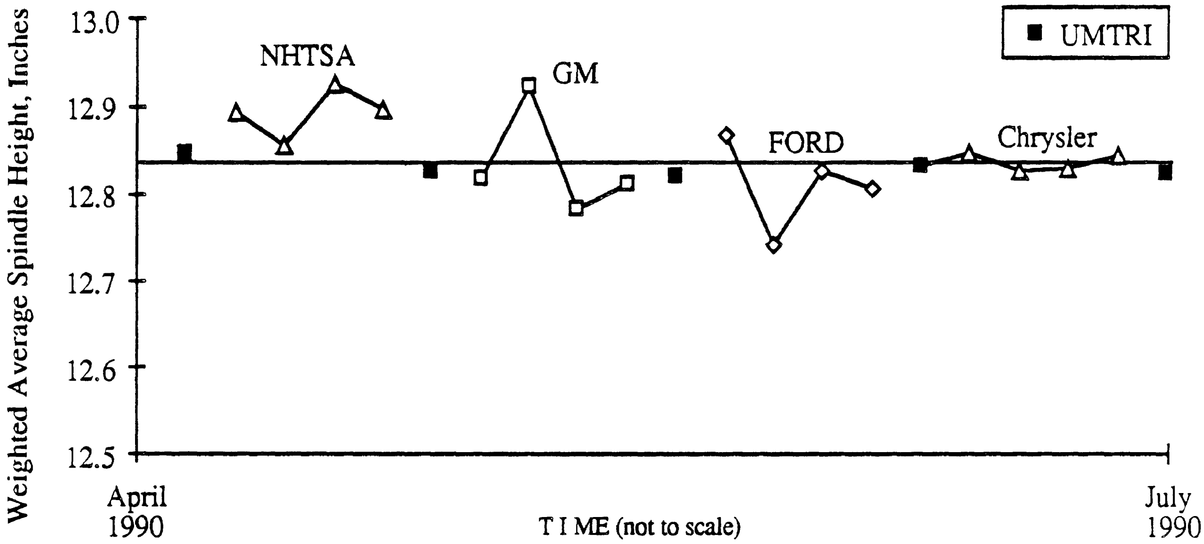
Chrysler Mini-Van



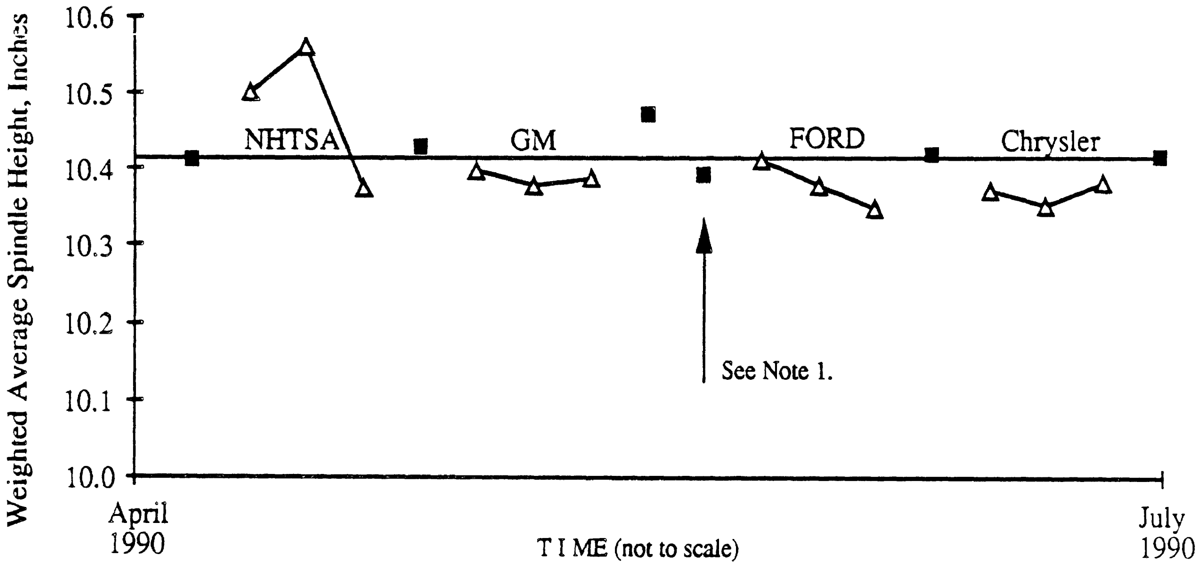
Notes: 1. The erratic nature of the Ford data for this measure is a result of misinterpretation of intent. Ford measured and reported the position of their own reference marks rather than those of UMTRI. These marks were different for each repeat measurement.

Figure A2. Review of Sprung Mass Reference Height for the GM Sport Utility and the Chrysler Mini-van.

Ford Pickup



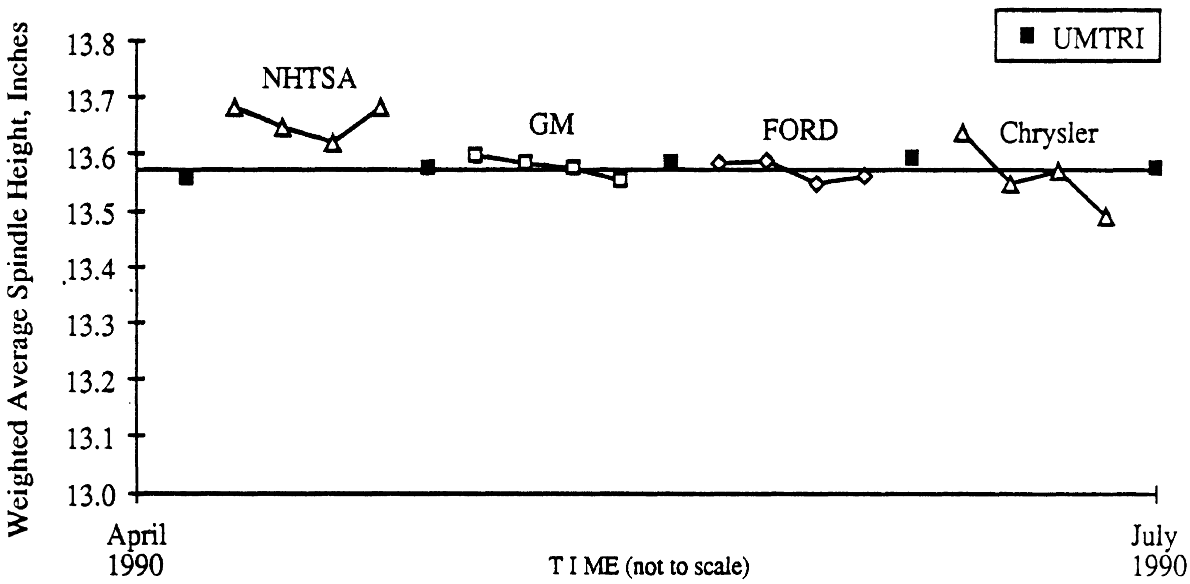
G.M. Buck



Notes: 1. UMTRI measurements for the third test of the Buck were retaken because of obvious errors in the reference height measurement.

Figure A3. Review of Spindle Height Measurements for the Ford Pickup and the GM Buck.

GM Sport Utility



Chrysler Mini-Van

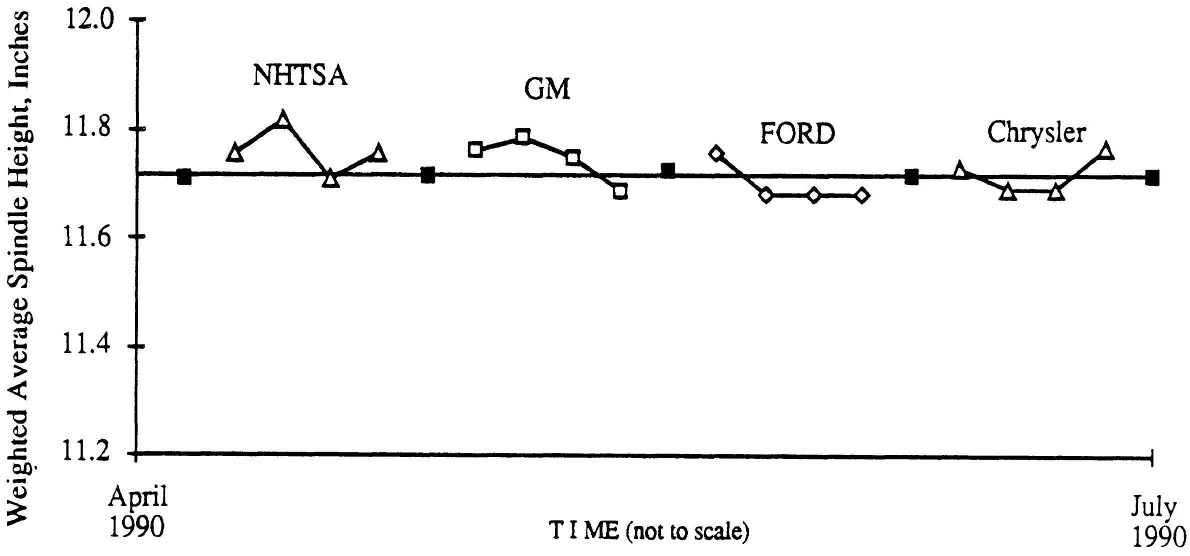
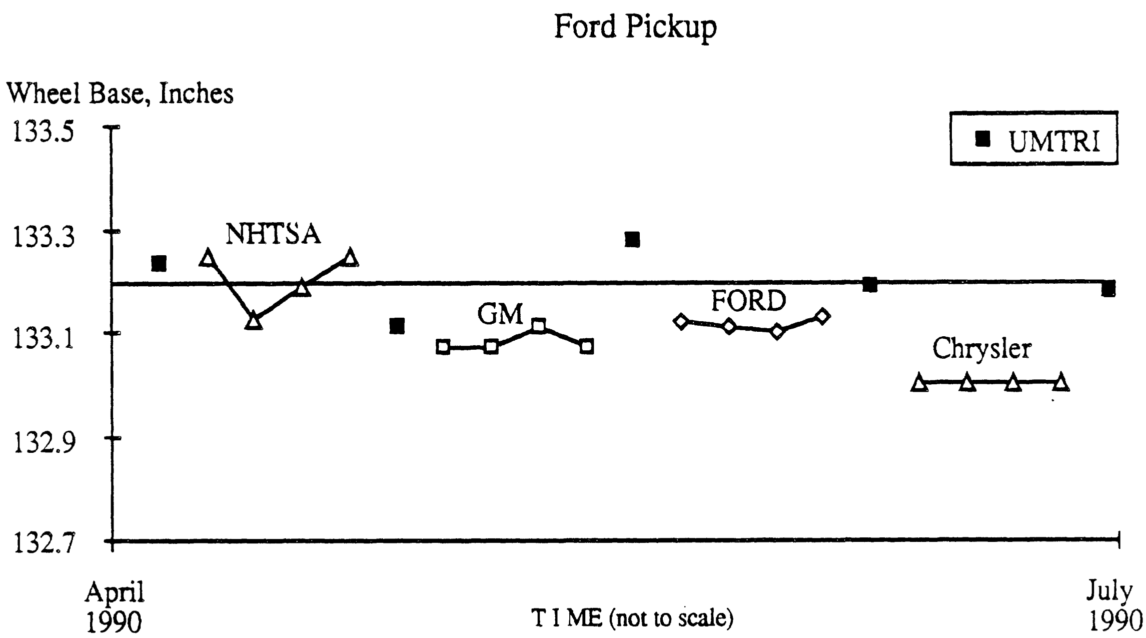
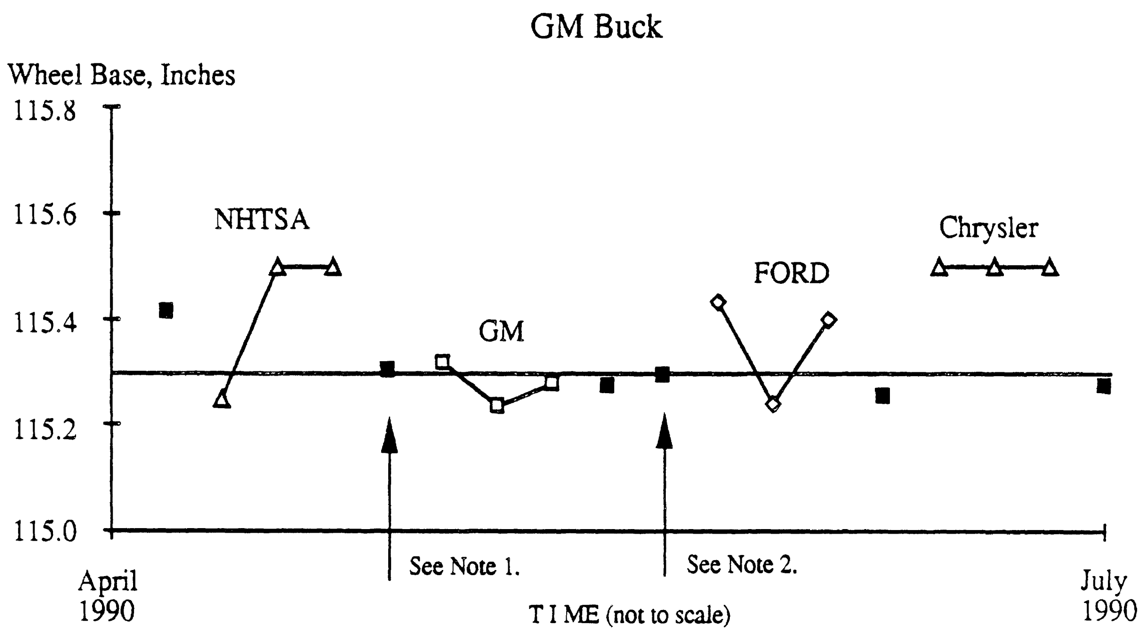


Figure A4. Review of Spindle Height Measurements for the GM Sport Utility and the Chrysler Mini-van.

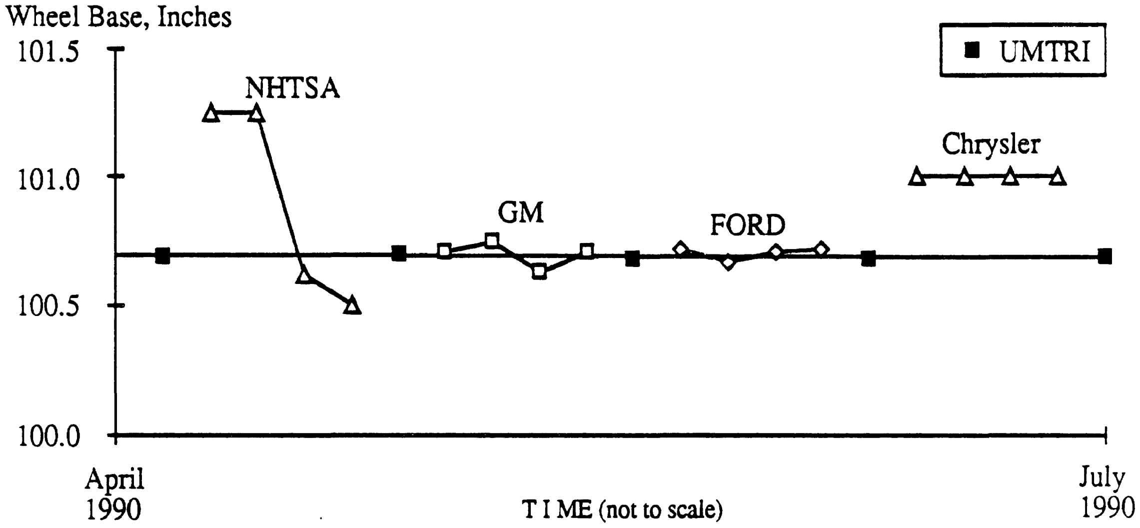




Notes: 1. The mounting bolts for the front axle of the Buck were found to be "hand tight", allowing small motions of the axle. The bolts were tightened at this time.
2. UMTRI measurements for the third test of the Buck were retaken because of obvious errors in the reference height measurement.

Figure A5. Review of Wheel Base Measurements for the Ford Pickup and the GM Buck.

GM Sport Utility



Chrysler Mini-van

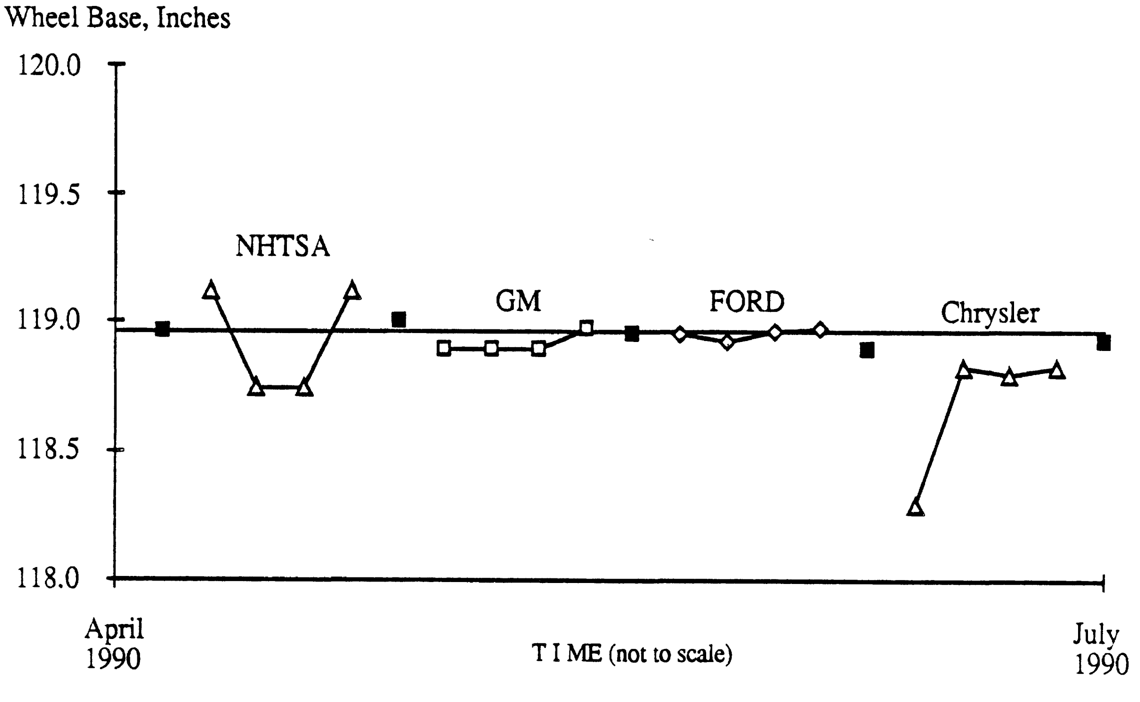
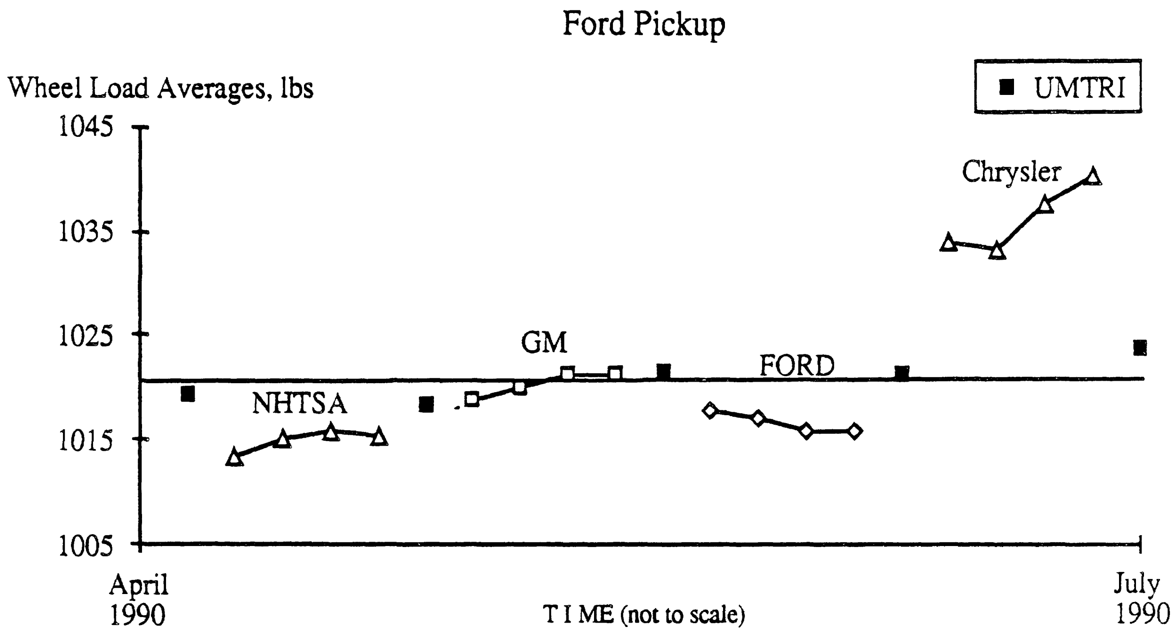
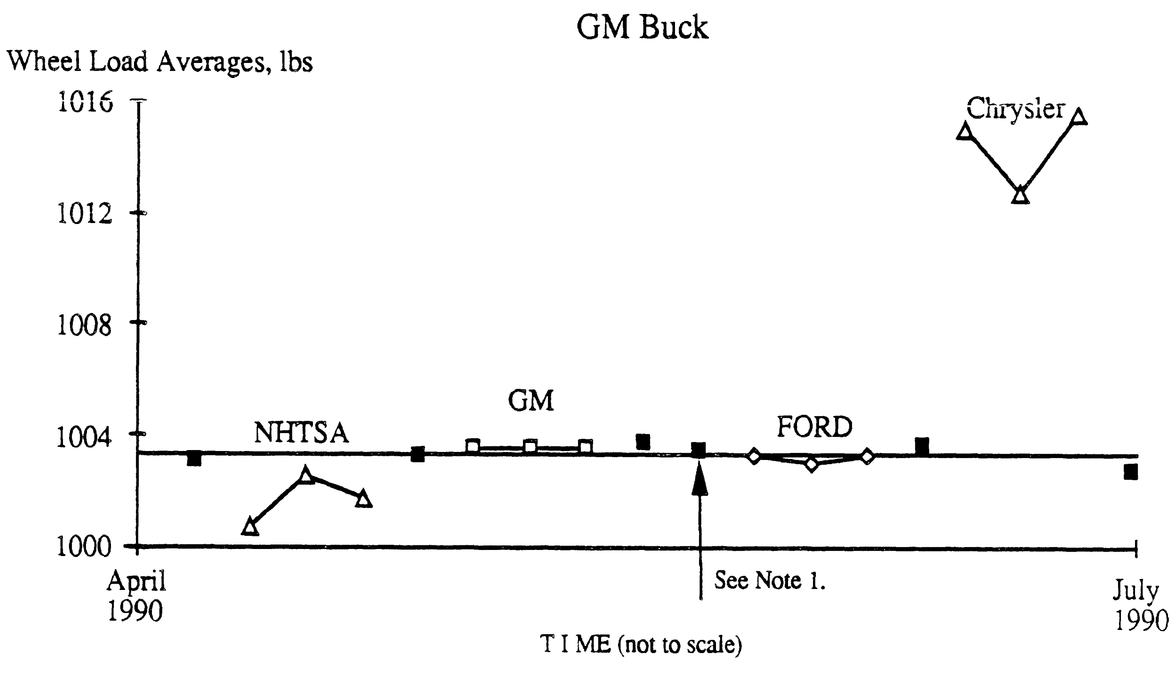


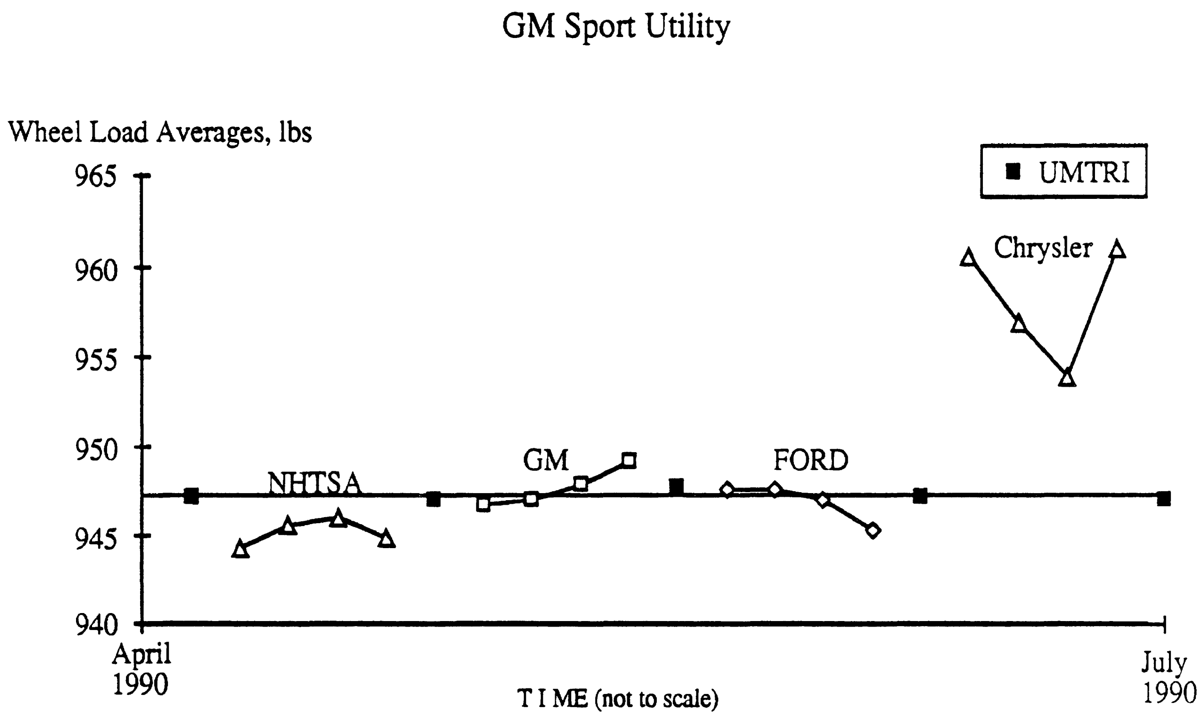
Figure A6. Review of Wheel Base Measurements for the GM Sport Utility and the Chrysler Mini-van.





Notes: 1. UMTRI measurements for the third test of the Buck were retaken because of obvious errors in the reference height measurement.

Figure A7. Review of Wheel Load Measurements for the Ford Pickup and the GM Buck.



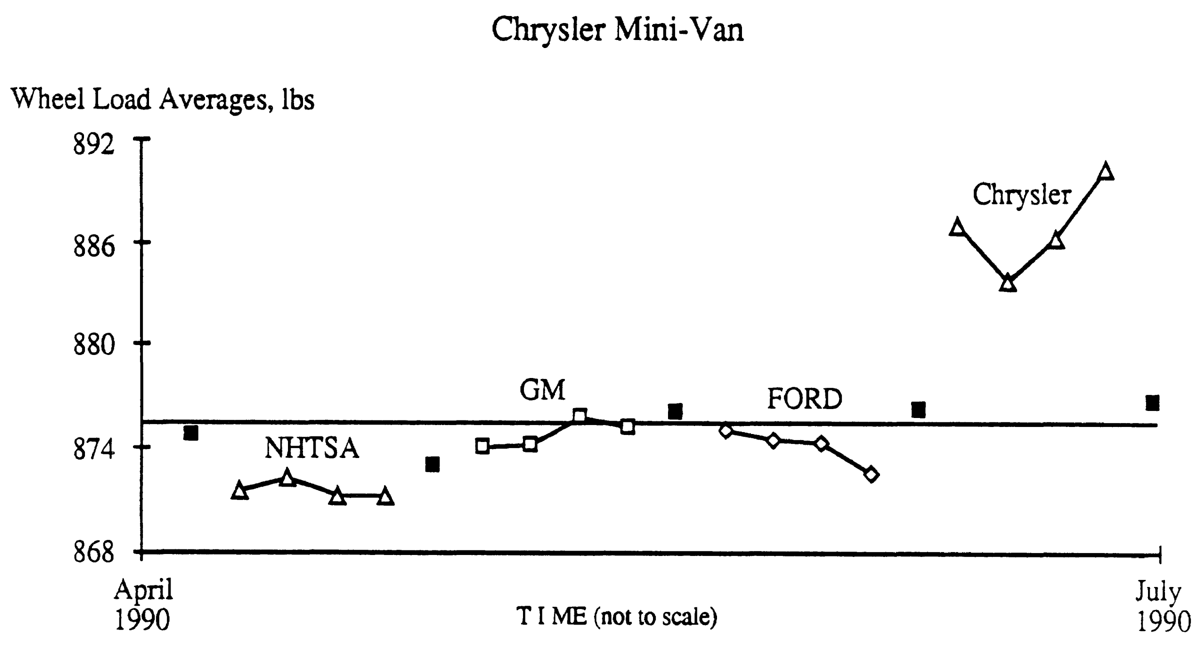
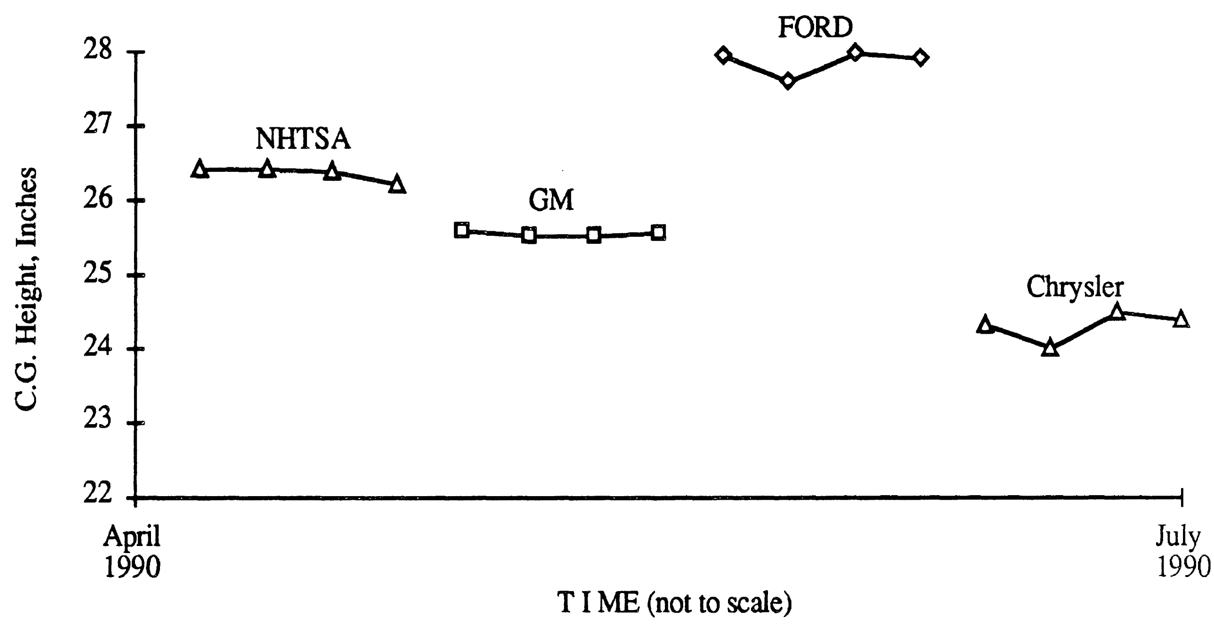


Figure A8. Review of Wheel Load Measurements for the GM Sport Utility and the Chrysler Mini-van.

GM Sport/Utility



Chrysler Mini-Van

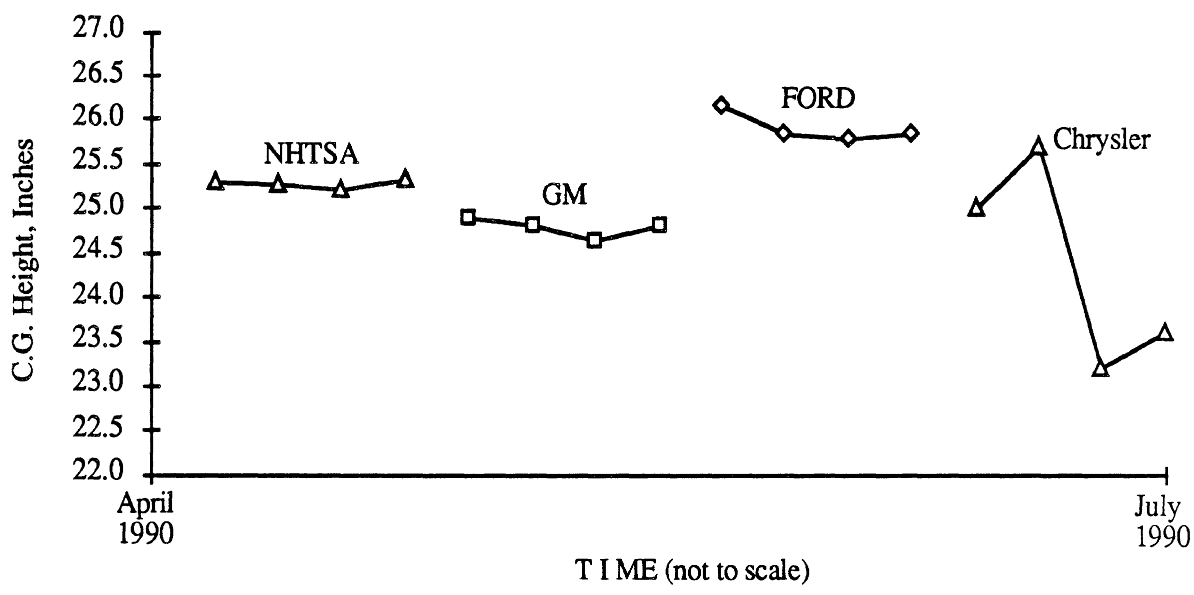
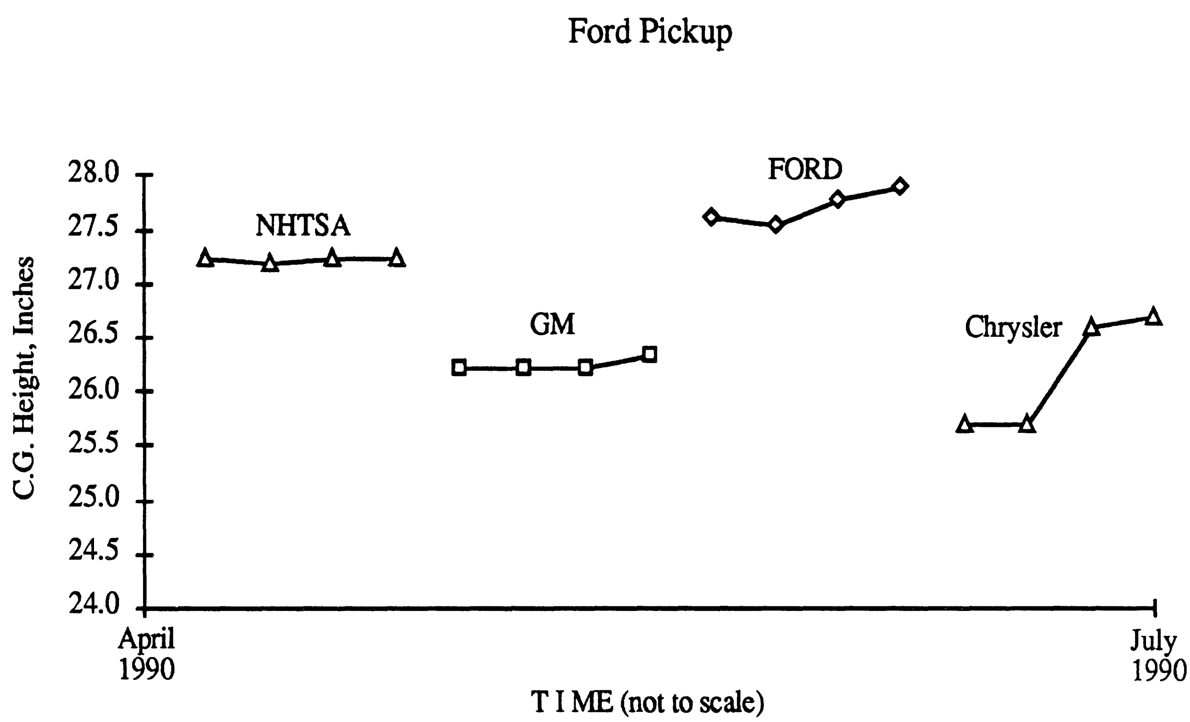


Figure A9. C.G. Heights for the GM Sport Utility and the Chrysler Mini-van.



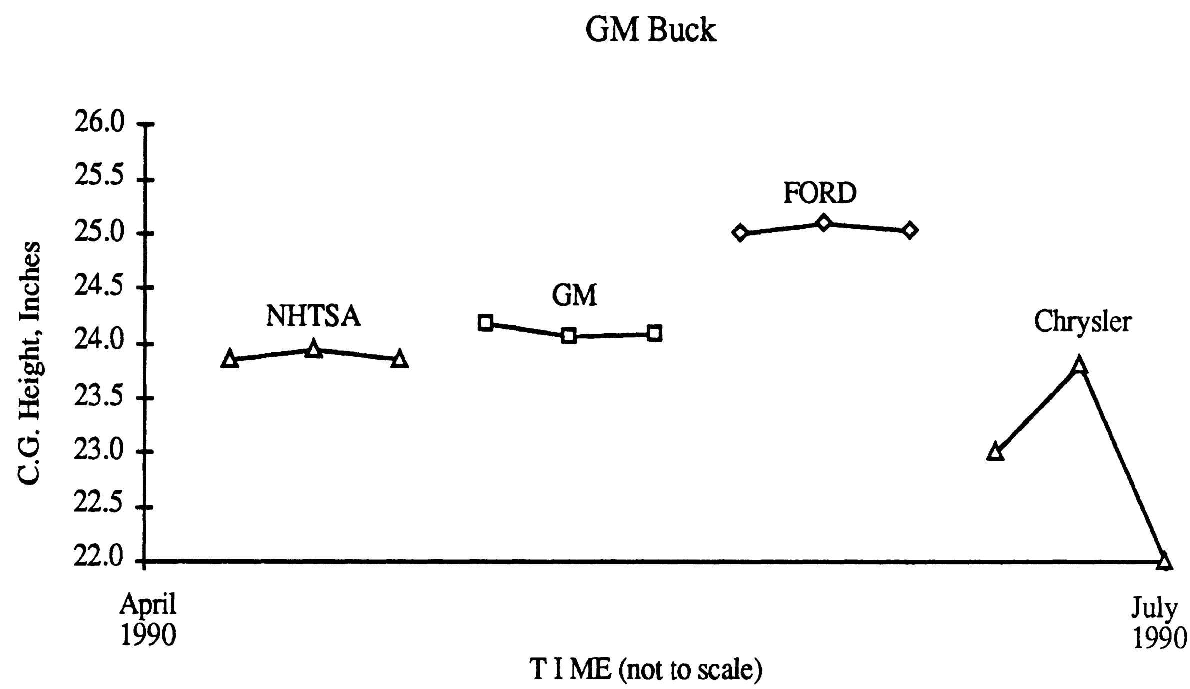


Figure A10. C.G. Heights for the Ford Pickup and the GM Buck.

Table A1. Center of Gravity Measurement Program

Test Number	Rep. Number	Lab Site	Test Vehicle	C.G. (inches)	C.G. (mm)
1	1	NHTSA	Pickup	27.23	692
2	1	NHTSA	Buck	23.85	606
3	1	NHTSA	Sport/Utility	26.44	672
4	1	NHTSA	Minivan	25.29	642
5	2	NHTSA	Buck	23.94	608
6	2	NHTSA	Sport/Utility	26.41	671
7	2	NHTSA	Minivan	25.27	642
8	2	NHTSA	Pickup	27.19	691
9	3	NHTSA	Minivan	25.21	640
10	3	NHTSA	Sport/Utility	26.39	670
11	3	NHTSA	Pickup	27.23	692
12	3	NHTSA	Buck	23.86	606
13	4	NHTSA	Pickup	27.22	691
14	4	NHTSA	Sport/Utility	26.22	666
15	4	NHTSA	Minivan	25.33	643
1	1	GM	Pickup	26.22	666
2	1	GM	Buck	24.17	614
3	1	GM	Sport/Utility	25.59	650
4	1	GM	Minivan	24.88	632
5	2	GM	Buck	24.06	611
6	2	GM	Sport/Utility	25.51	648
7	2	GM	Minivan	24.80	630
8	2	GM	Pickup	26.22	666
9	3	GM	Minivan	24.65	626
10	3	GM	Sport/Utility	25.51	648
11	3	GM	Pickup	26.22	666
12	3	GM	Buck	24.09	612
13	4	GM	Pickup	26.34	669
14	4	GM	Sport/Utility	25.55	649
15	4	GM	Minivan	24.80	630

Table A1 Cont. Center of Gravity Measurement Program

Test Number	Rep. Number	Lab Site	Test Vehicle	C.G. (inches)	C.G. (mm)
1	1	Ford	Pickup	27.61	701
2	1	Ford	Buck	24.99	635
3	1	Ford	Sport/Utility	27.95	710
4	1	Ford	Minivan	26.17	665
5	2	Ford	Buck	25.09	637
6	2	Ford	Sport/Utility	27.61	701
7	2	Ford	Minivan	25.84	656
8	2	Ford	Pickup	27.54	700
9	3	Ford	Minivan	25.78	655
10	3	Ford	Sport/Utility	27.98	711
11	3	Ford	Pickup	27.77	705
12	3	Ford	Buck	25.03	636
13	4	Ford	Pickup	27.88	708
14	4	Ford	Sport/Utility	27.91	709
15	4	Ford	Minivan	25.85	657
1	1	Chrysler	Pickup	25.70	653
2	1	Chrysler	Buck	23.00	584
3	1	Chrysler	Sport/Utility	24.30	617
4	1	Chrysler	Minivan	25.00	635
5	2	Chrysler	Buck	23.80	605
6	2	Chrysler	Sport/Utility	24.00	610
7	2	Chrysler	Minivan	25.70	653
8	2	Chrysler	Pickup	25.70	653
9	3	Chrysler	Minivan	23.20	589
10	3	Chrysler	Sport/Utility	24.50	622
11	3	Chrysler	Pickup	26.60	676
12	3	Chrysler	Buck	22.00	559
13	4	Chrysler	Pickup	26.70	678
14	4	Chrysler	Sport/Utility	24.40	620
15	4	Chrysler	Minivan	23.60	599