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16. Abstract

The study was performed by UMTRI for the Motor Vehicle Manufacturers Association. The study was undertaken in order to investigate the sensitivity of tilt table measurement results to variables associated with the methodology and/or facility. To do this, one hundred and thirteen tilt table measurements of a single test vehicle were conducted at one facility. A number of facility and procedural parameters were deliberately altered during the testing to determine the sensitivity of the method to these changes. The results of the program showed: (1) Changes in trip rail geometry (which included the use of one-inch and two-inch high rails and locations of the rails at zero, one, or two inches from the tires) altered measurement results by as much as five percent. (2) Significant changes in surface friction alone appeared to produce a change of slightly over one percent. (3) Caution should be used when interpreting data signals from clinometers mounted on the test vehicle. (In the vicinity of the static roll stability limit, small accelerations of the vehicle can significantly influence these signals and may lead to erroneous conclusions.) (4) Very slow table speeds in the vicinity of the stability limit are advisable. Behavior in the immediate vicinity of the static stability limit is dominated by highly non-linear events such as encountering suspension stroke limits and tire liftoff. The quality of vehicle response in the region may depend on the particular non-linearities of the vehicle. This study did not address the relevance of tilt table measurements to "real world" rollover events.

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Sensitivity Analysis of the Tilt Table Test Methodology

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The Motor Vehicle Manufacturers Association
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The University of Michigan
Transportation Research Institute

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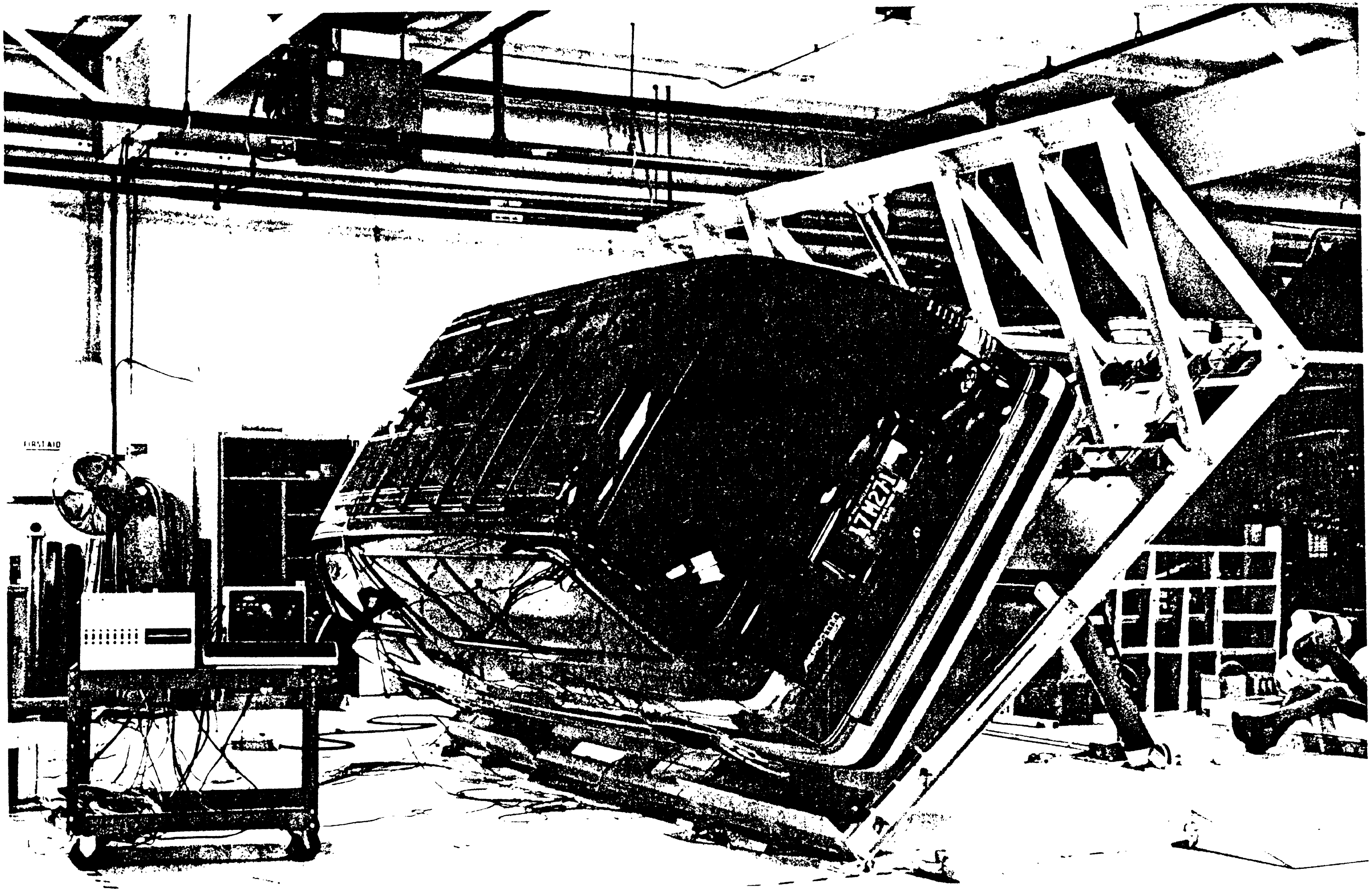
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SUMMARY

This study was conducted to examine the sensitivities of the tilt table test method as applied to light truck-like vehicles. Specifically, the purpose was to investigate the sensitivity of tilt table measurement results to variables associated with the methodology and/or facility. The study was performed by the University of Michigan Transportation Research Institute (UMTRI) for the Motor Vehicle Manufacturers Association (MVMA).

The purpose of the tilt table test is to estimate the static roll stability limit of the test vehicle. This is done by placing the vehicle on a rigid surface (the tilt table) and inclining the surface in roll to determine the minimum inclination angle (ϕ) required to cause rollover of the vehicle. When the table is tilted, the component of gravity acting perpendicular to the table surface is ($g \cos\phi$) and the component acting parallel to the table surface is ($g \sin\phi$), where "g" is the gravitational constant. This loading condition is taken to be analogous to a steady-state (that is, static) turning condition wherein the vehicle is subject to gravity loading of 1 g perpendicular to the ground and steady-state lateral acceleration loading parallel to the ground. Recognizing that the loads on the vehicle in the tilt table test are "scaled down" by a factor of ($\cos\phi$) relative to the static loadings they represent, the represented static lateral acceleration is ($g \sin\phi/\cos\phi$) or ($g \tan\phi$). Thus, ($\tan\phi$) is taken to represent static lateral acceleration in gs, and the tangent of the minimum tilt angle required to rollover the vehicle is taken as an estimate of the static roll stability limit of the vehicle. The tilt table measurement, that is, the tangent of the minimum tilt angle required to rollover the vehicle, is refereed to herein as "the tilt table ratio" or TTR.

The quality of TTR as an estimate of static roll stability depends, in part, on how closely ($\cos\phi$) approximates unity. In the tilt table experiment, both the vertical and lateral loading of the vehicle are reduced by the factor ($\cos\phi$) relative to the static loads they are meant to represent. Because of the reduced vertical loading, the vehicle may rise on its compliant tires and suspensions relative to its normal ride height, resulting in a higher center of gravity position and, possibly, an unrealistically low estimate of the static roll stability limit. At the same time, static lateral loading is also reduced by the factor ($\cos\phi$). This may result in compliant lateral and roll motions of the vehicle that are unrepresentatively small, tending to produce an unrealistically high estimate of the static roll stability limit. For vehicles whose static roll stability limit is in the range of 1 g, either of these opposing mechanisms may be significant, since the tilt angles involved are approximately 45 degrees. At such an angle, the lateral and vertical loads on the test vehicle are both only about 70 percent of the "real" loading components that they represent.

Fully recognizing this limitation, the practical values of simplicity and repeatability may still make the tilt table test a very attractive method for estimating the static roll stability limit of a vehicle.

The goal of this project was to quantify the sensitivity and repeatability of the tilt table procedure experimentally. To do this, one hundred and thirteen tilt table measurements of a single test vehicle were conducted. A number of facility and procedural parameters were

deliberately altered during the testing to determine the significance of these changes on the results. The test program was conducted on the tilt table facility operated by DST of Romulus, Michigan. Tests were conducted under the direction of UMTRI personnel. The test vehicle was a Ford Aerostar van.

The matrix of test conditions was structured to investigate five general areas that were presupposed to influence tilt table measurement results. The areas of interest were: (1) facility and vehicle placement geometry, (2) facility rigidity, (3) vehicle lateral constraint, (4) dynamics, and (5) hysteresis. Each of these issues is outlined below.

Facility and vehicle placement geometry. It is the premise of the method that the static lateral and vertical loadings experienced by the test vehicle are (g $\sin\phi$) and (g $\cos\phi$), respectively. This premise is based on the assumption that certain parallel and/or orthogonal relationships exist between the tilt axis, the tilt table surface, and the longitudinal axis of the vehicle. The test result depends, in part, on the accuracy with which these relationships are established. The test matrix included provisions to examine the sensitivity of results to reasonable levels of "error" in the geometry of the facility and the orientation of the test vehicle.

Facility rigidity. Facility rigidity is basically a sub-component of geometry. That is, if the assumed geometric relationships are to be maintained throughout the test, they require an adequate level of facility rigidity. The test matrix included elements to examine the influence of facility compliance on test results.

Vehicle lateral restraint. In the tilt table procedure, lateral forces are developed at the tire/road interfaces in opposition to the lateral component of gravitational loading. At higher tilt table angles, tire friction alone may not be adequate to resist lateral motion and prevent the vehicle from sliding on the table surface. Accordingly, a "trip rail" may be placed against the side-wall of the low-side tires to help sustain the needed lateral force. However, the height of the lateral constraint force (as well as the height of the vehicle's center of gravity) is important when determining the TTR. When a trip rail is used, tire/road friction, tire lateral stiffness, and trip rail geometry (height, shape, location) all combine to establish the representative height of the constraint force. The influence of tire/road friction (on the low-side tires), and trip rail height and placement were examined both individually and together.

Dynamics. The tilt table method is intended to estimate a *static* stability limit. The approach is to increase tilt angle so slowly as to effect a quasi-static experiment. Response of the vehicle in roll is very slow when it approaches and passes through the static rollover threshold. The appropriate table speed to achieve a quasi-static experiment depends on the properties of the vehicle being tested, as well as on certain response properties of the instrumentation system. The test program included elements to examine the influence of tilt table rate and the properties of the instrumentation and data handling system.

Hysteresis. Static roll stability is largely dependent on the height of the vehicle's center of gravity. Hysteretic effects of the vehicle tire and suspension systems can appreciably alter the height of the center of gravity, at least at the outset of the experiment. There is a potential concern that hysteretic effects might play a larger part in the tilt table experiment than in real life because the tires are not rolling forward in the tilt table experiment. The test matrix included provisions for investigating the influence of tire-to-table surface friction (on the high-side tires) and initial vehicle configurations.

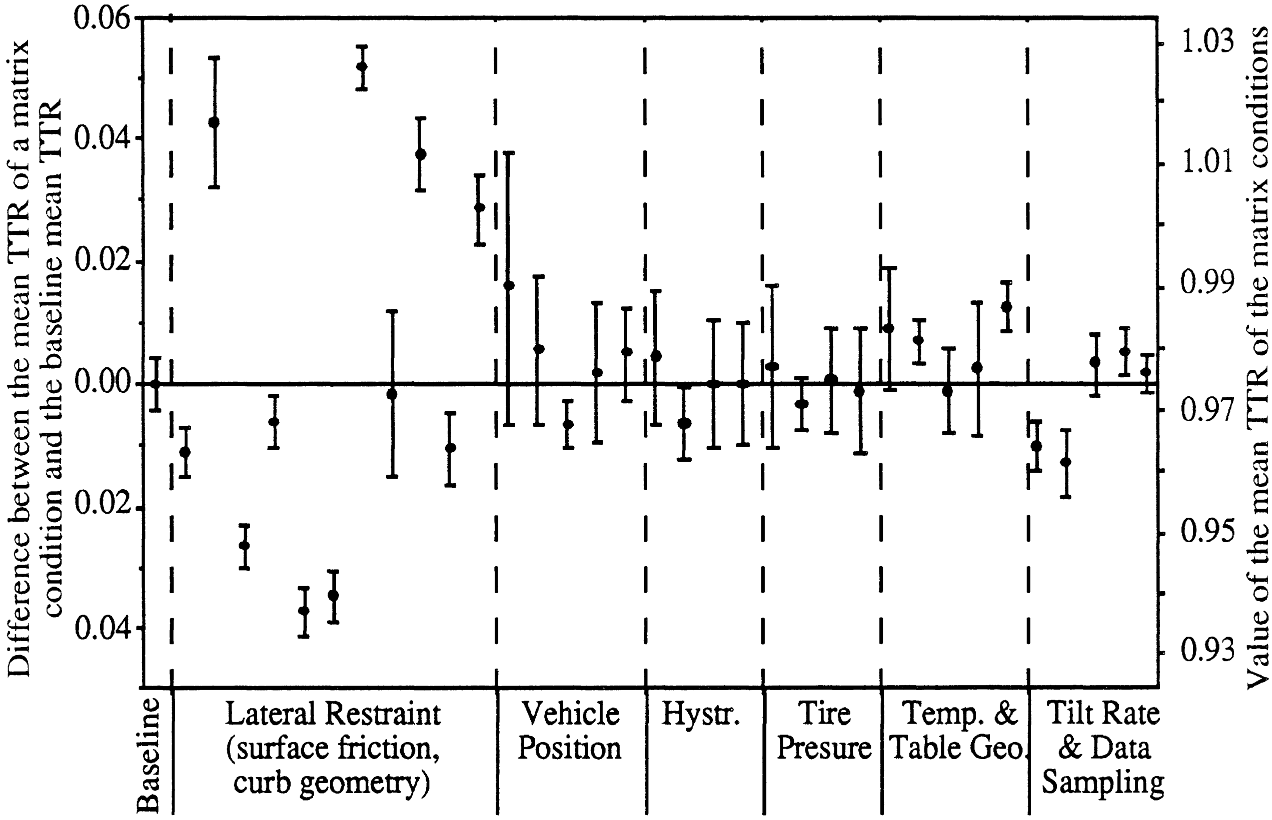
The testing program was structured around a baseline condition of twelve different variables. Thirty-three off-baseline test conditions were identified in the matrix. (Often more than one change was made in a particular variable.) Most test conditions were defined by changes of a single variable away from the baseline condition. In some cases, when synergistic effects were expected, multiple variables were changed simultaneously. In general, the magnitude of the changes were selected to cover rather large "errors" that might be made within reasonable experimental practice.

Three repeats of each of the off-baseline tests were conducted. An entire pass through the test matrix was completed before the next pass was undertaken. A baseline test was conducted on each day of testing. (Eleven baseline tests were eventually conducted.) The order of testing was random, including the position of the baseline test within a testing day. Between each test run, with the exception of one test condition, the test vehicle was completely removed from the tilt table and then reinstalled.

The figure on the following page reviews the statistical results of the testing program. The figure is intended to show whether a given, off-baseline test condition produced a significantly different result than the baseline test condition. The left-hand scale shows the difference between the mean of the TTR measured in the baseline runs and the mean measured in the off-baseline runs. This value is plotted, along with its 95 percent confidence interval, for each of the individual test conditions. (In this summary, only the major groupings of test conditions are identified on the figure.) If the bar indicating the confidence interval for a particular off-baseline condition crosses the zero-difference line, then the observed value of the TTR measured in this condition is not significantly different from the TTR measured in the baseline condition. The scale on the right side of the figure shows the absolute value of the measured TTR. (This scale is applicable only to the mean values, not to the confidence intervals.) The mean TTR for the baseline measurements was 0.974, and the mean values of all of the test conditions fell in the range of 0.93 to 1.03.

The figure indicates that, in general, the changes in test parameters that were examined in this program produced changes in the measurement results that were either insignificant, or if significant, resulted in changes of only about 1% of baseline. The only exceptions to this are associated with changes in the vehicle lateral constraint mechanism—the geometry of the restraining trip-rail and the friction quality of the table surface. Changes in trip rail geometry (which included the use of one-inch or two-inch high rails and locations of the rails of zero, one, or two inches from the tires) altered the measurement result as much as five percent. A significant change in surface friction alone appeared to produce a change of slightly over one percent in the mean of the observed TTR. The observed variations suggest the use of a high friction surface and low trip-rail to enhance the accuracy of the TTR as an estimate of static roll stability limit.

Changes in surface friction and some details of trip-rail geometry also appeared to influence the variance of the results, as well as the mean. The statistical quality of these



The difference between the mean of a matrix condition and the baseline mean with 95% confidence interval

results are relatively weak and should be confirmed, but they also tend to argue for the use of a high friction surface with a low trip rail.

The statistical analysis also indicates:

1) The tilt table method does not appear to be sensitive to moderate errors in vehicle yaw alignment (± 1/2 deg).

2) Moderate deviations of the table tilt axis from the horizontal (±1/3 deg) appear insignificant.

3) Errors in table surface geometry (±0.5 inch deviations from a planar surface) may have a significant influence on measurement results. However, this influence appears to be simply and directly accounted for by the discrepancy between transduced tilt angle and the effective tilt angle immediately beneath the vehicle's axles.

4) Variations in the initial ride height of the vehicle, as might typically result from suspension hysteretic effects, appear insignificant.

5) Small variations in tire inflation pressures (variations of ± 2 psi) appear insignificant.

6) Large changes in vehicle temperature (as might derive from indoor and outdoor testing in cold weather) appear to influence results about one percent.

7) Table tilt rate changes over the range of 0.25 deg/sec to 1 deg/sec appear to have small or insignificant effects. (However, see 9 below.)

Detailed engineering analyses add to the conclusions reached through statistical analysis. Additional conclusions are:

8) Caution should be used when interpreting data signals from clinometers mounted on the test vehicle. In the vicinity of the static roll stability limit, small accelerations of the vehicle can significantly influence these signals and may lead to erroneous conclusions.

9) Very slow table speeds in the vicinity of the static roll stability limit are advisable. The sensitivity of the measured TTR to table speed may vary among vehicles. Behavior in the immediate vicinity of the static roll stability limit is dominated by highly non-linear events such as encountering suspension stroke limits and tire liftoff. The quality of vehicle response in the region may depend on the peculiar non-linearities of the test vehicle. At this time, engineering judgment argues for a use of a low rate in the vicinity of instability.

The results of this study tend to indicate that the tilt table test is rather repeatable and is not unduly sensitive to small changes in parameters associated with method and facility. However, all of the findings and conclusions of this study derive from measurements of a single vehicle tested only in the curb condition and only on one facility. Results might vary for different test vehicles, loading conditions, or test facilities.

TABLE OF CONTENTS

1. INTRODUCTION

This study was conducted to examine the sensitivities of the tilt table test method as applied to light truck-like vehicles.[1] Specifically, the purpose was to investigate the sensitivity of tilt table measurement results to variables associated with the methodology and/or facility. The study was performed by the University of Michigan Transportation Research Institute (UMTRI) for the Motor Vehicle Manufacturers Association (MVMA).

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1 Herein, light truck-like vehicles are a group of vehicles whose static roll stability is in the general region of 1.0 g. Passenger cars for the most part have stability limits well above 1.0 g and heavy trucks generally fall well below 1.0 g.

Fully recognizing this limitation, the practical values of simplicity and repeatability may still make the tilt table test a very attractive method for estimating the static roll stability limit of a vehicle.

The goal of this project was to quantify the sensitivity and repeatability of the tilt table procedure experimentally. To do this, one hundred and thirteen tilt table measurements of a single test vehicle were conducted. A number of facility and procedural parameters were deliberately altered during the testing to determine the significance of these changes on the results.

The test program was conducted on the tilt table facility operated by DST of Romulus, Michigan. Tests were conducted under the direction of UMTRI personnel. The test vehicle was a Ford Aerostar van, shown in Figure 1.1, and supplied by the Ford Motor Company. Funding for the study was provided through the MVMA.

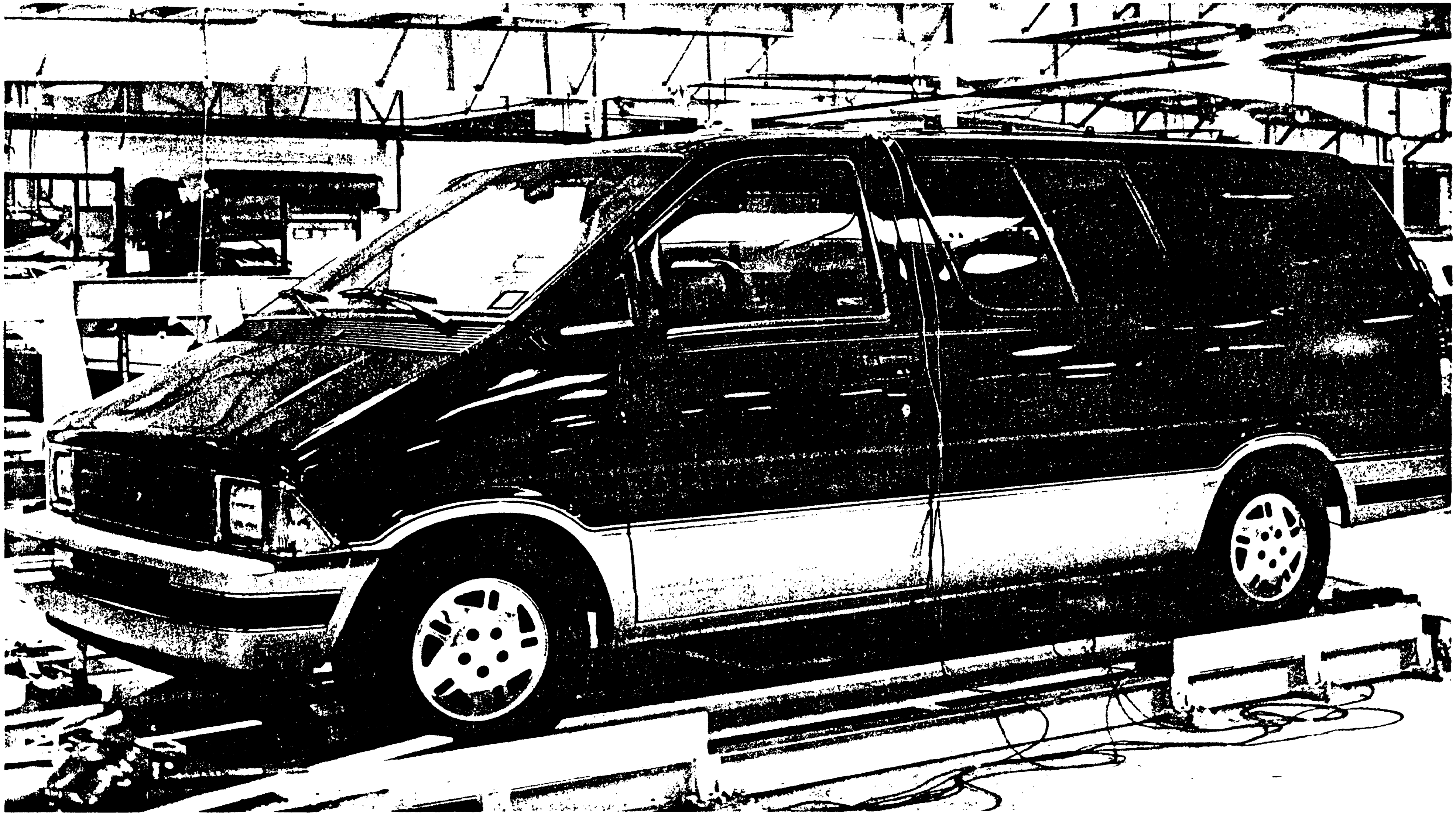

Figure 1.1. The test vehicle

2. METHODOLOGY

General remarks

The purpose of this study was to evaluate the repeatability of the tilt table test procedure for estimating the static roll stability limit of light truck-like vehicles. That is, how sensitive might tilt table measurement results be to relatively subtle differences between test facilities and procedures, as might be found among different testing agencies.

The method for doing this study was purely experimental. A test matrix was constructed of procedural and facility changes thought to possibly influence the estimate of the static roll stability determined by the tilt table test. The test results from each change were analyzed to determine if the change had a statistically significant influence on the tilt table measurement. Although not part of this report, an analytical approach to determine the influence of such changes is also possible. Such work has been done by Chrstos [1].[2]

Mechanics of the Static Rollover Process

The tilt table experiment is intended to measure the static roll stability limit of a vehicle by subjecting it to a physical analogy of its experience during a steady turn.[3] To better understand the mechanics of the experiment, a brief discussion of the fundamental steady-turn roll behavior of two-track vehicles is helpful. A more detailed discussion of this behavior may be found in [2,3].

Consider Figure 2.1, which illustrates the roll plane response of a vehicle in the static situation of a steady turn. The vehicle achieves a steady lateral acceleration condition by means of lateral tire forces in the ground plane. Assuming small roll angles, the three moments acting on the vehicle are:

$W \cdot Ay \cdot h$	the primary destabilizing moment generated by the lateral D'Alambert force acting through the center of gravity.
$W \cdot \Delta y$	another destabilizing moment resulting from the lateral displacement of the center of gravity that occurs as the vehicle rolls toward the outside of the turn.
$(F_2 - F_1) \cdot T/2$	the stabilizing roll moment resulting from the lateral transfer of load from the inside to the outside tires.

The summation of these moments satisfying steady-state equilibrium yields the expression:

$$\mathbf{W \cdot Ay \cdot h = (F_2 - F_1) \cdot T/2 - W \cdot \Delta y} \quad (1)$$

[2] Numbers in brackets indicate references listed at the end of this report.

[3] The term "steady turn," as used herein and generally in the technical literature, has a very specific definition. A steady-turning situation is one in which velocity, turn radius, and lateral acceleration of the vehicle are all constant, or not changing, with time. Since the vehicle's situation is not changing with time, it is said to be in a "static," as opposed to "dynamic," condition.

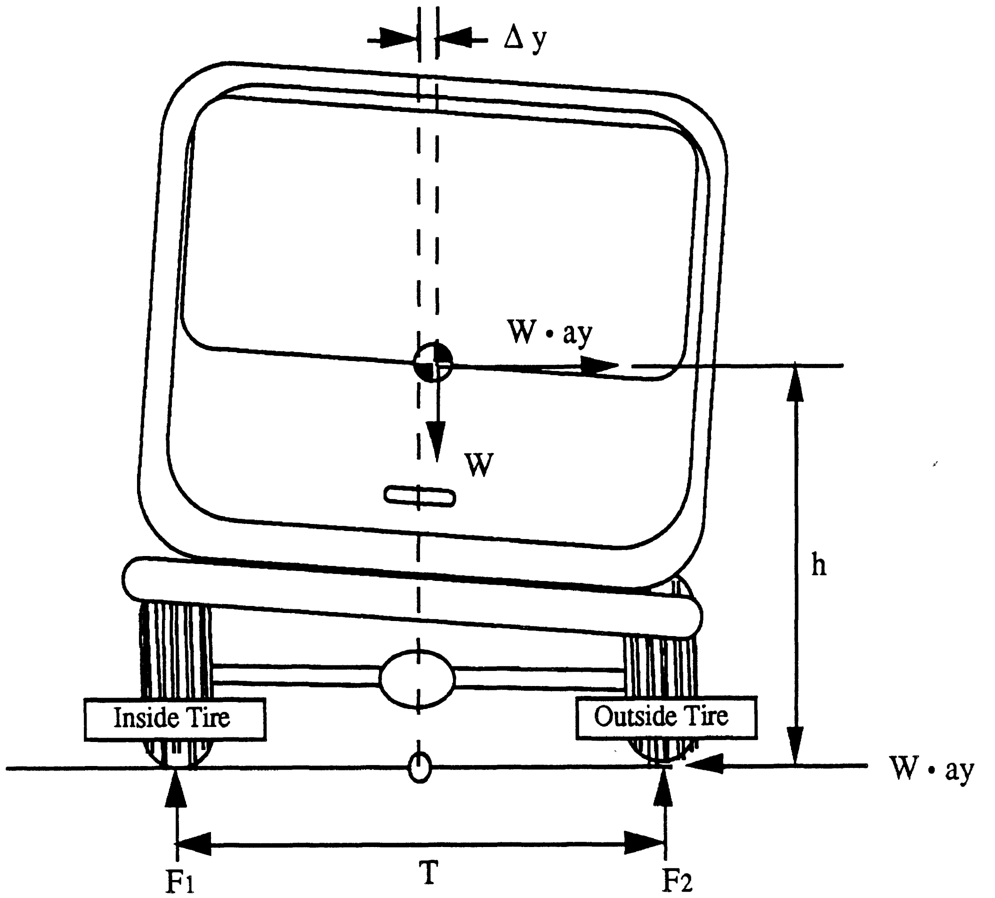

Figure 2.1. Free body diagram of the roll plane response of a vehicle in a steady turn

The elements of this equation are represented graphically in Figure 2.2.

Plotted on the right-hand side of the graph are the representative terms from the right side of Equation (1) as functions of the roll angle, ϕ. Equation (1) assumes the suspensions of the vehicle are lumped and that their properties are linear. The line labeled Suspension Moment describes the behavior of $(F_2 - F_1) \cdot T/2$ as a function of roll. The initial slope of this function depends on the roll stiffness of the suspension and tires and on the height of the vehicle's roll center. The peak value of the Suspension Moment is $(W \cdot T)/2$ and occurs when the inside tire lifts off the ground (i.e., $F_1 = 0$ and $F_2 = W$). At this roll angle, ϕ_1, the Suspension Moment is saturated. Roll motion beyond this point will not generate more restoring roll moment. Vehicles with infinitely stiff suspensions and tires would have an initial slope of infinity and would achieve liftoff at zero roll angle. Those with soft suspensions would attain larger roll angles before lifting their inside tire and saturating.

The line on the right-hand side of Figure 2.2 labeled, "Offset Moment," represents the overturning moment coming from the lateral displacement of the center of gravity (i.e. $W \cdot \Delta y$). Its destabilizing quality is represented by a negative slope in Figure 2.2. The Offset

Moment is a function of tire and suspension roll stiffness, the height of the sprung and unsprung masses, and the height of the roll center.

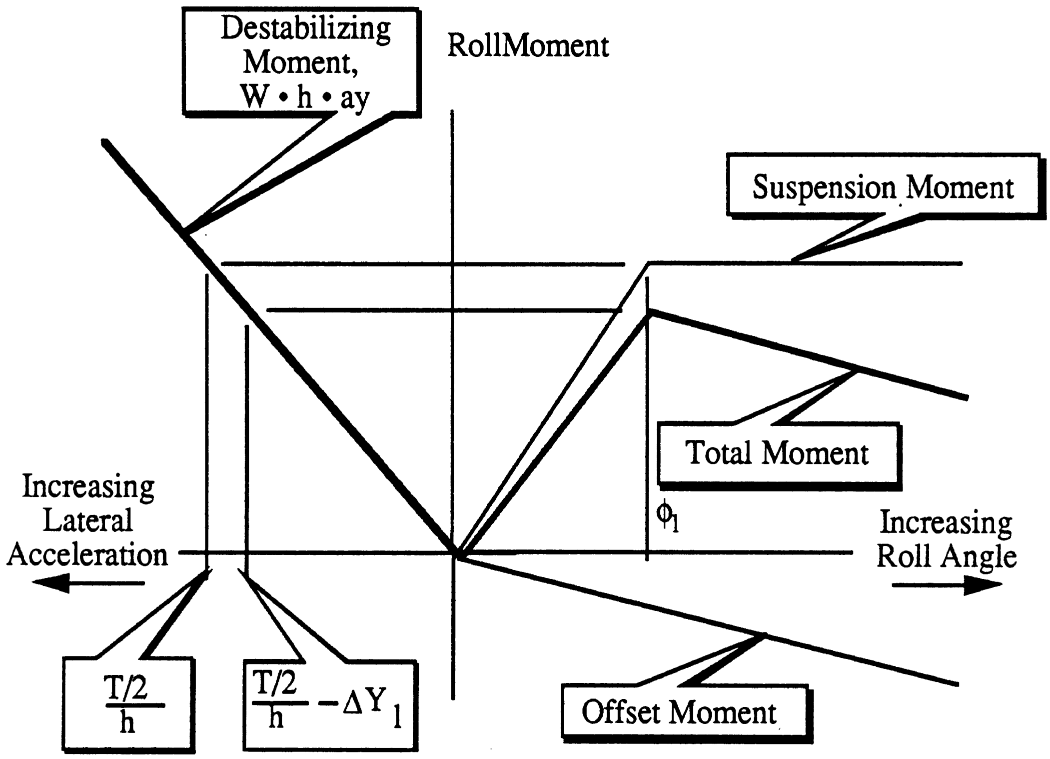

Figure 2.2. Graphic representation of the static roll equation

The sum of the Offset Moment and Suspension Moment is the line of Figure 2.2 labeled, "Total Moment." This is the total of the right-hand side of Equation (1). The Total Moment peaks with the liftoff of the inside tire. The total moment at the peak is less than the full available Suspension Moment because the center of gravity has shifted outboard due to system compliance.

The left side of Equation (1) is represented on the left side of Figure 2.2. It shows the primary Destabilizing Moment (W • Ay • h) as a function of the lateral acceleration level. The Destabilizing Moment constitutes an overturning moment and is limited only by the lateral traction capabilities of the tires. The slope of (W • Ay • h) is influenced by the height (h) of the vehicle's center of gravity. A higher center of gravity will cause the slope to increase.

By drawing a horizontal line from the peak of the Suspension Moment to the primary Destabilizing Moment, the maximum possible static rollover threshold is found. This value, expressed in terms of lateral acceleration, has a value of (T/2h) for a rigidly suspended vehicle. But, because the vehicle has compliant suspensions and tires, the true static rollover threshold is found by using the peak of the Total Moment. It corresponds to a rollover threshold of (T/2h - Δy). The static roll stability has degraded because the compliant vehicle must roll outboard in order for the suspensions to deliver their full available restoring moment.

Multi-Suspension Vehicles

In the above discussion, it was assumed that the vehicle is collapsed into a single roll plane. This is a valid assumption only as long as the inside tire of each suspension lifts off at the same vehicle roll angle.

Figure 2.3 shows the right-hand side of Equation (1) including the influence of multiple axles. The line labeled, "Front Suspension," shows the stabilizing contribution of the front axle. The front suspension moment saturates, and front tire liftoff occurs at a roll angle of ϕ_F. Similarly, the rear axle lifts off at a roll angle of ϕ_R which, in this case, is larger than ϕ_F. The Total Moment line shows the vehicle reached its peak roll moment when the rear axle lifted. It also shows how the stiffness of the system softened (decreased slope) when the front suspension lifted.

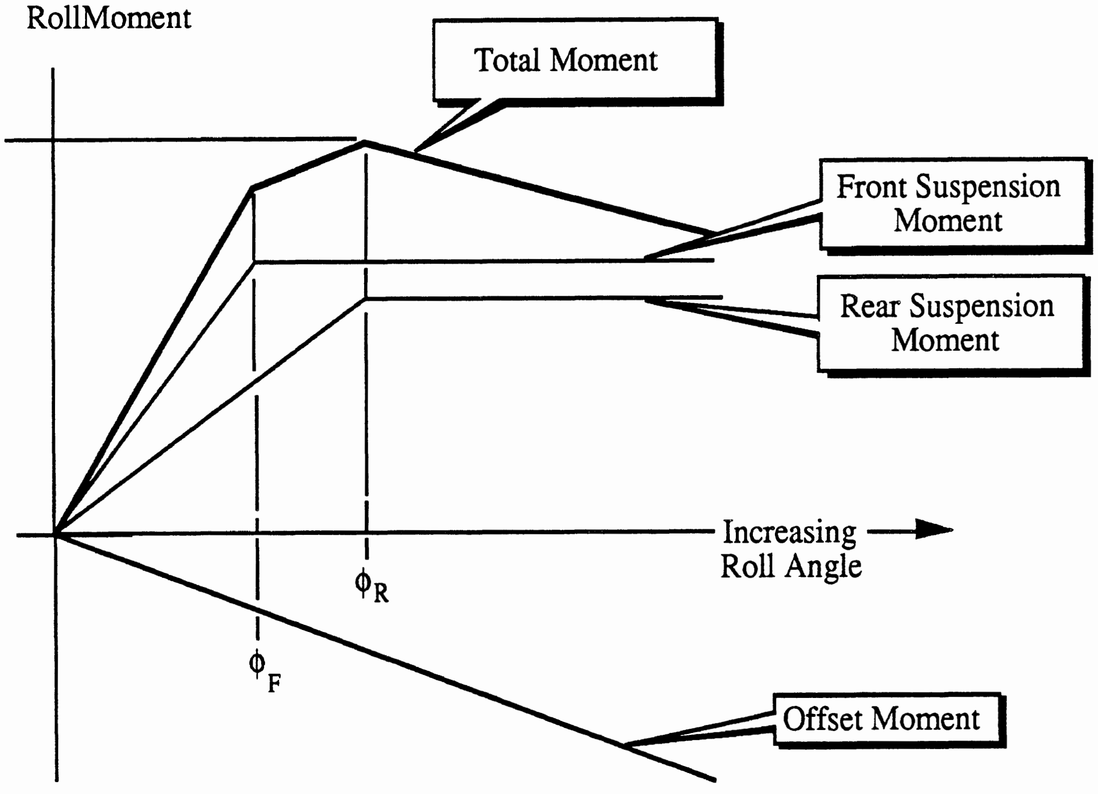

Figure 2.3. Graphical illistration of the influence of multiple suspensions

It is of interest to note that, as depicted in Figure 2.3, the vehicle remained stable after the front tires lifted off. That is, the stiffness of the rear suspension alone is sufficient to overcome the destabilizing influence of the Offset Moment, causing the slope of the Total Moment to remain positive until the rear tires lift. It is, however, possible for the vehicle to become statically unstable with tires still on the ground. For example, Figure 2.4 depicts a situation where the Offset Moment is steeper, perhaps due to a higher vehicle center of gravity. Now, the slope of the Total Moment becomes negative with the first tire liftoff and the rear suspension alone is not stiff enough to stabilize the vehicle. This type of situation is common for large commercial trucks, but very uncommon for passenger cars. It may be possible some heavily loaded light trucks behave in this manner, but no confirming data is known.

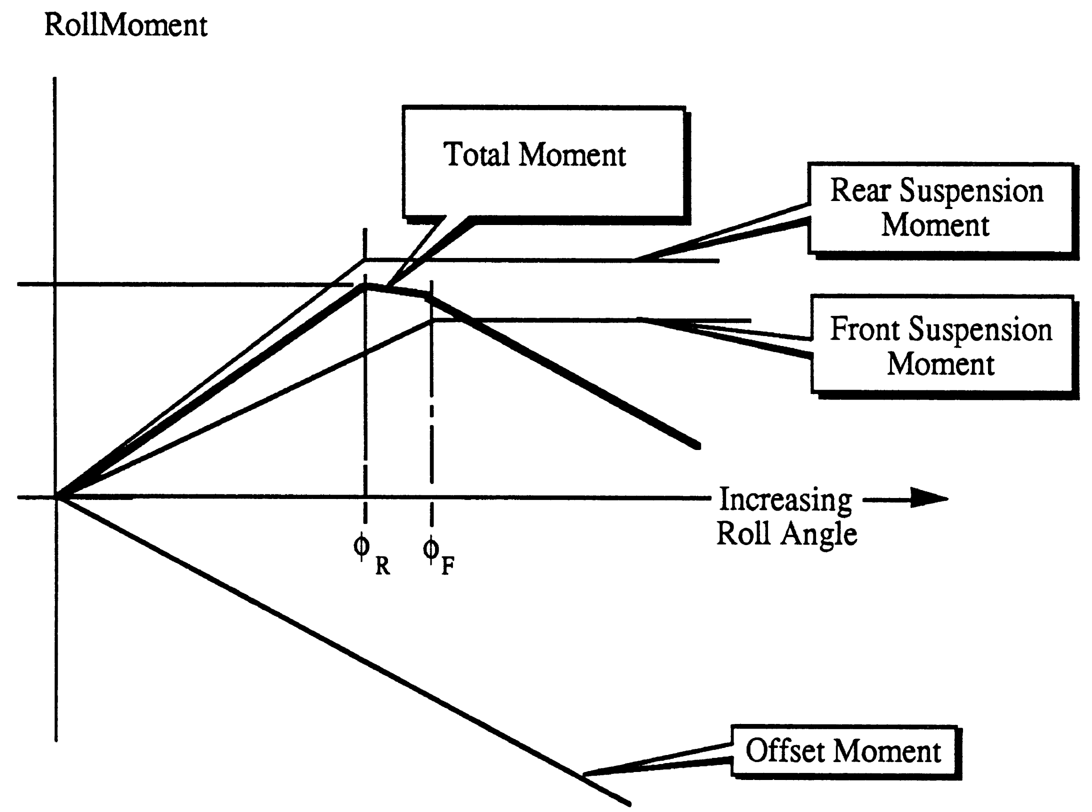

Figure 2.4. Vehicles can become statically unstable with tires still on the ground.

Suspension Non-Linearities

Passenger car and light truck suspensions show distinctly non-linear behavior when suspension deflection limits are reached. Roll stiffness increases markedly when either a shock reaches full extension or a suspension bump stop is contacted. Figure 2.5 illustrates how these types of non-linearities might influence the static roll stability analysis.

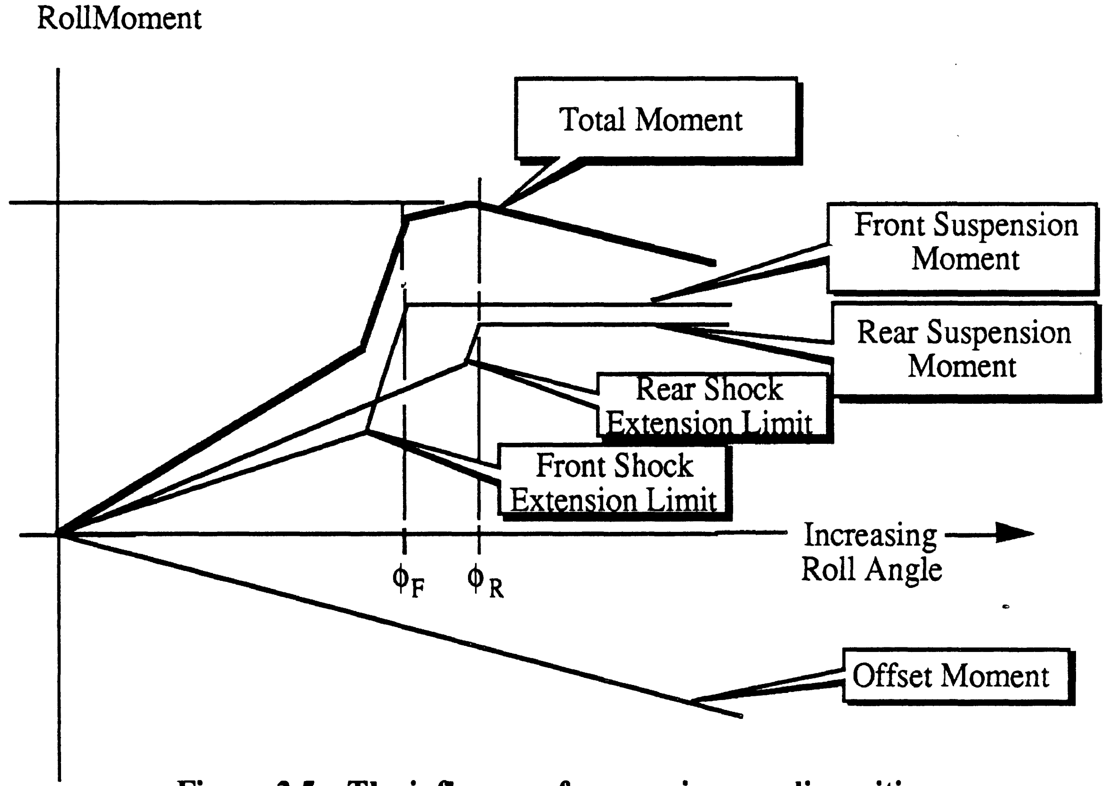

Figure 2.5. The influence of suspension non-linearities

The Tilt Table Analogy

In the tilt table method, the roll plane behavior of a steady state turn is simulated by tilting the vehicle to some angle, ϕ, on a table inclined in the roll direction (See Figure 2.6). In this state, the component of gravity acting perpendicular to the table surface is (g cosϕ) and the component acting parallel to the table surface is (g sinϕ), where "g" is the gravitational constant. This loading condition is analogous to the steady-state turning condition wherein the vehicle is subject to gravity loading of 1 g perpendicular to the ground and steady-state lateral acceleration loading parallel to the ground, but the tilt table loadings are "scaled down" by a factor of (cosϕ) relative to the steady-turn loadings they represent. Thus, the represented static lateral acceleration is (g sinϕ/cosϕ) or (g tanϕ). The value (tanϕ) can, therefore, be taken to represent static lateral acceleration in g's. It follows that the tangent of the minimum tilt angle required to rollover the vehicle on the tilt table can be taken as an estimate of the static roll stability limit of the vehicle. Thus, if the table angle is increased very slowly, so as not to violate the assumption of a static condition, the tangent of the tilt angle at which the vehicle rolls over is an estimate of the lateral acceleration at which the static roll stability limit of the vehicle is reached. The tilt table measurement, that is, the tangent of the minimum tilt angle required to rollover the vehicle, is refereed to herein as "the tilt table ratio" or TTR, to distinguish it as an estimate of the static roll stability threshold, rather than the static roll stability threshold, itself.

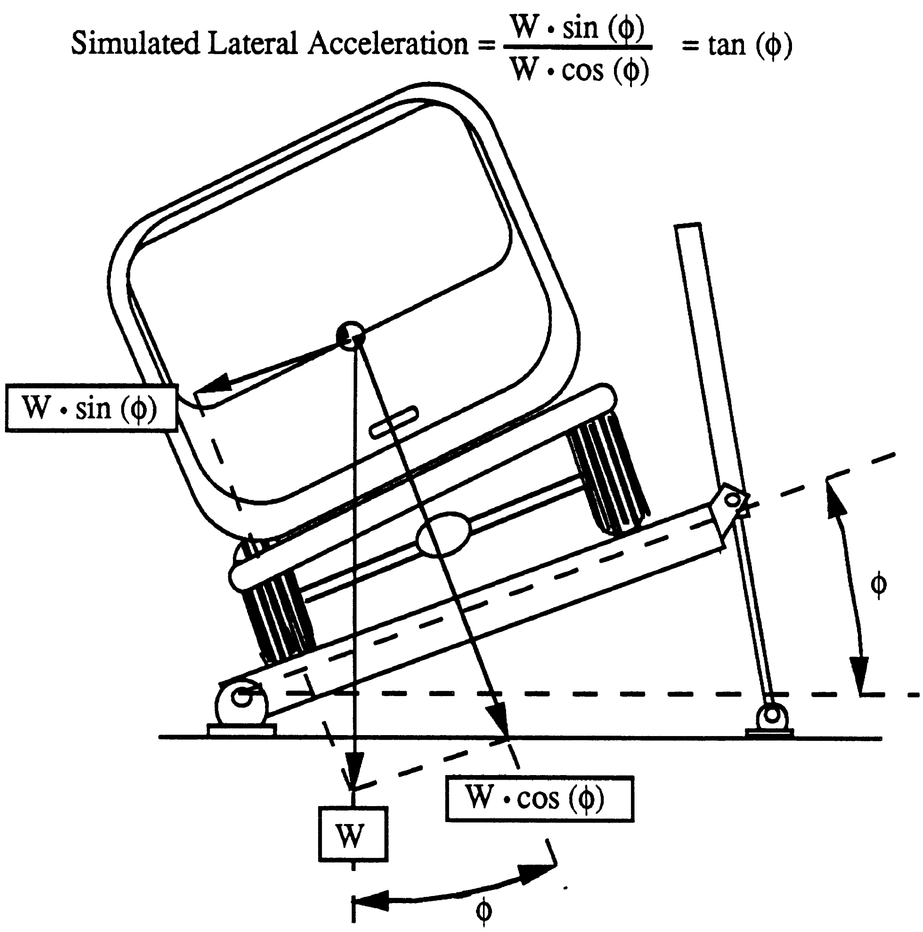

Figure 2.6. Tilt table method

The quality of TTR as an estimate of static roll stability depends, in part, on how closely (cosϕ) approximates unity. In the tilt table experiment, both the vertical and lateral loading of the vehicle are reduced by the factor, (cosϕ), relative to the static loads they are meant to represent. Because of the reduced vertical loading, the vehicle may rise on its compliant tires and suspensions relative to its normal ride height, resulting in a higher center of gravity position and, possibly, an unrealistically low estimate of the static roll stability limit. At the same time, static lateral loading is also reduced by the factor (cosϕ). This may result in compliant lateral and roll motions of the vehicle that are unrepresentatively small, tending to produce an unrealistically high estimate of the static roll stability limit. For vehicles whose static roll stability limit is in the range of 1 g, either of these opposing mechanisms may be significant, since the tilt angles involved are approximately 45 degrees. At such an angle, the lateral and vertical loads on the test vehicle are both only about 70 percent of the "real" loading components that they represent.

Figure 2.7 is an example of the results from a tilt table test conducted in this study. The figure is a plot of the vehicle's body roll angle relative to the table versus tan(tilt angle).

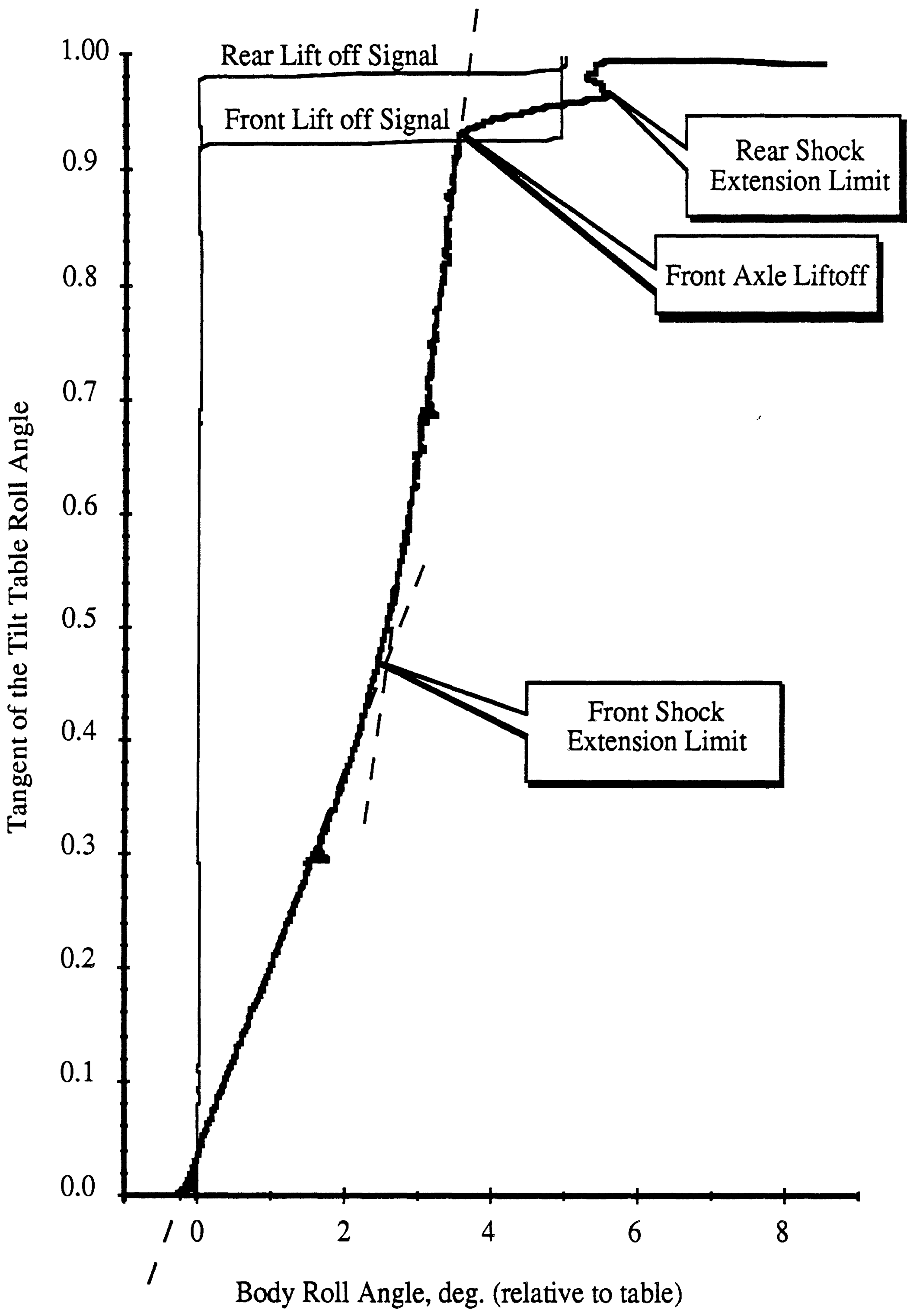

Figure 2.7. Recorded data from a baseline tilt table test

Several of the front and rear suspension events which occur during the experiment are identified. The value of tan(tilt angle) at which front and rear tire liftoff occurs are indicated by data signals on the plot. The actual experimental behavior shown in Figure 2.7 is clearly similar to the hypothesized behavior of Figure 2.5.

One interesting aspect of Figure 2.7 is the very shallow slope of the data immediately after front axle liftoff. The shallow slope at this point indicates that the vehicle is only marginally stable. That is, the stiffness of the rear suspension alone is just adequate to overcome the destabilizing influence of the offset moment. This test was conducted with an empty vehicle. These results suggest that a vehicle with a heavy load and/or a load with a high center of gravity might become statically unstable at the occurrence of front axle liftoff—with the rear wheels still on the ground. In such an event, the experimenter would have to pay close attention to the nature of the experiment to correctly identify the actual static stability limit of the vehicle in the experiment.

Facility

The tilt table used in the test program was provided by DST of Romulus, Michigan. Figure 2.8 shows the facility in the zero-tilt position without a test vehicle. Figure 2.9 shows the facility at a high angle of tilt and with the test vehicle in place. The static roll stability limit of the vehicle has been exceeded. The vehicle is prevented from fully rolling over by restraining straps attached to the high-side of the vehicle.

A sketch of the facility pointing out some of its features appears in Figure 2.10. The tilt axis of the table lies in the longitudinal direction along one side of the table. Hinges are attached to the shop floor providing very rigid support for this edge of the table. The opposite edge is also quite rigid due to a rather large truss-like structure along its length. The tilt action of the table is motivated by a three stage hydraulic cylinder providing lift at the center-point of this truss. Tilt rate is adjustable from about 0.25 degrees/second to 1+ deg./sec. Speed control is "open loop" and is accomplished by adjustment of flow-control valves. Three valves, corresponding to the three stages of the lift cylinder, must be "matched" to provide equal tilt rate over the whole range of motion. A string-potentiometer measures cylinder position and provides the signal used to trigger shifting between the three valves. Oil temperature and other operating variables effect tilt rate somewhat. As a result, speed control is not "precise," but is adequate.

A detailed view of the table surface in the area of the low-side tires is presented in Figure 2.11. The low-side tires of the test vehicle are supported on a painted-steel surface next to the tilt hinge. Since the static roll stability of many test vehicles (in g's) can be expected to exceed the friction coefficient of tires on this surface, there is provision for installing "trip rails" beside the low-side tires. When the friction capability of the tires is exceeded in testing, the rails would prevent the vehicle from sliding downhill and off of the table. In some of the tests, the low-side tire support areas were covered with 3M medium grit SafetyWalk™ to provide a high-friction support surface.

The trip rails themselves were fabricated from heavy gage (3/8 inch thick) angle iron. Trip rails of one and two inch heights were used in this program. (A one-inch trip rail is visible in the figure.) The positioning of the trip rails was adjustable. In this study, they

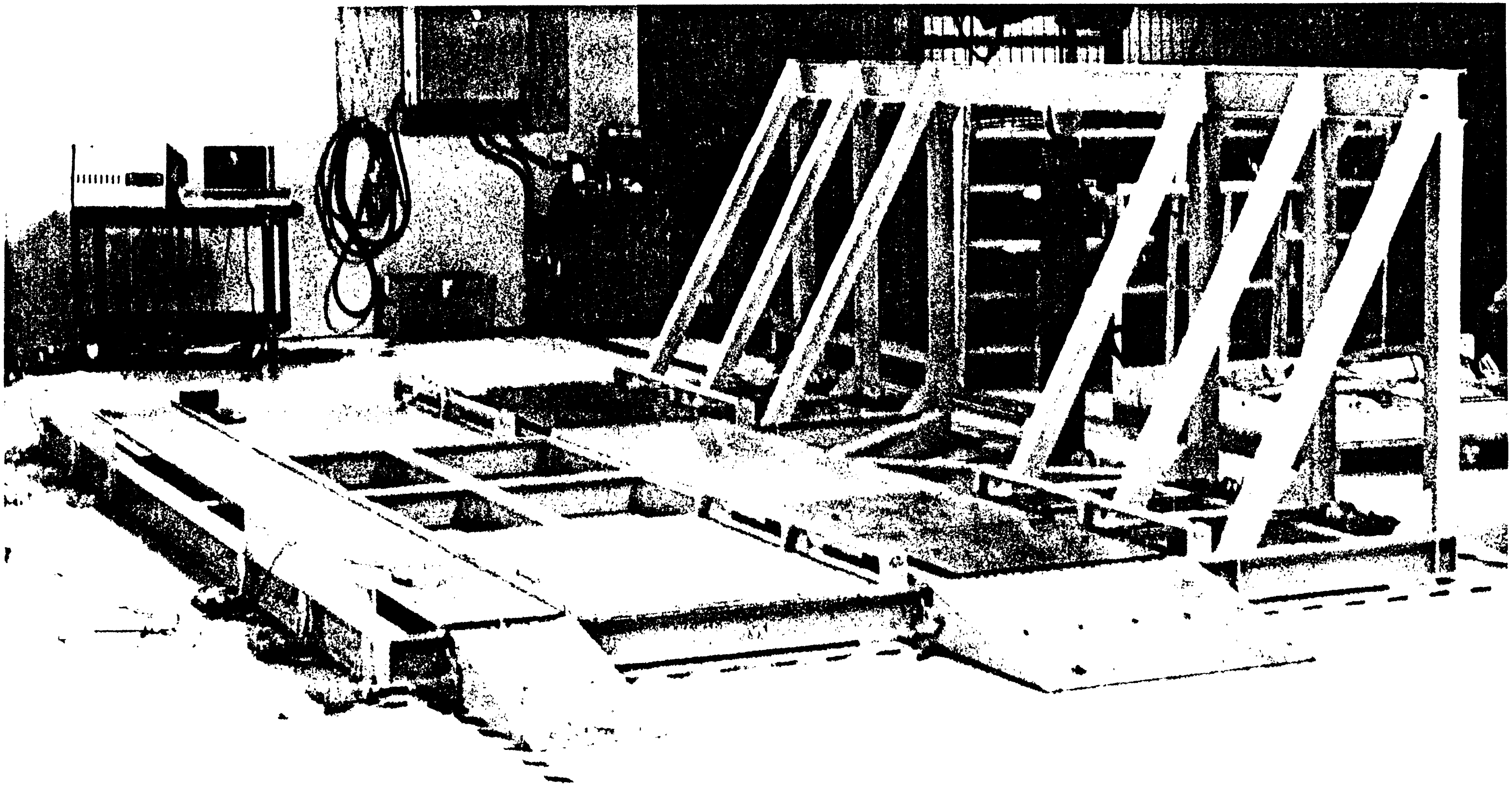

Figure 2.8. Photograph of the tilt table used for testing

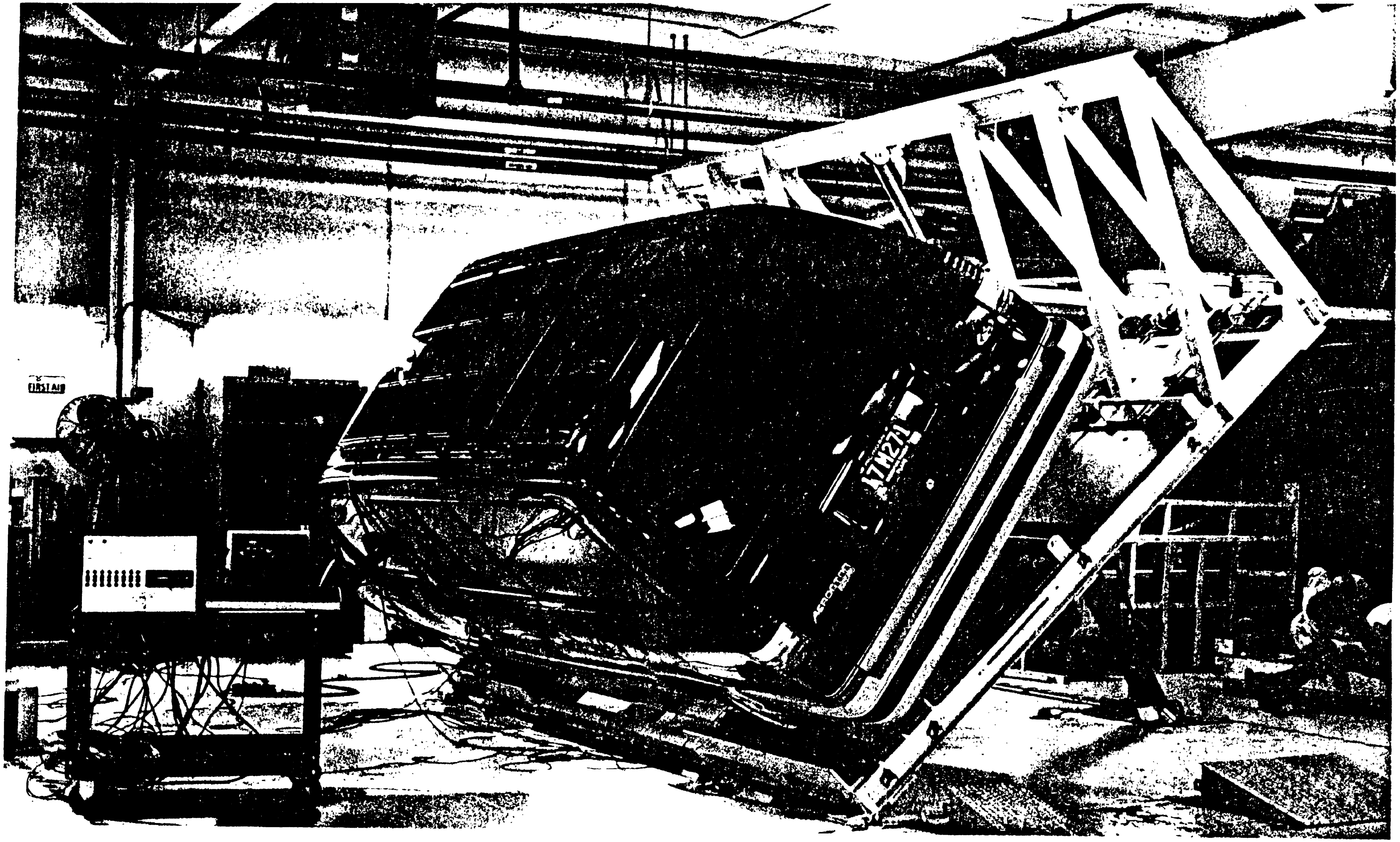

Figure 2.9. The test vehicle and tilt table at high tilt angle

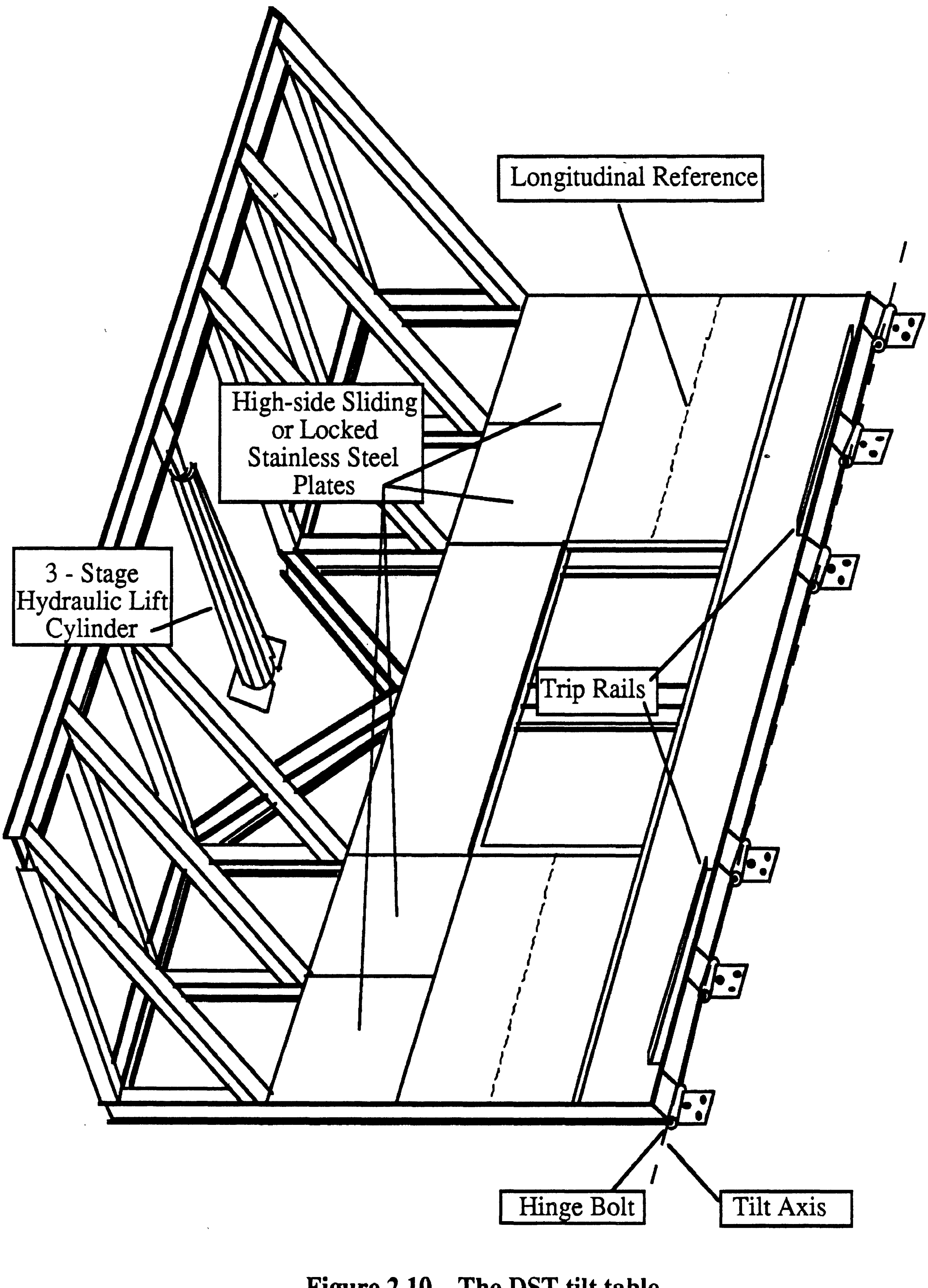

Figure 2.10. The DST tilt table

Figure 2.11. Photograph of the low-side tires and trip rails

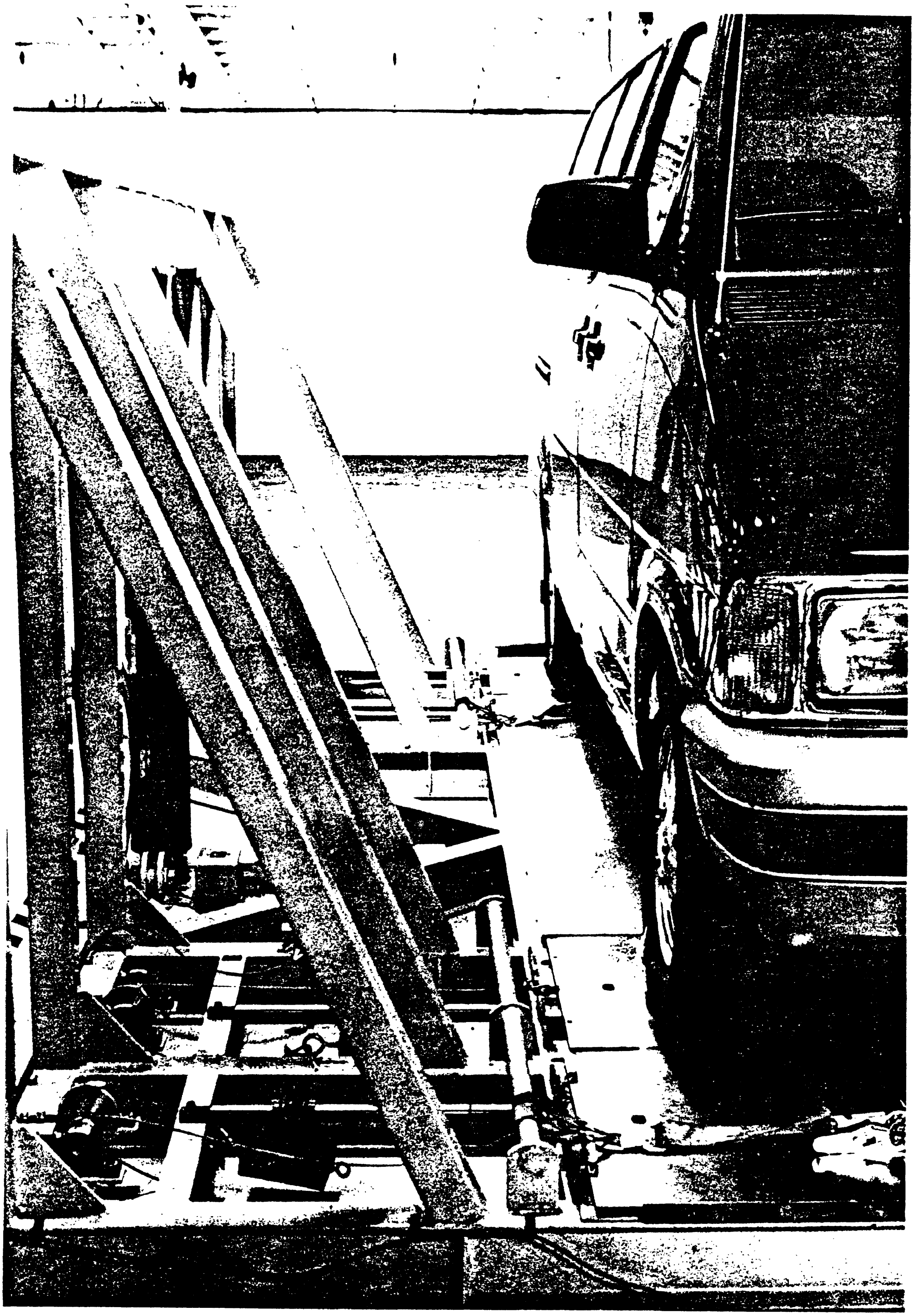

Figure 2.12. Photograph of the high-side tires with the "sliding" stainless steel plates

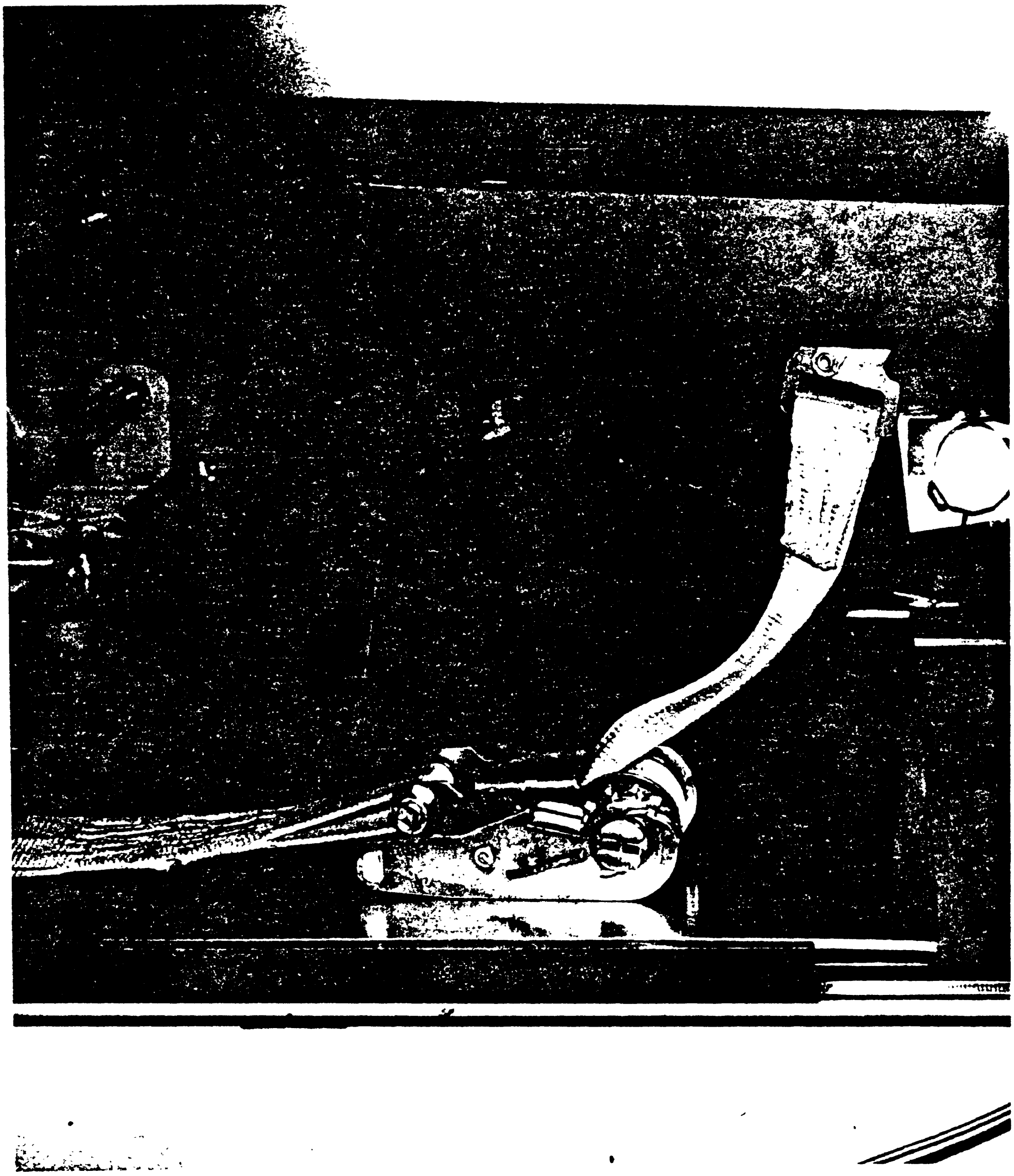

Figure 2.13. The front suspension restraining strap with buckle

were installed, either in light contact with the tires at the outset of the test, or with an initial clearance of one or two inches.

The high-side tire of the test vehicle were supported on special "pads" built into the surface of the tilt table. Seen in Figure 2.12, these pads were unpainted stainless steel plates. The plates themselves were supported beneath by low-friction linear bearings allowing free lateral motion. Provision was also made to lock the pads in place. Thus, the high-side wheels could either be subject to lateral friction forces in a "natural manner," or they could be free of any significant lateral constraint.

Finally, the facility is equipped with safety straps to prevent the test vehicle from fully rolling over. Two such restraining straps are provided, one between the table and front suspension and one between the table and rear suspension. The front suspension strap appears in Figure 2.13.

Tilt Axis

Part of the design intent of the tilt table is for the tilt axis to be horizontal. An independent contractor measured the lateral alignment and "levelness" of the tilt axis. Using a machinist transit for their measurements, they determined the tilt axis hinges to be level and aligned to within 0.03 inch over the length of the table (165 inches). The longitudinal reference for trip rail alignment was measured to within 0.001 inch relative to the tilt axis established by the center of the hinge bolts.

Longitudinal Axis Reference

In the tilt table test, it is generally intended that the vehicle's longitudinal axis be aligned parallel to the table's tilt axis. In order to provide a convenient reference for aligning the test vehicle, a longitudinal reference line was painted on the table surface. This line was parallel to the table's tilt axis within 0.03 inch over the table length. The painted line itself was approximately 0.1 inches wide.

Table Surface

To document and measure the planar quality of the tilt table surface, the following procedure was followed. The table surface was marked to indicate the proper position of the center of contact of the four tires of the vehicle. The table was rotated approximately two degrees to establish that only the tilt axis' hinges and lift cylinder were supporting the table. (In the horizontal position, the table is supported at many points by shims between it and the floor.) With an electronic level, the table inclination was measured both laterally and longitudinally along the four sides of the rectangle defined by the tire position markings. Ideally, the measured inclination along the two longitudinal "track" sides should be zero. In the lateral direction, the measured inclination at both the front and rear axle positions should be equal and the same as the table. To help make the measurements, two raised aluminum straight edges, with a straightness tolerance of 0.03 degree, provided a way to avoid any "local" frame or plate warping. They also helped to work around the guide rails, fastening brackets and different level surfaces on the table. The electronic level used has a tolerance of 0.05 degree at angles between 0.0 and 20.0 degrees. At angles between 20.0 and 60.0 degrees, it has a tolerance of 0.1 degree. A subset of this measurement was also made with the table rotated to approximately 45 degrees. Due to the sensitivity of the level, it was found unreasonable to measure the table longitudinally while inclined to 45 degrees. For this case, only the lateral measurements are reported. Three repeat measurements were taken for each of the two table inclinations. Between each set of measurements, the table was lowered to its "resting," horizontal condition. A string potentiometer, with an accuracy of 0.01 inch, measured the vertical distance from the ground to the table at the cylinder lift point. This signal was used to insure that the measurements were taken at consistent table inclinations. The results of this procedure demonstrated that, within the tolerance of the equipment used, the planar quality of the table was quite reasonable. With the table inclined to approximately two degrees, the high- and low-side longitudinal results were 0.04 and 0.06 degrees, respectively. Laterally, the front and rear axle angles were 1.83 and 1.80 degrees, respectively. With the table raised to 84.99 inches, the lateral front and rear angles measured 44.20 and 44.17 degrees, respectively.

Table Rigidity

As mentioned in the description of this facility, the lower edge of the table was quite rigid by virtue of its attachment to the floor, and the upper edge of the table was quite rigid due to the large truss structure. However, the table did not provide a rigid torsional (about a lateral axis) coupling between the two edges. Thus, it was found that the truss could rotate in pitch about the cylinder support position, warping the planar quality of the table. This compliance could lead to different table tilt angles, locally, in the vicinity of the front and rear axles, respectively.

Two experiments evaluated the torsional rigidity of the tilt table. As in the Table Surface experiment, three repeats for each test condition comprised the results and the table was inclined to approximately two degrees. In the first experiment, two 500 lb. weights were centered on the rear tire/table contact centers as defined in the Table Surface experiment. Due to the weights, it was necessary to measure the rear lateral and the longitudinal angles in locations other than the tire/table contact points. The rear lateral measurement was taken 23.25 inches forward of the rear tire/table contact patch. Longitudinally, the measurements had a lateral offset of 5.5 inches away from the table center. The results of this measurement show that some table warping did occur. The high- and low-side longitudinal numbers indicate an angle of 0.12 and 0.07 degrees, respectively. As expected, the low-side angle is virtually zero due to the support of the tilt axis' hinges. Laterally, angles at the positions of the front and rear axles were 1.93 and 1.76 degrees, respectively. Based on these lateral results, and with a table length of 168 inches, the total table front to rear deflection is 0.50 inch.

In the second experiment, the test vehicle was used to load the table. Measurements were made with the vehicle in three positions: parked as far forward as possible, as far rearward as possible, and with its center of gravity aligned with the lift cylinder (i.e. the center of the table). Some table warping did occur when the test vehicle was parked at the extreme ends of the table. As in the first experiment, the warping remained close to 0.50 inch over the length of the table.

Results from these somewhat crude tests helped determine that table warping would probably have little influence on the test results. This conclusion was based on two hypotheses,: (1) In most test conditions, the vehicle's center of gravity would be aligned with the lift point of the hydraulic cylinder. Under this balanced loading, very little table warping would be induced. (2) Most warping was due to the position of loads on the high-side of the table. Since the high-side tire loads approach zero at high tilt angles, table warping should be small at the critical angles.

Instrumentation

The instrumentation for the experiment consisted of eight electronic clinometers or accelerometers, two contact switches and, in a few tests, a manually controlled switch for visual confirmation of tire liftoff. Three of the instruments (supplied by Ford) were model LSOC-90 servo-accelerometers made by the Schaevitz Company. These are relatively high precision, fast response transducers that measure acceleration in g's with a full scale range of ± 1 g The other five instruments (supplied by UMTRI) were AccuStar™ electronic clinometers by Lucas Sensing Systems. These use a liquid mechanism to sense their tilt angle. They have a full scale range of ± 60 degrees. Static and dynamic calibrations of instruments will be reviewed in the Results section of this report.

Clinometer Positions

The locations of the eight clinometers on the vehicle and table were as follows:

1) One Schaevitz accelerometer was permanently mounted on the table. It was approximately 15 inches inward from the high-side of the table and was 35 inches forward of the hydraulic cylinder lift point.

2) Two Lucas clinometers were mounted on the table directly under the locations of the vehicle's front and rear axles in the baseline condition. Laterally, they were below the center line of the vehicle.

3) A Schaevitz accelerometer and a Lucas clinometer were mounted together on the roof of the sprung mass. They were positioned longitudinally at the center of mass of the test vehicle, and laterally at the geometric vehicle center (See Figures 1.1 and 2.9).

4) A Schaevitz accelerometer and a Lucas clinometer were mounted together on the rear axle of the vehicle. Their lateral position was 18 inches from the inside rim of the low-side tire.

5) One Lucas clinometer was clamped to the lower A-arm of the high-side front suspension (See Figure 2.13).

Contact Switches

Two electrical contact switches made of conductive foil indicated electronically the liftoff event of the front and rear high-side tires. The conductive foil had adhesive on one side and was approximately 3 inches wide. It was cut to a length sufficient to cover the tire from its outside sidewall, across the tire/table contact area, and half way up the inside sidewall. Front and rear electrical wires from the data acquisition equipment were then, respectively, "alligator" clipped to the foil on the inside sidewall of each tire. When the tires were in contact with the table, the foil tape contacting the table completed the circuit. At tire liftoff, the foil/table contact would be broken; effectively switching the electrical circuit off. On a few of the conditions done toward the end of the testing period, a manual switch was also used to indicate front and rear tire liftoff. This switch only served to support the accuracy of the foil switches.

Data Acquisition Equipment

All electronic data were gathered using digital data acquisition equipment supplied by UMTRI. Analog signals were filtered at 10 Hz. The digital sampling rate was 20 Hz. for the baseline condition and 5 Hz. in two conditions from the baseline. All data was stored on digital cartridge tape. Data acquisition started with the table in its full "resting" position and continued for 1 to 3 seconds past the rollover event.

Test Vehicle

The test vehicle was a 1991 Ford Aerostar van with the Eddie Bauer options package and is shown in Figure 1. The van had approximately 6200 miles on it and was in a clean condition throughout the testing period. The vehicle's wheelbase measured 118.9 inches with front and rear track widths of 60.0 and 61.4 inches, respectively. As tested, the total weight was 3933 lbs. The front to rear axle weight ratio was 1.148. For this condition, the longitudinal mass center was calculated to be 63.5 inches forward of the rear axle.

Center line paint marks made on the rear differential and on the frame between the front tires referenced the lateral alignment of the vehicle. The center line reference mark for the front axle was located midway between the lower ball joints. The reference for the rear axle was located midway between the wheel rims.

Before conducting any tests, the vehicle's nominal ride height was established and measured. The height was characterized by the distance from the ground to the highest point of the fender-lip at each of the four wheels, respectively. The left-front, left-rear, right-front, and right-rear ride heights were 26.75, 27.25, 27.25, and 27.5 inches, respectively. Also, before testing, the accuracy of the front tire alignment was verified. In all tests, the vehicle was in the curb weight condition and as follows:

1) All fluid levels were full;
2) All vehicle tires were clean and dry;
3) Tire pressures were set to placard numbers $\pm$ 0.5 psi; and
4) No driver, passengers or other additional loads were in the vehicle.

Test Matrix Discussion

The matrix of test conditions used in this study was structured to investigate general areas that were presupposed to influence tilt table measurements results. The areas of interest were: (1) facility and vehicle placement geometry; (2) facility rigidity; (3) vehicle lateral constraint; (4) dynamics; and (5) hysteresis. Each of these subjects are briefly discussed below, and then the matrix itself is presented and discussed.

Facility and Vehicle Placement Geometry

It is the premise of the method that the lateral and vertical loading experienced by the vehicle are (g sin ϕ) and (g cos ϕ) respectively. This premise is based on the assumption that certain parallel and/or orthogonal relationships exist between the tilt axis, tilt table surface, and longitudinal axis of the vehicle. The accuracy of the results depends, in part, on the accuracy with which these relationships are established. This study included documentation of some of the basic geometric parameters of the facility, and the test matrix included provisions to examine the sensitivity of results to vehicle orientation.

Facility Rigidity

Facility rigidity is basically a sub-component of geometry. That is, if the assumed geometric relationships are to be maintained throughout the test, they require an adequate level of facility rigidity. The rigidity of the test facility was documented and monitored during the program. The test matrix included elements to examine the influence of this facility's compliance on test results.

Vehicle Lateral Restraint

In the tilt table procedure, lateral forces are developed at the tire/road interfaces in opposition to the lateral component of gravitational loading. At higher tilt table angles, tire friction alone may not be adequate to resist lateral motion and prevent the vehicle from sliding on the table surface. Accordingly, a "trip rail" may be placed against the side-wall of the low-side tires to help sustain the needed lateral force. However, the lateral restraint force and the D'Alembert force are the couple that constitutes the primary destabilizing moment that leads to rollover. The height of the lateral constraint force (as well as the height of the vehicle's center of gravity) is, therefore, important when determining the TTR. Tire/road friction, tire lateral stiffness, and trip rail geometry (height, shape, location) all combine to establish the representative height of the constraint force. The influence of tire/road friction (low-side tires), and trip rail height and placement were examined both respectively and synergistically.

Dynamics

The tilt table method is intended to estimate the *static* roll stability limit. The approach is to increase tilt angle so slowly as to affect a quasi-static experiment. The appropriate table speed to achieve this depends on the properties of the vehicle being tested as well as on certain properties of the instrumentation system. The test matrix included elements to examine the influence of tilt table rate and digital data sampling rate. Dynamic response of the vehicle in roll, and response properties of the instruments used to determine the point of instability, were monitored and their influence was analyzed.

Hysteresis

Static roll stability is highly dependent on the height of the vehicle's center of gravity. Hysteretic effects of the vehicle tire and suspension systems can appreciably alter the height of the center of gravity, at least at the outset of the experiment. There is a potential concern that hysteretic effects might play a larger part in the tilt table experiment than in real life because the tires are not rolling forward in the tilt table experiment. That is, the height of the center of gravity and the distribution of lateral tire force side-to-side might be influenced more by initial condition because normal tire mechanics and yaw response are not in play. The test matrix included provisions for investigating the influence of tire/road friction (high-side tires) and initial vehicle configurations.

Test Matrix

The test matrix presented in Table 2.1 is structured around a baseline condition of twelve different variables. In the matrix, thirty-three test conditions other than the baseline are identified. Most are defined by changes of a single variable away from the baseline condition. In some cases, when synergistic effects were expected, more than one variable was changed from the baseline condition.

The intention was that at least one baseline test be conducted on each testing day. For the thirty-three conditions, three repeats of each condition were conducted. Table 2.2 presents three sets of the numbers 1 through 28, each randomly ordered. It details the chronological order in which the non-baseline tests were conducted. Table 2.3 presents the position in each day's testing sequence of the baseline condition. This position was also randomly selected from the numbers 1 through 8 and was based on performing at least eight tests per day. Test Condition 29 and 30 were exempt from this random ordering procedure for practical reasons. It was felt that having them in the random sequence would be too costly a time burden on the program. Test conditions 31, 32, and 33 were added to the test after all the other tests had been completed. The following paragraphs discuss specific properties of the baseline condition and the variables related to the different test conditions.

Baseline

Below are the conditions for a baseline test:

1) All tire pressures were within ± 0.5 psi. of the placard specification. For this test vehicle the front and rear tires were 32 and 35 psi., respectively.

2) The platform tilt axis was virtually horizontal (i.e., at the nominal condition of the facility).

3) The vehicle was positioned with its longitudinal axis parallel to the table's tilt axis. The accuracy requirements for this orientation were for the lateral position of the center line of the two axles to be within 0.25 inch of one another relative to the longitudinal reference line.

4) The trip rail clearance was zero. That is, the trip rails were positioned to just touch the vehicles low-side tires. Before securing the rails, their

No	Variation	Tilt Speed deg./ Sec.			Sampling Rate Hz.		Vehicle Long. Position			Vehicle Orientation inch				Ride Height				Tire Pressure Psi All Tires			Tire Pressure Psi Low	Tire Pressure Psi High
		0.25	0.5	1.0	5.0	20.0	Rrwd.	Cntr.	Forw.	0.0	1.0	3.0	-3.0	Low	Norm.	High	Repeat	-2.0	Norm.	2.0	-2.0	-2.0
0	Baseline		X			X		X		X					X				X			
1	Tilt Speed	X				X		X		X					X				X			
2	Tilt Speed			X		X		X		X					X				X			
3	Smple Rate		X		X			X		X					X				X			
4	Smple Rate			X	X			X		X					X				X			
5	Long. Pos.		X			X	X			X					X				X			
6	Long. Pos.		X			X			X	X					X				X			
7	Orientation		X			X		X			X				X				X			
8	Orientation		X			X		X				X			X				X			
9	Orientation		X			X		X					X		X				X			
10	Ride Height		X			X		X		X				X					X			
11	Ride Height		X			X		X		X						X			X			
12	Ride Height		X			X		X		X					X		X		X			
13	Tire Pres.		X			X		X		X					X			X				
14	Tire Pres.		X			X		X		X					X					X		
15	Tire Pres.		X			X		X		X					X						X	
16	Tire Pres.		X			X		X		X					X							X
17	L Frct./Off.		X			X		X		X					X				X			
18	L Frct./Off.		X			X		X		X					X				X			
19	L Frct./Off.		X			X		X		X					X				X			
20	L Frct./Off.		X			X		X		X					X				X			
21	L Frct./Off.		X			X		X		X					X				X			
22	H Frct./Off.		X			X		X		X					X				X			
23	H Frct./Off.		X			X		X		X					X				X			
24	H Frct./Off.		X			X		X		X					X				X			
25	H Frct./Off.		X			X		X		X					X				X			
26	H Frct./Off.		X			X		X		X					X				X			
27	H Frct./Off.		X			X		X		X					X				X			
28	Tire Sup.		X			X		X		X					X				X			
29	Temp °F		X			X		X		X					X				X			
30	Tilt Axis		X			X		X		X					X				X			
31	Shim Front		X			X		X		X					X				X			
32	Shim Rear		X			X		X		X					X				X			
33	Light Straps		X			X		X		X					X				X			

Table 2.1. The test matrix

No	Variation	Low Side Friciton		Trip Rail Clearance inch			Trip Rail Height inch		High Side Tire Suprt.		Vehicle Temp. °F		Tilt Axle Inc Deg.		Shim Front inches		Shim Rear inches		Light Straps	
		High	Low	0.0	1.0	2.0	1.0	2.0	Lock	Free	Norm.	Low	0.3	0.0	0.0	0.5	0.0	0.5	Norm	Lght
0	Baseline		X	X			X		X		X			X	X		X		X	
1	Tilt Speed		X	X			X		X		X			X	X		X		X	
2	Tilt Speed		X	X			X		X		X			X	X		X		X	
3	Smple Rate		X	X			X		X		X			X	X		X		X	
4	Smple Rate		X	X			X		X		X			X	X		X		X	
5	Long. Pos.		X	X			X		X		X			X	X		X		X	
6	Long. Pos.		X	X			X		X		X			X	X		X		X	
7	Orientation		X	X			X		X		X			X	X		X		X	
8	Orientation		X	X			X		X		X			X	X		X		X	
9	Orientation		X	X			X		X		X			X	X		X		X	
10	Ride Height		X	X			X		X		X			X	X		X		X	
11	Ride Height		X	X			X		X		X			X	X		X		X	
12	Ride Height		X	X			X		X		X			X	X		X		X	
13	Tire Pres.		X	X			X		X		X			X	X		X		X	
14	Tire Pres.		X	X			X		X		X			X	X		X		X	
15	Tire Pres.		X	X			X		X		X			X	X		X		X	
16	Tire Pres.		X	X			X		X		X			X	X		X		X	
17	L Frct./Off.		X		X		X		X		X			X	X		X		X	
18	L Frct./Off.		X			X	X		X		X			X	X		X		X	
19	L Frct./Off.		X	X				X	X		X			X	X		X		X	
20	L Frct./Off.		X		X			X	X		X			X	X		X		X	
21	L Frct./Off.		X			X		X	X		X			X	X		X		X	
22	H Frct./Off.	X		X			X		X		X			X	X		X		X	
23	H Frct./Off.	X			X		X		X		X			X	X		X		X	
24	H Frct./Off.	X				X	X		X		X			X	X		X		X	
25	H Frct./Off.	X		X				X	X		X			X	X		X		X	
26	H Frct./Off.	X			X			X	X		X			X	X		X		X	
27	H Frct./Off.	X				X		X	X		X			X	X		X		X	
28	Tire Sup.		X	X			X			X	X			X	X		X		X	
29	Temp °F		X	X			X		X			X		X	X		X		X	
30	Tilt Axis		X	X			X		X		X		X		X		X		X	
31	Shim Front		X	X			X		X		X			X		X	X		X	
32	Shim Rear		X	X			X		X		X			X	X			X	X	
33	Light Straps		X	X			X		X		X			X	X		X			X

Table 2.1. The test matrix (cont.)

Chronological Order of Testing

Run No.	Repeats 1	2	3
1	5	7	28
2	4	28	11
3	20	15	12
4	12	2	26
5	15	17	21
6	8	22	7
7	24	19	24
8	11	24	3
9	25	12	6
10	22	6	13
11	19	5	15
12	13	21	27
13	18	27	19
14	2	3	16
15	21	4	25
16	10	1	4
17	26	9	9
18	3	23	5
19	9	11	17
20	17	16	14
21	7	8	10
22	1	26	18
23	16	14	23
24	23	10	22
25	6	20	20
26	28	25	2
27	14	18	1
28	27	13	8

Table 2.2 Test order

Test Baseline Day	Position
1	3
2	6
3	6
4	4
5	7
6	1
7	5
8	3
9	1
10	6
11	7

Table 2.3 Baseline order

longitudinal axis was adjusted parallel to the table's longitudinal reference line.

5) Trip rail height was 1.0 inch.

6) The longitudinal center of gravity of the vehicle was aligned with the lift point of the hydraulic cylinder.

7) The high-side tire support plates were locked preventing their lateral motion.

8) Low-side tire surface was painted carbon steel.

9) The vehicle's ride height was verified to be within ±1/8 inch of the established ride height.

10) The vehicle temperature was between 60 - 80 ° F.

11) Tilt rate was set to 0.5 deg./sec.

12) Data sampling rate was set to 20 Hz.

Changes from the Baseline

The discussion below outlines the matrix of changes from the baseline condition. Related areas of concern are also included.

Tilt Table Speed and Sampling Rate -

These two variables are related to potential errors in measuring the exact angle producing static instability. The dynamics (that is, the very long response time) of the vehicle system at the point of instability, as well as the accuracy of the liftoff event switches, are also involved.

To assess the accuracy of the contact switches, a manual switch was added to the instrumentation set-up so that one could manually confirm the liftoff event with the switch. Results of the manual tests show that the contact switches were an accurate method of electronically recording the time of tire liftoff.

Four tests were done to study the sensitivity of sampling rate and tilt table speed. The two tilt table speeds used were approximately 0.25 and 0.9 deg./sec. The sampling rate was changed from 20 Hz. to 5 Hz. to examine how sampling affects capturing the critical liftoff time. One test involved increasing the table speed and changing the sample rate.

Table and Vehicle Geometry -

Three baseline changes examined the influence of table geometry. Two of them consisted of conducting the test with the vehicle located as far forward and as far rearward as practical. The third studied the effect of a non-horizontal tilt axis. By inserting shims under the hinges, the angle of the tilt axis relative to horizontal was changed by 0.34 degree over the length of the table.

An additional condition was made to examine the influence of table surface geometry. After analyzing the results of the longitudinal position tests and determining that table surface warping had been very small, it was decided that the low-side tires should be shimmed to simulate the effect of a badly warped table. In two separate tests, a 0.5 inch plywood shim was added to the table at the front and then the rear, low-side tire/table contact areas. The trip rail was also shimmed by 0.5 inches to maintain the one inch height of the baseline condition.

Vehicle Orientation -

Three tests were done to examine the effect of a vehicle's yaw orientation. In the first test, the center line of the rear axle was offset laterally relative to the table center line by 1.0 inch. A 3.0 inch rear, lateral offset was used in the second test. In both of these tests, the rear axle was oriented in the "uphill" direction relative to the front axle. In the third test, the other yaw polarity was tested and the front axle was laterally offset by 3.0 inches. Spacers were used to fill the gap created between the tire and the trip rails for all the vehicle orientation tests.

Suspension Hysteresis -

To examine the potential influence of suspension hysteretic effects, measurements were conducted in three "off standard" ride height conditions. The first two consisted of "minimum" and "maximum" ride height conditions. The low position was established by manually depressing the front and rear bumpers simultaneously. This procedure was undertaken with the vehicle on the table and the high-side tire supports free to move laterally (the plates were then locked for the test). To establish the maximum ride height, a similar procedure was used, but with lift applied to the bumpers. The third condition, called "ride repeat," was one in which the ride height and all other conditions of the vehicle were *not* reset following the previous test. The table was returned to the horizontal position, the vehicle position and ride height measured, and a repeat test was conducted immediately. This was seen as a "worst case" condition relative to all the "hysteretic" influences.

A fourth hysteresis-related condition measured the effect when the high-side tire support plates were unlocked and allowed to move in the lateral direction.

Tire Pressure -

Tire inflation pressure clearly can influence static roll stability by changing tire stiffness. The purpose here was not to investigate the sensitivity in a general sense, but to examine whether "small" inflation pressure errors would significantly alter the results. To do this, four different inflation pressure conditions were considered. In two of the cases, the inflation pressure of all tires was changed by -2.0 and +2.0 psi. In the other two cases, a -2.0 psi. change was made to the low-side and high-side tires, respectively.

Low-Side Surface Friction, Lateral Offset, and Trip Rail Height -

A key element in determining a vehicle's static rollover threshold value is the vertical location of the lateral force vector at the low-side tires. Two components combine to supply this lateral force and determine its location. The first is a result of the friction between the tire and the tilt table surface. This force acts laterally at the tire/table interface. The second is provided by the trip rail and will be located at some height above the tire/table interface. When a high friction surface is used with enough lateral offset to allow tire deformation, a significant part of the lateral resultant force will be at the interface. The properties of surface friction and trip rail height and clearance will combine to determine the vertical position of the total restoring force.

The baseline surface friction condition was a lower friction condition in which the low-side tire support was painted carbon steel. The higher friction condition was created by the application of median grit, 3M Safetywalk™. Lateral offsets of the trip rail from the tire were tested at 1.0 and 2.0 inch clearances. Tests with a non-standard rail height of 2 inches were also done. In some cases, when synergistic effects were expected, more than one of these conditions was changed simultaneously.

Vehicle Temperature -

Toward the end of the testing, one condition was done with the vehicle at a relatively extreme temperature. For this test, the vehicle was parked outside overnight when the temperature dipped to 19 °F. The following morning, the vehicle was brought in and tested immediately. The outside temperature at the time the vehicle was brought inside was approximately 22 °F. Measuring equipment was not subjected to the temperature change.

Light Straps -

Following the testing, there was some concern about the weight of the buckle on the straps used. The weight of the buckles was approximately 3 lbs. per strap. To verify that they had little influence on the answers, an additional set of baseline tests was done using much lighter straps made to the appropriate length and without a buckle.

"Zero Speed Test" -

At the end of all testing, an additional test was conducted to evaluate the "true" static rollover threshold. With the vehicle in the baseline condition, the test simulated a rollover with a virtually zero table speed. To conduct the test, the vehicle was inclined to an angle just before front wheel liftoff. The vehicle was lightly restrained while the table was inclined an additional 0.07 deg. (0.002 g). At this new inclination, the vehicle was released. This "step and pause" process was continued through the rear tire liftoff event. Like the other conditions, this test was repeated three times.

General Test Procedure

The general test procedure can be broken down into two parts. The first involves steps taken only at the beginning of each test day to insure a consistent condition of the vehicle and table. During the first days of testing, these steps were part of the procedure for each tilt test. However, the conditions were so consistent that it was practical to verify and/or adjust them only at the beginning of each test day. The second procedure involves steps taken to set-up for a baseline test. Conditions off the baseline usually only involved a slight change to one of the steps in the procedure.

Before conducting any tests on a given day the following set-up steps were taken:

1) Raise and lower the table without a vehicle to warm the hydraulic oil and verify tilt rate. (Oil temperature had a large influence on the tilt rate of the table.)

2) Measure and "top off" the fuel if necessary. At any given time, not more than a half-gallon of gasoline was needed to re-fill the gas tank.

3) Measure and adjust tire pressure if necessary.

Below is the general set-up procedure for a baseline test:

1) Drive the vehicle onto the table with approximately the correct lateral and longitudinal alignment.

2) With the driver out of the vehicle and the engine off, measure the lateral alignment relative to the table's longitudinal reference line. This measurement was taken by dropping a plumb bob from the center line paint mark on the front and rear axles. If the front to rear alignment was not within 0.25 inch, then the front was carefully maneuvered closer to alignment. Measure front and rear lateral alignment again and continue moving the vehicle until within the tolerance.

3) Put the vehicle in neutral and manually align its longitudinal center of gravity with the hydraulic cylinder lift point or appropriate lateral reference according to the particular test.

4) Using a grease pencil, mark the center of the tire/table contact patch on both the front and rear high-side tires.

5) Manually push the vehicle either forward or backward to expose the tread of the tire associated with the pencil mark. Center with the pencil mark and attach a strip of conductive foil from the outside tire sidewall across the tread and up the inner tire sidewall.

6) Manually re-align the vehicle longitudinally with a plumb line.

7) Put the vehicle's transmission into park and set the parking brake. Roll up all windows and turn ignition to the locked position.

8) Attach safety straps. Connect all electronic instruments.

9) Align and secure trip rails.

10) Measure, record and adjust ride height if it is different from the established ride height.

11) Verify or establish a zero steer condition.

12) Calibrate data acquisition system to zero all offsets and verify gains.

3. RESULTS

Before discussing the primary statistical results of the sensitivity study, a discussion of the data processing and related issues will be presented. This discussion elucidates some interesting "mechanistic" findings of the study.

Data Processing

In most experiments where data are collected electronically, some processing must be done prior to analysis. In this study, the data were first filtered to remove noise, corrected for static offsets and gains, and finally shifted for dynamic lag. All of this was accomplished by computer. The sections below detail the general program flow and describe the different methods used to process the data.

Zero Shift

The first step in data processing was to correct for a non-zero initial value in the three table signals (see Instrumentation for locations). Before inclining the tilt table in each test, data were collected for at least a half second. Using this initial data, a zero offset value for each table channel was calculated. Each table signal was then shifted by its offset value to reflect a zero initial angle.

Static Calibration

Before testing, UMTRI had performed physical calibrations of its five clinometers. Ford provided gain calibrations for its three accelerometers. All of these gain calibrations were checked with the instruments in place on the tilt table. To do this, table angles were sampled electronically and manually. The manual measurements were taken with a pendulum clinometer accurate to ± 1 minute. Manual measurements were made at the initial and final table angles and at approximately the same location as the electronic clinometers. The results of the tests are shown in Table 3.1. The calculated gain corrections from Table 3.1 were applied to the three table signals in subsequent data processing. The overall result of the gain correction was an average of 0.06 degree (0.002 g) difference at rollover. This was based on the average of the front and rear UMTRI clinometers and the center Ford clinometer. Figure 3.1 shows an example of the correction on a baseline test.

Dynamic Lag

The instrumentation for measuring table inclination consisted of eight electronic clinometers or accelerometers. The three Ford accelerometers were servo-accelerometers with a fast response time. The other five clinometers (supplied by UMTRI) used a viscous liquid mechanism to sense their tilt angle and had a response time slow enough to affect measurement results. Comparison of data signals from the fast and slow transducers revealed that the (UMTRI) liquid clinometers had a lag of approximately 0.4 second. Figure 3.2 shows the lag of the signals of the front and rear liquid clinometers as compared to the

Front Axle Position

	Manual Clinometer, deg. Down	Manual Clinometer, deg. Up	Electronic Clinometer,deg. Down	Electronic Clinometer,deg. Up	Manual Clin. Difference, deg.	Electronic Clin. Difference, deg.	Gain Correction
Test.1	-0.23	44.53	0.12	44.12	44.76	44.00	1.0173
Test.2	-0.24	44.65	0.06	44.21	44.89	44.15	1.0168
Test.3	-0.19	44.00	0.05	43.51	44.19	43.46	1.0168
						Average =	1.0170

Center Position

	Manual Clinometer, deg. Down	Manual Clinometer, deg. Up	Electronic Clinometer,deg. Down	Electronic Clinometer,deg. Up	Manual Clin. Difference, deg.	Electronic Clin. Difference, deg.	Gain Correction
Test.1	0.08	44.88	-0.02	44.57	44.81	44.59	1.0049
Test.2	0.06	45.15	-0.03	44.7	45.09	44.73	1.0081
Test.3	0.08	44.30	-0.07	44.01	44.22	44.08	1.0031
						Average =	1.0054

Rear Axle Position

	Manual Clinometer, deg. Down	Manual Clinometer, deg. Up	Electronic Clinometer,deg. Down	Electronic Clinometer,deg. Up	Manual Clin. Difference, deg.	Electronic Clin. Difference, deg.	Gain Correction
Test.1	-0.93	43.87	0.06	44.84	44.80	44.78	1.0004
Test.2	-0.87	44.02	0.06	44.96	44.88	44.90	0.9996
Test.3	-0.88	43.33	0.06	44.28	44.22	44.22	0.9999
						Average =	1.0000

Table 3.1. Static gain corrections

more responsive center clinometer. The 0.4 second lag was confirmed using the results of rollover tests employing the three different tilt speeds. In subsequent data analysis, signals from the liquid clinometers were "shifted in time" by 0.4 sec. to compensate for transducer lag.

Determining the Point of Static Instability

To determine the point of instability (static rollover threshold), the front and rear liftoff switches and Ford clinometer signals where analyzed. Figure 3.3 is a typical data plot of the behavior in the immediate vicinity of front and rear tire liftoff. The plot includes a trace of body roll angle versus simulated lateral acceleration, plus traces showing the occurrence of front and rear tire liftoff as a function of simulated lateral acceleration. Simulated lateral acceleration is the tangent of the table tilt angle. Body roll is calculated by taking the difference of the table tilt angle and the (absolute) body tilt angle. The liftoff signals derive from the tire contact switches.

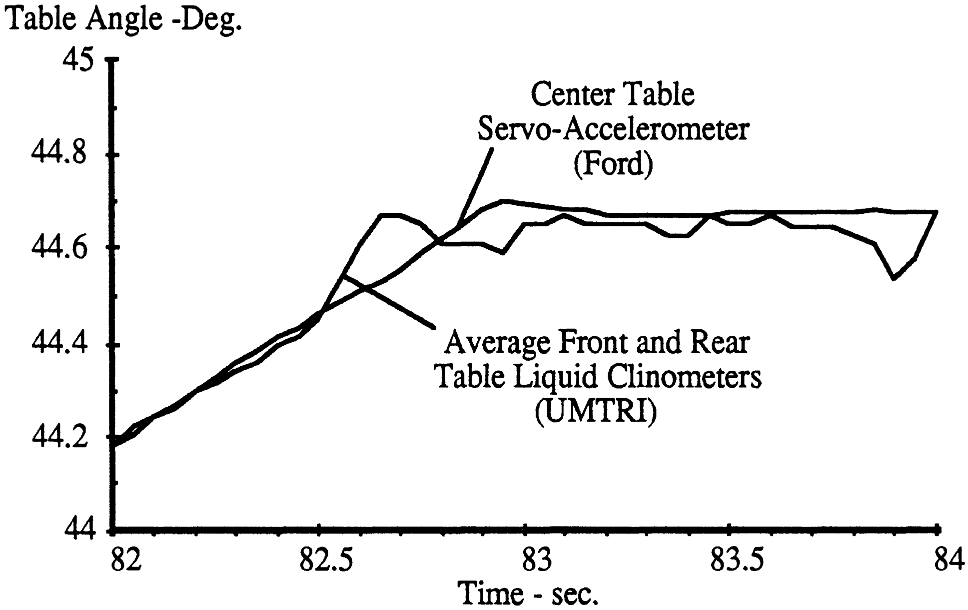

Figure 3.1. Gain correction based on the average of the front and rear table clinometers and the center table accelerometer

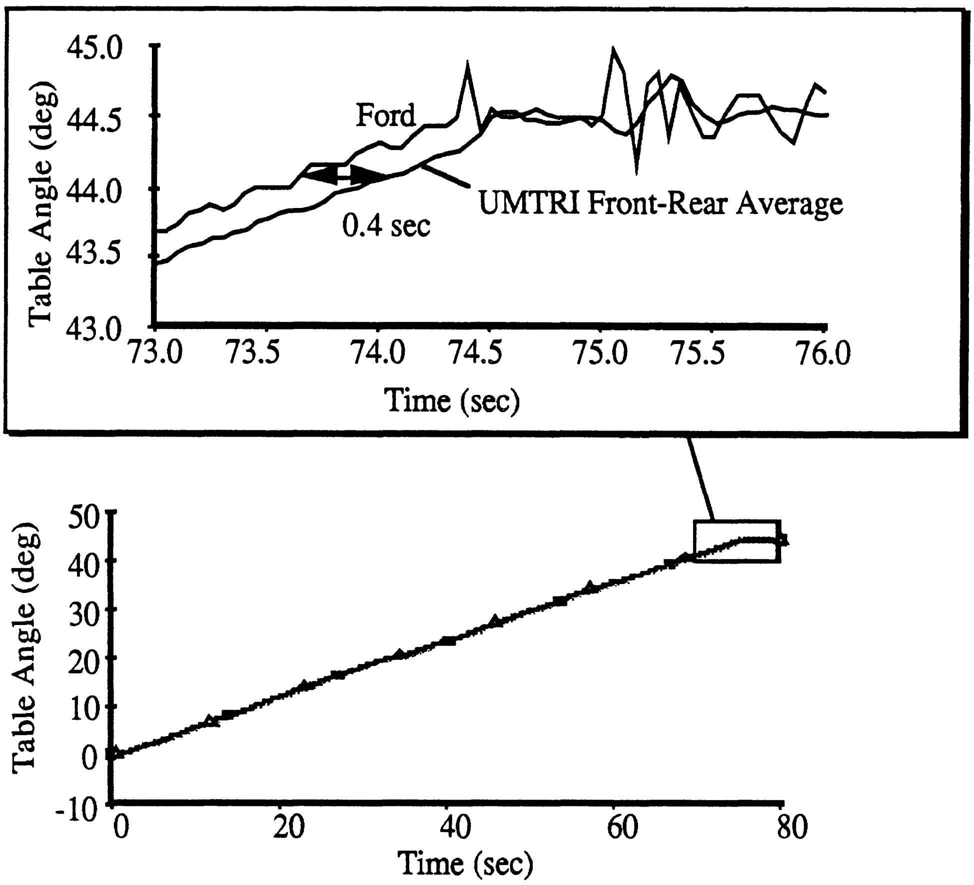

Figure 3.2. The dynamic lag of UMTRI clinometers

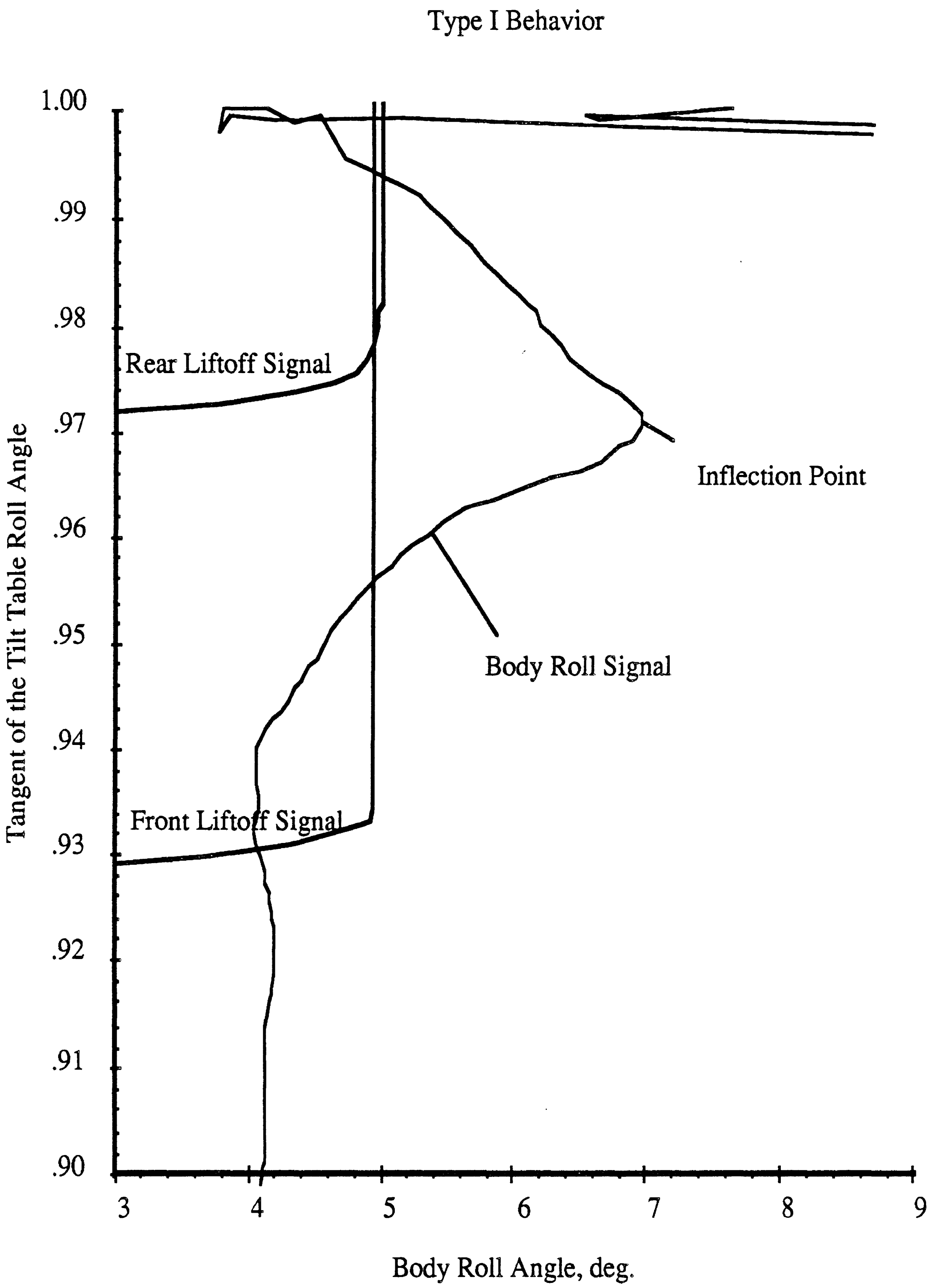

Figure 3.3. A typical data plot of the body roll angle (deg.) versus tangent of the tilt taable roll angle with front and rear liftoff signals

A distinct inflection point is seen in the roll angle plot at approximately the same time when the rear switch indicates liftoff. Initial thoughts were that the inflection could be taken as the point of rollover instability for the vehicle. However, closer scrutiny of the inflection phenomenon revealed its inaccuracies.

When a vehicle is being tilted, one would expect the body roll angle to increase steadily until rollover. At rollover, it would then become dramatically larger as the vehicle rolled over. The point of rollover instability would correspond to an inflection point in the signal. The trace of Figure 3.3, however, is quite different from this expectation. Instead of a marked increase in body angle at rear tire liftoff, the data shows a large decrease. Clearly, the vehicle was not re-approaching the table after tire liftoff. It was hypothesized that the sensitivity of the clinometers to acceleration was the cause of this inconsistent behavior.

Clinometers are, in fact, accelerometers. They measure inclination by sensing the gravitational acceleration component along their sensitive axis, when that axis is inclined from the horizontal. But, the clinometer can not distinguished between the component of gravity and "true" acceleration along its sensitive axis. Thus, the clinometer only "works" in the absence of other acceleration.

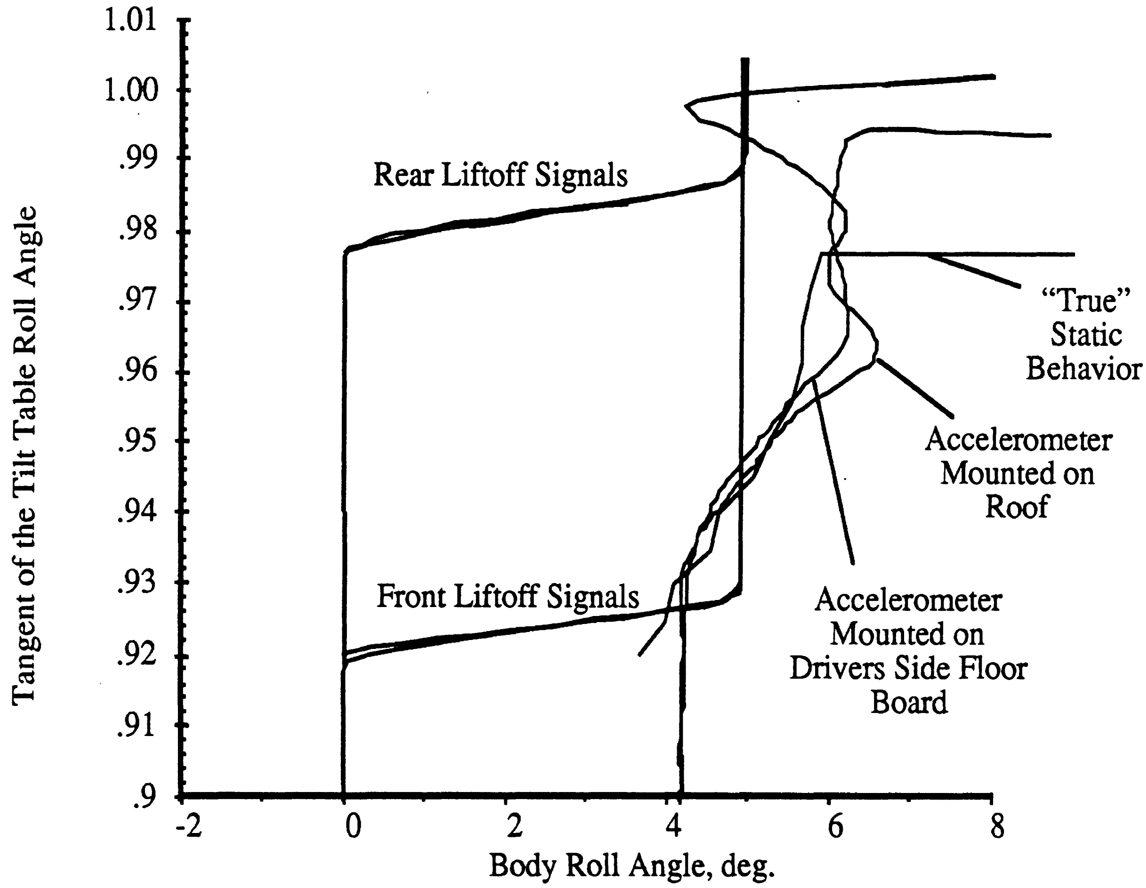

Figure 3.4. The influence of all accelerations on the body accelerometer

In the tilt table test, as the vehicle becomes unstable, it accelerates in roll about a pivot axis that is located along the low-side tire contact patches. Clinometers mounted on the vehicle will experience linear acceleration in proportion to their distance from this rotation center. The influence of the acceleration on the clinometer's signal appears as an inclination whose polarity is opposite the acceleration polarity. To verify the hypothesis, three tests were performed with the body clinometer moved from the vehicle's roof to the driver's side floor board. This reduced the distance from the rotation center to the clinometer by approximately two-thirds. The results, shown in Figure 3.4, indicate reduced effects in the peaks caused by the affects of acceleration.

To validate the hypothesis even further and to very clearly document the "true" tilt table static behavior of the vehicle in the vicinity of instability, a set of "zero speed" tests were conducted. These tests were described earlier in the "Changes from the Baseline" section. The "true" static behavior is also included in Figure 3.4.

Type I and Type II Behavior

In a majority of the tests, a single peak in the body roll angle signal seemed to correspond with the indication of liftoff by the rear contact switch. This type of behavior, called Type I behavior, was shown in Figure 3.3. However, in certain tests, a different phenomenon occurred. Instead of there being only one peak in the body roll angle signal, a second smaller peak occurs after the first. In these cases, the rear tire liftoff corresponds closely to the second peak. This phenomenon, called Type II behavior, is shown in Figure 3.5. Both peaks are caused by changes in the vehicle's acceleration. The "true" static behavior has been included on Figure 3.5 to aid the following explanation.

In both types of behavior, the first peak appears to be due to deceleration as the rear suspensions stiffens due to encountering the shock absorber extension limit. As this deceleration subsides, the signal subsides toward the true value. In Type I behavior, it appears that the vehicle's small amount of momentum is enough to cause it to continue rolling and lift the rear tire from the table surface. In Type II behavior, with slightly less momentum, the vehicle begins to "settle down" briefly with the rear tire still on the table. The second peak appears to signal one small "bounce" on the rear tire before rollover occurs, and the signal drops sharply due to acceleration.

Whether Type I or II behavior occurs seems to depend strongly upon table speed. In all the tests where the table speed was approximately 0.25 deg./sec., Type II behavior occurred. Conversely, in the test with a fast table speed (0.9 deg./sec.) only Type I behavior occurred. Tests where the table speed was approximately 0.5 deg./sec., had both types of behavior. This speed appears be close to the threshold for either Type I or II behavior. Whether this kind of behavior is unique to this vehicle is unknown. It is believed, however, that the best approach is to perform all tilt tests at the slowest table speed possible. It is also believed that most of the testing was done near the transition between Type I and Type II behavior, and this probably contributed to the general scatter in the results.

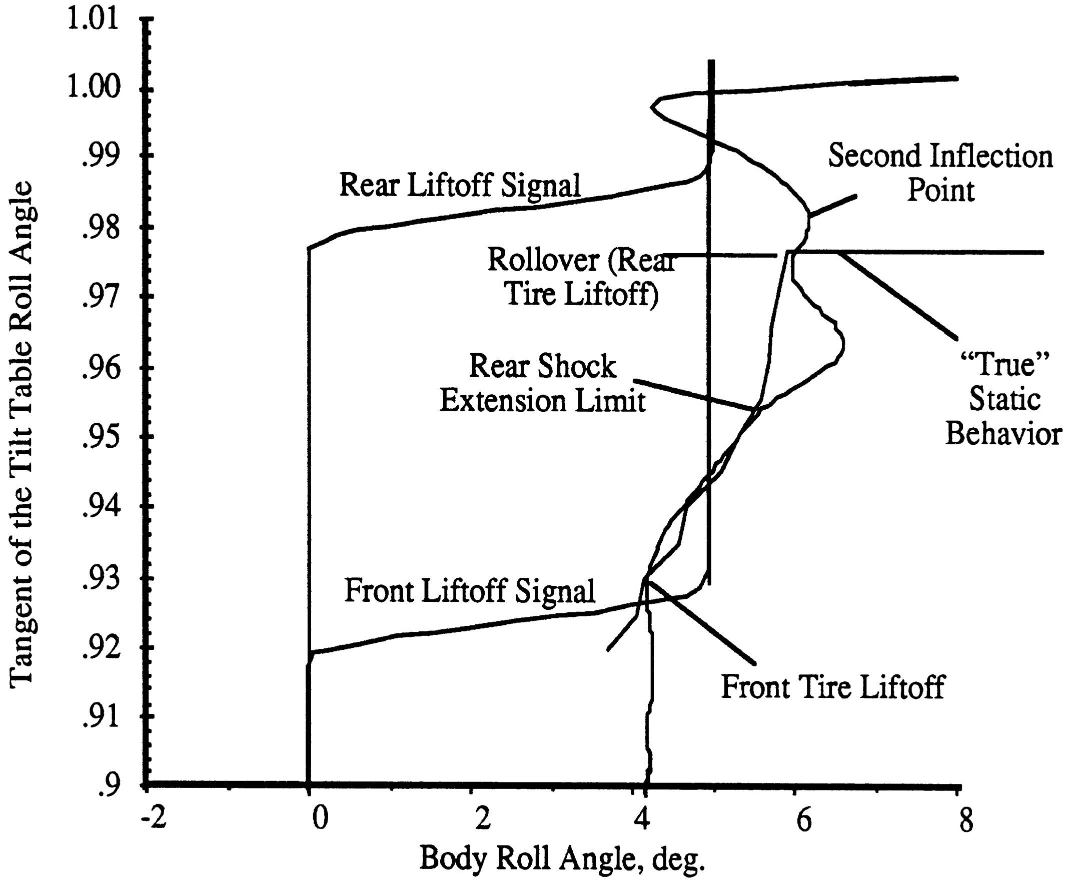

Figure 3.5. Type II behavior and "true" static behavior

Final Method Used to Determine The Point of Static Instability

While UMTRI and others have previously used roll angle signal inflection as an indicator of the occurrence of static instability, these analyses clearly warn against that practice. In the end, the method used to determine the rollover threshold angle was based on the rear tire liftoff switch signal. To confirm that the front and rear switches were a highly reliable way of indicating liftoff with both types of behavior, a series of tests was conducted with a third manually operated switch. In these tests, the liftoff of the front and rear tires were closely watched. When liftoff occurred at each tire, the switch was pressed and released. This caused pulses in the signal time history marking the two events. The results of these tests (twelve tests total) clearly showed that the foil tire switches were accurately indicating liftoff of the tires.

Statistical Results of the Sensitivity Study

Mean and One Standard Deviation of the Observations

A summary of the test results is shown in Figure 3.6. The figure shows the mean and the standard error of the observed values of TTR for the baseline and for all changes from the baseline. The shaded region indicates the standard error of the baseline test results.

The test conditions have been grouped into six categories listed across the top of Figure 3.6. Along the bottom of the figure are test names representing each condition. Figure 3.7 describes each test name in more detail. The "true" TTR, as determined by the "zero speed" test, is shown as the last condition in the "Sample & Tilt Rate" category.

Significance of the Results — The Influence of Test Conditions on the Observed Means

To examine the significance of the baseline changes, confidence intervals were calculated for the mean of the three replications at each condition. A $(1 - \alpha)$ confidence interval is given by:

$$\bar{y} \pm t_{n-1;1-\frac{\alpha}{2}} \bullet \frac{s}{\sqrt{n}} \qquad (2)$$

where

$t =$ value of Student's t distribution with n-1 degrees of freedom at the

$1-\frac{\alpha}{2}$ significance level

$s =$ standard error of the observations

$n =$ number of observations

$\bar{y} =$ mean

Figure 3.8 shows the results of using this equation with a $t = 4.303$, which corresponds to having three observations and a two-sided 95 percent confidence level. The resulting confidence intervals are rather large. The large bands essentially result from the small number of samples (three per test condition except for the baseline). As can be seen in Equation (2) the "t-test" penalizes you twice for a small number of samples. First, in the denominator of the equation, the standard error is divided by the square root of the number of observations. Second, the value of t increases with an decreasing number of observations. The baseline test is a good example of these two effects. The corresponding t value for the baseline test with eleven samples is 2.228. Figure 3.8 shows the relatively small 95 percent confidence interval that results. Intervals calculated in this manner illustrate the accuracy of the mean of each test condition.

A more powerful statistical test is to compare the results of each condition to the results of the baseline tests. The purpose of the experiment was to find the effect of a parameter change on the tilt table rollover threshold as compared to the baseline condition. By defining a statistic for the comparison of two events, it is possible to determine if the mean of a baseline change is significantly different from the baseline mean. This is different from the previous application where the mean of each baseline change is being evaluated "on its own."

For this "difference" approach statistic of interest is defined as the difference between the mean of a test condition and the baseline mean, where:

$$\text{Difference,} \quad D = (\text{Mean})_{\text{test condition}} - (\text{Mean})_{\text{baseline}}$$

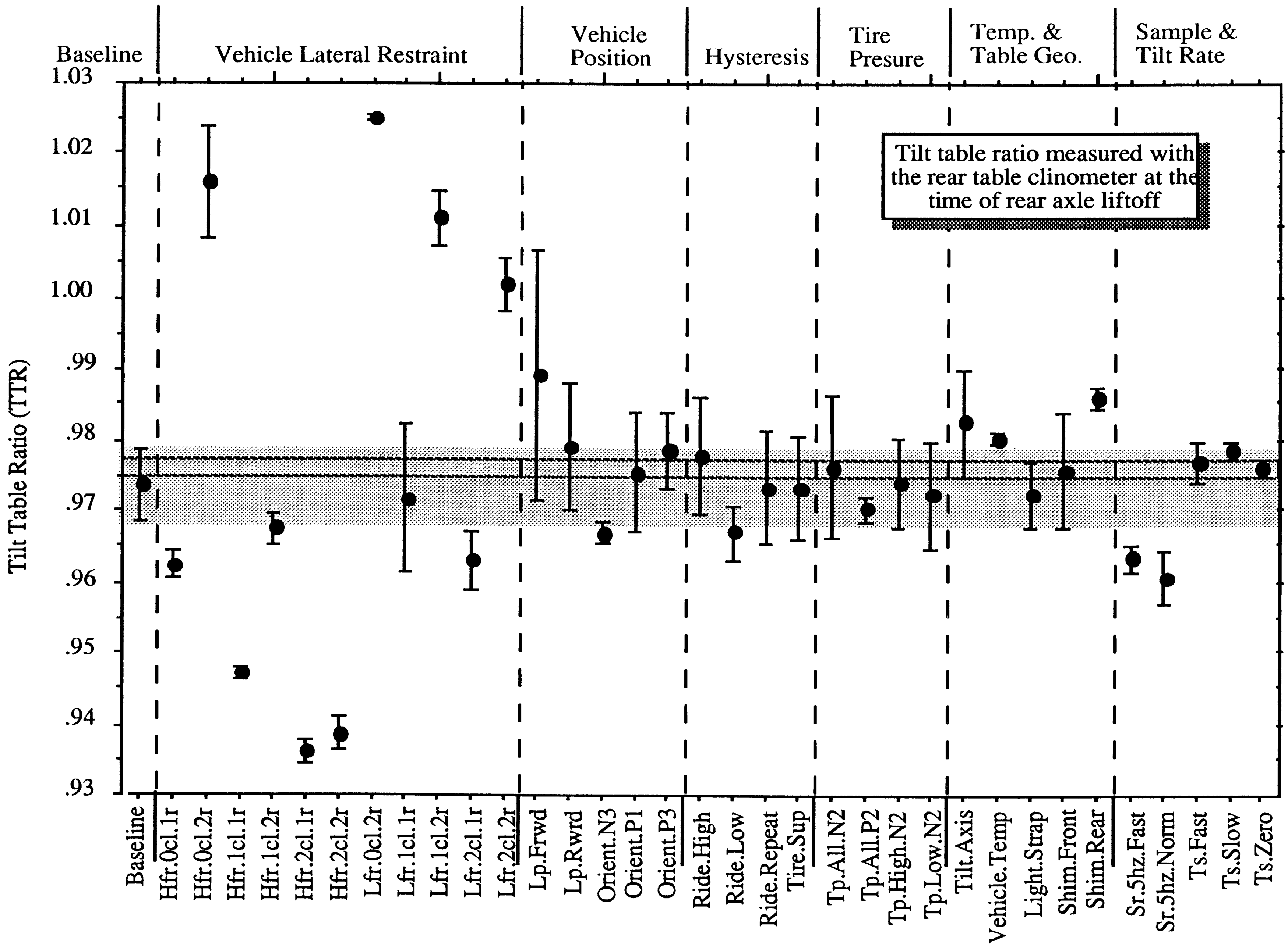

Figure 3.6. Mean and standard error of the observations

Baseline	Baseline
Hfr.0cl.1r-	Low-side tires on high friction; 0 clearance; 1 in. rail height (1)
Hfr.0cl.2r-	Low-side tires on high friction; 0 clearance; 2 in. rail height (1)
Hfr.1cl.1r-	Low-side tires on high friction; 1 in clearance; 1 in. rail height (1)
Hfr.1cl.2r-	Low-side tires on high friction; 1 in clearance; 2 in. rail height (1)
Hfr.2cl.1r-	Low-side tires on high friction; 2 in clearance; 1 in. rail height (1)
Hfr.2cl.2r-	Low-side tires on high friction; 2 in clearance; 2 in. rail height (1)
Lfr.0cl.2r-	Low-side tires on baseline friction; 0 clearance; 2 in. rail height (2)
Lfr.1cl.1r-	Low-side tires on baseline friction; 1 in clearance; 1 in. rail height (2)
Lfr.1cl.2r-	Low-side tires on baseline friction; 1 in clearance; 2 in. rail height (2)
Lfr.2cl.1r-	Low-side tires on baseline friction; 2 in clearance; 1 in. rail height (2)
Lfr.2cl.2r-	Low-side tires on baseline friction; 2 in clearance; 2 in. rail height (2)
Lp.Frwd-	Vehicle positioned full forward on table (3)
Lp.Rwrd-	Vehicle positioned full rearward on table (4)
Orient.N3-	Vehicle rotated in yaw with rear axle down 3 in.
Orient.P1-	Vehicle rotated in yaw with front axle down 1 in.
Orient.P3-	Vehicle rotated in yaw with front axle down 3 in.
Ride.High-	Initial vehicle ride height set high (5)
Ride.Low-	Initial vehicle ride height set low (6)
Ride.Repeat-	Immediate run repeat without suspension reset (7)
Tire.Sup-	High-side tires on "zero-friction" surface
Tp.All.N2-	Inflation pressure of all tires -2 psi (8)
Tp.All.P2-	Inflation pressure of all tires +2 psi (8)
Tp.High.N2-	Inflation pressure of high-side tires -2 psi (8)
Tp.Low.N2-	Inflation pressure of low-side tires -2 psi (8)
Tilt.Axis-	Table roll axis inclined 1/3 degree
Vehicle.Temp-	Test vehicle in cold condition (9)
Light.Strap-	Light restraining straps
Shim.Front-	Low-side front tire on 1/2 inch shim (10)
Shim.Rear-	Low-side rear tire on 1/2 inch shim (10)
Sr.5hz.Fast-	5 hz sampling and fast table speed (11)
Sr.5hz.Norm-	5 hz sampling and baseline table speed (11)
Ts.Fast-	Fast table speed (12)
Ts.Slow-	Slow table speed (12)
Ts. Zero -	"Zero" table speed (12)

3. Forward 15 inches
4. Rearward 12.5 inches
5. Front ride height ≈ +0.06 in
   Rear ride height ≈ +0.03 in
6. Virtually no change in ride height
7. Front ride height ≈ +0.4 in
   Rear ride height ≈ +0.1 in
   Results reference to baseline
8. Baseline: 32 psi front; 35 psi rear
9. Outside overnight; down to 19° F
10. Equivalent to ≈ 1/2° table angle
11. Baseline sampling rate, 20 hz.
12. Baseline speed ≈ 0.5 deg/sec
    Fast speed ≈ 0.9 deg/sec
    Slow speed ≈ 0.25 deg/sec

Figure 3.7. Reference for abbreviated test names

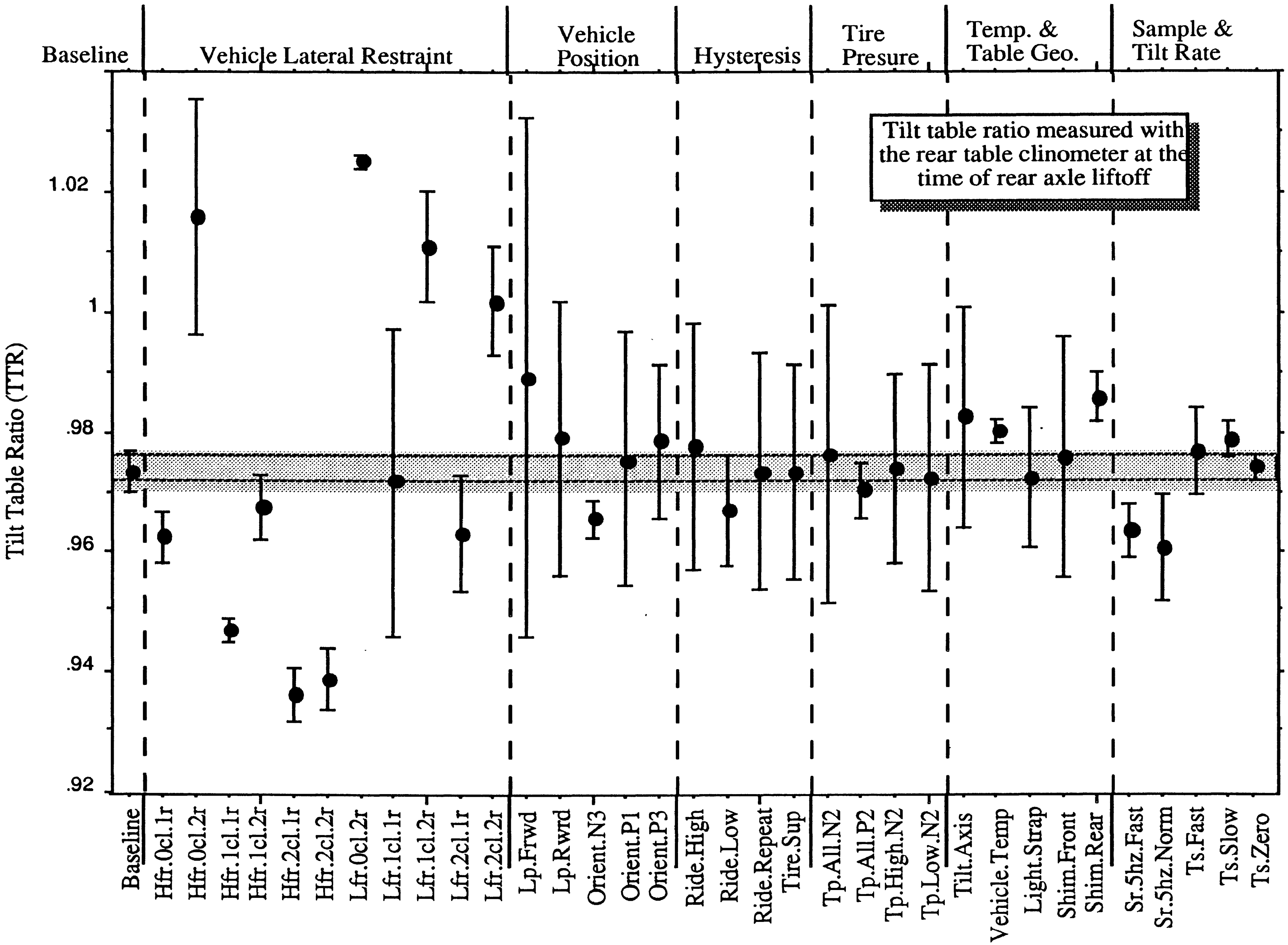

Figure 3.8. The 95 percent confidence interval based upon three repeats of each variation

$$s_D = \left[\frac{s^2_{baseline}}{11} + \frac{s^2_{test\ condition}}{3} \right]^{\frac{1}{2}}$$

s = standard error of the observations

and the 95 percent confidence interval is:

$$D \pm t_{12;\ .025} \cdot s_D$$

The results are shown in Figure 3.9 where the difference between the mean of a baseline change and the baseline mean are plotted for each matrix test. The 95 percent confidence interval was calculated using the corresponding "t - test" value of 2.179 for a 12 degree of freedom system. The null hypothesis, of course, is that the difference is zero. In interpreting this figure, it is appropriate to say a set of trials lacks a significantly different mean result if its 95 percent confidence interval does cross the 0.0 difference line. Conversely, the more distance between the confidence interval and the zero line, the more significant the result.

Mechanisms of Important Sensitivities

Vehicle lateral restraint -

The test conditions in this area had the most significant effect on the TTR of the vehicle as compared to the baseline results. This comes as no great surprise. The destabilizing roll moment is composed of the component of vehicle weight, parallel to the table surface, coupled with the lateral constraining force. By varying tire/table friction, tire lateral stiffness, and trip rail height, the effective vertical location of this lateral stabilizing force changes. This, in turn, changes the magnitude of the destabilizing roll moment.

In the baseline condition, the low-side tires rest on a moderate friction surface. The trip rail is one inch high and is placed in light contact with the tire at the outset of the test. As tilt angle is increased, some of the lateral constraint derives from friction coupling between the tire and the surface, and some from the tire sidewall bearing on the trip rail. The vertical position of the resultant constraining forces lies somewhere between the surface and the top of the one-inch rail.

When changes in trip rail height, trip rail clearance, or surface friction are made, there is a potential for the height of the resultant constraint force to change. Clearly, when the height of the trip rail is increased from one to two inches, the tendency is for the lateral restraint to rise. As initial clearance between the trip rail and the tire is increased from zero to one and two inches, one of two results is possible. If tire friction is not saturated during the test (i.e., the tire does not slide), the tendency would be for the height of the resultant force to decline. If the tire breaks loose, slides and then strikes the rail, either an up or down change seems possible.

On the high friction surface, sliding never occurred. The results of this series of tests are orderly and fit our expectations. Using a two-inch rail at zero clearance raised the constraint force and resulted in higher values of TTR. All other changes lowered the

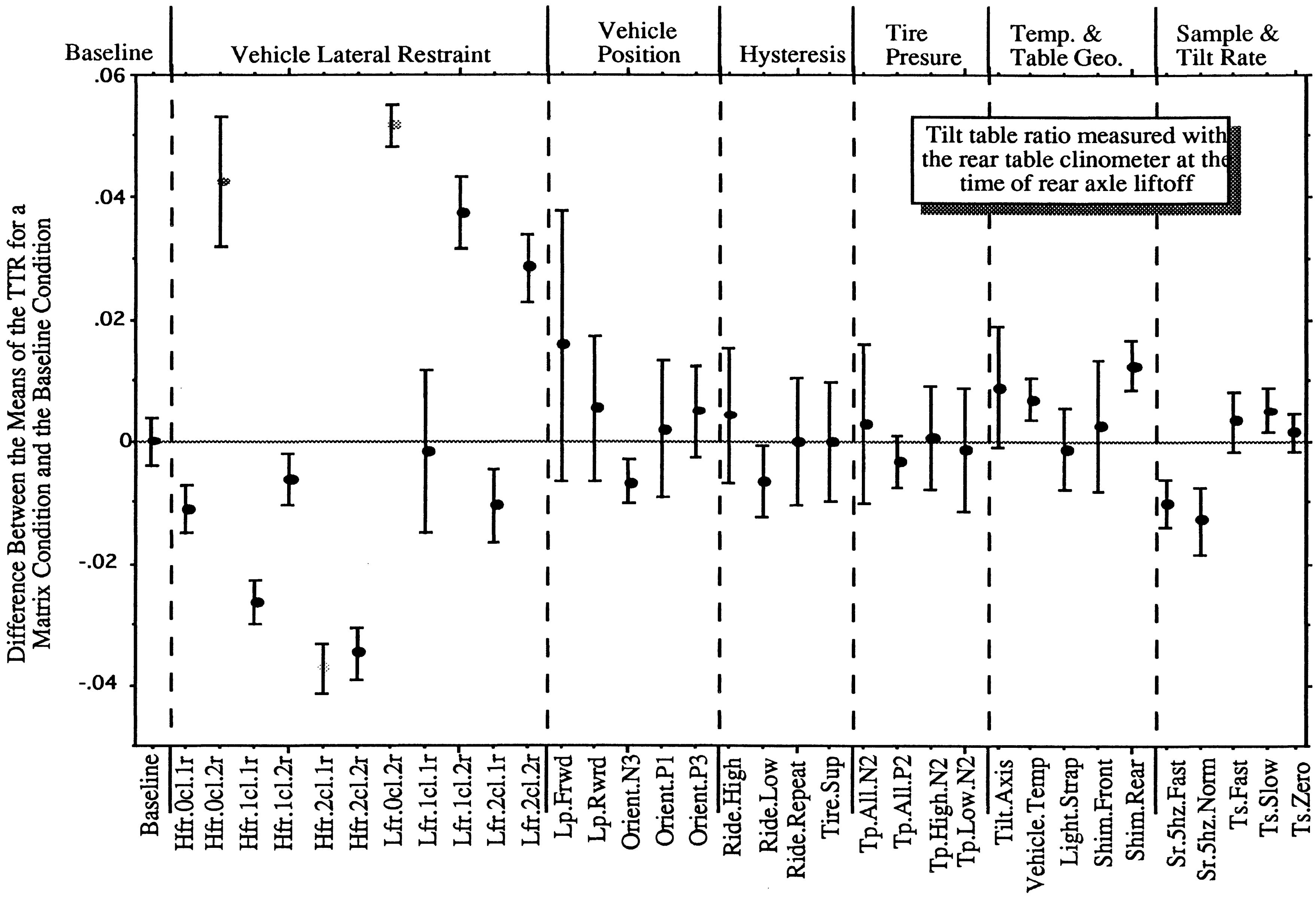

Figure 3.9. The difference between the means of the tilt table ratio for a matrix condition and the baseline condition with 95% confidence intervals

constraint force and lowered the observed TTR. Moreover, with a two-inch clearance, the tire did not deflect enough to reach the trip rail, be it one or two inches high. Thus, the constraint force is at ground level for each of these two conditions. The data show that the results for these two conditions are virtually identical and reflect the lowest observed TTR.

On the lower friction (baseline) surface, sliding did occur when clearance was provided between the curb and the rail. The results indicate that this tended to produce a higher location of the constraint force and a higher measured TTR.

Several regression models were tried in order to further investigate the relationship between friction, trip-rail height, and trip-rail clearance and the TTR. The most successful model was the linear regression model outlined in Table 3.2. The model contains the main effects of the three primary variables plus the effect of their product. (The estimated values of friction used were 0.75 for the low friction surface and 1.25 for the high friction surface. Unity was added to the clearance in calculating the product to avoid the masking influence of multiplying by zero.)

For this model, $R^2 = 0.961$ and $F = 237$. As can be seen by comparing the coefficients with the standard errors, all of the variables except the estimated friction are highly significant. From the partial F values, it can be seen that the main influence of trip-rail height is very strong, but the influence of the trip-rail clearance and surface friction is mostly embodied in the product, not in the main effects. Indeed, the influence of surface friction alone is virtually nil. These observations are certainly consistent with a mechanistic understanding of the process, and they tend to suggest that using a high friction surface with the minimum required trip rail will enhance the accuracy of the observed TTR as an estimate of the static roll stability limit.

Variable	*Coefficient*	*Standard Error*	*Partial F*
INTERCEPT	0.9186	---	---
Trip-rail height	0.0714	0.00306	544.1
Trip-rail clearance	0.0107	0.00215	24.6
Estimated friction	-0.0041	0.00504	0.7
Ht*(Clr+1)*Frct	-0.0187	0.00141	175.9

Table 3.2 A linear regression model for the lateral restraint test data

Vehicle Position -

The changes in longitudinal position of the vehicle did not produce significantly different results compared to the baseline. As explained previously, these position changes were intended to produce warping of the table surface, but the effect was found to be very small.

The TTR did change significantly in one of the three tests with the vehicle rotated in yaw. Even in this case, however, the significance was small and the yaw misalignment was so great that, when setting-up for the test, it took additional effort to create such a gross misalignment.

Hysteresis and Tire Pressure -

These changes showed little or no significance when compared to the baseline test. As might be expected, the relatively small differences in the initial condition of the vehicle suspension are insignificant when the suspension is deflected in as severe a manner as it is during the rollover process.

Also, as the vehicle approaches rollover, the lateral constraint of the high-side tires approaches zero because the vertical load on these tires approaches zero. Thus, the tire/surface friction quality at the high-side tires appears to have little influence.

Temperature and Table Geometry -

Two conditions in this category showed some significance. The vehicle temperature test was, in effect, like testing a different vehicle due to the extreme temperature involved. The cold vehicle appears to have stiffer suspension properties and, therefore, a higher value of TTR is observed. Clearly, however, the effect is not strong.

The other condition showing some significance was shimming the rear low-side tire by 0.5 inch. Given the 61.4 inch rear track width, this is effectively a change in the table angle at the rear axle of 0.46 degree. Intuitively then, the table will have to rotate an additional 0.46 degree (0.0159 g) to overcome the effect of the angle change caused by the shim. The actual result is very close to this expectation. An increase of 0.0123 in TTR was observed between the mean of the condition and the baseline mean. No significant influence was seen when shimming was done at the front axle. Presumably, this is because front tire liftoff has already occurred, and the slope of the table at the front axle therefore has little influence, when the point of instability is reached.

Sampling and Tilt Rate -

The two conditions showing some significance in this category involved changing the sampling rate from 20 Hz. to 5 Hz. This is somewhat confusing because, by decreasing the sampling rate, one would expect the data acquisition to "miss" the precise time of the event and record the event as occurring later. This would correspond to a reading that is greater than the true TTR. For both conditions, however, the change in sampling rate resulted in a lower static rollover threshold. Why the result was lower is not clear and no satisfactory explanation has been found.

Slowing the tilt rate appeared to have a small, but significant, effect resulting in a higher TTR. This was expected since a slower rate would remove any of the dynamic effects that tend to lower the TTR.

Significance of the Results — The Influence of Test Conditions on the Observed Variances

The previous discussion dealt with the influence of the various test conditions on the mean of the observed TTR, and concluded that several of the conditions of lateral constraint and a few of the other test condition variations produced significant effects on the observed means. Another question of interest is whether or not the different test conditions produced a significant difference in the observed variance of the test results. That is, are the differences in variances observed under the different test conditions, and represented by the differences in the lengths of the bars of Figure 3.6, statistically significant?

Generally, the data gathered in this study are, except in a few instances, insufficient to draw statistically significant conclusions regarding the influence of test condition on the variability of the test. The proper test for significance in comparing variances is the F-test. This test typically demands much larger sample sizes than the t-test to achieve comparable fidelity, and it requires normality in the underlying distribution for validity. Since each individual test condition (except the baseline) is represented by only three samples, little can be said about the differences between variances for the individual conditions. This is true even when comparing the results of individual test conditions, or groups thereof, against the baseline condition.

Using the F-test, it can be shown that, at a significance level of 10%, five test conditions have a significantly smaller variance than the baseline condition, and four test conditions have a significantly larger variance than the baseline condition. These test conditions are identified in Table 3.3. It is interesting to note, however, that if the five small variances are compared to one another, there are no significant differences among any of them. Similarly, if the four large variances are compared to one another, there are no significant differences among any of them either.

Test Condition	Degrees of Freedom	Variance of TTR
Baseline	10	26.07 E-6
Significantly smaller variance than baseline variance		
Hfr.1cl.1r	2	0.56 E-6
Lfr.0cl.2r	2	0.30 E-6
Orient.N3	2	1.75 E-6
Vehicle temp	2	0.64 E-6
Ts.Slow	2	1.47 E-6
Significantly larger variance than baseline variance		
Lfr.1cl.1r	2	106. E-6
Lp.Frwd	2	303. E-6
Lp.Rwrd	2	83. E-6
Tp.All.N2	2	102.31 E-6

Table 3.3. Test conditions with a variance significantly larger or smaller than the variance of the baseline condition.

The subset of tests associated with the lateral constraint mechanisms may be of particular interest. Those tests involved three variables, viz., surface friction (high and low), trip-rail height (1 and 2 inches) and trip-rail clearance (0, 1, and 2 inches). The possibility that these conditions influence variability can be examined.

Table 3.4 presents pooled variances from groupings of the lateral restraint subset, including the baseline. The tests are split into high friction and low friction groups and pooled variances calculated, respectively. They are also broken down by trip-rail geometry (height and clearance) and the appropriate pooled variances are calculated. However, two samples, Hfr.2cl.2r and Hfr.2cl.1r, have been omitted from the groupings by geometry. In these two cases, the tires did not slide on the surface, and no tire-to-rail contact occurred. Thus, rail geometry was irrelevant. (However, surface friction clearly was important.) Instead, these two sets of three are pooled as one group of "no rail" tests.

Applying the F-test, the data of Table 3.4 would imply:

Ref. No.	Test Conditions	Degrees of Freedom	Pooled Variance of TTR
1	All low friction surface tests (includes baseline)	20	2.80 E-5
2	All high friction surface tests	12	1.30 E-5
3	All 1-inch rail test (includes baseline, excludes Hfr.2cl.1r)	18	2.85 E-5
4	All 2-inch rail tests (excludes Hfr.2cl.2r)	10	1.89 E-5
5	All "no rail" tests (Hfr.2cl.1r and Hfr.2cl.2r)	4	0.37 E-5
6	All 0-inch clearance test (includes baseline)	16	2.45 E-5
7	All 1-inch clearance test	8	3.16 E-5
8	All 2-inch clearance tests (excludes Hfr.2cl.1r and Hfr.2cl.2r)	4	1.43 E-5

Table 3.4. Degrees of freedom and pooled variances of TTR for several groupings of the vehicle lateral restraint testing subset

(1) The pooled variance of the high friction tests is significantly less than the pooled variance of the low friction tests.

(2) The pooled variance of the "no rail" tests is significantly less than the pooled variance of either the one-inch or two-inch high trip-rail tests. But there was no significant difference in the pooled variances of the one-inch and two-inch high trip-rail test results.

(3) There are no significant differences among the pooled variances of the various groupings by trip-rail clearance.

The F-tests supporting these points are reviewed in Table 3.5, where test yielding significant results are highlighted with bold type.

These results, taken as a whole, would tend to argue for conducting the tilt table test on a sufficiently high friction surface such that a trip rail is not required. In this, they are compatible with the implications of the previous analysis of the means of the observed values. It should also be restated, however, that the evidence relating to variance is statistically weak, and probably should be considered tentative until challenged by a test program characterized by larger sample sizes.

Test of: (Ref No of Table 3.3)	Ratio of Variances of TTR	Required Ratio for Significance at 10 %
1 and 2	**2.15**	2.06
3 and 4	1.51	2.21
3 and 5	**7.70**	3.85
4 and 5	**5.1**	3.92
6 and 7	1.29	2.09
7 and 8	2.21	3.95

Table 3.5. F-test of several pooled variances of TTR

4. CONCLUSIONS

The results of this study tend to indicate that the tilt table test is a rather repeatable method for estimating the static roll stability limit of light truck-like vehicles. That is, at least with respect to the variables considered here, the tilt table test is not unduly sensitive to small changes in parameters of either facility or methodology.

However, it should be remembered that this optimistic conclusion implies good repeatability, but not necessarily a high degree of accuracy. The tilt table procedure is intended to estimate the static roll stability limit of a vehicle by subjecting it to a physical analogy of the roll plane experience of steady turning. While tilt table results are likely to be more accurate than the simple "T/2h" estimate of roll stability, the analogy is certainly not perfect, and the highly repeatable results of the tilt table test may, therefore, be in error with respect to the true static stability limit.

The statistical analysis of the results of the study indicate that, in general, even the fairly gross changes in test parameters that were examined in this program tended to produce changes in the measurement results that were either insignificant, or that resulted in well under a two percent change of the measured value.

The only exceptions to this are associated with changes in the vehicle lateral constraint mechanism—the geometry of the restraining trip rail and the friction quality of the table surface. Changes in trip-rail geometry altered the measurement result as much as five percent. A significant change in surface friction alone appeared to produce a change of slightly over one percent in the mean of the observed TTR. The observed variations suggest the use of a high friction surface and low trip rail to enhance the accuracy of the TTR as an estimate of static roll stability limit.

Changes in surface friction and some details of trip-rail geometry also appeared to influence the variance of the results, as well as the mean. The statistical quality of these results are relatively weak and should be confirmed, but they also tend to argue for the use of a high friction surface with a low trip rail.

Beyond the issue of lateral constraint, the statistical analysis indicates:

1) The tilt table method does not appear to be sensitive to moderate errors in vehicle yaw alignment (± 1/2 deg).
2) Moderate deviations of the table tilt axis from the horizontal (±1/3 deg) appear insignificant.
3) Errors in table surface geometry (±0.5 inch deviations from a planar surface) may have a significant influence on measurement results. However, this influence appears to be simply and directly accounted for by the discrepancy between transduced tilt angle and the effective tilt angle immediately beneath the vehicle's axles.

4) Variations in the initial ride height of the vehicle, as might typically result from suspension hysteretic effects, appear insignificant.

5) Small variations in tire inflation pressures (variations of ± 2 psi) appear insignificant.

6) Large changes in vehicle temperature (as might derive from indoor and outdoor testing in cold weather) appear to influence results about one percent.

7) Table tilt rate changes over the range of 0.25 deg/sec to 1 deg/sec appear to have small or insignificant effects. (However, see 9 below.)

Detailed engineering analyses add to conclusions reached through statistical analysis. Additional conclusions are:

8) Caution should be used when interpreting data signals from clinometers mounted on the test vehicle. In the vicinity of the static roll stability limit, small accelerations of the vehicle can significantly influence these signals and may lead to erroneous conclusions.

9) Very slow table speeds in the vicinity of the static roll stability limit are advisable. The sensitivity of the measured TTR to table speed may vary among vehicles. Behavior in the immediate vicinity of the static roll stability limit is dominated by highly non-linear events such as encountering suspension stroke limits and tire liftoff. The quality of vehicle response in the region may depend on the peculiar non-linearities of the test vehicle. At this time, engineering judgment argues for a use of a low rate in the vicinity of instability.

As a final precautionary note, all of the findings and conclusions of this study derive from measurements of a single vehicle tested only in the curb condition and only on one facility. Results might vary for different test vehicles, loading conditions, or test facilities.

5. REFERENCES

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