McCormick
27084

Final Report
Contract DOT-HS-031-1-159

Vehicle Handling Performance

Summary Report

R. D. Ervin
P. Grote
P. S. Fancher
C. C. MacAdam
L. Segel

Highway Safety Research Institute
The University of Michigan
Huron Parkway and Baxter Road
Ann Arbor, Michigan

November 1972

Prepared for
National Highway Traffic Safety Administration
U. S. Department of Transportation
Washington, D.C. 20591

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle	5. Report Date
VEHICLE HANDLING PERFORMANCE	November, 1972
	6. Performing Organization Code
7. Author(s) R.D. Ervin, P. Grote, P.S. Fancher, C.C. MacAdam, L. Segel	8. Performing Organization Report No. UM-HSRI-PF-72-2-1
9. Performing Organization Name and Address Highway Safety Research Institute The University of Michigan Huron Parkway and Baxter Road Ann Arbor, Michigan 48105	10. Work Unit No. 11. Contract or Grant No. DOT-HS-031-1-159
12. Sponsoring Agency Name and Address National Highway Traffic Safety Administration U.S. Department of Transportation Washington, D.C. 20591	13. Type of Report and Period Covered Summary Final Report 6/71 - 11/72 14. Sponsoring Agency Code
15. Supplementary Notes	

16. Abstract

The test methodology which was originally developed in the Vehicle Handling Test Procedures study was extensively refined in this program. Redesigned test apparatus was utilized in the conduct of refined test procedures on a sample of 12 contemporary passenger vehicles. The resulting data was reduced through a fully computerized data processing system. A permanent digital tape library was generated and will be preserved for public use.

Significant findings were made with respect to certain tire properties which impose a serious confounding influence on limit turning measurement.

The test vehicle sample was seen to exhibit a large range of emergency maneuvering capability. It was seen that certain vehicles exhibit properties which appear desirable over a great variety of maneuvers—while certain other vehicles exhibit consistently "poorer" performance, in terms of the safety-related hypotheses.

It is recommended that research be conducted to identify the causative mechanism behind the sensitivity of tire side force capability to shoulder wear. Research is recommended in the area of driver/vehicle system performance such that an evaluation can be made of the validity of certain expressed hypotheses related to interpretation of open-loop responses.

17. Key Words	18. Distribution Statement
Vehicle mechanics, vehicle performance, open-loop measures, limit performance, emergency maneuvers, test procedures, data base	Unlimited Availability

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified		

Form DOT F 1700.7 (8-69)

TABLE OF CONTENTS

1.0 Introduction. 1

2.0 Vehicle Handling Test Procedures
- Further Developments. 3

3.0 Full-Scale Test Program 7

4.0 Conclusions and Recommendations 17

5.0 References. 21

1. INTRODUCTION

This report presents findings, conclusions and recommendations derived by the Highway Safety Research Institute (HSRI) in a research study for the National Highway Traffic Safety Administration (NHTSA) entitled "Vehicle Handling Performance" (VHP). The objectives of the study involved:

1) review and refinement of test procedures derived in a parent NHTSA-sponsored study, "Vehicle Handling Test Procedures" (VHTP), which was completed by HSRI in 1970;

2) application of these refined test procedures to the objective measurement of safety-related vehicle handling properties of a representative sample of vehicles;

3) determination of the minimum physical requirements for the execution of these test procedures.

This report presents material which can be more fully understood if the reader is acquainted with the concepts and methods put forth in the above cited report on the VHTP study. In that work, a rational pragmatic viewpoint was developed, from which a relationship between highway safety and vehicle performance was hypothesized.

Based on the hypothesis that such a relationship exists, this study refines and extends the performance measurement methodology developed earlier and applies this experimental method to the construction of a data library documenting six vehicle handling properties in objective terms. The objective measures selected express vehicle performance properties in the context of the hypothesized relationship. Whereas the current state of highway safety research does not provide scientific proof for the hypothesized performance/safety relationship, it is postulated that this study provides safety-related performance data of value to the highway safety community, and whose value can be enhanced by further research.

The data library generated in this study contains measurements of vehicle handling performance exhibited at the limits of tire-road adhesion. It follows that these measures do not constitute an evaluation of the handling properties manifested in normal driving, but rather characterize the emergency maneuvering capability of the tire-vehicle system. Further, the term "open-loop" is applied to these measures since the driver has been removed as an active element in the system.

The report documents the further development of vehicle handling test procedures and the application of the developed methodology to a test sample. With regard to the presentation of test data, "summary" is the key word. Sixteen data plots are presented that serve as a condensation of over one quarter of a million time histories that were recorded during the test program. A complete tape file of these test data will be preserved for public use, a documentation step believed to constitute a significant fruit of this study. Conclusions and recommendations are expressed based upon vehicle-test data, tire-test data, overall test experience, and the authors' convictions relative to the directions that future research should take.

2. VEHICLE HANDLING TEST PROCEDURES - FURTHER DEVELOPMENTS

Considerable advancements were made within this program, in the design of certain test hardware specifically for the use in open-loop limit maneuver testing. Notable among these apparatus are the following:

1) quick detach outriggers for the restraint of vehicle rollover (Fig. 1);

2) automatic lift fifth wheel assembly to permit repeated testing in the proximity of a spinout limit condition (Fig. 2);

3) steering limiter assembly made integral with a steering wheel for rapid application to any test vehicle, which provides a precision, adjustable constraint to driver-applied steer inputs (Fig. 3).

Certain open-loop maneuvers involve such complex inputs of steering and braking that driver control is considered impractical. An automatic vehicle controller was built for use in this study which incorporated a number of new features, expanding upon the original concept derived in the Vehicle Handling Test Procedures contract to provide a test apparatus whose performance could be relied upon under a continuous testing routine. With this system, servomechanisms replace the driver at the steer, brake, and accelerator controls (Fig. 4). This system can be programmed such that precise time histories of control inputs are obtained, as desired, even under the most severe of emergency conditions.

For test vehicles with manual transmissions, the unmanned controller-equipped vehicle is pushed initially by a "chase" vehicle (Fig. 5), from which a radio link operator controls clutch actuation as well as the steer brake and accelerator in a drone fashion.

In addition, advancements were made in data acquisition such that all control input and vehicle response data could be gathered on magnetic tape, permitting a computerized processing of all test data. This effort was undertaken not only in recognition of the tremendous quantity of data to be gathered during the full-scale test program, but also to permit the generation of a permanent tape file of data to be made available for public use after the conclusion of the study.

The test procedures which were developed during the VHTP study were reviewed in this program and extensively refined. Much of the refinement derived from observations made during the Pilot Test Program, in which a large number of alternative procedures were examined. It was determined that the six basic procedures should be conducted to the following format.

1) Straight Line Braking - the execution of straight line, constant-brake-level stops from an initial 40 mph, up to the point of lockup at two front or rear wheels.

2) Braking In A Turn - the execution of constant-brake-level stops from a 40 mph, 0.3g lateral acceleration turn, up to the point of lockup at two front or two rear wheels.

3) Roadholding In A Turn - the examination of wheel hop resonance through the execution of a steady 0.4g turn at 30 mph, along a trajectory which intersects a grid of road disturbance elements. Three grids are traversed, each from the same initial turn, with the disturbance elements arranged to

impose 9, 11, and 14 Hz fundamental frequency excitation to the vehicle running gear.

4) Trapezoidal Steer - using the automatic controller, a trapezoidal steering wave shape is applied, from an initial straight line course at 40 mph. A wide range of steer levels is examined, chosen to be inclusive of the limit turning performance of the vehicle.

5) Sinusoidal Steer - with the controller, one cycle of a sine wave of steering is applied from an initially straight line course at 45 mph and at 60 mph. Over a range of steer amplitudes, the emergency lane change performance of the vehicle is assessed.

6) Drastic Steer and Brake - one half cycle of a sine wave of steering, followed by a timed brake application are input from an initially straight path at 50 and 60 mph. Over a range of steer level and brake input timings, the vehicle's propensity for rollover is severely challenged.

Upon reviewing certain data generated during the pilot test program, large unexplained variations in peak lateral acceleration response were observed. Recognizing that the consistency of such performance properties was crucial to the viability of limit maneuver measurement, a substantial tire and vehicle test effort was undertaken to diagnose and correct this problem. The key finding, whose discovery led to a solution of the problem, is represented by Figure 6, showing a dramatic sensitivity of peak side force to tire shoulder wear—the type of wear which accrues during limit turning tests. Thus, a classic fault had been identified, by which the test process was acting to the alteration of the test condition. A practice was developed and employed to achieve a stabilization in side force capability of each vehicle's tires prior to collecting test data. This force stabilization method involved a preliminary set of limit turning tests which were selected to be sufficient for accruing shoulder wear, as shown necessary through testing of each vehicle's tires on a mobile tire test device.

In addition to procedure refinements, advances were also made in the crucial area of data presentation, with particular emphasis placed upon the provision of measures which are interpretable in a safety context. The rationale behind each maneuver and the interpretation of the resulting response was extended and refined, with particular advances deriving from the availability of new computed response variables, sideslip angle, and path curvature.

The sideslip response, β, is felt to be of major safety significance. It is argued that excessive sideslip responses, as occur under limit maneuvering conditions disorient the driver with respect to the normal view of his vehicle's path, and cause the vehicle to project a larger target for collision in the roadway. (See Figure 7.)

The path curvature response, $1/R$, permits the evaluation of turning response, without introducing any ambiguities in the measure due to a simultaneous sideslip response—as was the case in the original VHTP presentations.

3. FULL-SCALE TEST PROGRAM

A sample of vehicles was selected early in this study, to be representative of contemporary passenger vehicles in terms of their handling properties, the market representation of foreign and domestic manufacturers, and, to a limited extent, in terms of certain perceived overinvolvement in single vehicle accidents. Of the original sample of fifteen vehicles, twelve were selected for full-scale testing. Additionally, a 13th vehicle was tested as a joint activity with a companion DOT contract. The test vehicles are shown in Figure 8. Of this group, the Toyota Corolla was not subjected to the full battery of tests, following damages incurred during the rollover response shown in Figure 9. This response occurred during a trapezoidal steer maneuver being conducted for purposes of wearing-in the tire shoulders.

3.1 VHP FINDINGS

The VHP response data gathered during the full-scale test program are presented below in summary form. Condensed data plots are presented as a consolidation of the data from the entire sample, indicating, also, the range and the distribution of performance. These consolidated plots were obtained by graphical overlay methods.

3.1.1 STRAIGHT-LINE BRAKING. Three categories of limit response can be defined among the data collected:

a) front wheels lock up first (as typified by the Lotus Europa)

b) rear wheels lock up first (as typified by the AMC Ambassador)

c) 4-wheel antilock performance as represented in the sample by the Chrysler Imperial.

Typical raw data time histories are shown in Figure 10. Except for the case of rear-wheel lockup, in which a yaw divergency may result, all raw data from straight-line braking resembles the example in Figure 10. Figure 11 presents the distribution of performance for the test vehicle sample, including an overlay of the three response categories typified by the Lotus, Ambassador, and Imperial. This plot defines the range of longitudinal acceleration, A_x, vs. brake pressure, P_B, represented by the individual plots from each vehicle.

Clearly, the range of vehicle performance on this plot is determined both by differences in gain (A_x/P_B) and by differences in the peak longitudinal acceleration achieved without locking 2 wheels on the same axle. The spread of peak acceleration performance is indicated in the figure to be 0.22g.

3.1.2 BRAKING-IN-A-TURN. As with straight-line braking, the significant limit response categories are:

a) front-wheel lockup, as with the Mercedes

b) rear-wheel lockup, as with the AMC Gremlin

c) 4-wheel antilock performance, Imperial.

Figure 12 presents raw data deriving from a typical sub-limit condition, with no wheels locking. The longitudinal acceleration is seen to rise abruptly interrupting the initially steady turn; following which, path curvature increases.

Figure 13 presents a raw data sample of the limit response to braking-in-a-turn characterized by lockup of the front wheels. Characteristically, this limit is indicated by an immediate drop in the A_y and r time histories, with negligible sideslip ($\tan\beta$) and a decrease in path curvature to zero. The divergent end condition of the β and 1/R time histories reflects the computational instability that results when the forward velocity appearing in the denominator of both variables goes to zero. This nominal response also typifies the performance exhibited by vehicles with 4-wheel antilock systems.

In Figure 14, raw data are presented for the rear-wheel lockup limit case, clearly indicating the unstable directional response that typifies this limit category.

Sideslip-rate and path-curvature responses are presented in Figures 15 and 16, summarizing the performances exhibited across the vehicle sample. These plots indicate the range and distribution of braking-in-a-turn performance, together with lines representing the approximate mean performance of the vehicles typified by front-wheel lock, rear-wheel lock, and no wheel locking limit performance. It is clear that the only vehicles exhibiting substantial sideslip are those which exhibit rear-wheel lockup, while either front- or rear-wheel lockup can cause a dramatic loss in path-curvature response at the limit.

Interesting features of the path curvature presented in Figure 16 include the generally increasing trend in normalized 1/R with increased braking, as well as the predominance of sublimit points showing values greater than 1.0. An explanation of these characteristics is provided by reflection upon the understeer contribution to path curvature that accompanies a decreasing velocity with constant steer angle. As the understeer vehicle slows down, even in the absence of braking, path curvature gain increases. Thus, the results plotted in Figure 16 indicate the summation of two path-curvature responses; one deriving simply from understeer effects, and another deriving from factors related to the braking process.

3.1.3 ROADHOLDING IN A TURN. Two categories of limit response are observed in the roadholding in a turn data:

1) predominant wheel-hop resonance of front suspension is exhibited, resulting in significant loss in path curvature without large sideslip;
2) rear wheel-hop resonance dominates, causing a destabilizing yaw moment and a resulting sideslip excursion.

Example time histories characteristic of the response caused by dominant wheel-hop resonance of the front wheels are given in Figure 17. Note that the yaw-rate response decreases quickly, when the vehicle contacts the disturbance grid, causing the computed path-curvature response, 1/R, to drop likewise.

Dominant resonance at the rear wheels yields the time histories shown in Figure 18. With a substantial loss in rear-tire side force, $\dot{\beta}$ rises to a rather large level, and path curvature drops toward zero.

The responses among the sample are summarized in Figures 19 and 20, illustrating the range and distribution of the data from the 12-vehicle sample. As indicated in Figure 19, the range of normalized path curvature data essentially covers the range of conceptual possibilities. While certain vehicles showed rather slight loss in path curvature, upon encountering the road roughness grid, others exhibited an essentially tangential, zero curvature, response. Dominant front wheel resonance is overlaid on Figures 19 and 20 as exhibited by the Firebird. Dominant rear wheel resonance is overlaid on both figures as indicated by the Volkswagen.

It should be noted that the Figure 19 plot was constructed without the contribution of data from either the Mercedes or Lotus test vehicles. The omission of these vehicles from the summary plot is based upon the observation of response data anomalies which are not explainable through basic kinematic principles. In Figure 21, an example of raw data taken with the Mercedes test vehicles shows lateral acceleration not only decreasing during the traversal of the disturbance grid, but also making a large excursion of polarity opposite to that of the initial turn. As a result, the path curvature response indicates a change in polarity, suggesting a trajectory which is further out of the initial path than would be a nominal tangential trajectory. No mechanism has been defined by which this response could be understood.

3.1.4 SUMMARY OF RESULTS IN TRAPEZOIDAL STEER TEST. In the execution of the trapezoidal steer test procedure, a sequence of steer levels in conducted, by which increasing levels of lateral acceleration result, eventually saturating the lateral force output at certain tires. The sample was found to be grouped into three categories, distinguished by the manner in which tire side force saturation is achieved.

1) A "spinout" limit response is achieved, by which a dramatic yaw divergence is experienced as a result of rear tire side force saturation being incurred at an input level which still leaves considerable side force capability on the front tires.

2) A driftout limit is achieved in which the front tires saturate in side force prior to rear tires, resulting in residual unrealized side force capability on the rear, which provides for a stable yaw condition.

3) A rollover response can be exhibited due to the large moment arising during the high lateral acceleration

turn, as aggravated by dynamic factors in the transient portion of the test. The contact of the wheel rim with the test surface further contributes to the rollover response.

The two directional response limits, categories 1 and 2 above, indicate raw data time histories typified by the data shown in Figures 22 and 23, respectively. In Figure 22, the spinout limit is depicted by divergency in sideslip response.

In Figure 23, the driftout limit is represented by a stable directional response. This driftout limit defines a boundary in turning performance which the vehicle is incapable of exceeding, but which generally is accompanied by a small sideslip response. The driftout condition is thus representative of a certain inefficiency in a vehicle's performance but does not involve the controllability challenge of the spinout limit.

The trapezoidal steer performance exhibited across the sample is not reduced into spinout and driftout categories, however, but rather is summarized in a general form, as shown in Figure 24. In this presentation, an improved performance is hypothesized to be the maximum path curvature attainable with minimum sideslip. This figure represents a cross-plot of the sideslip rate and path curvature data shown in Figures 25 and 26. Example data from a spinout-limited vehicle (VW) and an apparently driftout-limited vehicle (Toronado) are presented as overlays on each of these plots. Whereas Figure 24 is useful for categorizing overall limit performance in terms of path curvature without excessive sideslip, the data in Figures 25 and 26 provide a clear view of the manner in which turning properties change as steer level is increased. It would seem reasonable to expect that these transitions are also relevant as determinants of vehicle controllability.

The data in Figure 27 represents the range and distribution of peak lateral accelerations exhibited during the tire shoulder break-in experiments. Clearly, a significant sensitivity to shoulder wear is the rule. Further, it can be said that contemporary vehicles exhibit a large range in lateral acceleration capabilities in both their unworn and their tire side-force-stabilized conditions.

Rollover responses were observed with the Volkswagen and Mercedes test vehicles in response to trapezoidal steer input. The Volkswagen, which was the first vehicle to be tested in the automatic series, was rolled completely over onto its roof (Fig. 28). This response made it clear that the use of outriggers was necessary for this maneuver.

Substantially more damage was incurred on the Mercedes 300 SEL, when it exhibited a rollover response of such severity that a complete transfer of vehicle weight to the outrigger was seen to occur, with all four wheels off the pavement. The ensuing oscillation, in which the vehicle mounted the outrigger and fell three times, caused major suspension failures. The repair of these extensive failures, such that testing could resume, indicated that, in certain cases, less damage might be incurred by permitting complete rollover rather than restraining it.

3.1.5 SUMMARY OF SINUSOIDAL STEER TEST RESULTS. In this maneuver, vehicles can exhibit a wide range of responses which are patently unlike a lane change. Most commonly, increasing steer amplitude simply results in lateral displacements which are in excess of the nominal dimensions of the roadway. Thus, with regard to lateral displacement response, the concept of a defineable limit would not seem to apply. Certain vehicles in the sample, however, indicated a remarkable propensity for near-perfect lane change trajectories over the entire range of steering amplitudes. Thus, a lateral displacement "saturation" or limit was exhibited, but the mechanisms by which certain vehicles achieved this limit involve very complex motions, for which no generalized understanding has been developed.

Two categories of yaw response limit have been identified, however, which can be characterized as asymmetries of directional gain in response to the leading and trailing half-waves of the sinusoidal steer input. These limit responses have been grouped into "undercorrective" and "overcorrective" yawing motions in which the 2nd half of the sine wave is viewed as the corrective or recovery stage, during which the driver is attempting to reestablish his initial heading.

In the undercorrective response, the vehicle accumulates a large sideslip angle early in the maneuver, such that the recovery half of the steer input is essentially nullified. A raw data sample typical of this condition is shown in Figure 29.

The overcorrective response, as typified by the raw data of Figure 30, results in a terminal heading which is directed back toward the original lane from which the maneuver began—the recovery half of the steering input being more effective than the initial input. The physical mechanism underlying this phenomenon remains to be identified.

Six summary plots are presented in Figures 31 through 36, indicating the range and distributions of:

1) sideslip response peak vs. steer level (Figures 31 and 32 [covering the 45 mph and 60 mph conditions]);

2) lane change deviation, Δ, vs. steer level (Figures 33 and 34 [45 mph and 60 mph]), where Δ expresses an average lateral deviation from a "target lane," 12 feet over from the initial path;

3) sideslip response vs. lane change deviation (Figures 35 and 36 [45 mph and 60 mph]).

In Figures 31 and 32 the peak sideslip angle is seen to exhibit a monotonic upward trend for all vehicles, and clearly indicates a narrow performance range for the sample.

Figures 33 and 34 clearly illustrate that certain vehicles manifest a reasonable approximation of the lane change trajectory over a wide band of steer inputs, while others exhibit lateral displacements of substantially larger dimension.

The basic trend for all vehicles illustrates a minimum value of Δ at some value of steer level, σ, between 4 and 10. Below that value of σ, the steering amplitude was not sufficiently large to result in a lateral displacement near 12 feet, (when σ=o, the value of Δ must be 12, because the vehicle will run a straight course, always 12 feet away from the adjacent lane). It was observed that the vehicles which exhibit the largest values of Δ at higher steer levels also manifest the undercorrective yaw response.

Figures 35 and 36 summarize the Δ/β responses for the sample. Whereas certain vehicles cluster their responses near the origin, which is considered desirable, others appear to define the range of both the Δ and β variables.

3.1.6 SUMMARY OF DRASTIC STEER AND BRAKE TEST RESULTS. The only limit response of interest in this maneuver is the manifestation of an unstable roll motion. A sample of the raw data time histories gathered for a limiting roll response are shown in Figure 37. With brake release, a dramatic increase in lateral acceleration is observed, accompanied by a roll moment imbalance which increases roll angle up to the region of outrigger contact.

Only the Volkswagen and Mercedes test vehicles exhibited such a limit response with peak roll angles exceeding 0.4 radians, before the motion was arrested by the outriggers, Figures 38 and 39.

A summary of the range and distribution of peak roll angles exhibited by the sample are presented in Figure 40, showing the range of stable responses to fall within a 0.2 radian band.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

The most significant single finding of the program bearing on the conduct of open-loop performance testing is that tire side-force capability is a first-order function of the shoulder wear resulting from limit turning maneuvers. Four specific conclusions result from this finding:

1) It appears that adequate measurements of "O.E." limit cornering performance cannot be made for certain tire-vehicle systems by a testing method that utilizes repetitive runs as a means of searching for the limit, since the testing process acts to alter the O.E. condition.

2) The rate of change of side-force capability with test runs is so large with many tire-vehicle systems as to render any compensating tire change procedure impractical.

3) Indiscriminate changing of tires at any of the wheels of a vehicle subjected to severe cornering maneuvers may result in a wide scattering of its directional response properties.

4) Those tires that indicate a substantial sensitivity to shoulder wear also illustrate a stable performance regime which is established at a sufficiently low level of wear that tire structural integrity is not yet compromised. Thus, certain performance envelopes can be obtained, although admittedly non-O.E. performance, on vehicles equipped with shoulder-worn (i.e., side-force stabilized) tires.

Major conclusions have been reached from the findings produced in the full-scale test program:

5) In general, modern vehicles vary widely in their limit maneuvering properties.

6) Certain modern passenger vehicles can be caused to roll over on a smooth surface, as a result of steer inputs alone.

7) Certain vehicles exhibit tire deflation due to bead unseating while maneuvering on a smooth surface.

8) Existing reduced-friction test technology is inadequate for conducting limit maneuver (open-loop) testing, at elevated velocities.

9) The application of automatic controllers to the open-loop measurement of limit responses appears to be a practical experimental method.

10) The automatic controller is a complicated system of mechanical, electrical and hydraulic assemblies which, in the event of breakdowns, does require the attention of a competently trained technical staff. Despite its high level of reliability and the ease of drone control, this equipment should be used only on a test facility of sufficiently generous dimensions as to permit a spatial margin for operator judgment and reaction.

4.2 RECOMMENDATIONS

It is evident that substantial progress has been made in refining the open-loop test methodology which was originally proposed and developed in the Vehicle Handling Test Procedures study. The discovery of the tire side-force sensitivity to shoulder wear has seriously challenged the viability of the limit test concept, however, and much research needs to be done to address the following related matters:

1) The physical mechanism must be identified by which small amounts of shoulder wear can produce first-order changes in peak side force.

2) There should be a review of tire design practice, upon identifying the above mechanism, such that the design variations required to assure reasonable side force stability are determined and recognized in the trade off with other desirable tire properties.

3) Tire properties research should be conducted to determine the range of shear force performance which accompanies tread wear under normal usage. It should be determined whether the shoulder wear produced during limit turning represents a performance state which the tire will naturally exhibit in the course of normal wearing.

Much research is needed to provide an understanding of those factors which determine driver-vehicle performance under emergency conditions. Specifically, experiments must be conducted which can demonstrate the relationship between driver-vehicle system performance and the open-loop properties of vehicles, such as have been measured in this study. The sensitivity of drivers to the sideslip response of the motor vehicle should be evaluated to determine whether a monotonic degradation in driver control performance derives from increasing sideslip response.

With regard to the data base which has been generated, considerable further use of the data library should be made.

Studies should be conducted to examine alternative response evaluation schemes. Various correlation studies could be conducted to evaluate the relationship between various design properties and the measured performance characteristics. Since the time history data exists intact in a tape library, computer simulations intending to model limit performance can be validated for a host of vehicle configurations and maneuver conditions.

As was made evident frequently during testing, the need for a broadened understanding of the mechanics of limit response is a major problem. Quite often, the test engineer finds himself in a position in which certain data is discarded because the indicated response is known to be counter to some physical principle. In some limit maneuver testing, this process fails because the motions are so complex that they deny any simple evaluation or challenge of validity. It appears that the only sure method for gaining this understanding is to undertake well-structured research directed towards improving the mathematical models of tire-vehicle systems. Efforts must be concentrated initially on the identification of those mechanisms in which the real nonlinear vehicle differs from existing models.

Basic research is needed to provide an accident reporting approach which will contribute toward the identification of the role played by handling factors in accidents. For example, the heavily sideslipping vehicle will frequently leave a visible pavement marking which can actually be reduced to a sideslip angle measure, knowing vehicle wheelbase and track. Such information as can give evidence of the extent to which corrective actions were attempted would also be most valuable.

5. REFERENCES

1. Dugoff, H., Ervin, R.D., Segel, L., Vehicle Handling Test Procedures, Final Report, NHSB Contract FH-11-7297, Highway Safety Research Institute, The University of Michigan, Ann Arbor, November 1970.

2. Bird, K.D., Belsdorf, M.R., Rice, R.S., Effects of Steering and Suspension Component Degradation on Automobile Stability and Control, Final Report, NHTSA Contract FH-11-7384, Cornell Aeronautical Laborabory, Inc., January 1971.

3. Gengenbach, W., "Experimantelle Untersuchung von Reifen auf nasser Fahrbahn (Experimental Investigation of Tires on Wet Tracks)," Automobiltechnische Zeitschrift, Vol. 70, 1968, pp. 310-316.

4. Harned, J.L., Johnston, L.E., and Scharpf, G., "Measurement of Tire Brake Force Characteristics as Related to Wheel Slip (Anti-lock) Control System Design," SAE Paper No. 690214, 1969.

5. Butkunas, A.A., "Random Vibration Analysis and Vehicle Development," SAE Paper No. 690109, January 1969.

6. Rasmussen, R.E. and Cortese, A.D., "The Effect of Certain Tire-Road Interface Parameters on Force and Moment Performance," General Motors Proving Ground, Engineering Publication A-2526, July 1969.

FIGURES

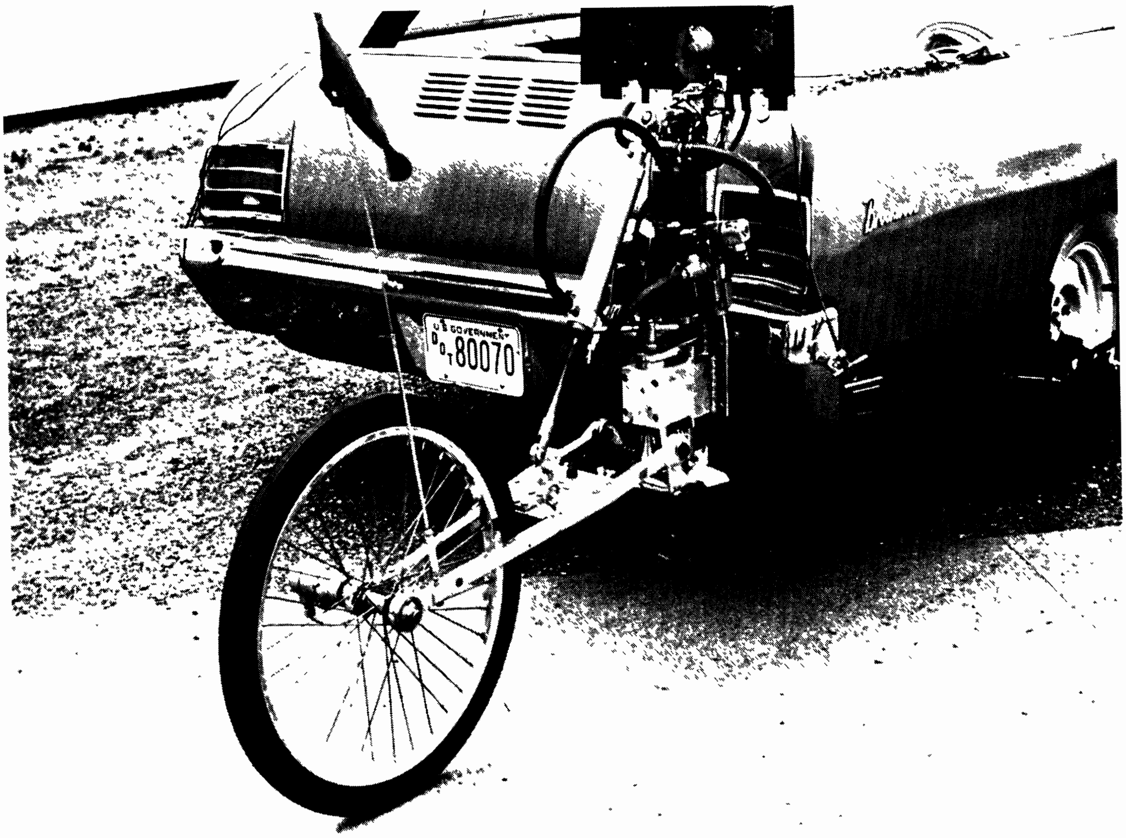


Figure 1

Figure 2

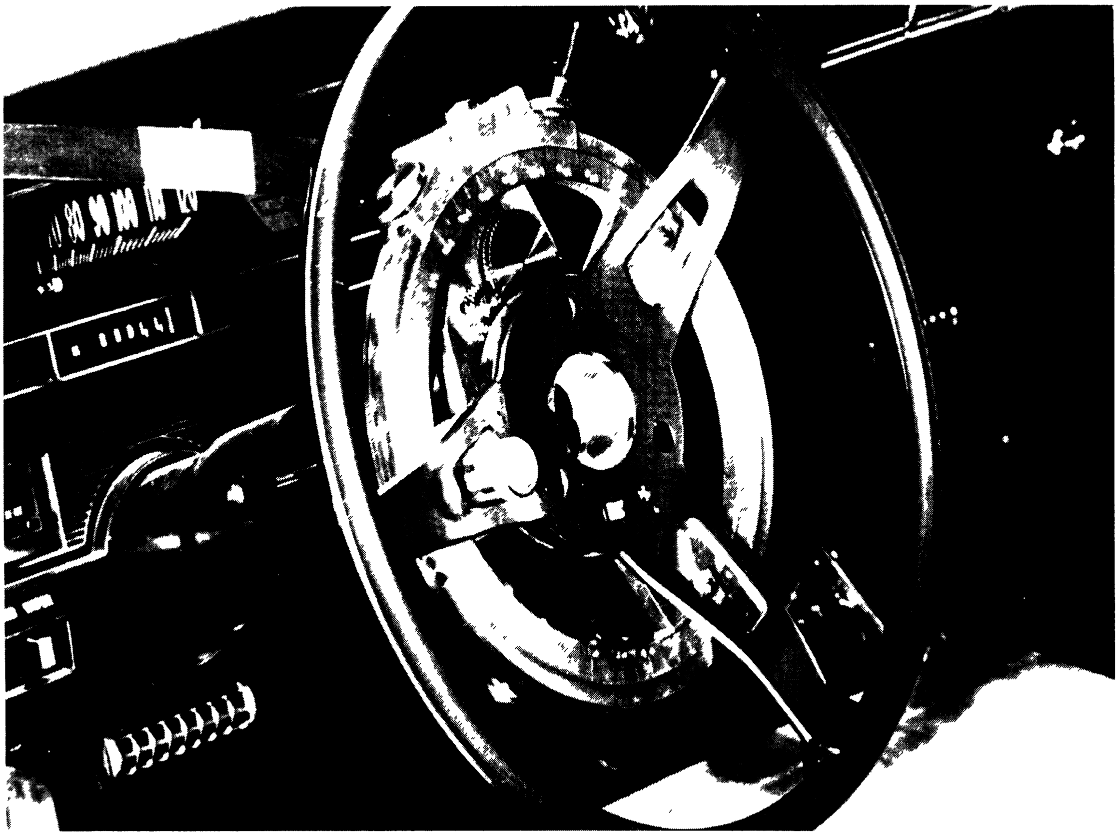


Figure 3

Figure 4.

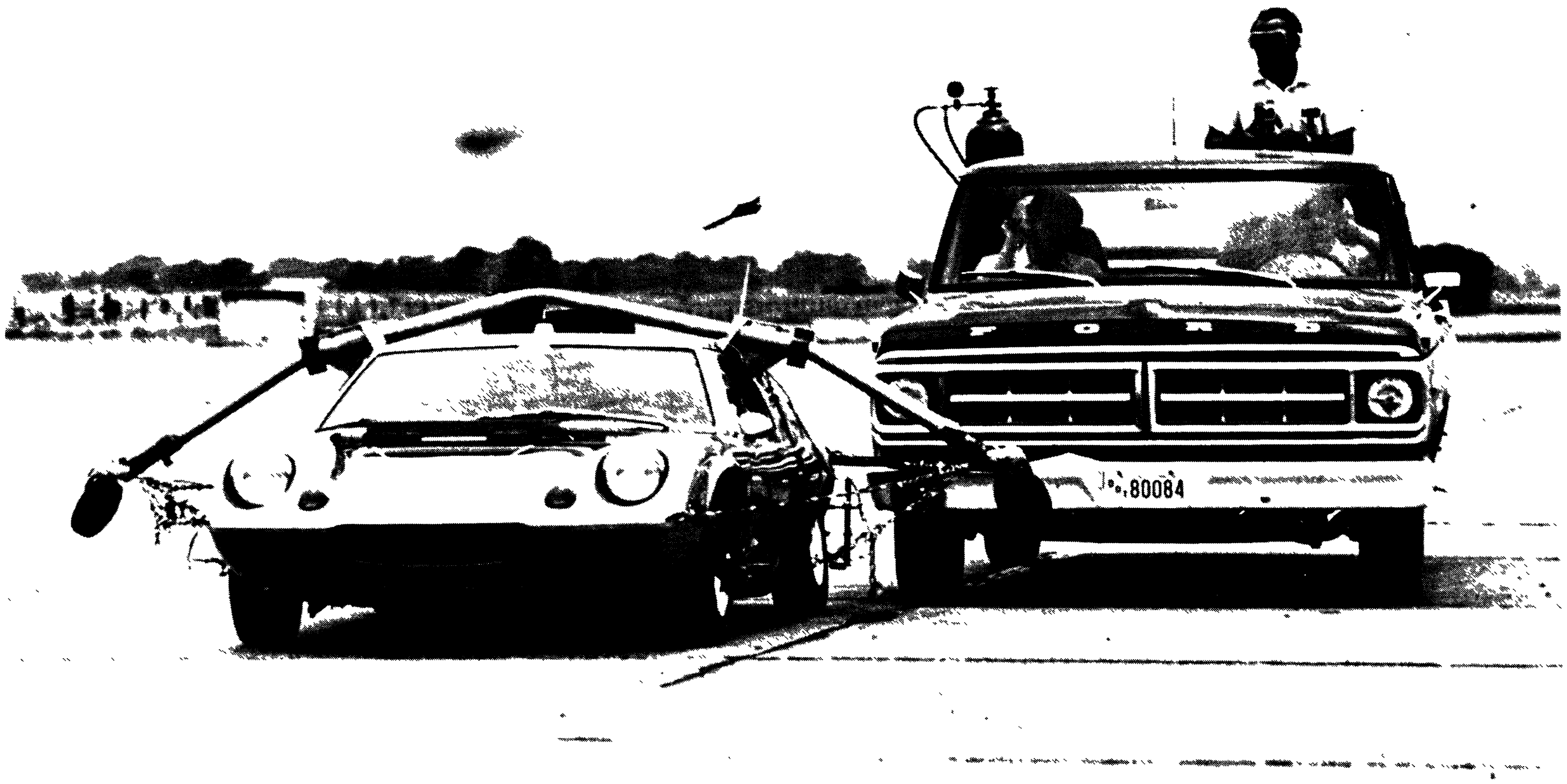
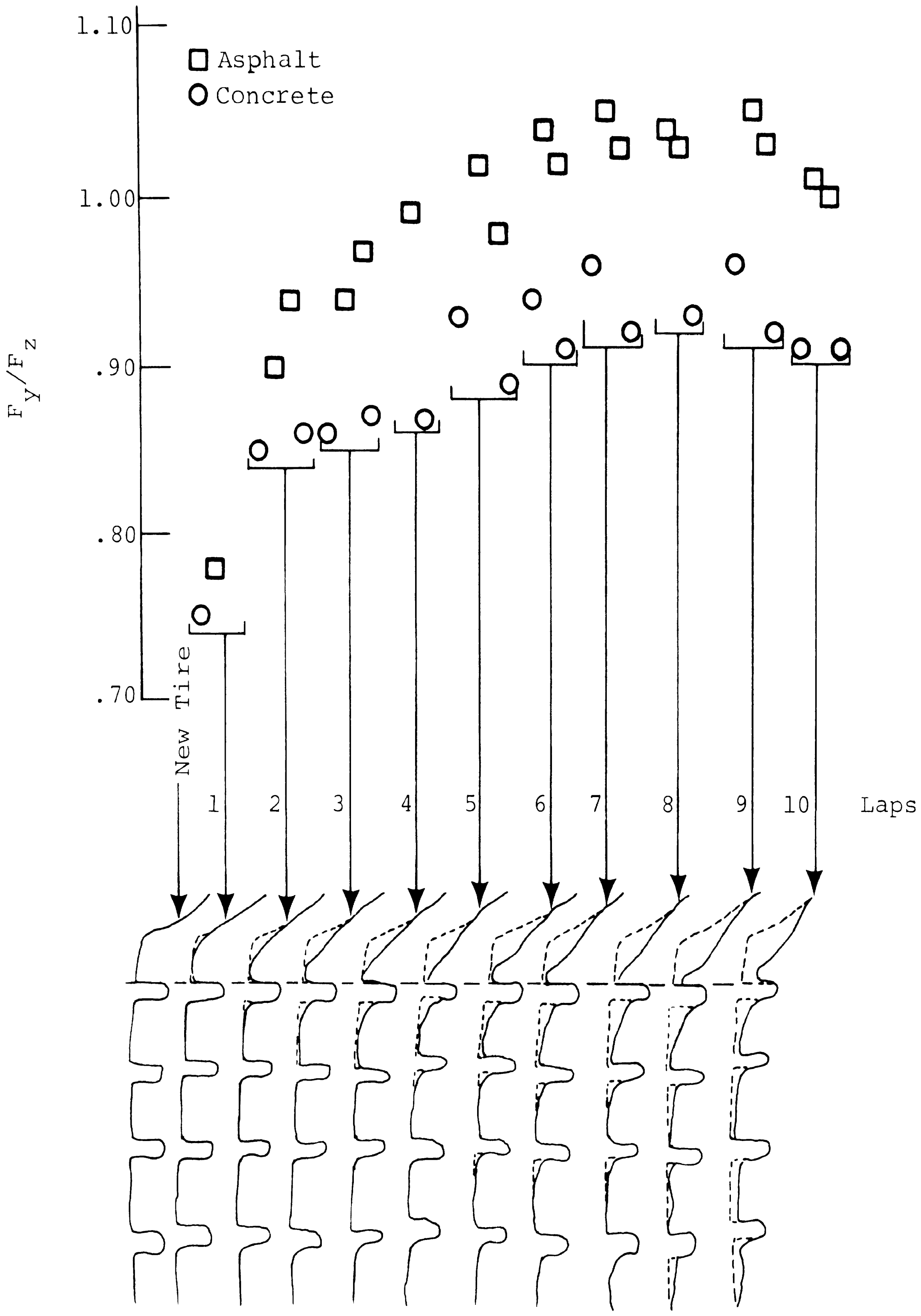


Figure 5



Tread Profile - Outside Shoulder

α=20° F_z=1550 Uniroyal L78-15 Fastrak

Tire Sample No. 1

Figure 6

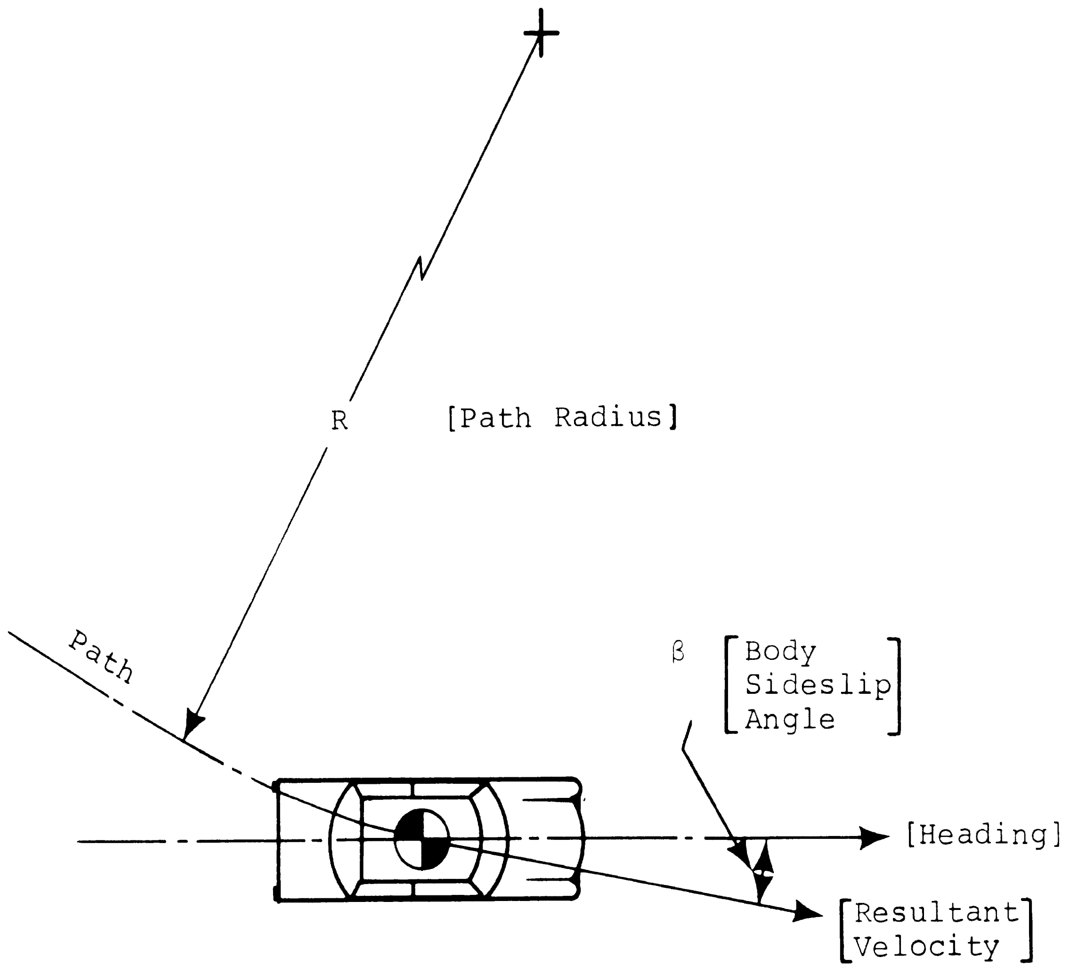
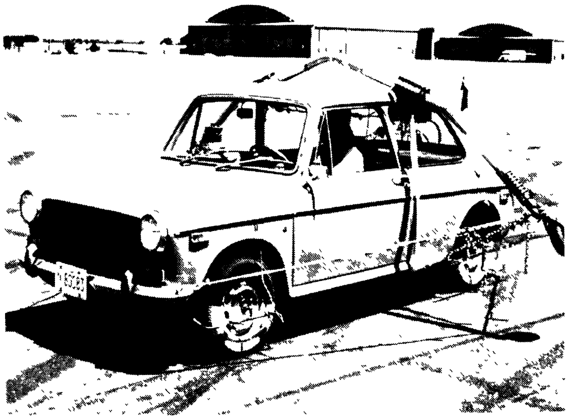


Figure 7

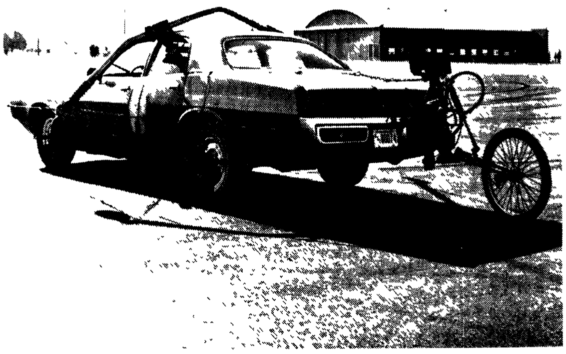
The Sideslipping Vehicle in a Curved Path

AMC Ambassador

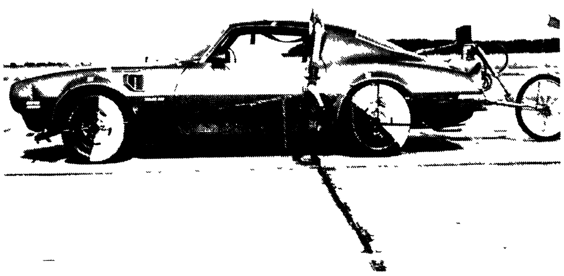


Austin America

Chevrolet Brookwood



Dodge Coronet

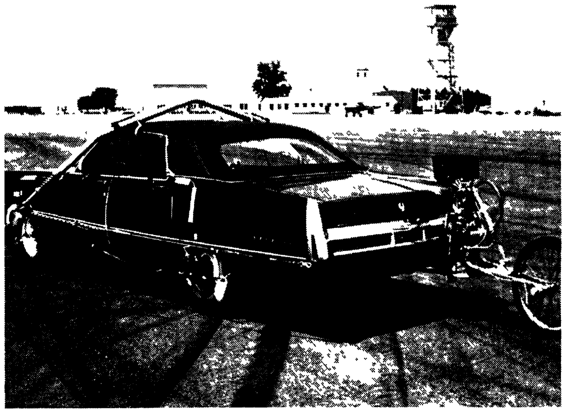


Pontiac Firebird TransAm

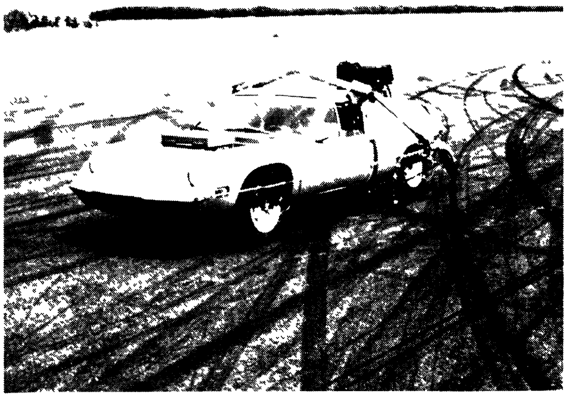
Ford Galaxie

Figure 8

AMC Gremlin

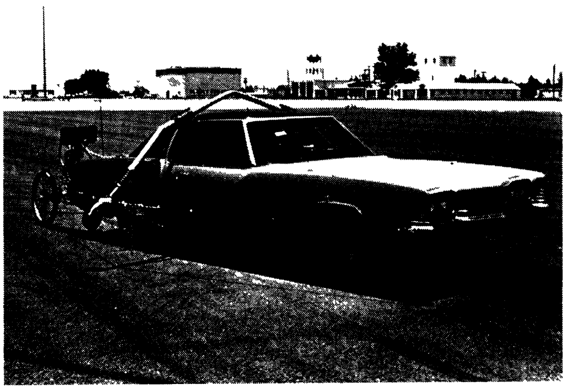


Chrysler Imperial



Lotus Europa

Mercedes 300 SEL



Oldsmobile Toronado

Volkswagen Super Beetle

Figure 8 (cont.)

Figure 9

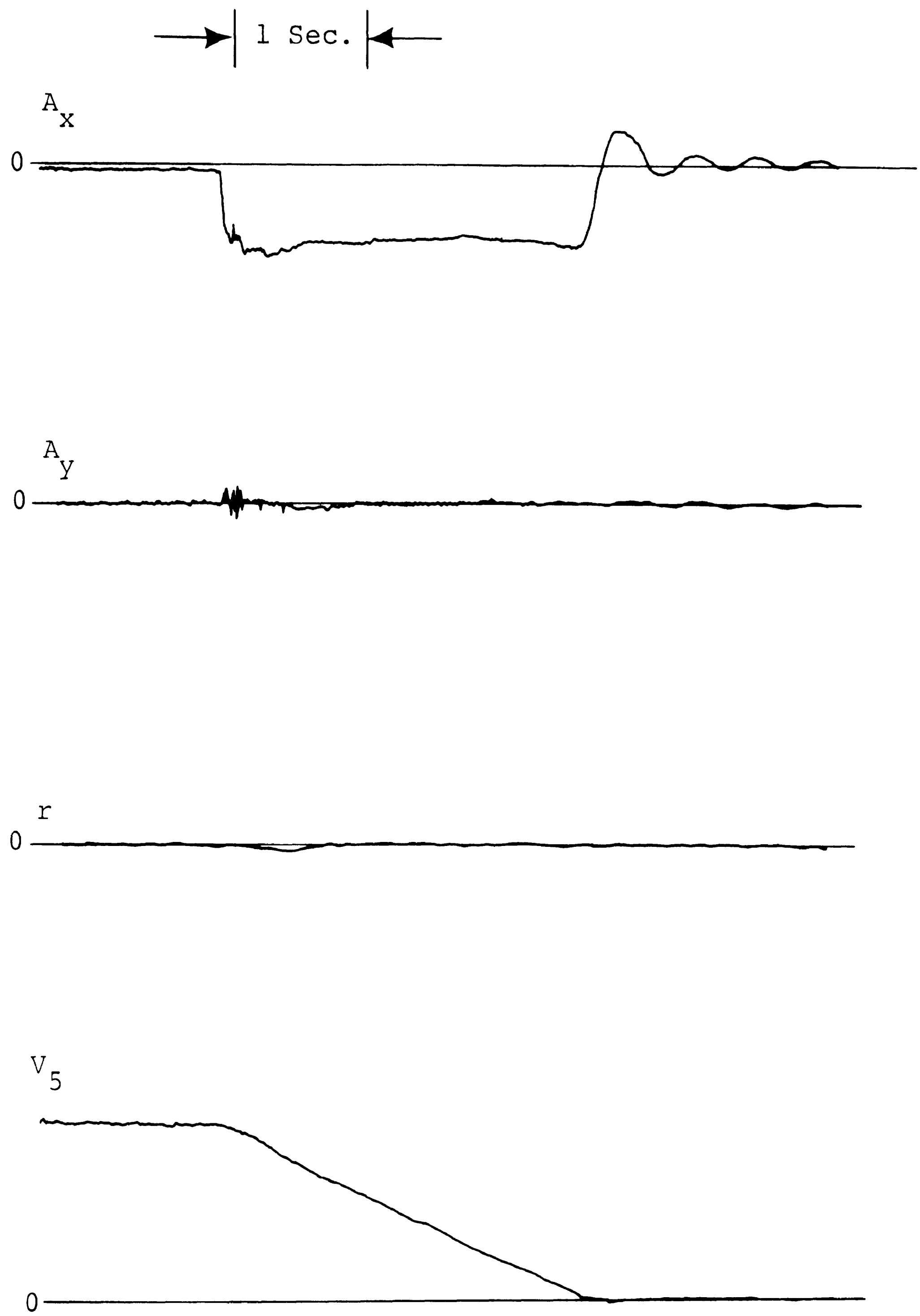


Figure 10

Straight Line Braking Raw Data Time Histories

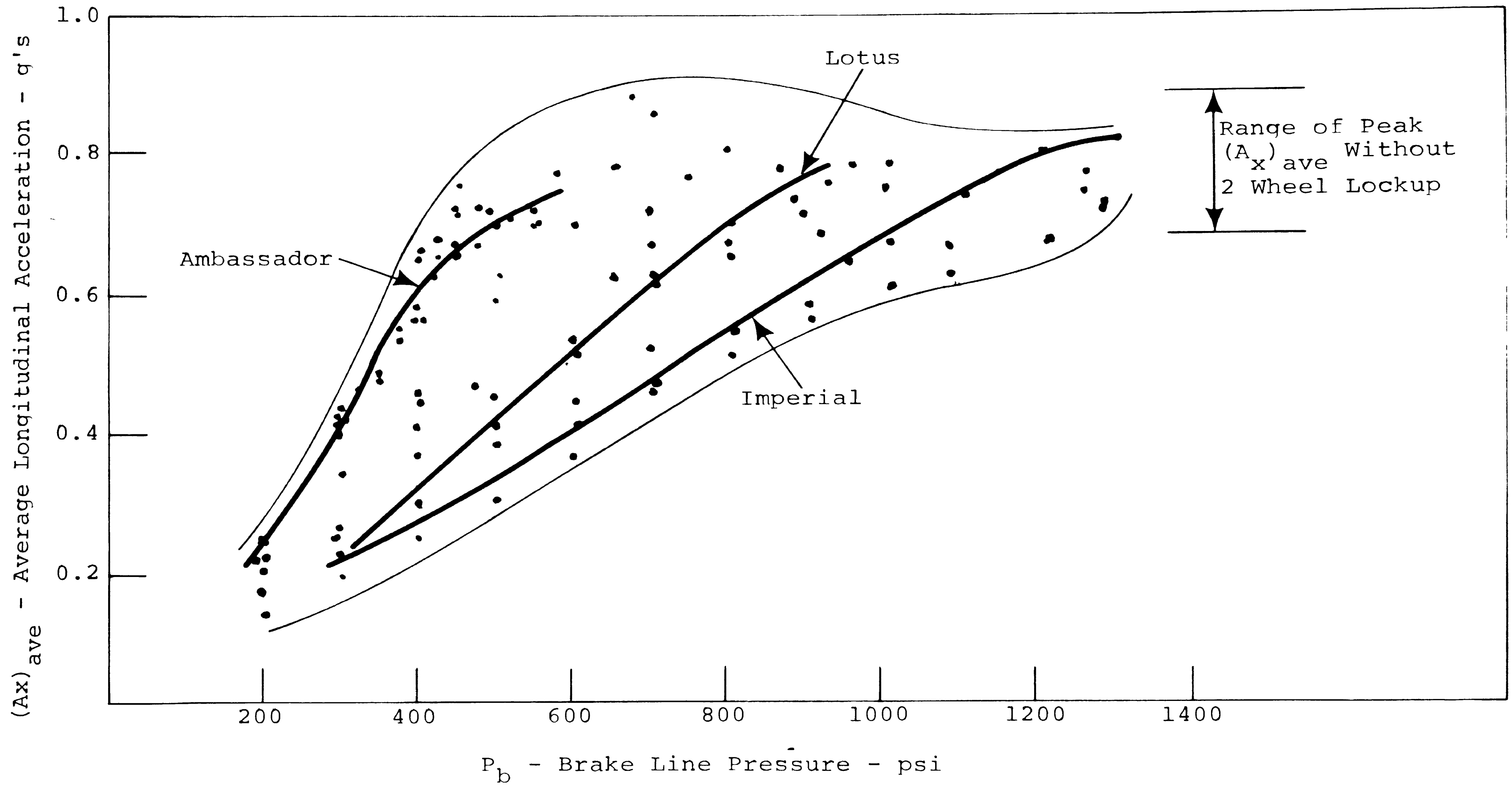


Figure 11
Summary Plot - Straight Line Braking

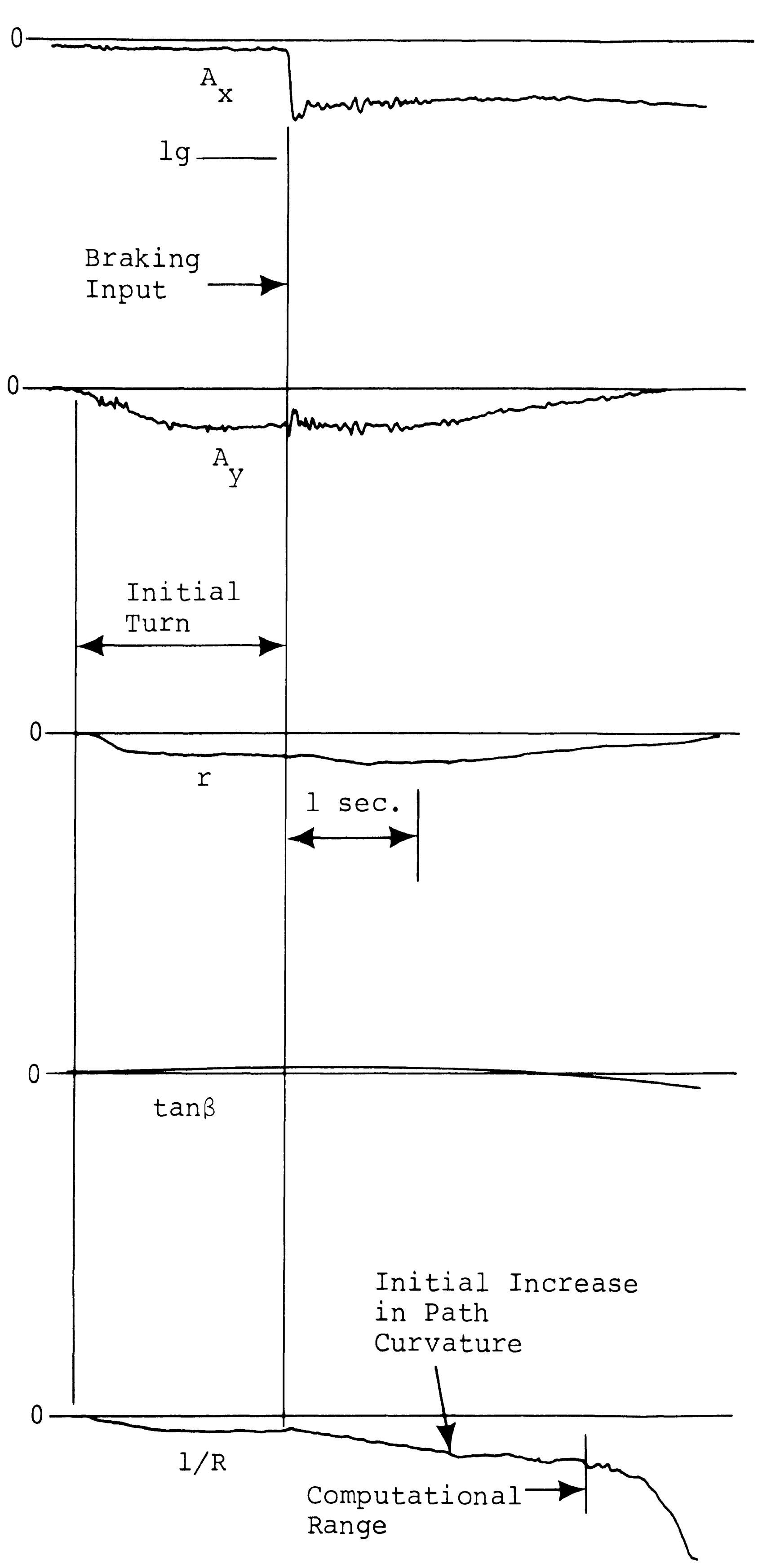


Figure 12
Braking In A Turn - No Wheels Locked

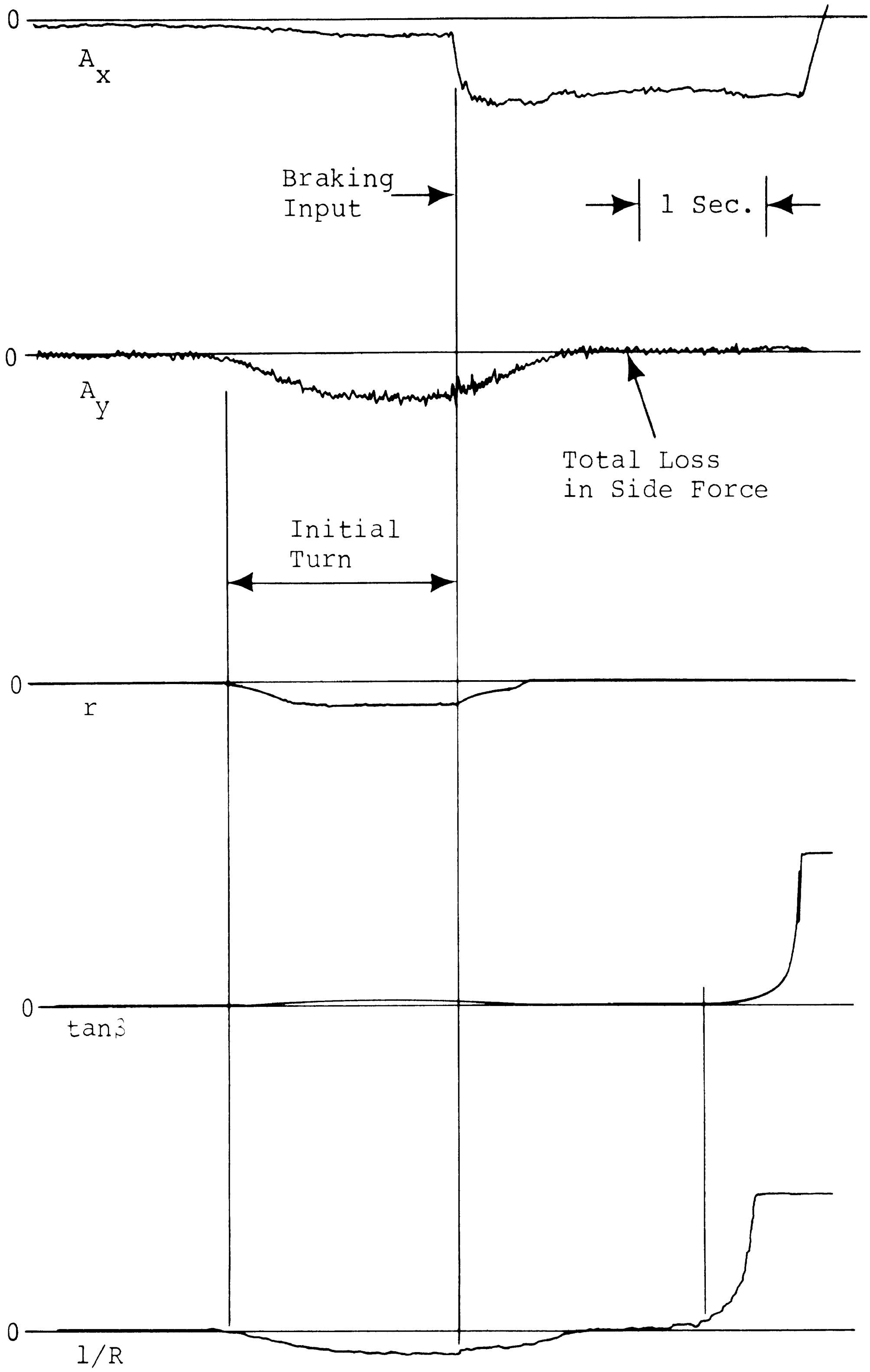


Figure 13
Braking In A Turn - Front Wheels Lockup

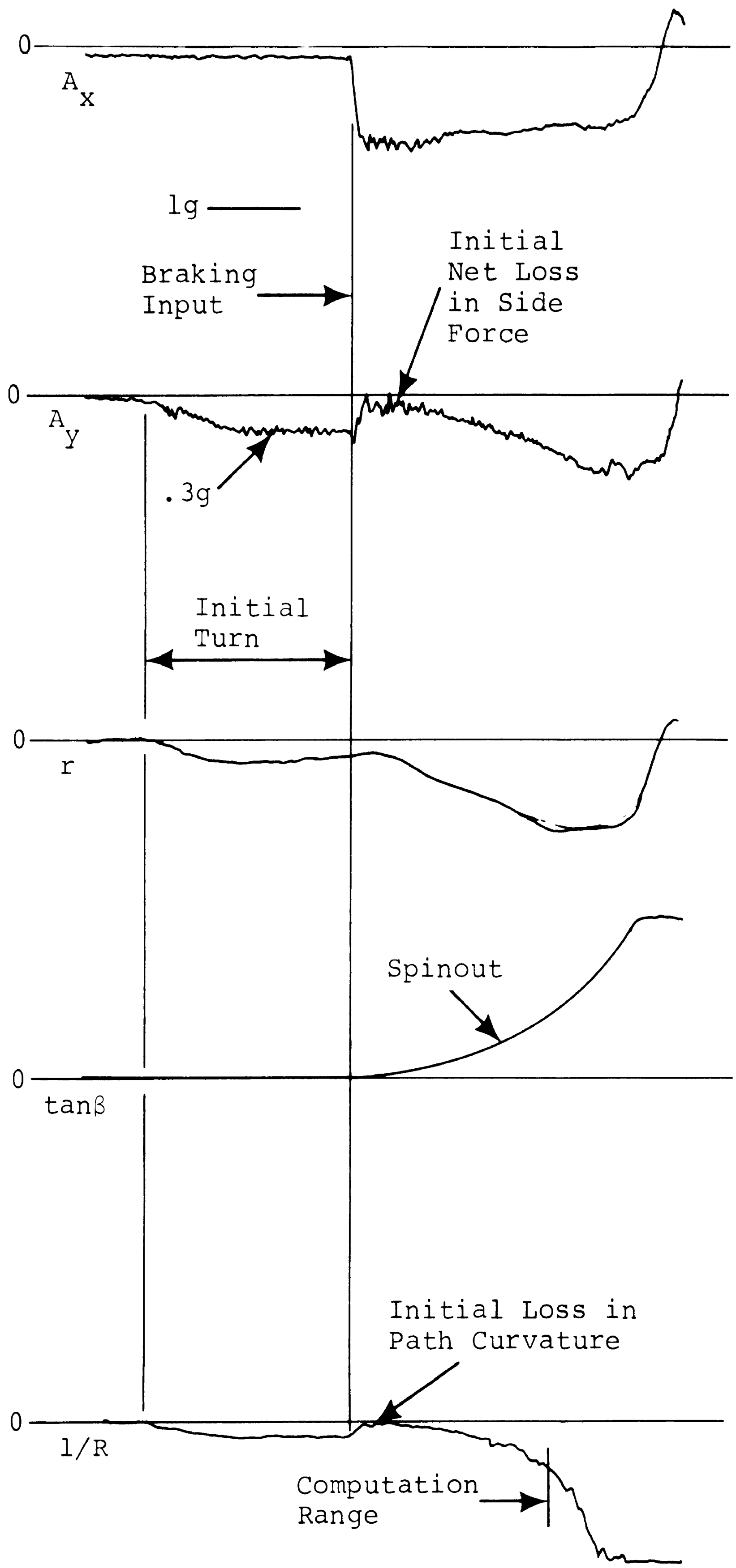


Figure 14

Braking In A Turn - Rear Wheels Lockup

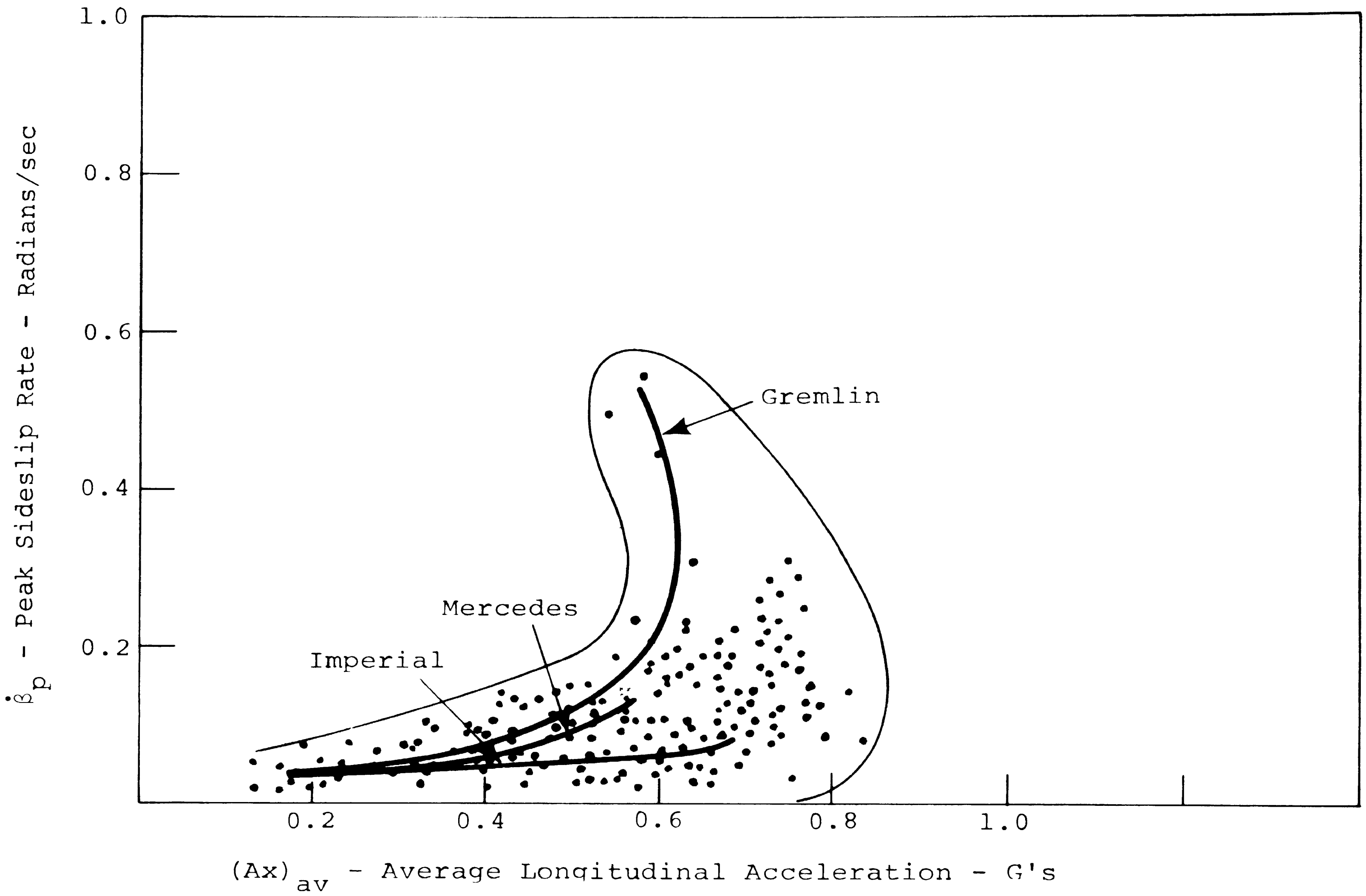


Figure 15

Summary Plot - Braking In A Turn

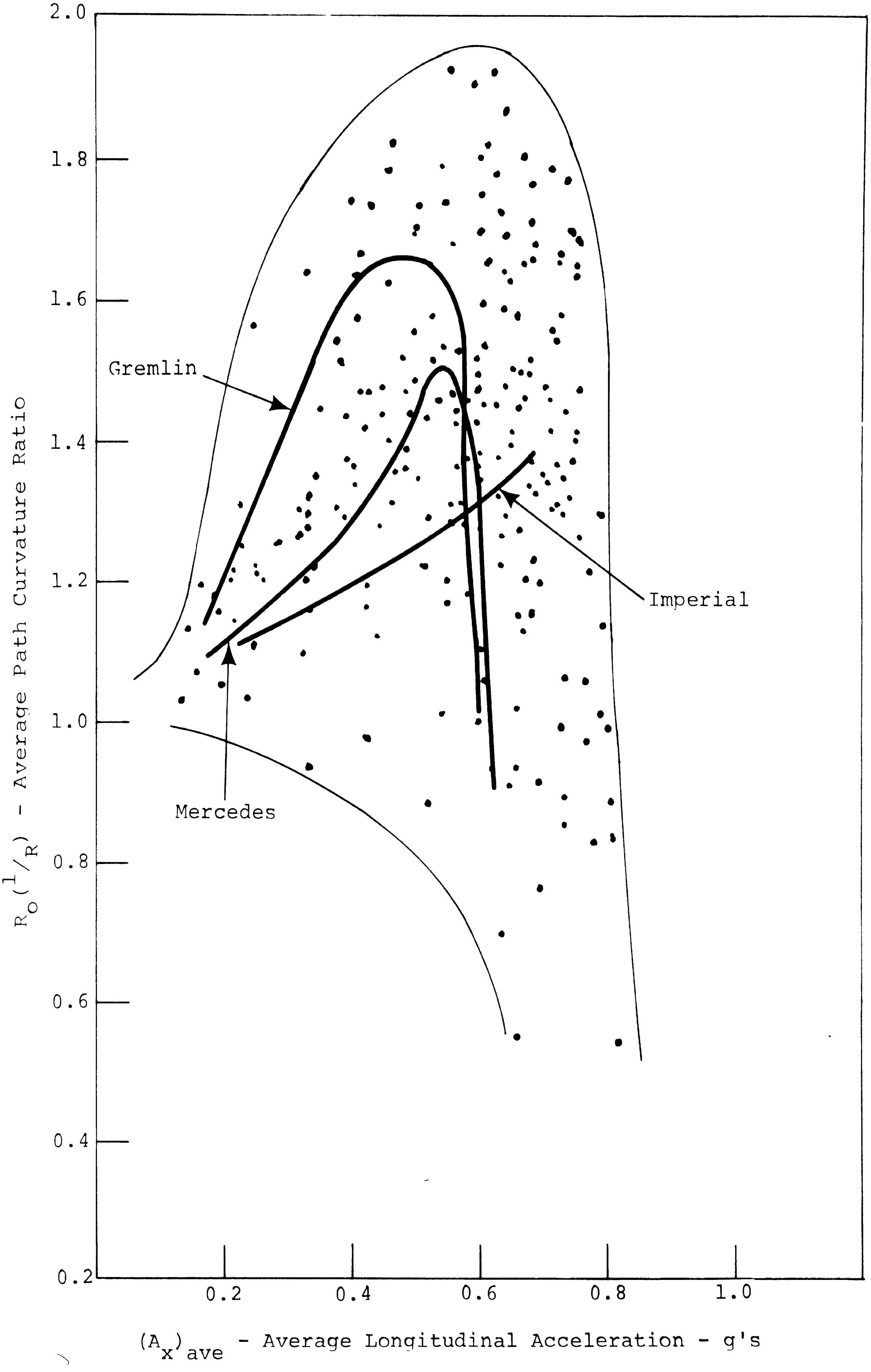


Figure 16
Summary Plot - Braking In A Turn

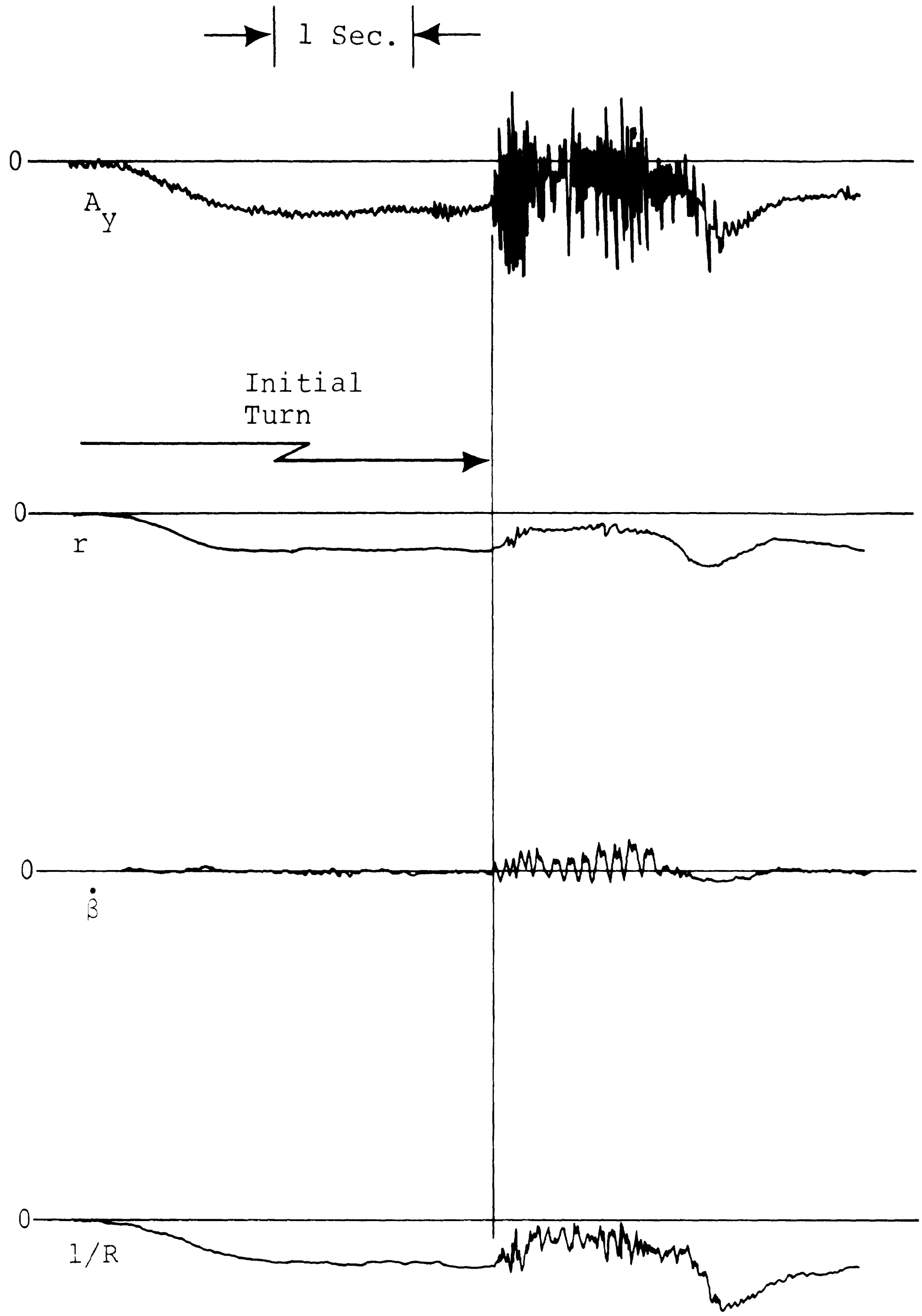


Figure 17

Roadholding In A Turn -
Dominant Front Wheel Resonance

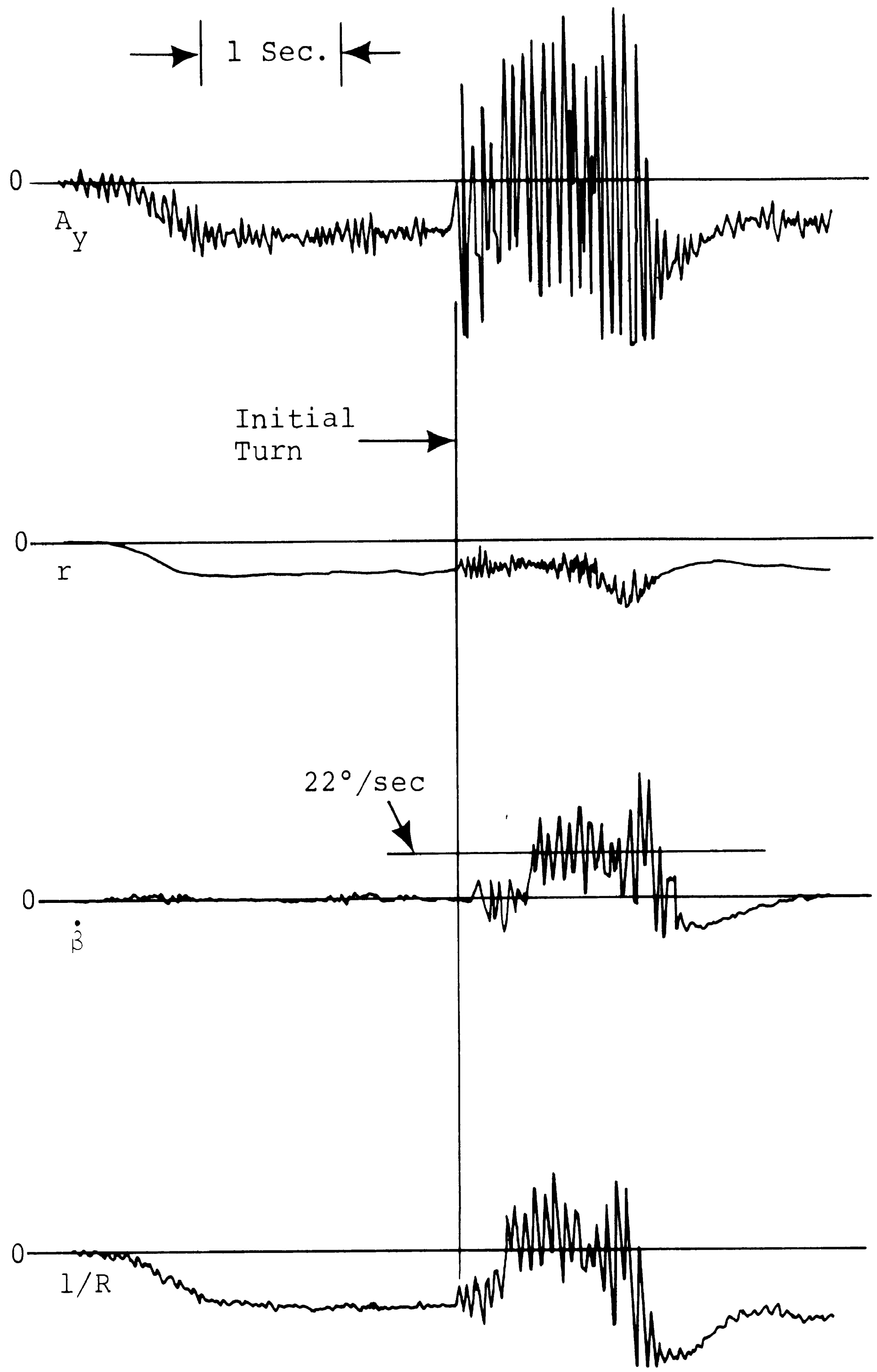


Figure 18

Roadholding In A Turn -
Dominant Rear Wheel Resonance

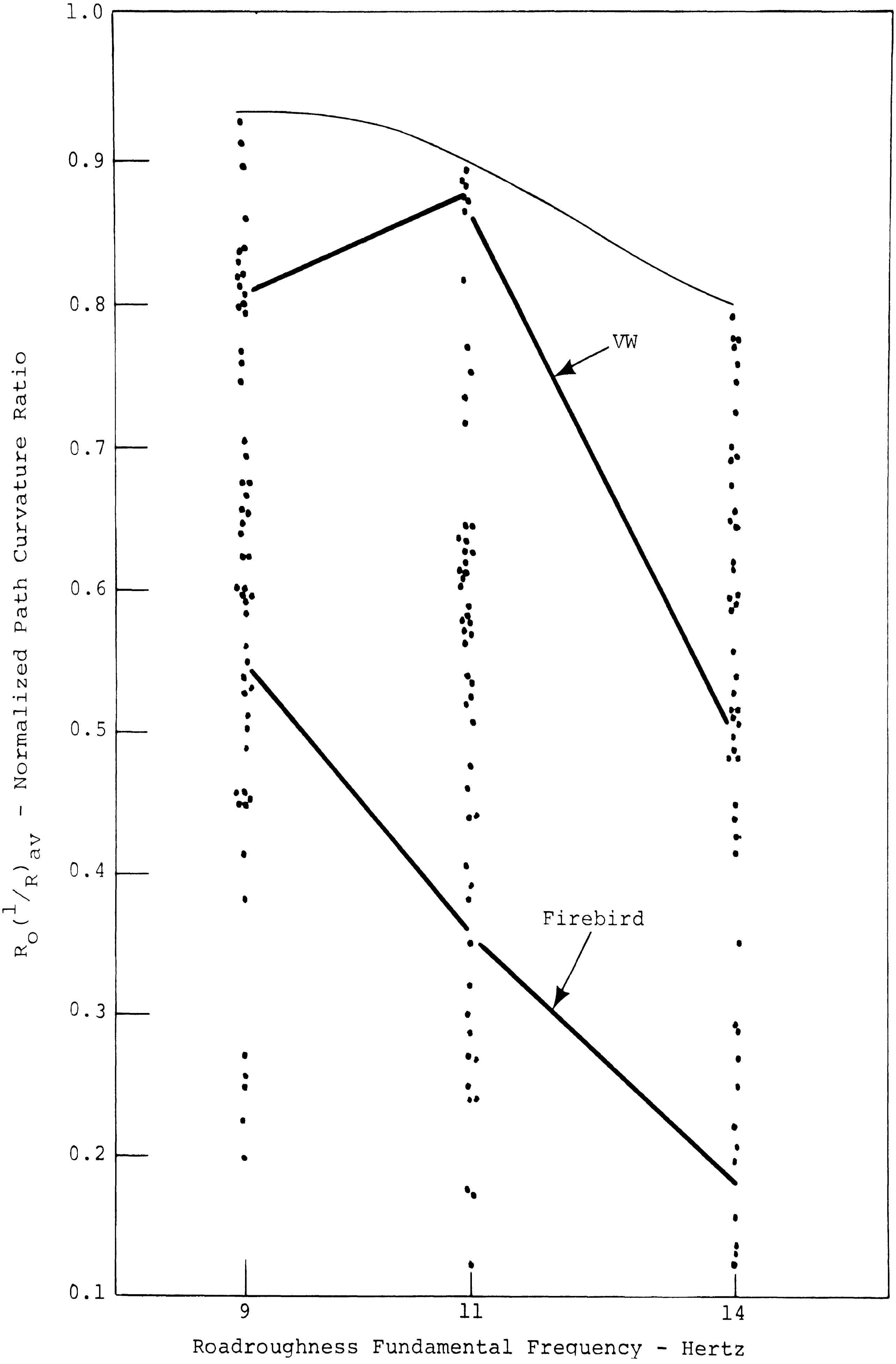


Figure 19
Summary Plot - Roadholding In A Turn

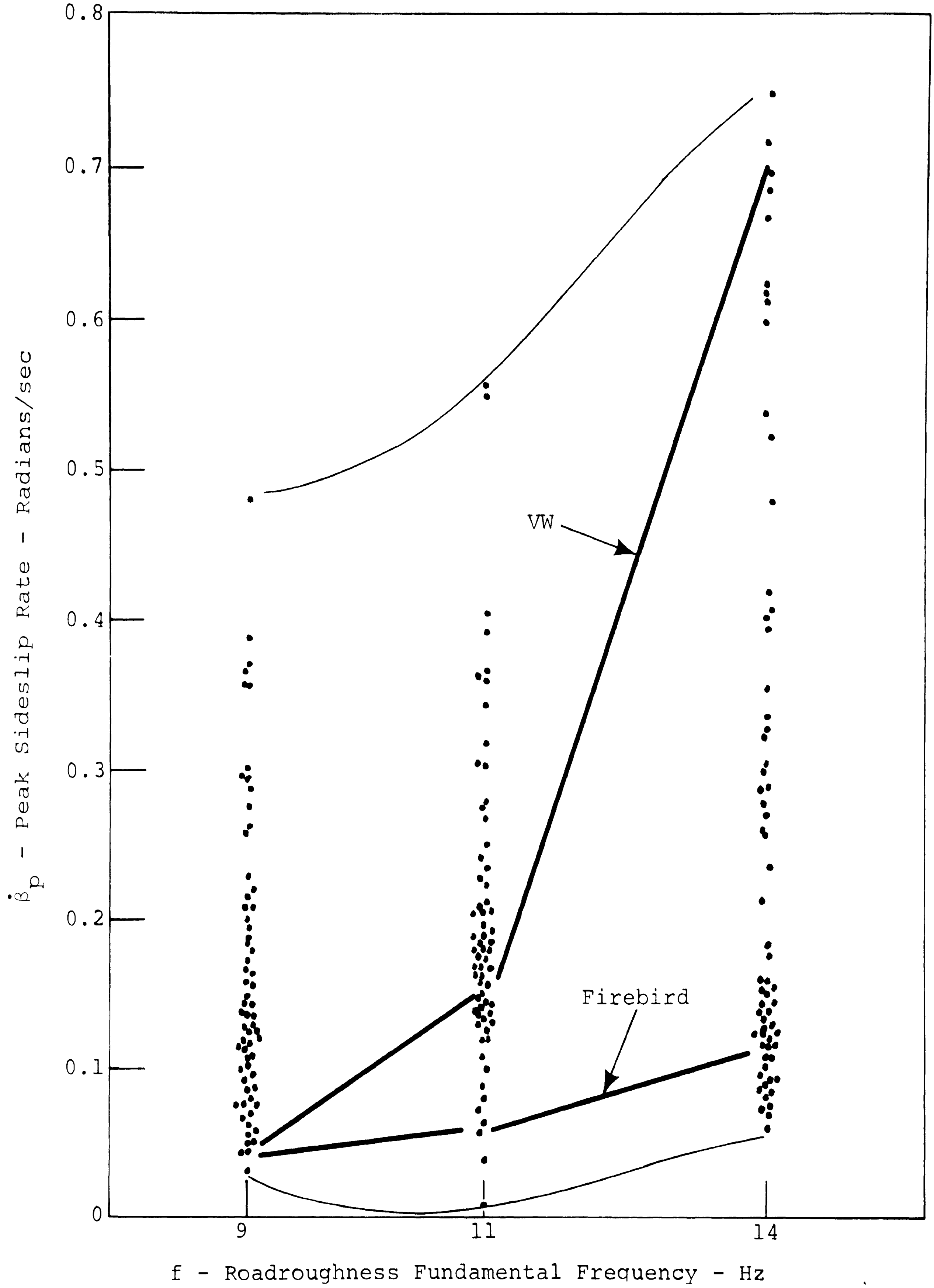


Figure 20

Summary Plot - Roadholding In A Turn

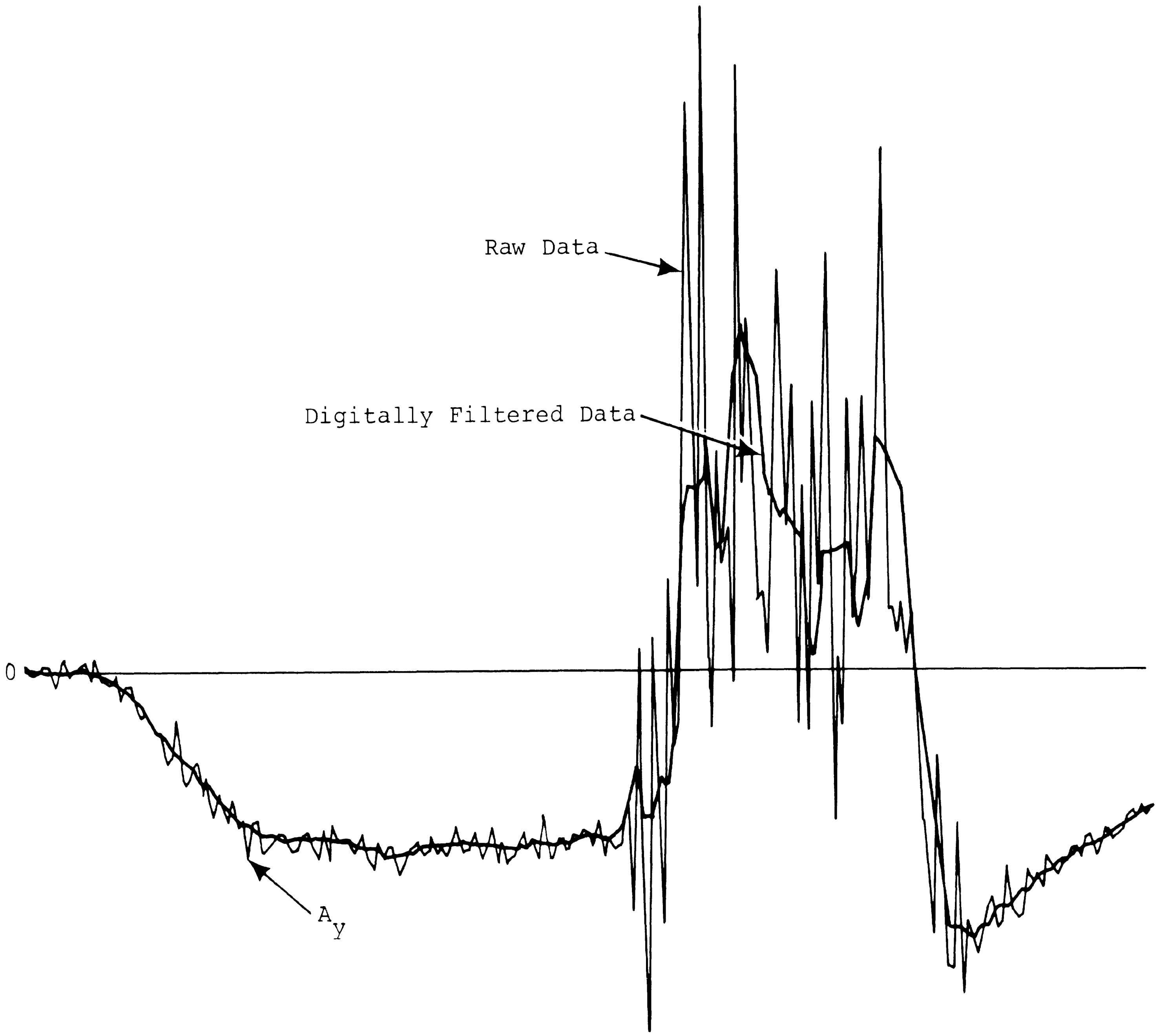


Figure 21

Raw A_y Data - Roadholding In A Turn - Mercedes 300 SEL

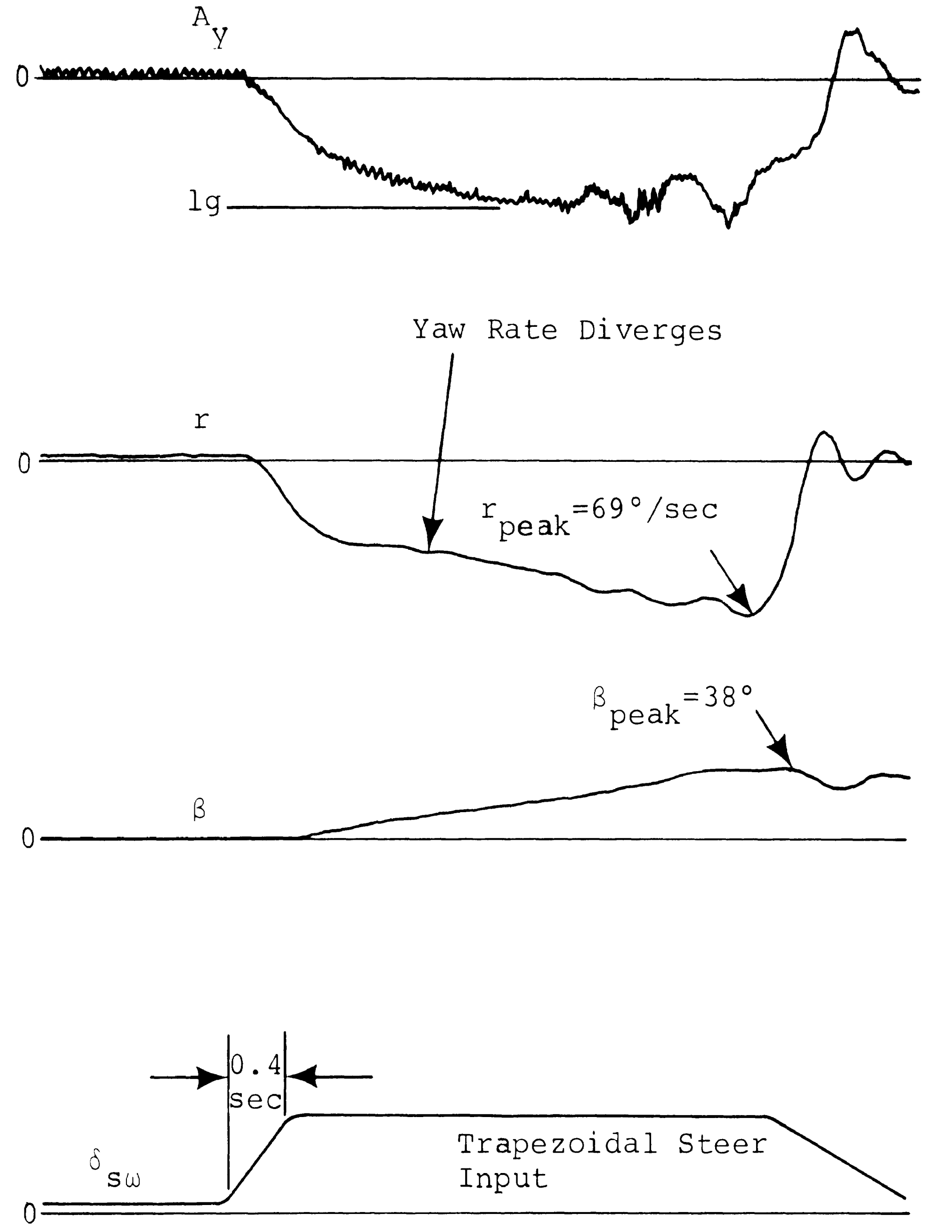


Figure 22

Trapezoidal Steer Rear Tire
Saturation - Spinout

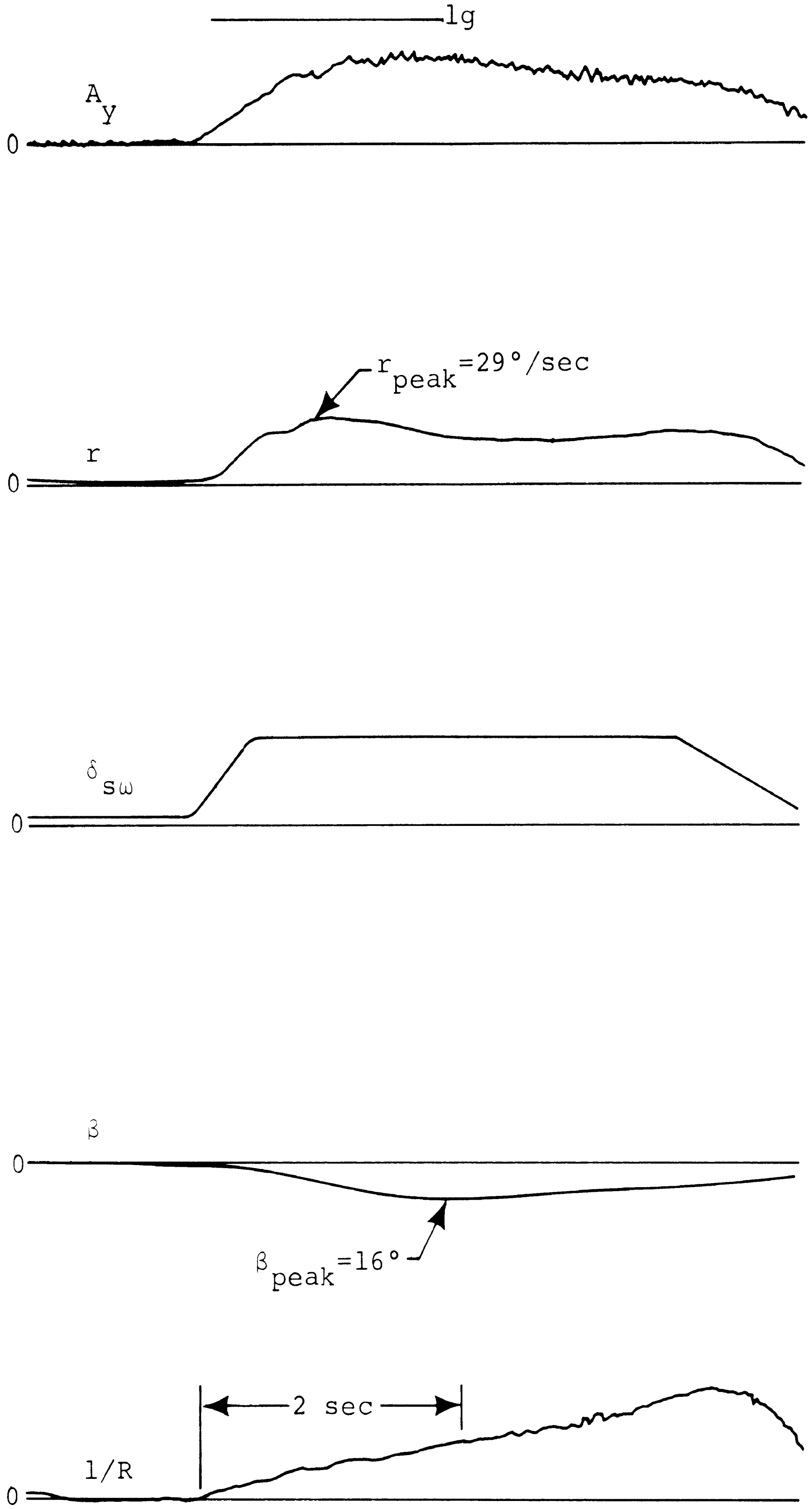


Figure 23

Trapezoidal Steer Front Tire Saturation - Driftout

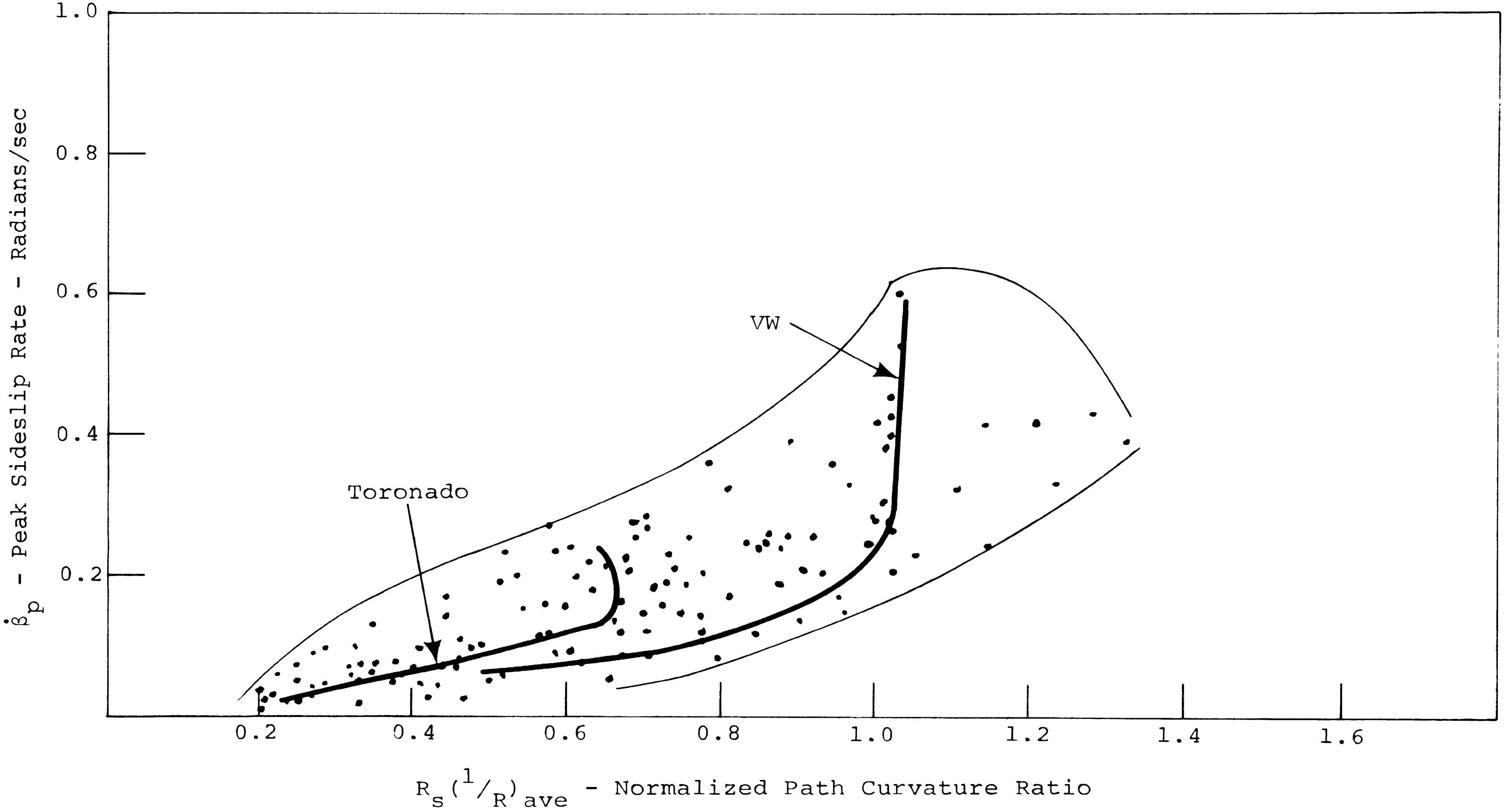


Figure 24
Summary Plot - Trapezoidal Steer

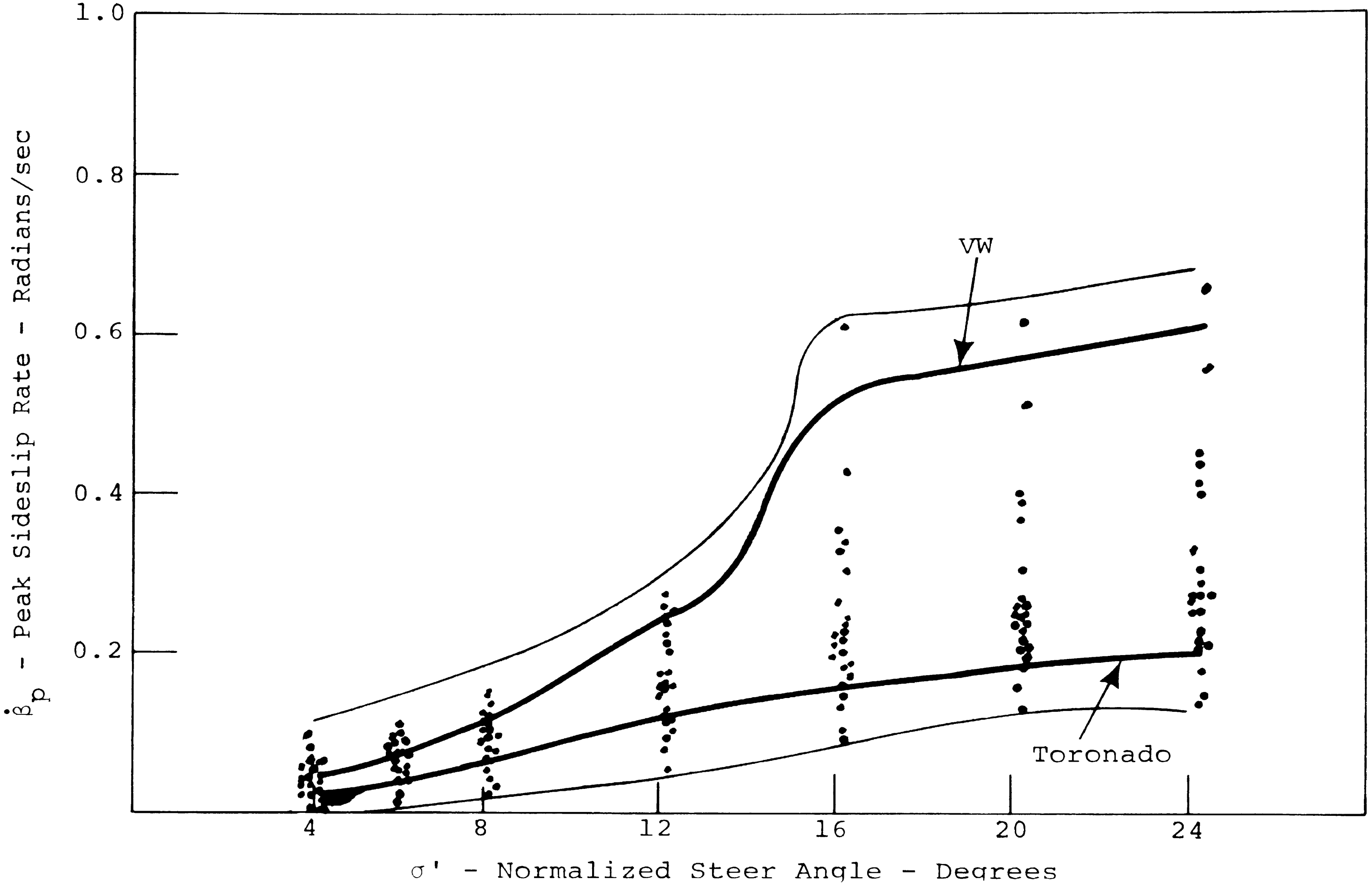


Figure 25
Summary Plot - Trapezoidal Steer

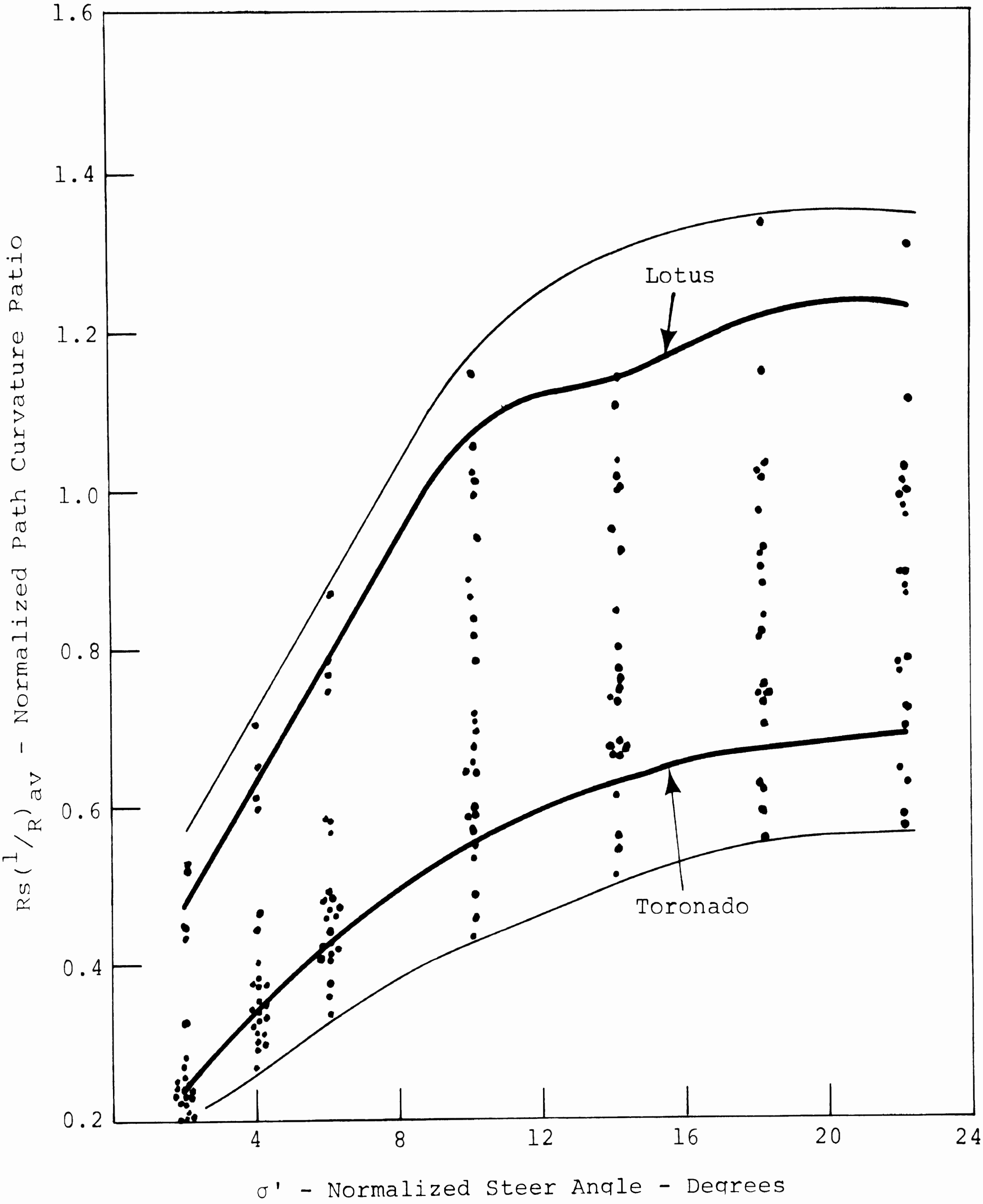


Figure 26
Summary Plot - Trapezoidal Steer

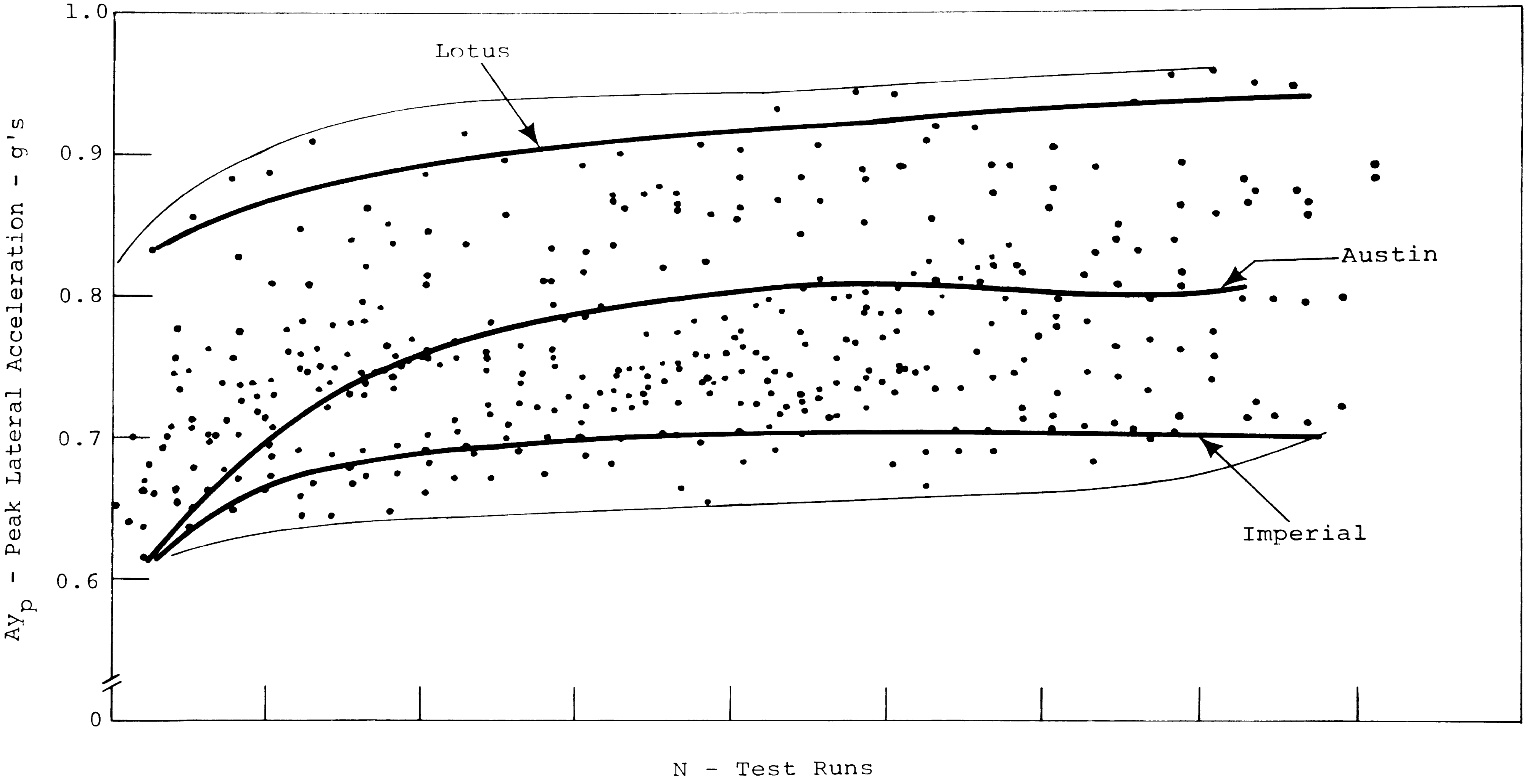


Figure 27

Summary Plot - Trapezoidal Steer - Tire Break-In Data

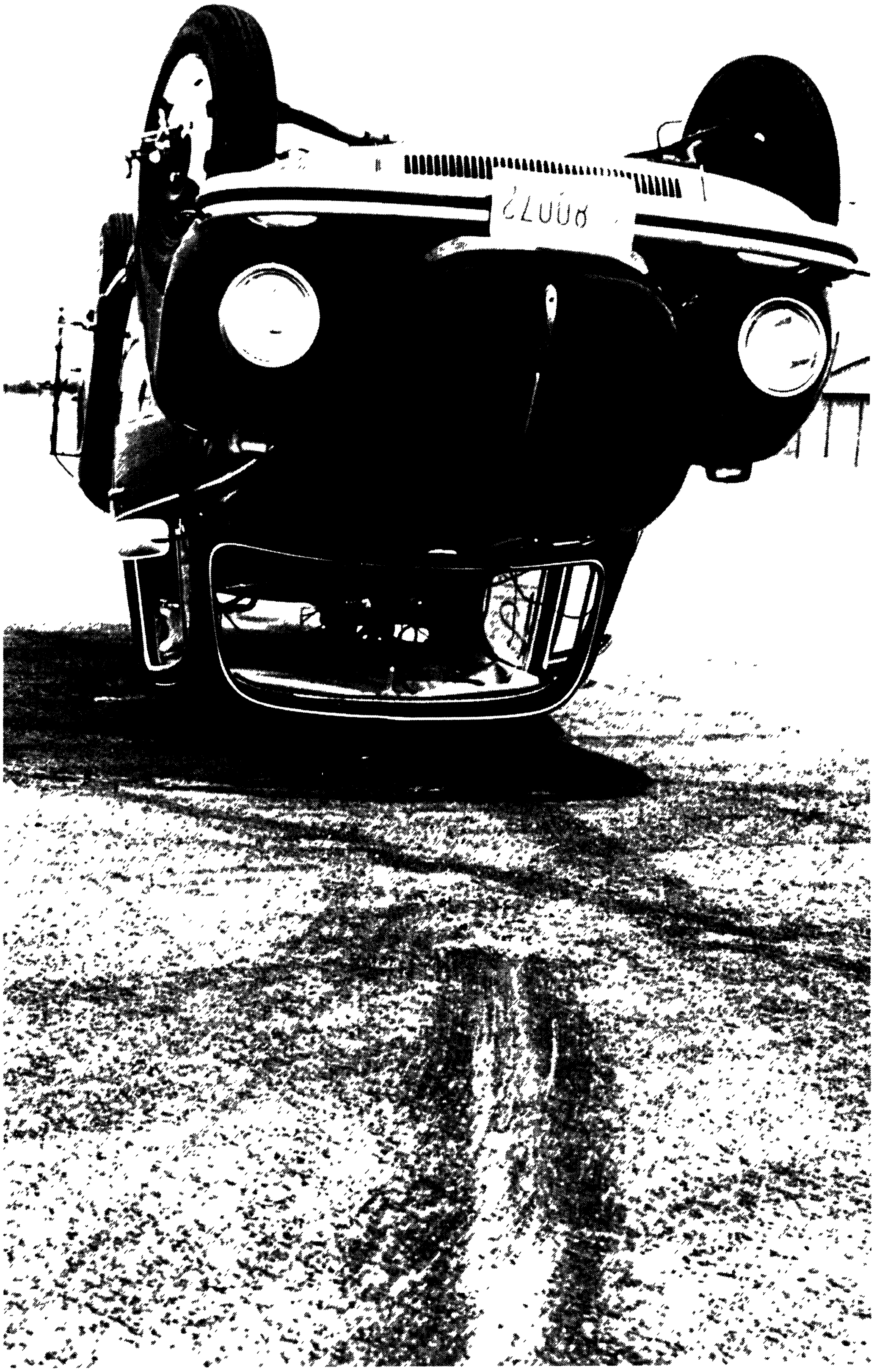


Figure 28

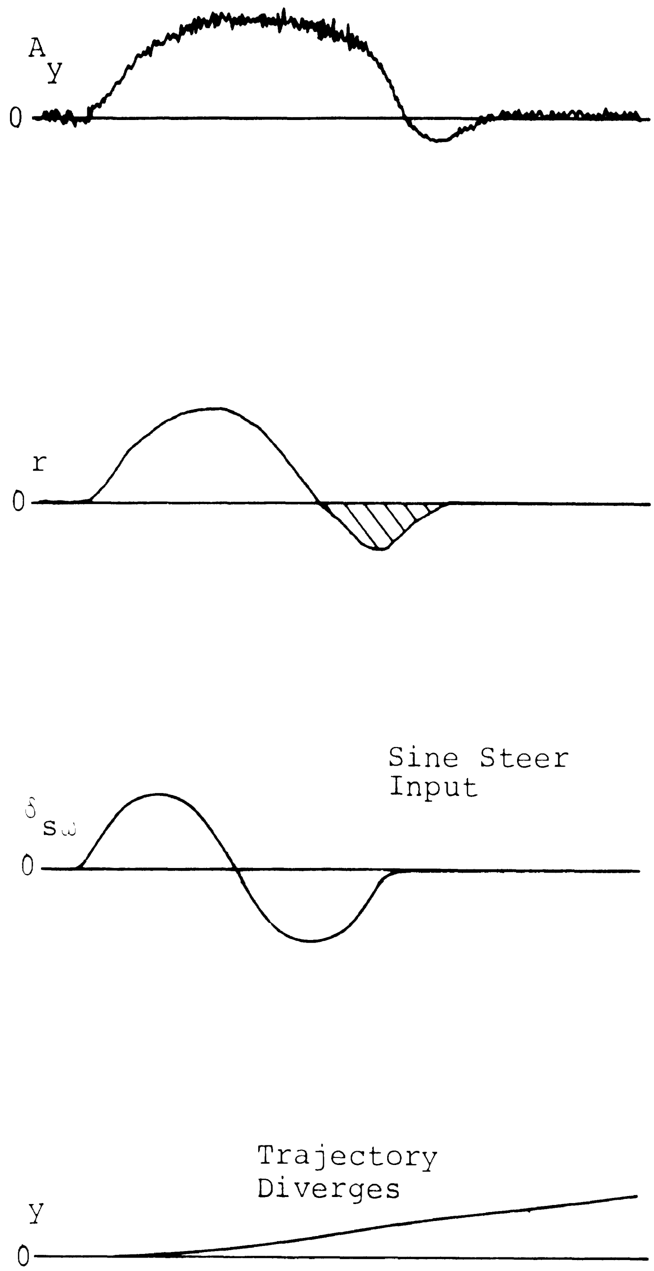


Figure 29

Sinusoidal Steer
"Undercorrective" Response

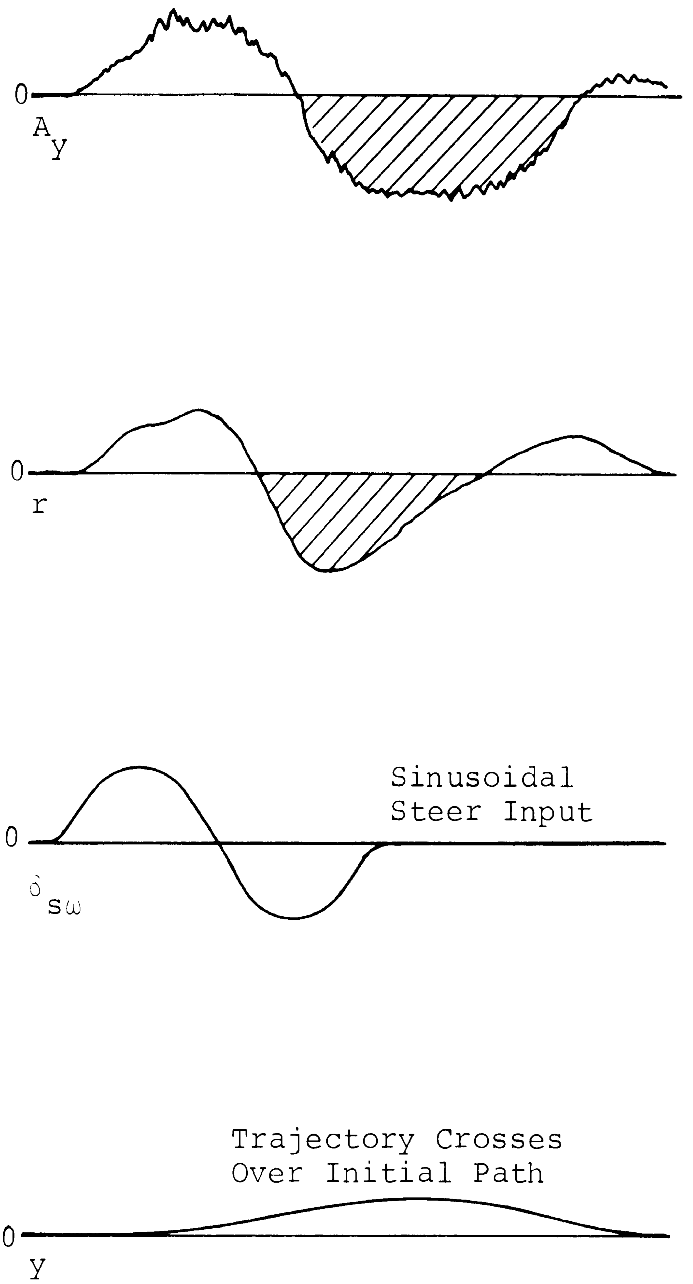


Figure 30

Sinusoidal Steer
"Overcorrective" Response

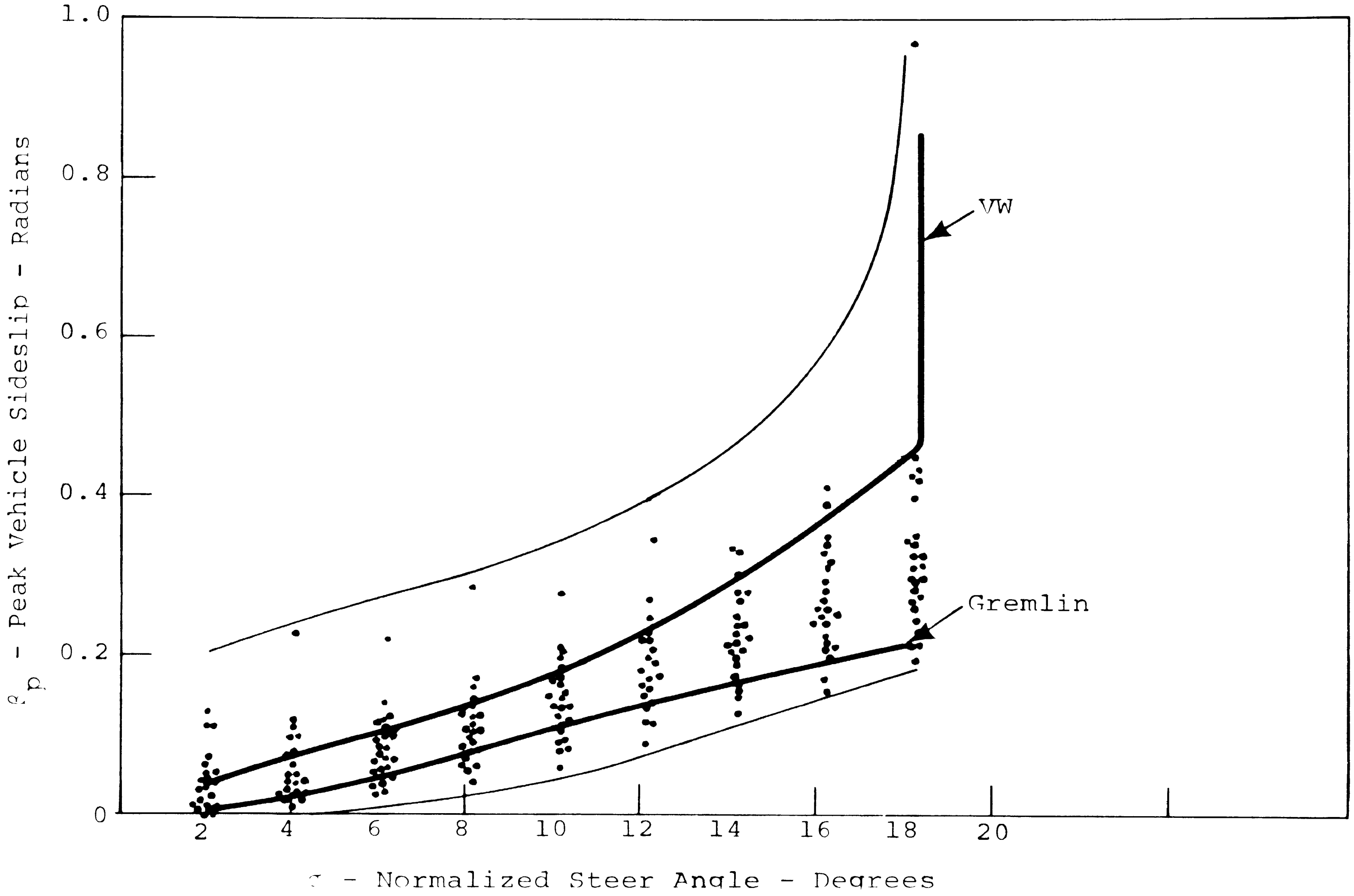


Figure 31
Summary Plot - Sinusoidal Steer - 45 mph

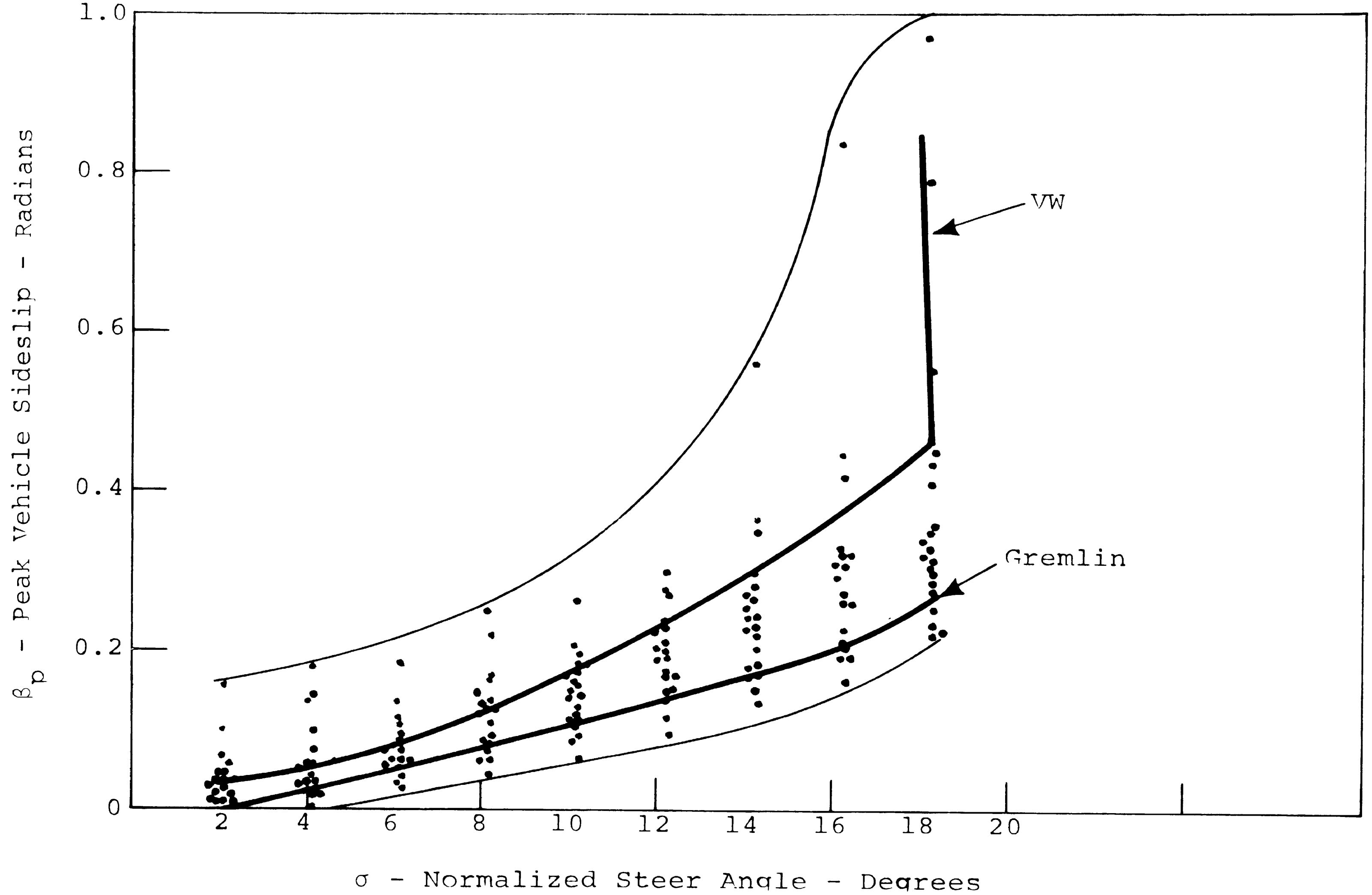


Figure 32

Summary Plot - Sinusoidal Steer - 60 mph

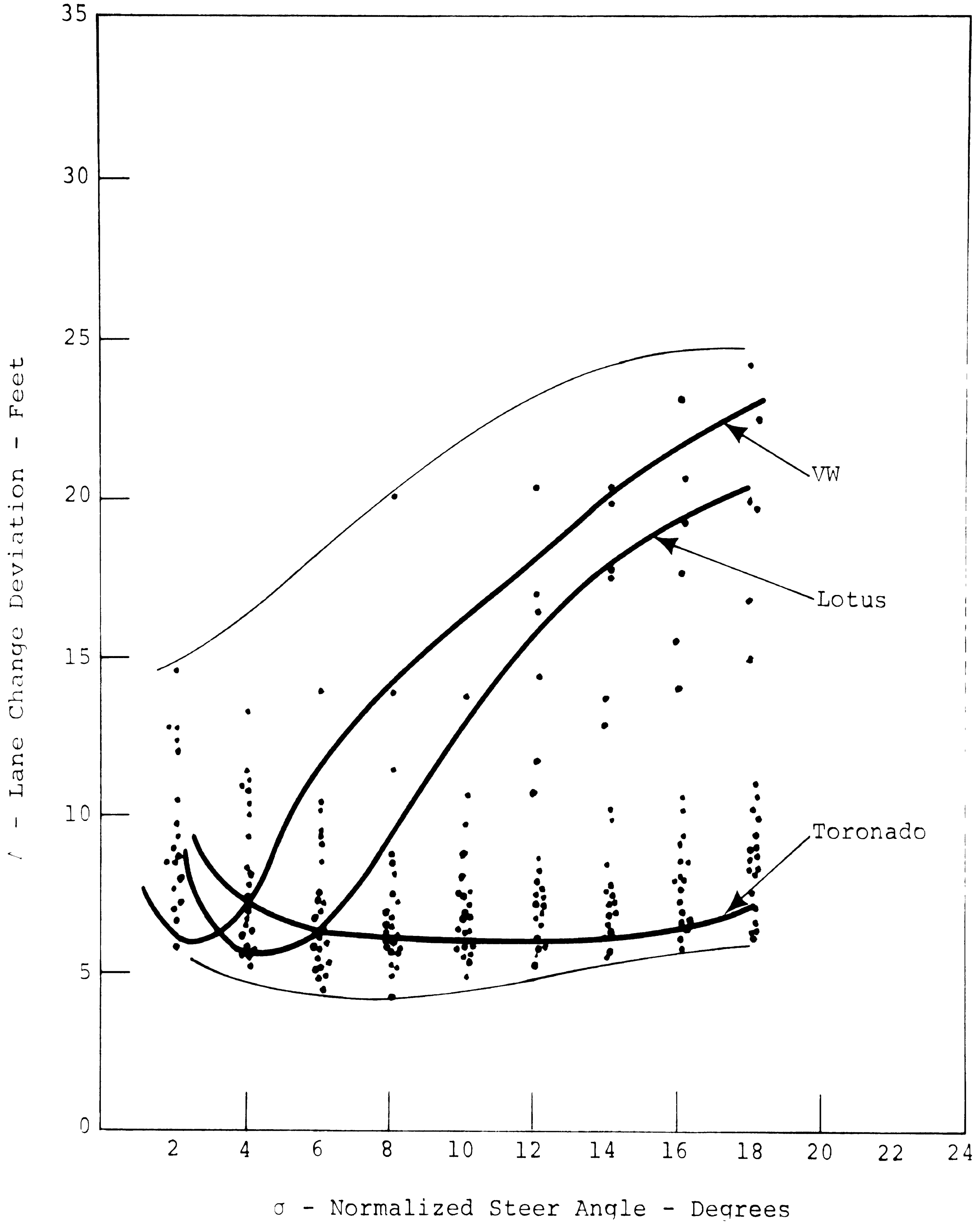


Figure 33

Summary Plot - Sinusoidal Steer - 45 mph

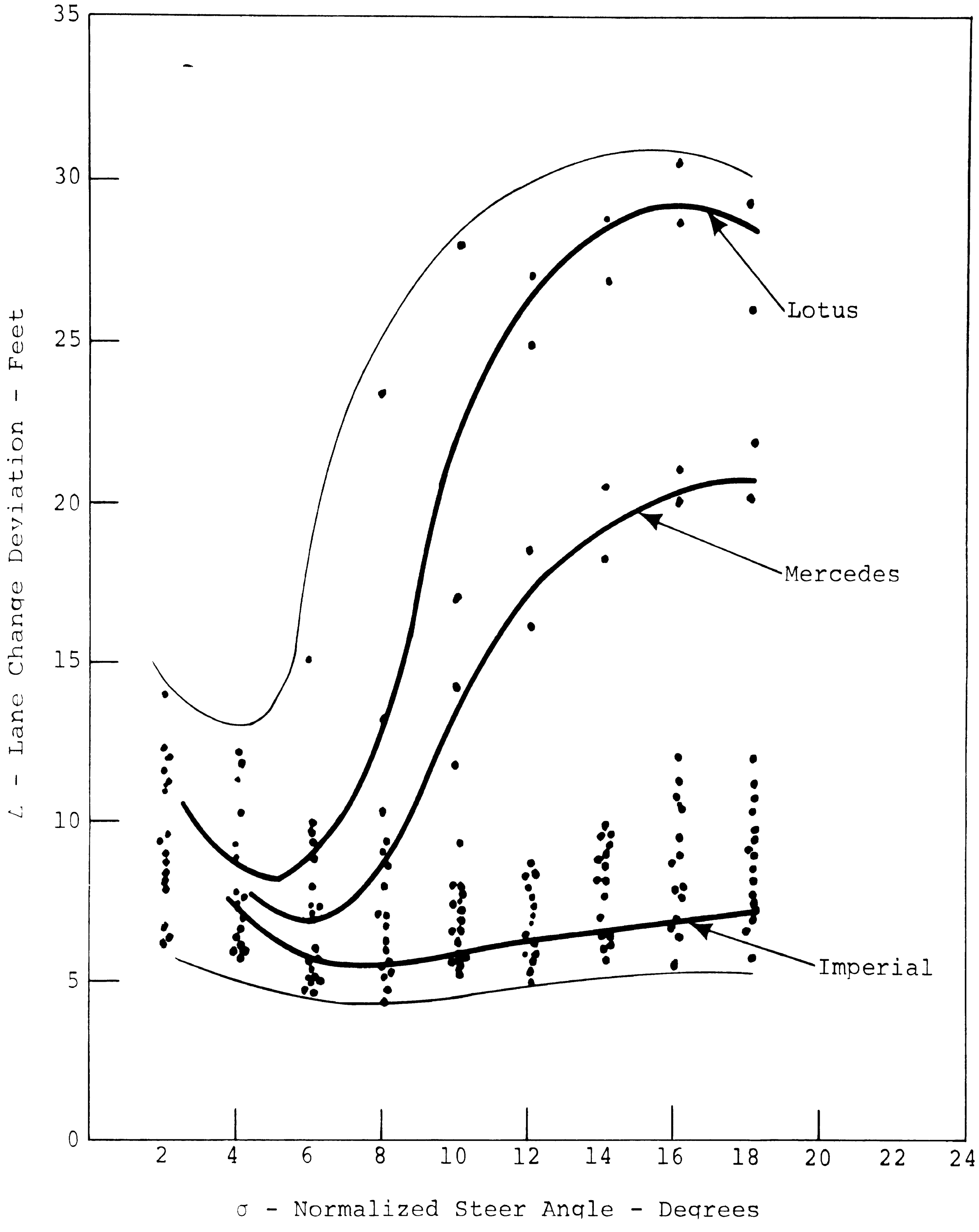


Figure 34

Summary Plot - Sinusoidal Steer - 60 mph

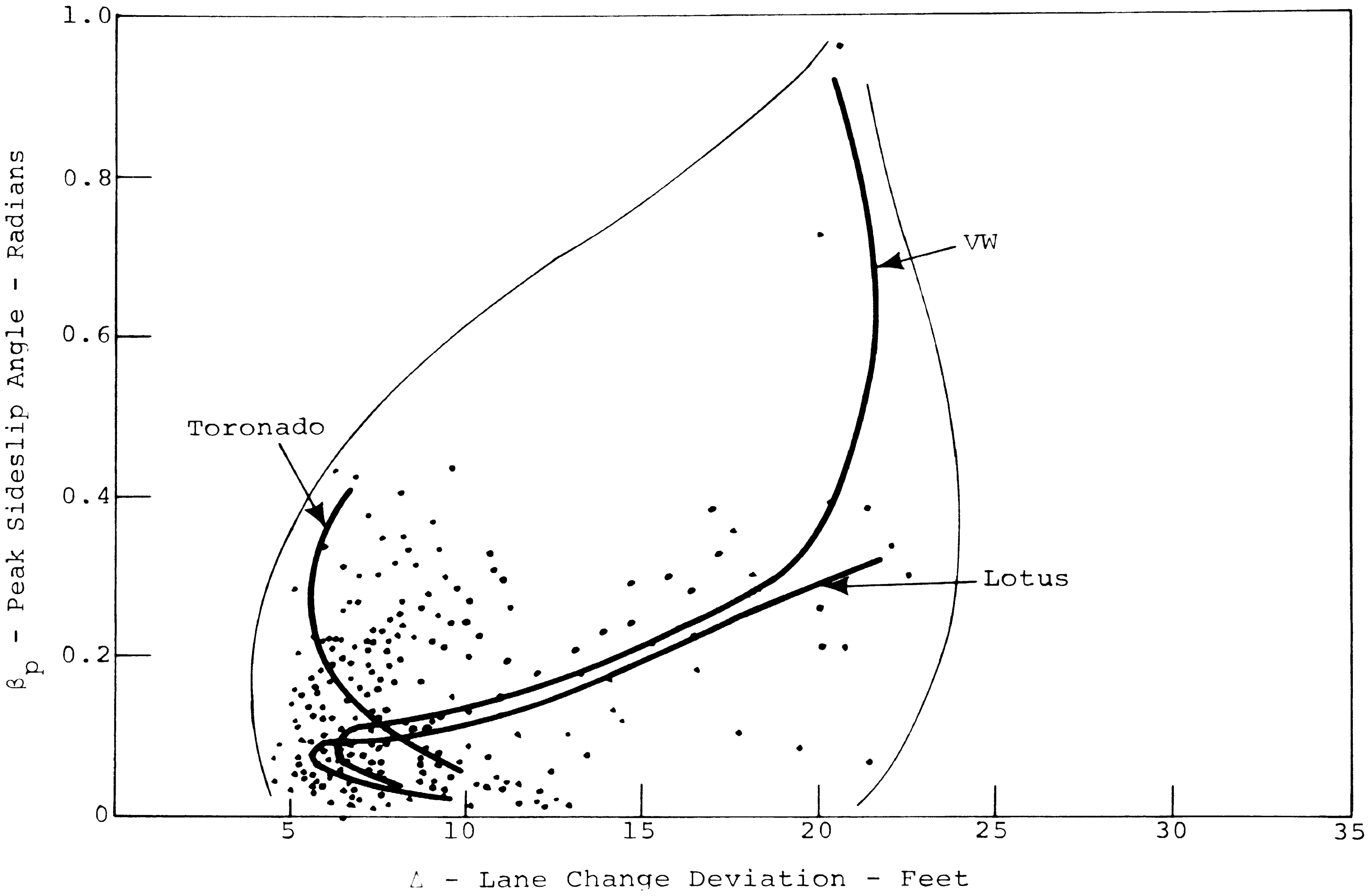


Figure 35
Summary Plot - Sinusoidal Steer - 45 mph

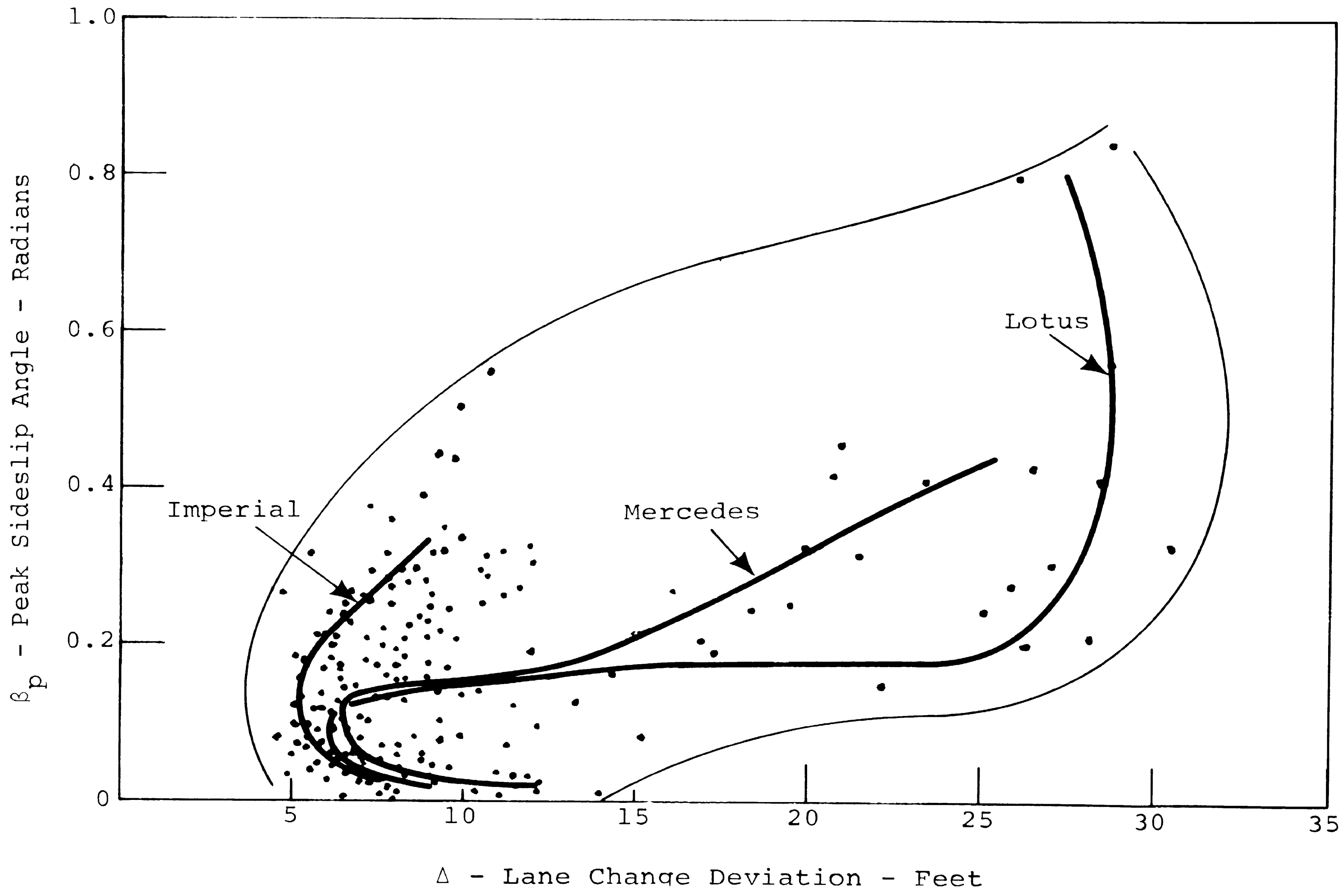


Figure 36
Summary Plot - Sinusoidal Steer - 60 mph

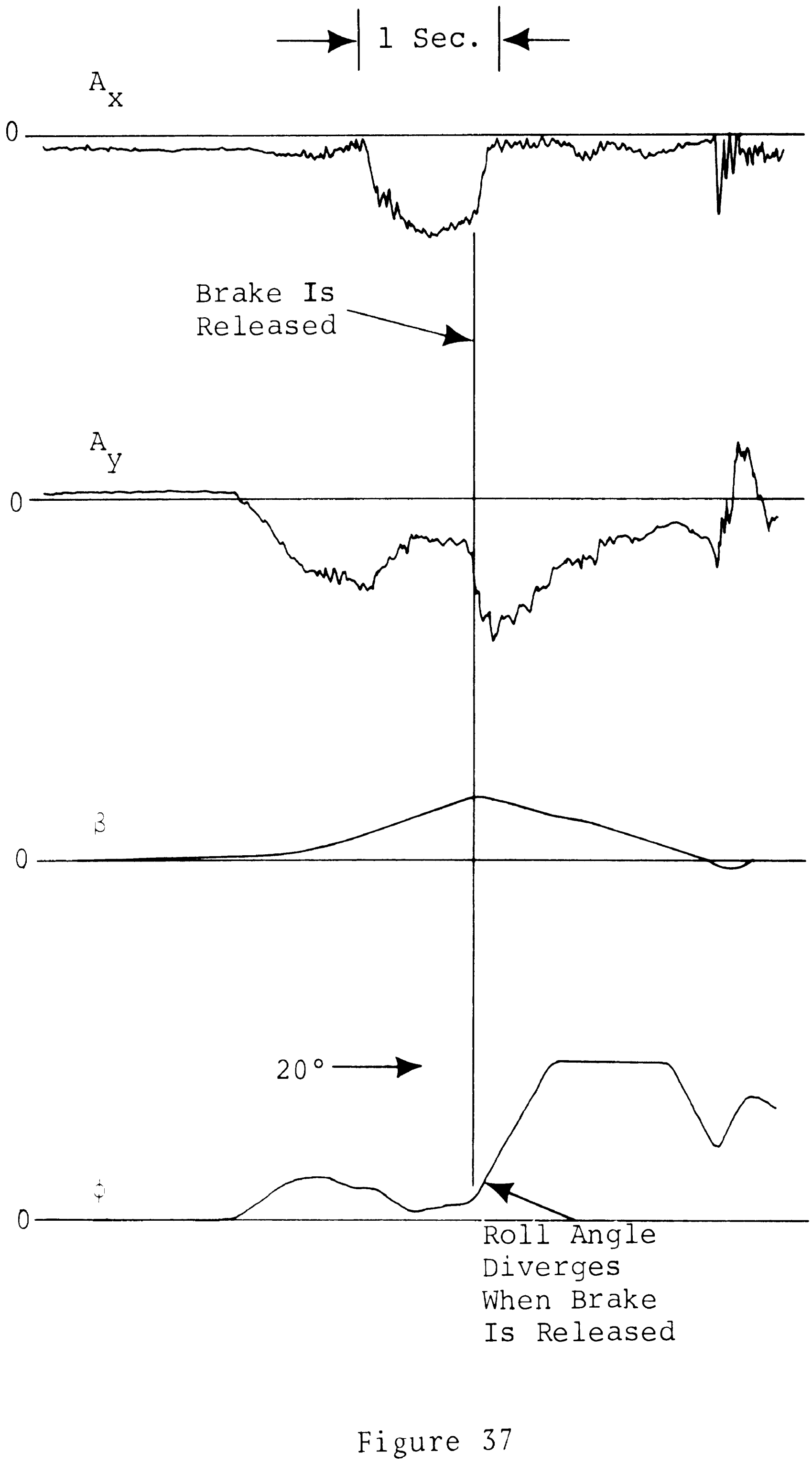


Figure 37

Drastic Steer and Brake
Divergent Roll Response

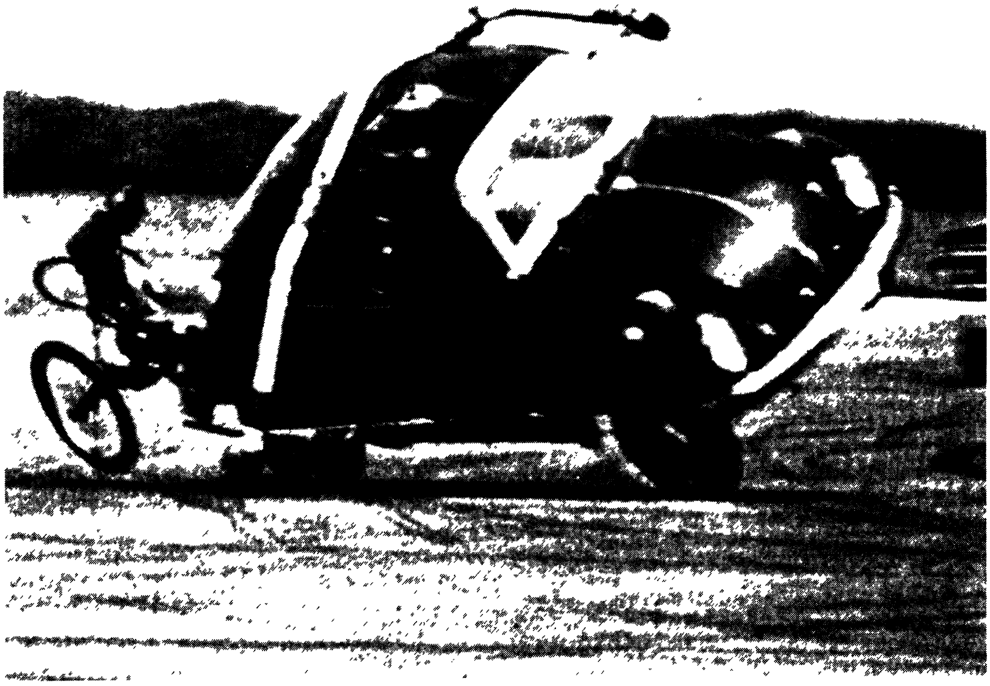


Figure 38

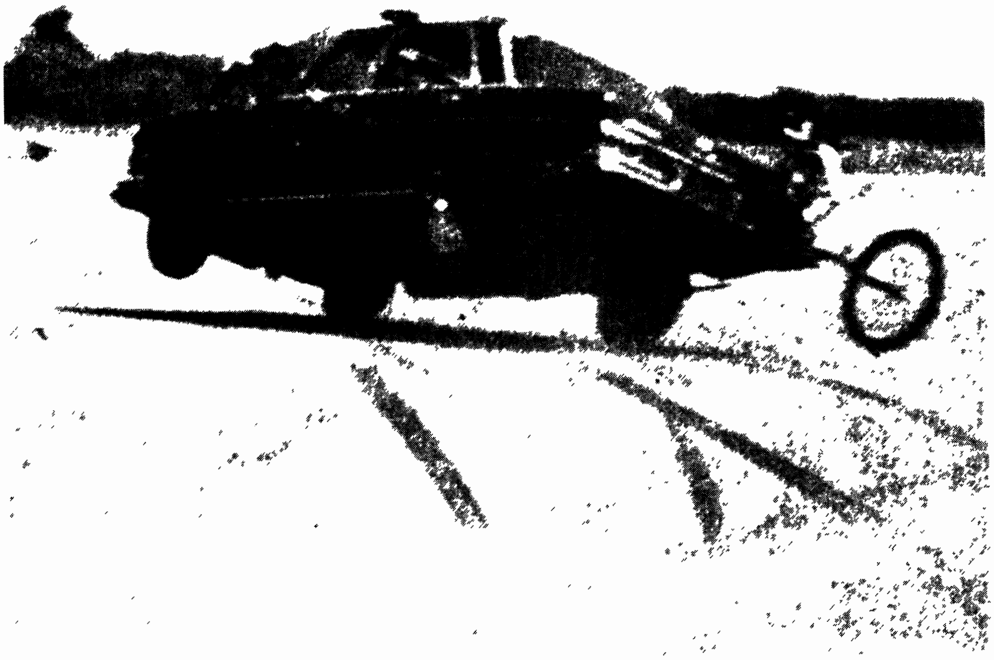


Figure 39

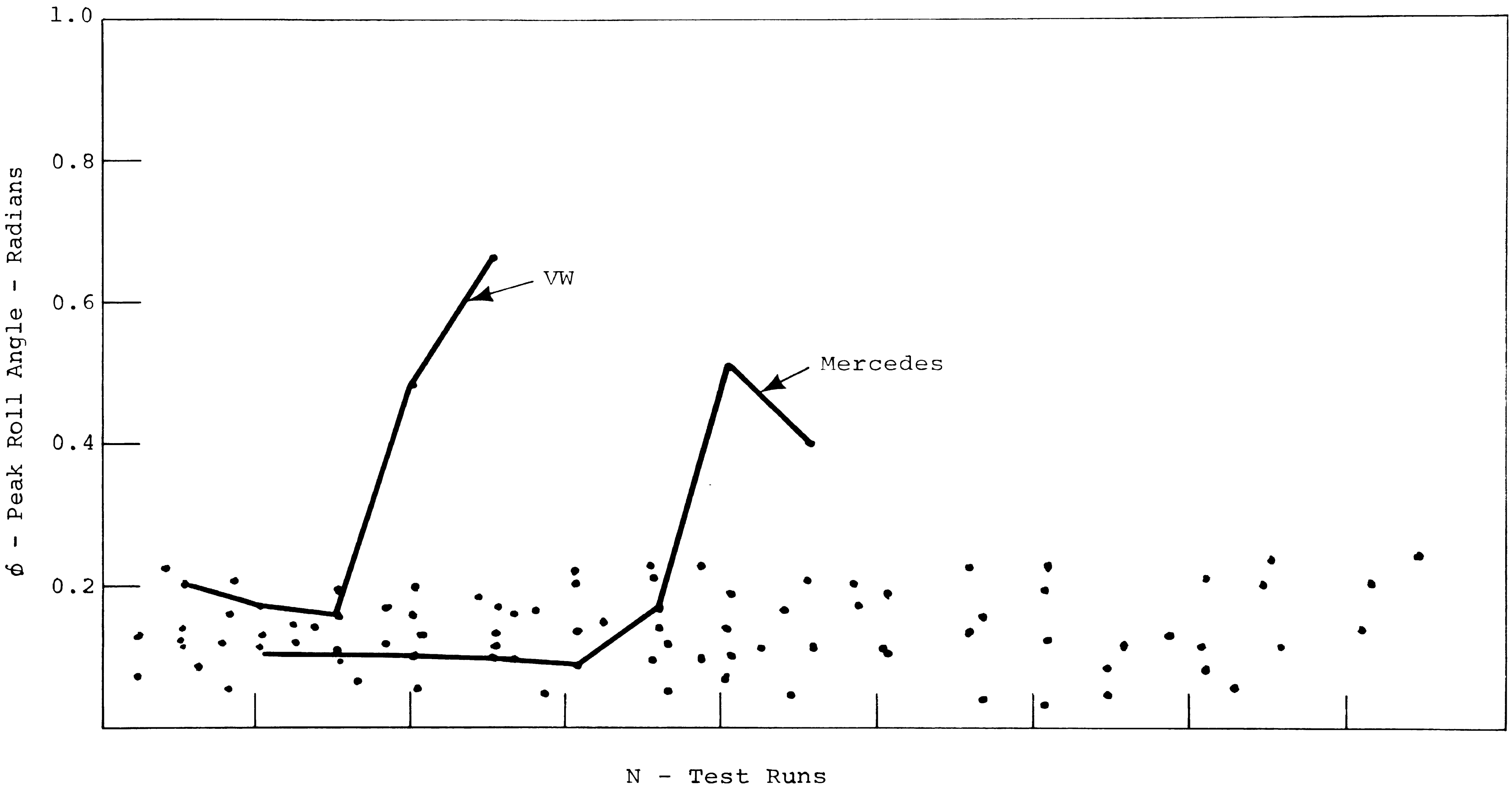


Figure 40
Summary Plot - Drastic Steer/Brake