Final Report
Contract DOT-HS-031-1-126
UM-HSRI-PF-72-3-3

Limit Handling Performance as Influenced by Degradation of Steering & Suspension Systems

Summary Report

P.S. Fancher
R.D. Ervin
P. Grote
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

HSRI

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/HS-800 763		27075

4. Title and Subtitle	5. Report Date
Limit Handling Performance as Influenced by Degradation of Steering and Suspension Systems Summary Report	November 1972
	6. Performing Organization Code
7. Author(s) P.S. Fancher, R.D. Ervin, P. Grote, C.C. MacAdam, L. Segel	8. Performing Organization Report No. UM-HSRI-PF-72-3-3
9. Performing Organization Name and Address University of Michigan Highway Safety Research Institute Huron Parkway and Baxter Road Ann Arbor, Michigan 48105	10. Work Unit No. 11. Contract or Grant No. DOT-HS-031-1-126
12. Sponsoring Agency Name and Address U.S. Department of Transportation National Highway Traffic Safety Administration Washington, D.C. 20590	13. Type of Report and Period Covered Summary Final Report 6/71 to 11/72 14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

The influence of degradations in steering and suspension system (S/SS) components on limit handling behavior of passenger vehicles is examined by means of analysis, simulation, laboratory measurement, and full-scale testing. The major single conclusion deriving from this study is that vehicle handling performance at the limits of tire-road adhesion is negligibly influenced by degradation in S/SS components, both singly and in combination. A principal exception as indicated by a positive sensitivity in certain performance measures, is degraded shock absorbers.

In view of the findings, it appears that benefits to the vehicle-in-use safety program deriving from additional research on this specific topic would be minimal.

17. Key Words	18. Distribution Statement
Vehicle mechanics, open-loop measures, component degradation, steering, suspension system	Unlimited

19. Security Classif.(of this report)	20. Security Classif.(of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	23	

TABLE OF CONTENTS

The contents of this report reflect the view of the Highway Safety Research Institute which is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflec the official views or policy of the National Highway Traffic Safety Administration.

1. INTRODUCTION

This report presents, in summary, the findings, conclusions, and recommendations deriving from a research study sponsored by the National Highway Traffic Safety Administration of the U.S. Department of Transportation entitled "Component Degradation; Inspection Requirements: Steering and Suspension System Performance."

The primary objective of this study was to evaluate the influence of degradation in steering and suspension system (S/SS) components on the limit handling performance of passenger vehicles. Specifically, the influence of S/SS component degradation upon vehicle response to six limit maneuvers, as originally developed in a DOT-sponsored study entitled "Vehicle Handling Test Procedures" [1], was to be examined.

These six test procedures were designed to evaluate the emergency maneuvering capabilities of the motor vehicle and, as such, render performance measures which characterize the limit domain of handling behavior without addressing in any way those properties which determine the ease of vehicle control during normal driving. It follows that the findings expressed herein relate S/SS degradations to limit performance while other later research may be undertaken to examine the normal driving properties of vehicles in use.

The methodology designed to achieve program objectives consisted of a number of activities (or methodological steps) which are described below, in summary form:

1. Various S/SS designs contained in a eight-vehicle sample were analyzed to characterize their functional mechanical properties in both the OEM and degraded condition.

2. An existing hybrid vehicle dynamics simulation was augmented and refined to explicitly represent the functional characteristics identified in (1).

3. An extensive set of laboratory measurements were made of the S/SS properties represented in the eight-vehicle sample. A host of other vehicle design parameters were measured as well, providing numeric characterizations for use in the simulation study.

4. The simulation was exercised to examine in a comprehensive manner the influence of S/SS degradation on limit maneuver performance.

5. Mechanical simulations of degraded components were fabricated for use in vehicle limit maneuver testing.

6. Pilot tests were conducted to develop experimental techniques and to confirm the trends indicated in the simulation exercises.

7. A full-scale test program was conducted to provide a set of hard experimental data relating S/SS degradation to limit handling performance.

2. STRUCTURE OF THE RESEARCH STUDY

The major challenge presented by this study derived from the size of the matrix of degradation conditions to be examined. It was determined that adequate consideration of the most important elements of this matrix could only be assured through the exercise of a multi-stage screening process by which the vast majority of degradation modes could be shown to be negatively related to vehicle performance. It was hypothesized that this effective reduction of the matrix would follow from certain precepts of vehicle mechanics which suggested that vehicle limit performance could be shown to have a negligible sensitivity to many S/SS component degradations. The principle observation, by which negative* sensitivities might be expected to predominate, derives from the phenomenon of tire shear force saturation. Since the maneuvering envelope of the pneumatic-tired motor vehicle is determined primarily by the order and distribution with which tire shear forces saturate, it follows that any change in vehicle limit performance must derive from a significant adjustment in tire forces under conditions of high angular slip (at which side force is quite insensitive to small changes in slip angle) and under conditions of longitudinal slip approaching wheel lockup. To the degree that degradation conditions would not cause significant changes in slip, tire forces would not be modified in any significant way at the limit of performance and the postulated lack of sensitivity would prevail.

Additionally, it was clear that many of the degradation modes could be represented by a common functional relationship. Steer indeterminacy thus is a generic representation

*In this report, the terms "positive" and "negative" sensitivities are meant to indicate conditions in which S/SS component degradation does degrade vehicle performance (positive sensitivity) or does not degrade vehicle performance (negative sensitivity).

of steering gear box lash, steering gear box looseness, tie rod end lash, wheel bearing play, etc..

The examination of basic sensitivities to generic degradation modes was undertaken by simulation. The findings deriving from the simulation study were then used to structure a program of pilot testing, by which the validity of the simulation was assessed, and quantification of certain performance sensitivities was obtained. The combined results were then used to structure a full-scale test program in which two vehicles were subjected to a comprehensive set of tests to provide experimental data indicative of the sensitivity of vehicle performance to critical degradations across a broad range of limit maneuvering conditions.

In each of these program stages, certain component degradation states were evaluated which represented the virtually maximum level of wear or deterioration as was felt to be achievable without jeopardizing structural integrity. This concept of a virtually maximum level of wear constituted the means by which artificial degradation of components was scaled, and thus represents a key element in the selected approach. The premise that a finding of negative sensitivity is indisputably solid and sufficiently general only if it is based upon a demonstration of insensitivity for the maximally degraded species appears to be rational and defensible. Thus, ball joints and tie rod ends were fabricated with ball studs ground down until structural continuity was threatened. Likewise, shock absorber degradation, wheel imbalance, brake imbalance, and other degradation modes were represented by extreme levels of deterioration.

If vehicle performance was seen to exhibit a positive sensitivity to an imposed maximum level of component wear, as was found to be the case for shock absorber degradation, other non-maximum degradation levels were examined.

3. EXECUTION OF THE RESEARCH STUDY

3.1 THE SIMULATION STUDY

The first two methodological steps constituted the development of a simulation capability in excess of that which had been developed earlier under NHTSA auspices [2]. This simulation augmentation involved the detailed treatment of the functional characteristics of degraded ball joints, tie-rod ends, wheel bearings, steering gear, and shock absorbers, as well as providing mathematical descriptions of wheel alignment variables, wheel-mass unbalance, and brake-torque imbalance.

Parameter data was gathered, characterizing the mechanical design properties of the eight vehicles (listed below), such that the simulation could be exercised to examine performance/degradation interactions for a significantly representative sample.

<u>Measurement Sample of Vehicles</u>

1971 Ford Mustang
1971 American Motors Ambassador
1971 Austin America
1971 Volkswagen Super Beetle
1971 Oldsmobile F-85
1971 Dodge Coronet
1971 Ford F-100 Pickup Truck
1971 Chevrolet Brookwood

Measurements of steering system properties, in both the O.E. and mechanically degraded states, were made using the apparatus shown in Figure 3.1 for each vehicle. Likewise, a set-up was constructed and utilized for making suspension system measurements. An existing high performance laboratory testing machine was employed to measure the force-velocity characteristics of shock absorbers, new and degraded. Brake system characteristics were measured on a brake dynamometer.

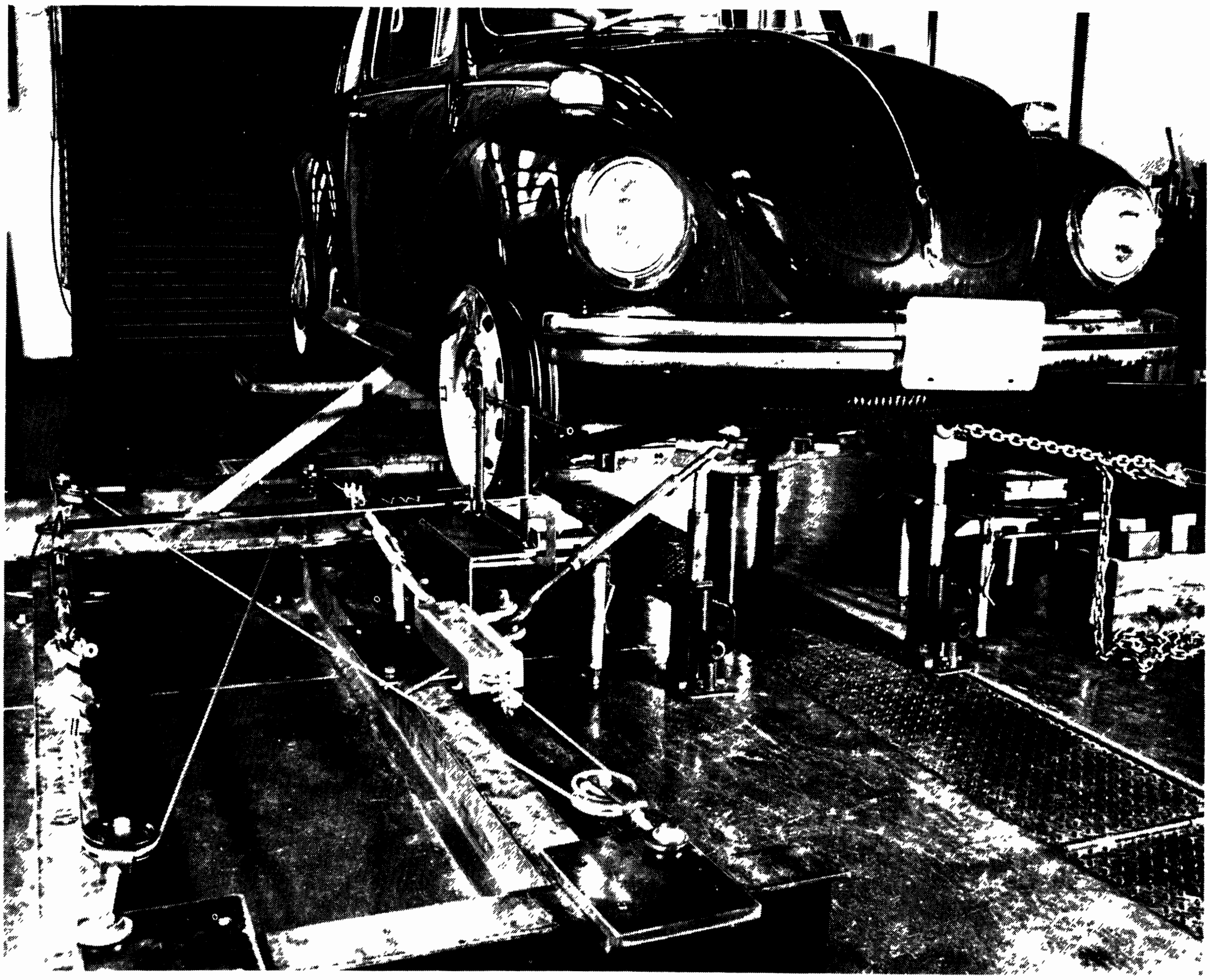


Figure 3.1. Steering system measurement fixture

The acquisition and subsequent analysis of simulation results provided a rational basis for structuring the pilot testing phase of the study.

3.2 TEST APPARATUS PREPARATION

Mechanical simulations of degraded components were fabricated, permitting the realistic representation of a comprehensive set of S/SS degradations. As an example, ball joints were modified as shown in Figure 3.2, providing not only the freedom of movement of the ball stud that accompanies an elevated level of wear, but also preserving the authentic load/lash relationship as is naturally exhibited by this spring loaded element when worn in service.

The "open-loop" character of the vehicle handling test procedures imposes the requirement for minimization of driver influence in conducting the test maneuvers. To this end, certain passive maehanical aids were developed such that three of the test procedures involving simple control inputs could be executed by a test driver.

Additionally, an automatic vehicle controller was constructed for use in conducting the other three test procedures which specify complex steering and braking inputs, such as represent emergency obstacle avoidance maneuvering. This apparatus, replacing the driver with servo mechanisms for actuation of steer, brake, and accelerator (Figure 3.3), provides for the automatic execution of programmed input time histories as stored in an on-board function generator.

Data acquisition packages were also assembled for use in the "driver-controlled" and "automatically-controlled" test series, providing FM tape recording of all response data. A large analog/digital data processing system was developed such that all test data could be handled uniformly, objectively, and efficiently.

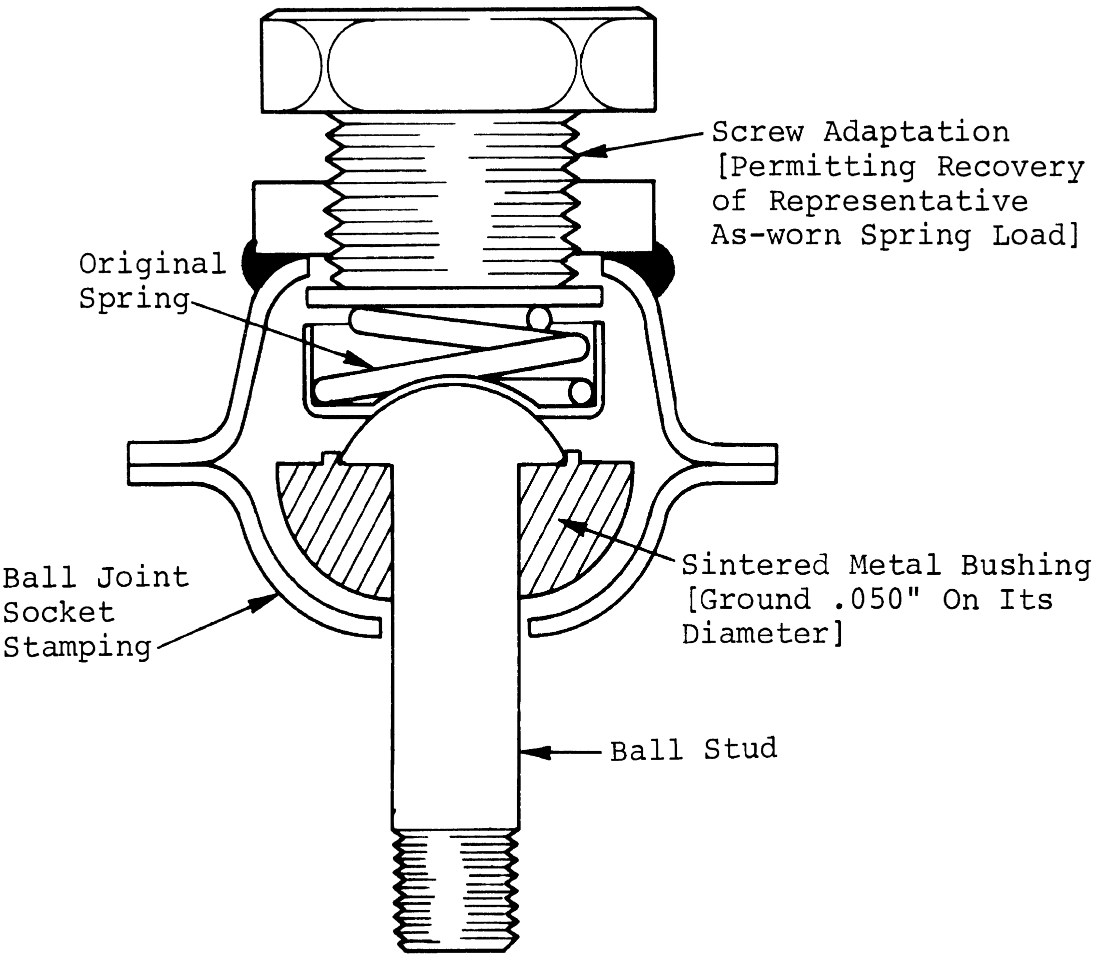


Figure 3.2 Modified Ball Joint Assembly. (This modification also typifies the alterations to tie rod ends.)

Figure 3.3

Servo actuators installed in a van-type vehicle

3.3 PILOT TEST EXECUTION

Two vehicles were outfitted for the pilot test series, and subjected to a preliminary set of technique-refinement tests, as well as a broad range of degraded condition tests. A Ford Mustang was utilized to examine the influence of component degradations on straight line braking, braking in a turn, and roadholding in a turn performances.

Concurrently, a Dodge Coronet was subjected to tests examining the influence of steering and suspension degradations on limit cornering, emergency lane change and rollover immunity performances. Although certain major response data variations invalidated much of the pilot test results from the Dodge series, a single pronounced positive sensitivity was observed, indicating deteriorated rollover immunity deriving from front end misalignment and shock absorber degradation (Figure 3.4). The complete rollover of this vehicle occurred when the early-design version of a roll-restraint outrigger failed.

The observation of large-scale data variability in the Dodge pilot test results, particularly in limit cornering performance, gave rise to a substantial investigative effort. It was determined that the resolution of this anomaly was required if experimental data were to be contributed to the examination of the influence of S/SS degradations on limit performance. This investigation involved a large number of vehicle tests, as well as tire tests conducted using a mobile tire tester device.

A remarkable finding resulted from this effort, relating tire side force capability to wear of the tire buttress (or shoulder), as derives from operation at severe cornering levels. (A data sample illustrating the side force/tire wear relationship is shown in Figure 3.5.) Such pronounced sensitivities in side force were discovered with a number of tires, indicating clearly that the observed variability

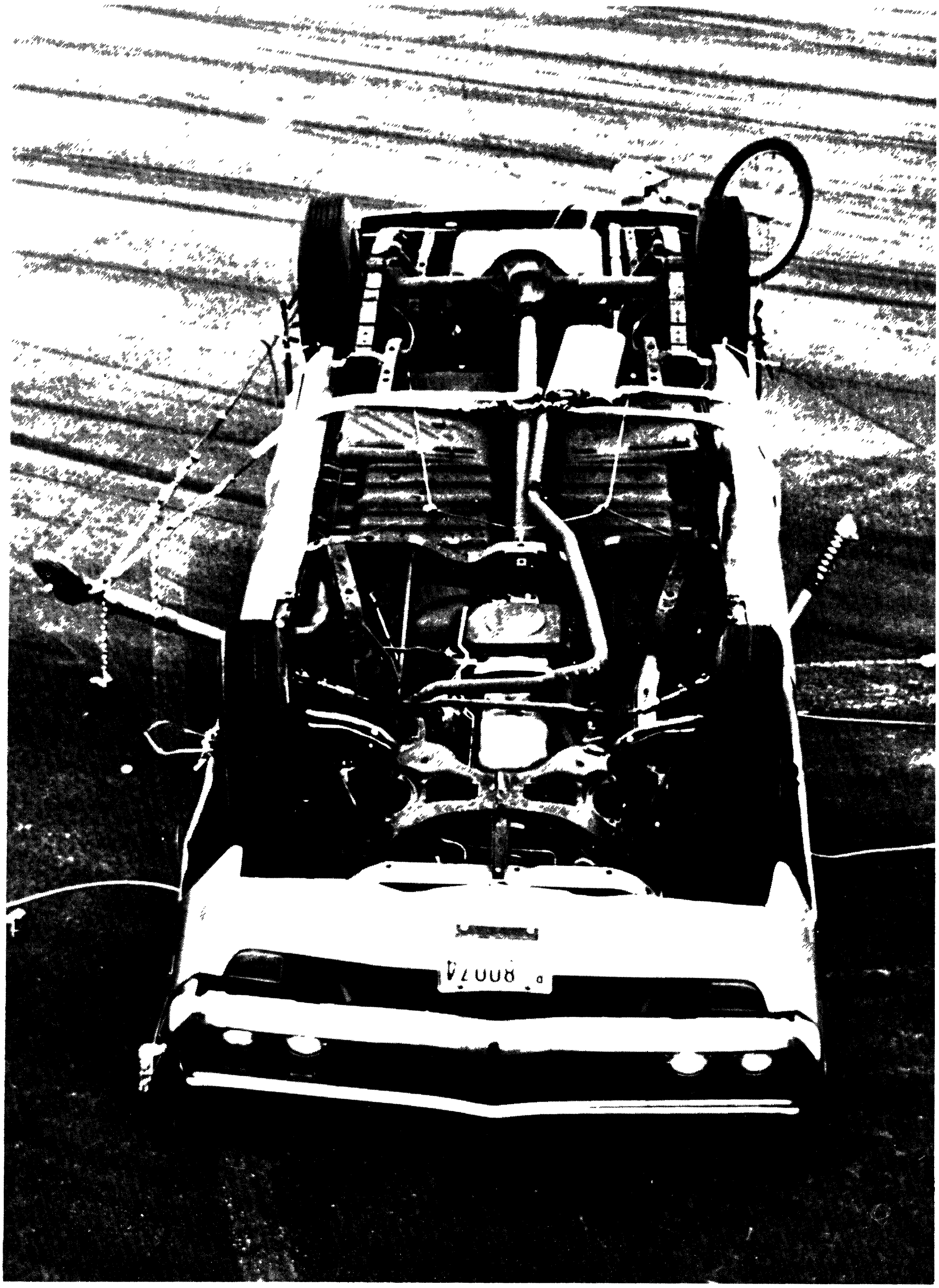
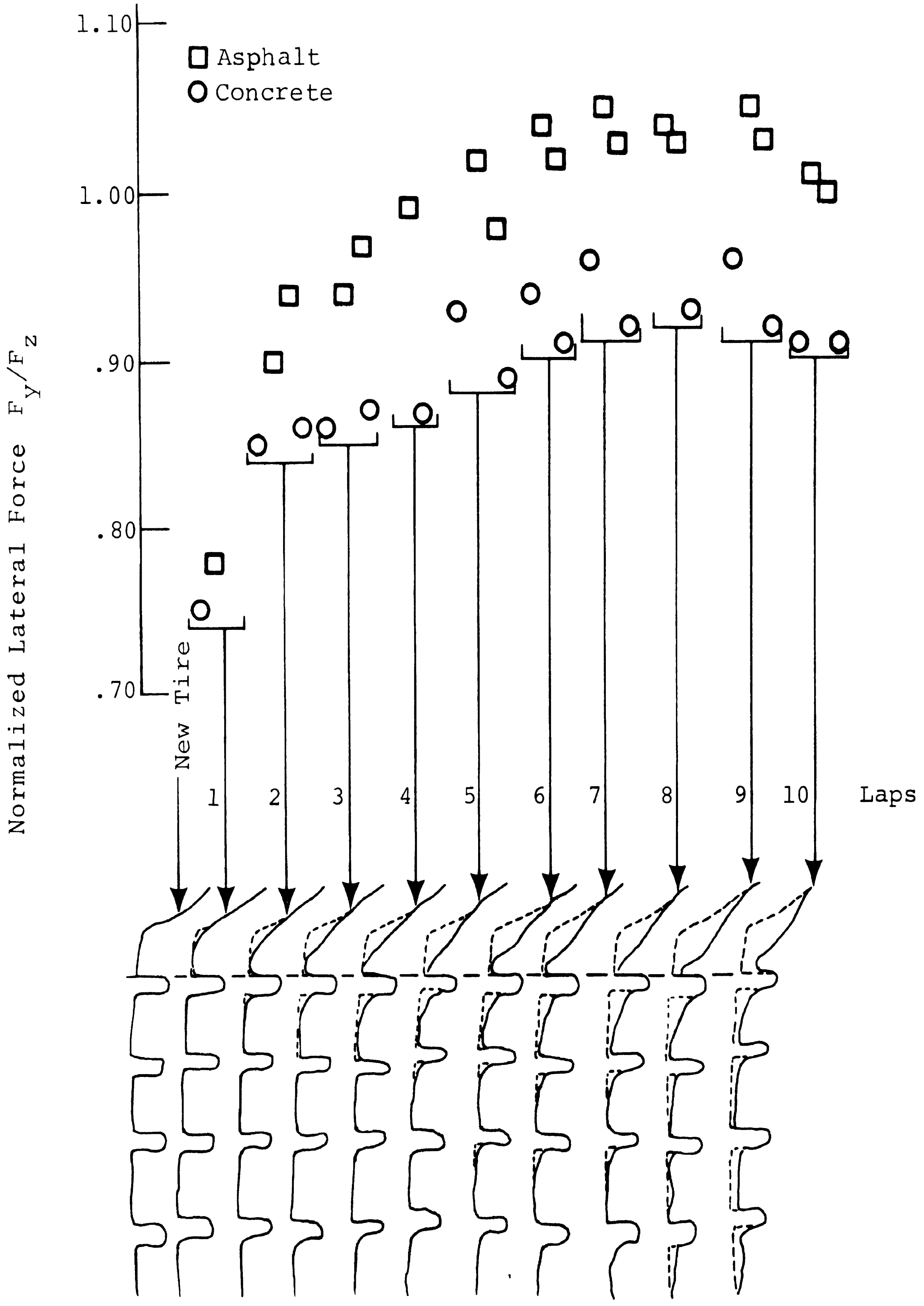


Figure 3.4 This vehicle rolled over in response to drastic steer/brake input while being tested with combined degradations. (Note the large degree of toe-in)



Tread Profile - Outside Shoulder

$\alpha=20°$ $F_z=1550$ Uniroyal L78-15 Fastrak

Tire Sample No. 1

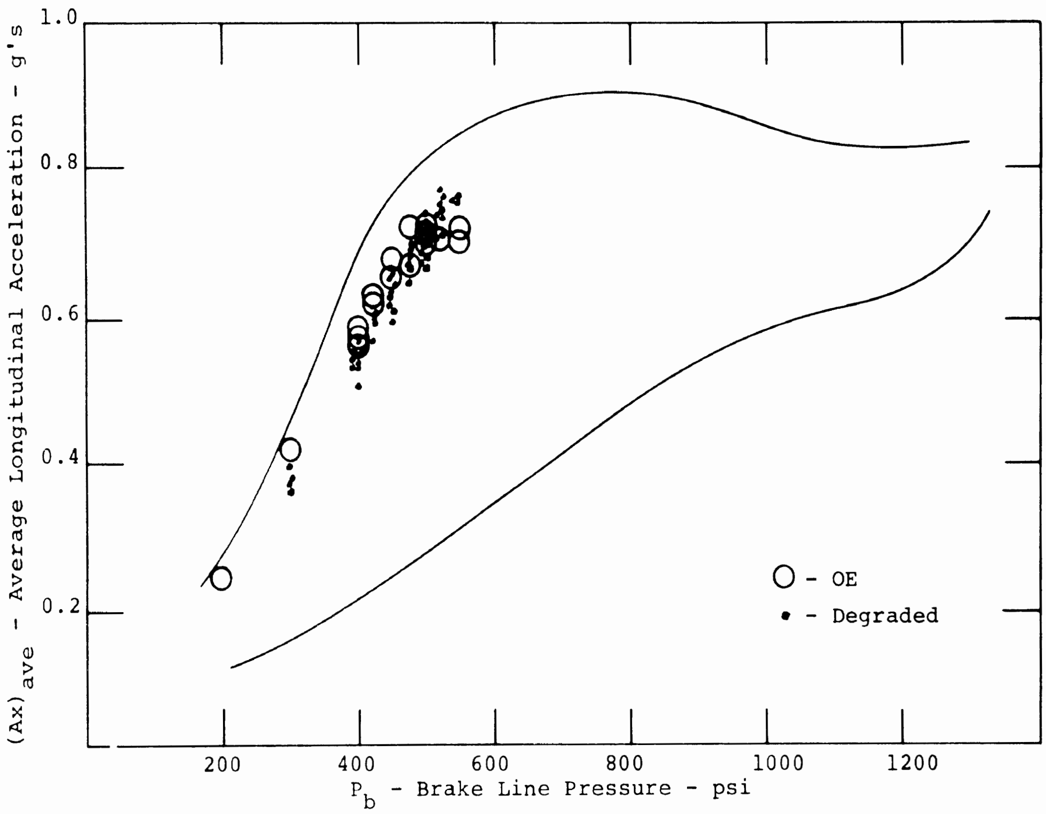
FIGURE 3.5.

in Dodge response data had arisen from a classic fault in experimental method—a test process which itself acted to the alteration of the test condition. A test practice was adopted, subsequent to this finding, in which tires were initially worn in by repeated running at limit cornering levels such that a stabilized side force performance was attained.

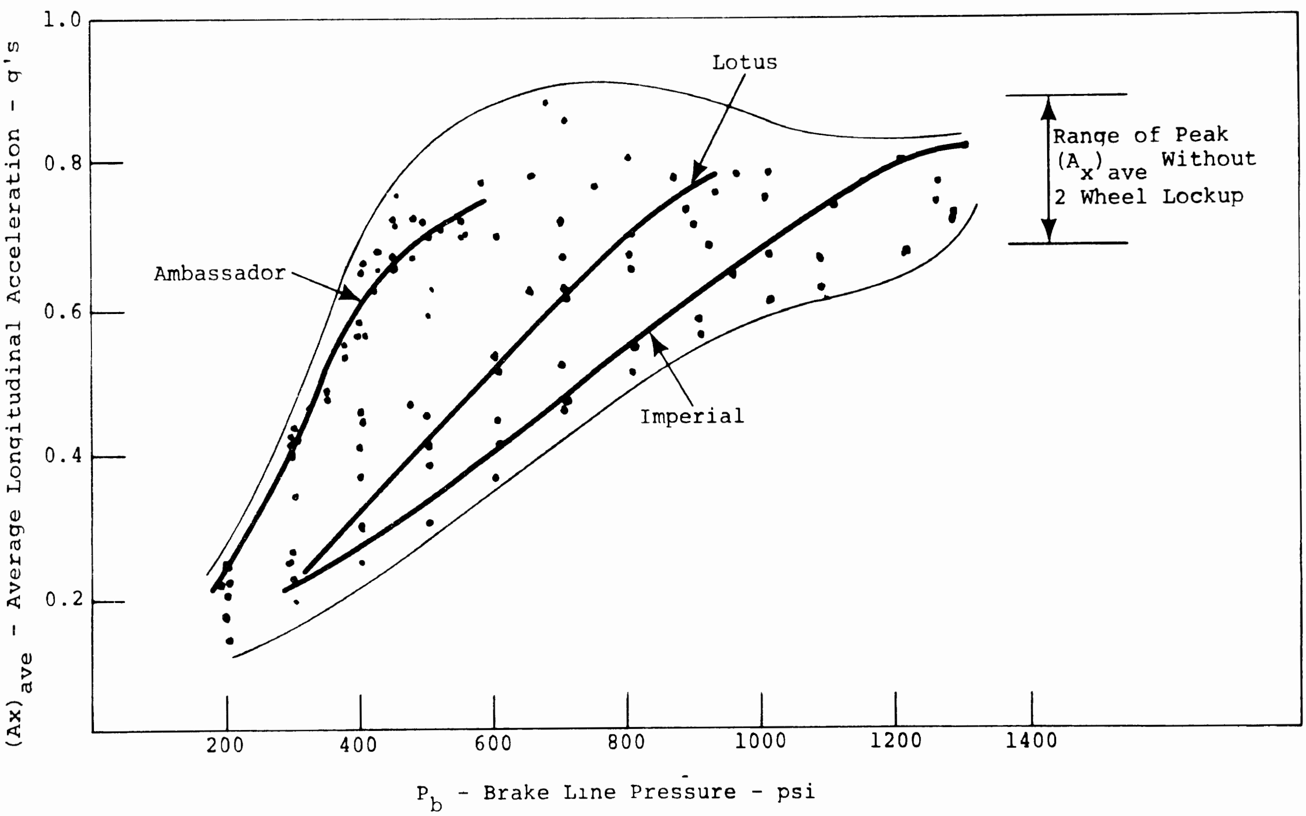
3.4 FULL-SCALE TEST EXECUTION

Two vehicles were tested through a large set of limit maneuver experiments and degradation conditions in the full-scale test program. The Dodge Coronet which was used previously in pilot testing and an American Motors Ambassador were each subjected to all six vehicle handling test procedures, in both their O.E. and degraded conditions. An elaborate set of test practices was observed such that the generated data would be of identical format and representation as a bank of new car data that was being gathered concurrently in the DOT-sponsored Vehicle Handling Performance study [3]. By this common observance of practice, the corresponding data sets can be directly compared, providing a valuable perspective to the evaluation of vehicle-in-use performance by comparison with the spread in new car performance which derives from design differences.

The resulting full-scale test data was reduced to the format typified by the data presentation in Figure 3.6, representing straight line braking performance, O.E. and degraded, with an accompanying plot showing the range and distribution of new car performance. Plots such as this were constructed covering all of the examined degradations for each of the six maneuvers.



Ambassador O.E./Degraded



New Car Performance

Figure 3.6 Summary plot - straight line braking

4. CONCLUSIONS AND RECOMMENDATIONS

Based upon the observations, analyses, computations, and test measurements generating from this study, the following conclusions may be drawn. It must be emphasized that these conclusions relate component degradation to limit handling performance, and not to the sublimit domain in which most normal driving is conducted.

(1) The range of limit handling performance exhibited among new cars, as derives from design differences, is much larger than the in-use changes in performance of individual vehicles deriving from degradation of steering and suspension system components.

(2) The principal suspension component whose likely degradation can be shown to influence limit performance is the shock absorber.

(3) Shock absorber degradation contributes a deterioration in limit performance principally under conditions which excite vertical motions of the unsprung masses; eliciting the "brake hop," "wheel hop," and "axle tramp" phenomena which result in net losses in tire shear force.

(4) Degradation in shock absorber performance can arise from a number of characteristically differing mechanisms. Given that these degradation mechanisms are manifested by coulomb friction, free travel, hysteretic effects, and other complex nonlinearities, it appears inadequate and thus inappropriate that shock absorber condition be represented by such simplistic characterizations as "percent effectiveness."

(5) Indeterminancies of front wheel steer angle which arise due to lash in wheel bearings, ball joints, tie-rod ends, or steering gear box, whether taken singly or in combination, do not exhibit a first-order influence on vehicle limit performance.

(6) Misalignment of front wheels, to the virtually maximum level achievable, has been shown to contribute a significant alteration in limit lane change performance, as measured by an open-loop technique.

(7) Vehicle limit braking performance, both in straight line and curved path conditions, is more severely degraded by the presence of brake imbalance than by any of the steering and suspension component degradations examined. The combination of certain steering and suspension degradations with brake imbalance can possibly further deteriorate limit braking performance beyond the level obtained with brake imbalance alone.

(8) Mass unbalance of the road wheels has been shown to have a negligible influence on limit braking and steering performance.

(9) The limit cornering capability of passenger vehicles has been shown to be insensitive to degradation in steering and suspension systems.

(10) The rollover resistance of passenger vehicles can be reduced through degradation of shock absorbers, and in certain cases may be also influenced by the addition of front end misalignment.

RECOMMENDATIONS

It is felt that this study, as conducted, has provided a sufficiently rigorous examination of the relationship between steering and suspension system degradation and limit handling performance, that the subject can be put to rest. This is not to say that all possible conditions of limit behavior and degradation have been exhausted, but rather that the authors see further research on this relationship as unwarranted. This investigation has clearly shown vehicle limit performance to be insensitive to steering and suspension degradations on a broad scale, and that further, this insensitivity is well supported by consideration of the vehicle mechanics involved. Thus, it is argued that interests of vehicle-in-use safety can best be served by the commitment of resources and effort to the investigation of the influence of steering and suspension degradations on vehicle behavior in the non-limit performance domain.

The many degraded system conditions which contributed relatively inconsequential adjustment to limit behavior are, nevertheless, known to involve factors which impose a challenge to the low level lane-tracking task. A level of driver attention may be required under such circumstances, which, giving rise to driver fatigue, constitute a safety hazard of substantially greater dimension than derives from the marginal deterioration of limit performance properties.

Degradation categories in which limit performance sensitivity is felt to be pronounced, include deterioration of tires and brakes. In this study a tire wear/side force relationship was identified which bears on limit performance to a much exaggerated degree, in comparison with steering and suspension degradation influence. Although the type of wear considered was that which derives from severe cornering, it is felt that these data and other data clearly indicate the need for an examination of limit maneuvering properties as influenced by the level of normal tire wear and its distribution around the vehicle.

With regard to the implications bearing on vehicle inspection which derive from the findings of this study, it is clear that the inspection for shock absorber degradation is an activity which merits attention. As recommended by the two major preceding studies of steering and suspension system degradation [4, 5], the need for an effective assessment of the degradation in damping of the jounce/rebound motion of the running gear is recognized. Although few systems are currently available for exercising vehicle running gear to evaluate damping level, one such system (contributed by Hartridge, Ltd. of England) was examined in the course of this study and shown to provide results which correlated well on a relative basis, with dynamic measurement of shock absorbers alone. A rigorous evaluation of such apparatus should be undertaken, not only for the sake of advancements in periodic motor vehicle inspection practice, but for application by the vehicle maintenance and servicing enterprise as well.

REFERENCES

1. Dugoff, H., Ervin, R.D., and Segel, L., Vehicle Handling Test Procedures. Highway Safety Research Institute, Univ. of Michigan, Ann Arbor, 2 Vol., a Report to NHSB, Nov. 1970.

2. Hartz, J.R., Computer Simulation of Vehicle Handling. The Bendix Corporation, Research Laboratories, a Report to NHTSA, Contract No. FH-11-7563, Sept. 1972.

3. Ervin, R.D., Grote, P., Fancher, P.S., MacAdam, C.C., and Segel, L., Vehicle Handling Performance. Highway Safety Research Institute, Univ of Michigan, Ann Arbor, 3 Vol., a Report to NHTSA, Nov. 1972.

4. Bird, K.D., Belsdorf, M.R., and Rice, R.S., Effects of Steering and Suspension Component Degradation on Automobile Stability and Control. Cornell Aeronautical Laboratory, Inc., 6 Vol., a Report to NHTSA, Contract No. FH-11-7384, Jan. 1971.

5. Merrill, M.S., Steering Diagnosis: A Study of Degraded Components Affecting In-Use Vehicle Handling. Clayton Mfg. Co., 2 Vol., a Report to NHSB, Contract No. FH-11-6629, Sept. 1969.