Safe Geometric Design for Minicars

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16. Abstract

Because minicars are less safe in both multivehicle and single vehicle collisions, this FHWA-sponsored project is designed to identify those types of accidents (and accident-related circumstances) where the small vehicles are overrepresented in either crashes or crash injuries. The analysis involved accident and roadway data from the States of Washington, Texas and North Carolina, and computer simulation runs related to vehicle dynamics. Results include the general finding of increased rollover propensity of these small vehicles in almost all type crashes, with specific problems with roadside shoulder and sideslope design, ditches in rural areas, pavement edgedrop, culverts and catch basins, median barrier faces, rural traffic islands, utility poles, and with head-on collisions on curves where the minicar is more often the striking vehicle. Potential treatments were identified for many of these issues, and research plans were prepared.

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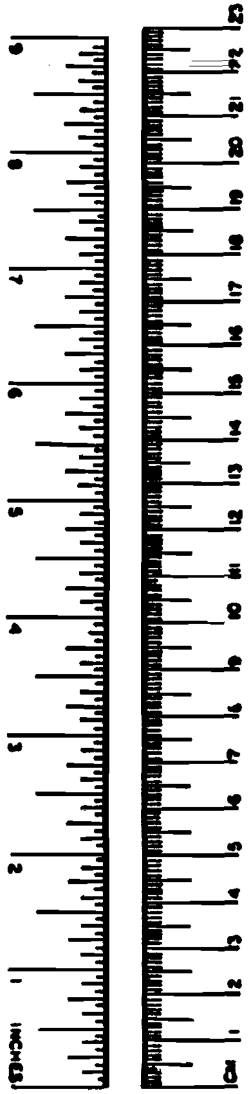
METRIC CONVERSION FACTORS

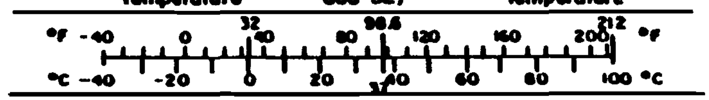
APPROXIMATE CONVERSIONS FROM METRIC MEASURES

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
	LENGTH			
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.6	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



APPROXIMATE CONVERSIONS FROM METRIC MEASURES

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	36	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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INTRODUCTION

For the past fifteen years, and particularly since the oil embargo of 1973, the United States passenger car fleet has been shifting to smaller vehicles. Various papers have presented projections of the degree of this shift. Ivey indicated that subcompacts would increase their share of the total vehicle fleet from 18 percent to 44 percent by 1990 and that minicars will increase from four percent to eight percent.(1) In a 1981 Transportation Research Board (TRB) study, Michie indicated that vehicles of 2250 pounds (1.02 Mg) or less should increase to 52 percent of the total fleet by 1990.(2) In the same report, Martin, citing an earlier paper by Ladd, projected continuing decreases in vehicle weight, vehicle length, and vehicle wheel base. Woods projected that the power to weight ratio would change substantially.(3) In a 1983 TRB report, Lave projected that minicars would capture up to 40 percent of the market for themselves by the year 2000.(4) In the same paper, Hemphill quoted the Automotive Consumer Profile in noting that this trend had already begun. This profile indicated that 6 to 9 percent of the 1985 car sales would be micro-minicars of less than 1650 pounds (0.75 Mg).(4)

On the other hand, very recent reviews of the current excess of petroleum and projected decrease in oil prices has led some researchers to predict that the shift to small cars may not be as significant as predicted in these earlier studies. However, even given the current fleet composition, there is no doubt that a substantial number of minicars will be part of the future U.S. vehicle fleet and accident picture.

The issue for highway and vehicle designers is that the shift to minicars has not yet been paralleled by a shift in roadway design practices nor by a substantial improvement in the crashworthiness of the small cars. Potential safety problems range from the fact that most roadside hardware was developed, tested and evaluated using larger vehicles to the fact that underpowered minicars may increase the variance in speeds on upgrades while high-powered minicars with more sensitive handling and steering capabilities may allow drivers to drive roads at higher speeds than the roads were designed for.

From the driver's point of view, the issues range from the potential differences in the handling and steering of the minicar itself to the fact that gap judgement may be affected by the size of the approaching vehicle (i.e., a smaller car may appear further away than it actually is, given driver expectations based on larger-sized vehicles). Indeed preliminary analysis of accident data prior to this study had shown that some of these incompatibilities with the roadway and between drivers were making themselves apparent in the accident statistics. A specific example of this is the preliminary evidence that minicars experience increased rollover when striking certain concrete median barriers.

In answer to these current problems and in anticipation of future minicar problems, the FHWA's Office of Research initiated this study to better define the minicar related accident issues. This study is to examine in detail: (1) the specific accident subcategories where minicars are overrepresented in terms of accident or injury occurrence as related to single and multivehicle crashes; (2) the causes of these minicar accidents; (3) the potential countermeasures that might be implemented to reduce the frequency of these accidents; (4) the benefits that might be accrued from these countermeasures; and (5) the effects of these minicar specific countermeasures on other parts of the vehicle fleet.

The three objectives of this research are to: (1) evaluate and define the minicar accident problem in order to provide a rational basis for reduction of minicar accidents; (2) determine those geometric features which contribute to minicar accidents and develop alternate designs which will minimize the consequences of those accidents; and (3) develop plans for the analysis of accident and geometric data. The required outputs of this research study include:

- A listing of critical accident subcategories in which minicars have safety problems.
- A listing of proposed countermeasures, some of which have been revised or designed using the Highway-Vehicle-Object Simulation Model (HVOSM) output.
- A prioritization of the critical accident subcategories based on the size of the problem and the potential for alleviation of the problem.

- o Plans for countermeasure evaluation/validation to guide future research and implementation.

A multi-task effort is being conducted to meet these goals (see figure 1). In brief, this effort involves critically reviewing the literature dealing with the probable causes of minicar accidents along with possible solutions; carrying out extensive accident and highway data analyses to derive a prioritized list of accident categories of particular interest in the minicar accident problem; devising a listing of possible countermeasures and required additional research studies needed to meet these problems; conducting mathematical simulations using HVOSM for certain selected countermeasures and accident types; and finally, developing written narratives describing full-scale validation test plans of roadway-related countermeasures along with non-geometric (i.e., vehicle and/or driver) countermeasures. This report describes the methodologies used and the results of a preliminary analytical effort to meet these needs.

METHOD

In the literature review process, project staff obtained pertinent studies from a number of different sources. Initially, an on-line search was conducted of the DIALOG system, a computerized system containing over a hundred files including the TRB TRIS, the NTIS and the Engineering Index. Abstracts of potential studies were then reviewed and reports were obtained from the most promising sources. Our reviews of the bibliographies in certain studies often uncovered other reports. In addition, a significant number of studies were forwarded to the project staff by the FHWA contract technical monitor (COTR).

We were looking for literature related to minicar problems in three basic areas: (1) problems inherent to the vehicle itself (e.g., narrow track width, power-to-mass ratio, driver familiarity, etc.). (2) problems with the roadway (e.g., edge discontinuity, horizontal curve design, etc.), and (3) problems with the roadside (e.g., roadside hardware, slope design, etc.). A number of studies were obtained and preliminary reviews conducted. Finally, the list was

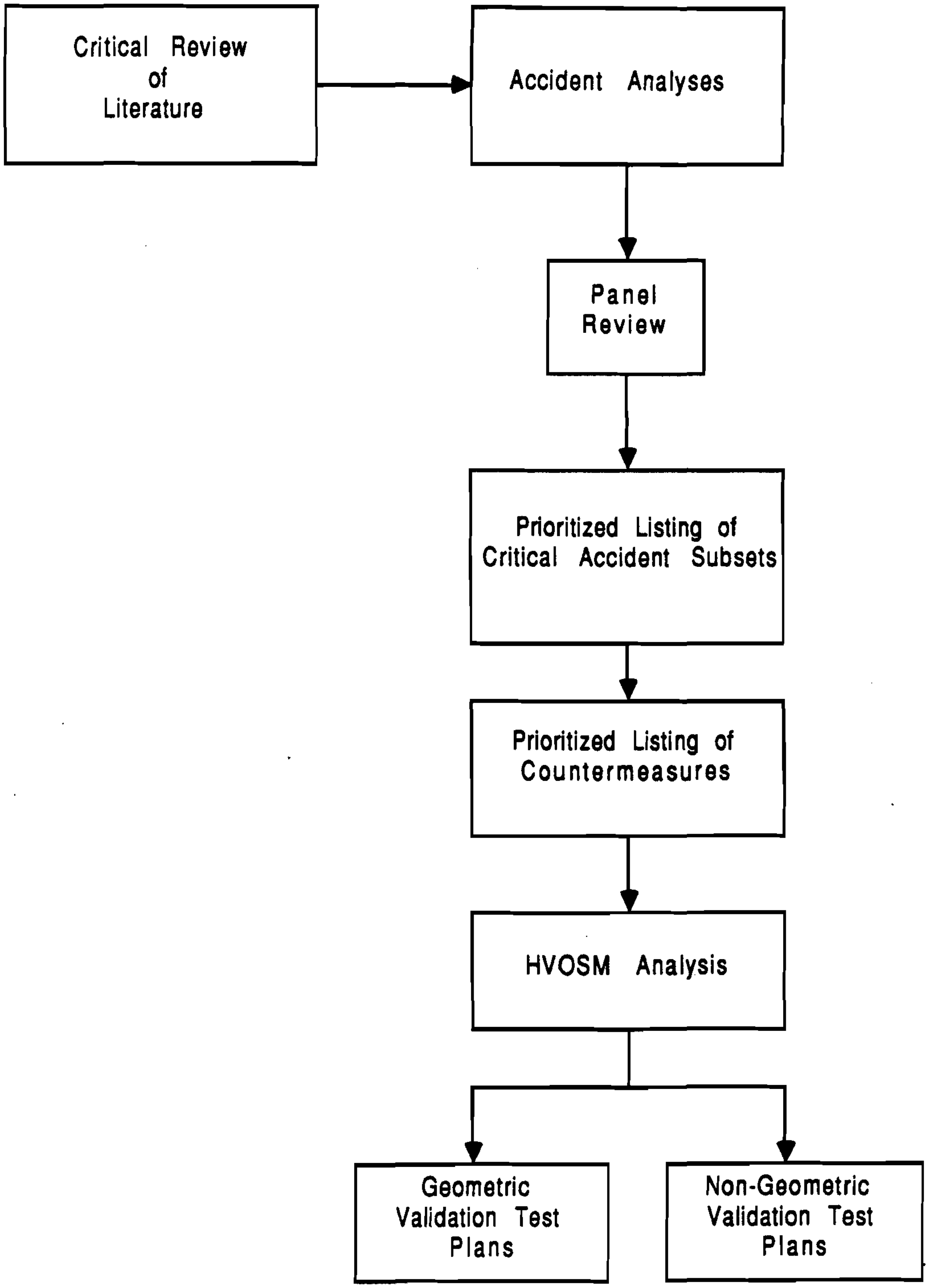

Figure 1. Overview of Project Activities

reduced to those studies that appeared to contain the most pertinent information. For each of these studies, a critical review was conducted (often with the same study being reviewed independently by more than one of the project staff). These critical reviews are included in appendix A of this report.

In order to insure consistency in the detailed reviews, a seven point checklist of questions related to scope, experimental method, analysis techniques, and reporting details was employed. (The checklist questions are also included in appendix A.) This critical review of issues helped define and clarify a number of potential minicar related problems. These problems and specific hypotheses were then further examined in the accident analysis tasks which followed.

In the Task B accident analysis efforts, project staff utilized data from the states of North Carolina, Washington and Texas. The North Carolina and Washington data were obtained and analyzed in-house at the Highway Safety Research Center while the Texas data were analyzed by the Texas Transportation Institute staff. While the details of the three data bases are presented in appendix B, it is noted that what made these data bases unique was (1) all three contained information which made it possible to assign a vehicle weight to each crash-involved vehicle, (2) all three could be computer-linked with roadway inventory and roadway characteristics files, and (3) they were geographically dispersed across the nation. These three States also provided a wide variety of terrain, road types, and road users and thus could potentially contain evidence on a wide range of issues.

(NOTE: At the time this project began, there was no universally accepted definition of "minicar". For the remainder of this study, the following definitions will be used:

Minicar	$\leq$ 2204 lb (1.0 Mg)
Mid-size	2205 to 3000 lb (1.0 to 1.4 Mg)
Large	> 3000 lb (1.4 Mg)

This minicar definition was specified in the project contract. The two remaining categories were defined such that approximately equal samples of crash data would exist. Since that time, a passenger car classification scheme has been proposed.[1])

The actual analysis of the data itself was a multistep, multirun process. In the majority of cases, the North Carolina data were initially analyzed and follow-up analyses were conducted on the Washington State data. To most efficiently use the analysis resources available in Texas, the Texas analyses then concerned issues that were either shown to be critical from the earlier analyses or issues which Texas alone could analyze.

While the specific data analyses are covered in more detail in appendix C, in general, the analyses involved first investigating the relationship between each of a host of accident variables (e.g., rollover, object struck, weather condition, etc.) and both minicar accident frequency and driver injury severity. Where potential problems (overrepresentation) were indicated, multivariate runs were carried out. It is important to note that this overrepresentation we were searching for could occur in terms of either accident frequency (e.g., where minicars roll over more often than larger vehicles) or accident severity (e.g., where minicar drivers or passengers are injured more often than occupants of larger cars). In the multivariate runs, the analysis attempted to control for as many of the "contaminating" variables as possible within sample size limitations. As is always the case with this type of data analysis, many preliminary results suggested potential minicar problems which, in turn, required further data runs.

In addition, a number of specific hypotheses were generated from the literature review, from project staff discussions, and from meetings with the COTR. These hypotheses were then tested using the available data resources to

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[1]The scheme was proposed in a 1984 study by the Passenger Car Classification Subcommittee of the TRB Traffic Records and Analysis Committee (A3B11), and reported in a committee report entitled, Recommended Definitions for Passenger Car Size Classification by Wheelbase and Weight (August, 1984). While the definitions stated above are based only on weight and the suggested definitions involve both weight and wheelbase, the "minicar" classifications appear to be similar, with the suggested upper limit being 2000 lb (0.91 Mg) and a wheelbase of under 95 in (2.41 m) in the proposed classification. The "mid-size" category used in this report includes the subcompact and compact categories in the proposed classification, and the "large" category includes the intermediate, full size, and largest cars.

see whether the potential minicar problems could be further refined. These multiple problem identification runs and hypothesis tests resulted in a series of issues which the project staff felt had been shown to be critical.

The initial goal of this early effort was to prioritize these critical accident subsets -- in the areas of both geometric and non-geometric problems. HSRC and FHWA agreed that it was important at this juncture to have an external review of these preliminary accident and literature findings to insure additional inputs into potential countermeasures, the ranking of the criticality of the accident subsets identified, and future research needs. To accomplish this, an external expert panel of six members was chosen, and arrangements were made for their participation in the project. This panel consisted of the following individuals:

William E. Fusetti -- Michael Baker Jr., Inc.
John C. Glennon -- Consultant
Lindsay I. Griffin, III -- Texas Transportation Institute
Ian S. Jones -- Insurance Institute for Highway Safety
Raymond R. McHenry -- McHenry Consultants
Geoffrey M. Nairn -- FHWA Region 7 Design Engineer, Retired

The panel was asked to:

- Review and critique our analysis results and suggest further analyses needed.
- Define specific countermeasures (roadway, vehicle and driver-related treatments) which may help overcome these problems, and estimate the potential level of benefit which will result from the implementation of each countermeasure.
- Specify which accident circumstances/treatments should be further refined using computer simulation (HVOSM runs).
- Help define a final priority listing of these critical minicar accident subclassifications.

A preliminary description of findings based on the review of the literature and accident analyses was distributed to each of the panel members. These panel members were then convened along with HSRC and Subcontractor project staff, the COTR and other FHWA staff for a one and one-half day meeting in Washington, D. C.

At the end of this workshop, each panel member was asked to propose countermeasures and/or additional research activities for each of a number of areas identified in the listing of results. These inputs were then combined into one master listing which was sent back to the review panel and project staff who were asked to provide a ranking of both the overall research areas and the individual countermeasures. Results of this ranking were then compared to the author's assessment of these and subsequent countermeasures.

Next, based on the literature review, accident analyses, and the panel input, the final listings of prioritized accident subclassifications, potential countermeasures and future research studies were developed. The ranking of critical accident areas, based both on the panel input and on the principal investigator's subjective weighting of the results of the accident analyses, indicated the following ordering (from highest to lowest) of critical issues:

Shoulder/pavement edge
Curbs/traffic islands
Sideslopes/embankments/ditch banks
Horizontal curvature
Culvert/drainage structures
Utility poles
Bridge piers
Longitudinal barriers

In addition, it is noted that the rollover issue seemed to overshadow most of the other issues, and that rollover is most definitely not only related to roadway parameters but also to vehicle parameters. Thus, an additional critical issue related to vehicle parameters would fit somewhere in the upper half of the above listing.

This information from the literature review, accident analyses and the rankings were then used to formulate limited additional accident analyses and analyses utilizing the HVOSM computer simulation model. Based on discussions between project staff, the HVOSM subcontractor, and the COTR, a decision was made to conduct simulation runs investigating (1) vehicle parameters associated with rollover, (2) sideslope related issues, and (3) traffic island related issues.

Finally, the results of all of the work described above were combined in order to define a listing of future research needs as related to the minicar.

While it is obvious that numerous research statements could be generated from the work that has been done, the funding constraints and the need to provide some priority to these research areas led to the decision to limit the preparation of research plans to eight basic areas. These included:

- Shoulder/sideslope treatments.
- Rural ditch bank designs.
- Pavement edge related research.
- Rural traffic islands.
- Rollover propensity as related to vehicle parameters.
- Horizontal curvature issues.
- Rollover propensity as related to rural catch basins, rural bridge piers, and median barrier faces.
- Utility pole-related research.

Each of the prepared plans includes a statement of the basic remaining research issues, background information related to the needed research and the proposed research methodology. The results of this effort, as well as all of those that preceded it, are presented in the following sections.

RESULTS

Based on the reviews of the literature and the preliminary computerized analysis, a series of minicar related accident problem areas were defined. These areas included:

- General minicar problems.
- Rollover potential.
- Weather-related issues.
- Horizontal and vertical curvature.
- Sideslope/embankment/ditch bank design.
- Guardrail/median barrier/bridge rail.

- o Culvert/drainage structures.
- o Utility and luminaire supports.
- o Curbs and traffic islands.
- o Bridge piers.

In each of these areas, a summary of findings from the literature will be followed by the results of the accident analyses which either support or disagree with the literature. (Many of the studies reviewed contained information on more than one of the above cited areas; thus, the same study will be cited a number of times in the following discussion.) Finally, some additional detail concerning other hypothesis testing efforts is presented.

General Minicar Problems

The literature review indicated that minicars experience numerous accident-related problems both in terms of accident frequency and accident severity. In terms of frequency-related problems, Kuroda, et al., in a study of minicar accident frequencies which controlled for a type of "induced exposure," found that small cars are more involved in single-vehicle accidents, particularly on rural roads and on wet or snowy highways.(5) In a study of small car accidents in Washington State in which registrations were used as the controlling variable, smaller cars experienced an increased number of accidents on wet, snowy or icy pavement, on both horizontal and vertical curves, and in rear-end accident configurations.(6)

Turning now to the question of crash severity, the same study from Washington indicated a higher proportion of fatal and injury accidents for drivers of minicars.(6) In like fashion, Evans examined car mass and fatality in three studies. In a carefully controlled study, he found that the lower the mass, the higher the percentage of drivers killed. More specifically, Evans concluded that the driver of a 2000-lb (0.91 Mg.) vehicle is 2.6 times as likely to be killed as the driver of a 4000-lb (1.81 Mg.) vehicle in similar crashes. With respect to seat belts, the belted driver of a 2000-lb (0.91 Mg) vehicle is a 2.3 times as likely to be killed as the belted driver of the heavier vehicle.[7,8,9]

In a similar vein, Martin noted that safety belts could make a tremendous difference in decreasing injury. However, he went on to note that the restrained small car occupant is only approximately as safe as the unrestrained occupant of the largest car.[2]

In contrast, Landwher found no difference in life expectancy resulting from a shift to small cars (a 0.2 year decrease in life expectancy compared to a 6.5 year decrease for smoking).[10] GAO, in their analysis of admittedly limited data, also found that small cars were not overrepresented in total accidents compared to the percent registered.[11] However, as presented, neither of these two studies utilized any controlling variables.

Joksch and Thoren conducted a similar analysis using vehicle registrations as the exposure measure, but in this case controlled for the most pertinent variables such as driver age, time of day, driver sex, etc., utilizing National Personal Transportation Survey information.[12] Using data from the Fatal Accident Reporting System (FARS) in developing accident rates, they found that in car-versus-car crashes there was a five-fold difference between the death rate for drivers of small cars and drivers of large cars. The death rate increased with decreasing weight and decreasing wheelbase. In the single-car accident case, there was a large difference in the smallest and largest cars. However, wheelbase rather than vehicle weight appeared to be the most important variable. More specifically, for a wheelbase of greater than 105 inches (2.67 m), they concluded that changes in vehicle weight resulted in no changes in fatality rate.

In terms of changes in the overall "safeness" of the smaller cars, it has been hypothesized that the small cars are getting safer as time progresses due to improvements in occupant packaging and vehicle handling. However, only one study was uncovered which attempted to look at this issue. GAO examined this hypothesis and noted that newer cars (1975-1980) had a lower rate of serious and fatal injuries for accidents involving poles and guardrails.[11] However, the New York State data used in that study failed to indicate any improvement in injury severity over time in single-vehicle accidents.

Rollover Accidents

Literature review. A major problem with minicars from both the literature reviews and subsequent data analyses and simulation runs involves the apparent overturn propensity of these vehicles. In terms of frequency of overturn, the Washington State study and the Kuroda et al. study both noted minicar overinvolvement in overturn accidents.[6,5] Viner, using FARS data, noted overturning as the most hazardous type of single-vehicle accident and as the leading cause of roadside fatalities.[13]

Griffin conducted an analysis of Texas single-vehicle accident data in which he controlled for highway class.[14] Using logistic regression techniques, he found that smaller cars are much more likely to roll over than larger cars on all highway classes. Compared to larger cars, he found that minicars were:

- Eight times more likely to overturn on county roads.
- 12 times more likely on limited access freeways.
- 37 times more likely on city streets.

Deleys and Parada found a rollover rate much higher for the lighter weight vehicles, with the increasing rollover propensity trend flattening out at approximately 3500 pounds (1.59 mg.).[15]

In terms of severity in these rollover accidents, these authors reported that rollovers produce more injuries than non-rollovers. They noted that 40 percent of the occupants in rollovers are ejected, and furthermore that ejection is the leading cause of serious injury in these rollover accidents with 50 to 70 percent of those killed in rollover crashes being ejected.[15] Viner, using unpublished data from Griffin, found that the fatal rate for rollovers is 1.9 times higher than for nonrollover crashes. More specifically, using data from the National Accident Sampling System (NASS), he found the fatal rate for rollover crashes to be 5.7 times higher than that for nonrollover accidents.[13]

On the other hand, again using the Griffin data, Viner noted no differences in driver injury by car size given a rollover has occurred. Thus, he noted that the increase in injury from rollovers may be the result of the increase in overturn rates for smaller cars rather than from an increase in injury per overturn. (As will be shown later, since it takes a more violent crash to result in a rollover for a larger car, it is perhaps not surprising that similar levels of serious injury occur.)

In terms of the possible causes of such rollovers, various hypotheses and analyses results have been put forward. As expected, most of these centered around the fact that smaller vehicles may "trip" more easily than larger vehicles do, or may roll over more abruptly when striking fixed objects. McGuigan and Bondy noted prior impacts with roadside objects in over one-half of the rollovers in the NASS and FARS data files, and found that given an impact with a fixed object, a rollover occurred in 59 percent of the cases.(16) Wright and Zador indicated that objects causing rollovers did not necessarily have to be large objects. They mentioned curbs, edge drop-offs, ditches, and soft soil as probable causes for these rollover crashes.(17) Griffin noted that the reasons for the high urban rollover rate found in his data may very well be due to the presence of small appurtenances such as curbs, drains, traffic islands, etc., which may not cause the larger vehicles to overturn but will trip the smaller vehicles.(14) Woods notes that 30 percent of the minicompact cars have clearance which is less than the old six-inch (152 mm) vehicle design standard, leading to possible vehicle snagging on roadside obstacles and overturning.(3)

In terms of vehicle attitude and maneuvers prior to overturns, Deleys and Parada note that 85.7 percent of rollover accidents involved locked wheels, and that 30.7 percent of all single-vehicle accidents involved "nontracking vehicles" (vehicles which are either skidding sideways with locked wheels or in some manner not under the steering control of the driver).(15) The authors noted that skidding sideways and "spinning out of control" are overrepresented in terms of rollover causative factors.

Finally, in terms of vehicle handling and design, in his book on vehicle characteristics, Jones indicated that the vehicle design and the three handling parameters of (1) "minimum velocity for overturning" (tripping in hard-steer maneuvers), (2) the ratio of vehicle height to track width, and (3) the ratio of height of the center of gravity to track width are all associated with increased proneness to roll over in rural areas. The strongest association is with the first of these parameters. None of these three were associated with increased proneness to rollover in urban areas.(18) It is interesting to note that Altsheular et al., in their study of the Future of the Automobile predicted that in the next 10 to 20 years three significant innovations would appear in new cars:

- o A good inexpensive passive occupant protection system for all positions.
- o Anti-lock brakes for most vehicles.
- o Anti-skid steering capabilities.

This latter capability might involve a computer-operated device to monitor wheel side slip and to change steering inputs as well as braking forces.(19)

Accident analysis results. Analysis of all three current data bases supported the above findings in the literature. The North Carolina data base indicated that minicars overturn more frequently than large cars in almost all situations. This held true for rural and urban locations on all highway types. In the rural areas, the minicar rollover percentages were lowest on the Interstates (28%) and increased progressively on the US (35%), NC (39%) and secondary routes (46%).

The Texas data indicated much the same thing. Here minicars had an elevated rollover propensity in single-vehicle accidents for all four highway types -- both urban and rural. The percent of single-vehicle accidents in Texas resulting in a rollover is shown in the table below for Interstate, U.S. and State, farm-to-market, and local roads. It is interesting to note that in the Texas data, the highest minicar rollover percentage in rural areas is on the Interstates, perhaps denoting differences in Interstate roadsides between North Carolina and Texas (i.e., that Texas Interstate roadsides may be forgiving enough at certain locations to "require" a rollover before a reportable crash is recorded).

Table 1. Rollover percentages by location and highway type (Texas data).

	Urban	Rural
Interstate	15.9%	50.5%
US/State	16.6%	39.1%
Farm to Market	19.7%	40.4%
Local (urban = city streets rural = county roads)	10.3%	32.4%

Using the North Carolina data, we further examined the issue of minicar rollover in crashes involving fixed objects (see table 2). Basically, when compared to larger vehicles, minicars have an elevated rollover rate in involvements with <u>any</u> fixed object as shown in the first column. Here, raw percentages of rollovers for each fixed object can be compared with each other and with the first column. Particularly troublesome here are rural traffic islands; catch basins on rural primary roadways; ditch banks on rural Interstates and other rural roadways; rural bridge piers; and median barrier faces in non-Interstate locations. (With respect to these median barrier faces, although the same pattern appeared on Interstate locations, the differences were not significant.)

To further highlight the fixed objects differentially affecting minicars, the ratio of minicar rollover percentage to large car rollover percentage was calculated for each fixed object (shown in parentheses). Here, the overrepresentation of minicar rollover appears to be related to collisions with rural bridge piers, non-Interstate median barrier faces, rural and urban traffic islands, and rural Interstate ditch banks.

In further examining the Texas data, TTI found that all three car sizes are involved in more rollovers on curves than on tangent sections. They further examined the data by comparing the percent of rollovers on curves with the percent on tangent sections for each of the car sizes and found that larger cars had the greatest percent increase in rollover for curve sections. This may result from the fact that minicars have an elevated "baseline" rate on the

Table 2. Percentage of rollovers in impacts involving selected fixed objects (NC data). (Ratio of mini-car percentage to big car percentage shown in parentheses.)

	All Objects (Compar)	Traffic Islands		Catch Basins (Rural Prim.)	Ditch Banks		Rural Grdrail Ends	Rural Bridge Piers	Median Barrier Face (US, NC, Sec.)
		Rural	Urban		Rural Int.	Other Rural			
Big	8.6%	7	3	18	9	18	7	0	4
Mid	17.5%	32	16	26	28	30	13	23	7
Mini	23.4%	33	18	30	36	38	18	33	28
Ratio	(2.7)	(4.7)	(6.0)	(1.7)	(4.0)	(2.1)	(2.6)	(NA)	(7.0)

tangent sections and thus their increase for curves is not as significant as that for large cars.

Finally, in terms of pavement condition, the Texas data indicated that the rollover rate on wet pavement is much lower than the rollover rate on dry pavement for all size vehicles. This may result from the fact that there is less tripping and more sliding on the wet pavement due to the lower coefficient of friction, or simply that single-vehicle accidents occur more often on wet pavement at lower speeds which would result in fewer rollovers for each of the car types.

In terms of injury severity in rollovers, we examined the North Carolina data in detail to look at serious injury given a rollover. As found by Viner, if one examines only rollover accidents, minicar drivers experience consistently lower (but not significantly lower) serious and fatal injury rates than do the drivers of larger cars.(13) Part of the issue, however, stems from the fact that (1) minicar drivers were shown to be belted more often than larger car drivers and (2) minicars get into rollovers at lower speeds.

An analysis of the North Carolina data was then conducted which controlled for speed and belt use. In all speed categories, the belted drivers experienced lower injury than their unbelted counterparts in the same size car. In the lower speed crashes, we found that unbelted minicar drivers in rollover crashes experience higher injury than their larger car counterparts, particularly drivers of age 16 to 20 and 26 to 35. (There were too few belted drivers to examine in this low-speed sample.) In moderate speed rollover crashes, belted and unbelted minicar drivers experienced slightly lower serious injury rates than drivers of larger vehicles. In the high speed crashes, the unbelted minicar drivers experienced slightly lower injury rates than did the unbelted large car drivers, and the belted minicar drivers experienced slightly higher injury rates than their large car counterparts. This latter finding of relatively higher injury for belted minicar occupants in high speed crashes may perhaps result from the fact that, while a high percentage (approximately 18 to 20 percent) of unbelted drivers in high speed crashes experience a serious injury regardless of car size (indicating little difference between sizes), the use of the restraint system may reduce rollover-related serious injuries more in the midsize cars and the large-size cars than in the minicars.

Again, the general finding may indeed be that, in total, minicars have problems with rollovers primarily because they roll over more frequently at lower speed. Their higher frequency of rollover-related injuries may be the result of this higher rollover frequency rather than the result of a heightened probability of injury per rollover.

Weather

Literature review. As noted earlier, the Washington State study indicated that smaller vehicles were experiencing a greater percentage of accidents on wet, snowy and icy roadways.(6) Kuroda, et al. noted similar findings where small cars were more likely to be involved in accidents on icy or snowy highway surfaces.(5) It is also interesting to note that Woods hypothesized that problems related to roadway friction (both stopping and turning) will be more critical as we move to lighter rear wheel drive vehicles since such vehicles are less stable on wet pavement than heavier vehicles.(3)

Accident analysis results. The Texas data was used to further examine the question of accidents on wet pavement. The analysis indicated that the midsize vehicles and minicars were overrepresented in single-vehicle accidents on wet pavement. (In the Washington and North Carolina data, minicars were also overrepresented in crashes on wet pavement.) This held true on urban, U.S. and State routes, urban local routes, and rural farm-to-market routes. Minicars were not overrepresented on urban or rural Interstate roadways.

Horizontal and Vertical Curvature

Literature review. The Washington study indicated that minicars were experiencing a higher accident rate per registered vehicle on horizontal and vertical curves when compared to rates of larger vehicles.(6) In terms of vertical curvature, in the TRB study, Woods and Ross examined the potential problems that might be found with the future 1200-lb (0.54 Mg.) vehicle (53 inches (1.35 m) high). They noted that driver eye height for the much smaller vehicle would only be some 0.6 inches (15 mm) lower than driver eye height in current subcompacts and thus would result in no additional problems in stopping sight distances. In terms of passing sight distance, they noted that perhaps the biggest problem would be with the acceleration capabilities of the vehicle rather than with the driver's ability to see for long distances.[4] Along the same lines, Farber examined the role of eye height in determining sight distances on hillcrests. Using engineering formulas used to specify clear sight distances, he found that stopping sight distance was not nearly as sensitive to eye height changes as to pavement friction, reaction time and speed.[20] It would appear from this literature that eye height changes resulting from switching to minicars may indeed not be a significant problem.

In terms of studies involving horizontal curvature, we did not find any study specific to minicars other than the general findings cited above in which minicars were overrepresented on horizontal and vertical curves. However, there were two studies which provided specific information on general curve-related problems for all size vehicles which perhaps gives insight into hypothesized minicar problems. In a large, multifaceted study involving accident analysis, computer simulation, field observations, and analytical work, Glennon et al. found that the probability of an accident is 75 percent greater on curves than on tangents.[21] Single-vehicle ran-off-road accidents accounted for 35 percent of all curve accidents and were more likely to be severe and to occur during poor environmental conditions. In general, the sharper and longer the curve and the narrower the shoulder and pavement width, the higher the probability of an accident. Interestingly, the major discriminant between high accident and low accident curves was roadside design (e.g., clear zone, sideslope), playing an even more prominent role than sharp curvature, narrow shoulders, or other factors.

Simulation runs indicated that spiral transitions could greatly reduce friction demands of critical curve transversals, and thus would be beneficial additions to curve geometry. Somewhat in contrast, field observations indicate that drivers position themselves in advance of the curve to affect a spiral transition whether a spiral is present or not.

Glennon, et al. concluded that driver behavior is most affected by sharpness of the curve rather than roadway width or other factors. Drivers almost always overshoot the curve radius and then have to overcorrect (producing a radius sharper than the curve) regardless of their approach speed. Finally, wider clearzones and milder slopes on the outside of the sharp curve may reduce skidding and rollovers, and thus the frequency and severity of accidents.

Zador, et al. examined the effect of grade and superelevation on curve-related accidents.[22] Using survey measurements, they found that superelevation was generally deficient for curves on grades when compared to similar curves on flat sections. They then compared crash locations on curves to non-crash curve locations and also found superelevation deficiencies at the crash sites, even when the analysis controlled for degree of curvature. This finding was valid regardless of state, road class, or grade.

Finally, in attempting to link some of these findings with car size, it might be noted that Jones had examined various vehicle handling and design parameters versus accident rates. He reported that vehicle weight, wheelbase, and load carried/total weight were significantly and positively related to single-vehicle accident rates. Power-to-weight ratio was inversely related, with more powerful vehicles being found in fewer single-vehicle accidents.[18] These findings might lead to an expected increase in single-vehicle curve accidents for the smaller-type vehicles we are studying.

Accident analysis results. Using the Texas data base, the proportion of total single-vehicle accidents involving minicars for a given highway class and location (i.e., rural or urban) can be compared to the proportion of single-vehicle curve-related accidents involving minicars at the same type location. If curvature is not important, these percentages should be virtually equal. As can be seen in Table 3 below, minicars experienced what looks like an overrepresentation of crashes on almost all curves except for rural Interstate and rural US/State Highways. The differences are statistically significant for the urban US/State Highways, and on the urban and rural farm-to-market and local roads, where one would expect to have poor horizontal alignment and geometric design.

TTI then attempted to examine single-vehicle accidents on curves as categorized by degree of curve, essentially taking the subclassifications above and further dividing them into curves of different degrees. Here, partially due to the smaller sample sizes, there was only one significant difference noted. Minicars experienced an overrepresentation on rural farm-to-market roadways, and this overrepresentation increased as degree of curve increased.

Table 3. Percentage of total single-vehicle and curve-related accidents involving minicars by location and highway type (Texas data).

	Urban			Rural		
	% SV Acc. Involving Minicars	% Curve-Accid. Involving Minicars	Ratio	% SV Acc. Involving Minicars	% Curve-Accid. Involving Minicars	Ratio
Interstate	14	17	1.21	18	18	1.00
US/State	11	14	1.27	12	12	1.00
Farm-to-market	11	12	1.09	12	14	1.17
Local	10	13	1.30	14	16	1.14

North Carolina data does not allow us to link accidents with horizontal curvature information, and thus the only information available has been taken off the accident report form (i.e., "curve" or "tangent"). Our initial analysis indicated that, in comparison to larger cars, minicars were overrepresented on highway curves, particularly on curves when the pavement is wet. In the Washington data, minicars were likewise overrepresented in crashes on highway curves.

It should be noted that neither the Texas data nor the North Carolina data could be controlled for exposure. That is to say, it may well be the case that the overrepresentation of crashes on curves is because minicars, in effect, travel more on curves than do the larger size cars. The only possible control for exposure was to categorize the roadways into urban/rural by highway type classes. The Washington State data, on the other hand, did allow us to conduct some analyses in which we attempted to control for exposure. Here we were able to develop a "quasi-exposure" method based on the hypothesis that single-vehicle accidents on a tangent section adjacent to the curve in question would reflect, to some extent, the composition of vehicles by car size approaching or departing from the curve in question. Thus, we matched adjacent tangent sections with the curves being examined. Here we examined curvature by both degree of curvature and by the presence or absence of spiral transitions. Two analyses were conducted -- one in which the accident locations were used as provided by the police and a second one which limited the data to cases where both the location from the characteristics file and the police-reported data agreed as to whether the accident occurred on a curve or a tangent.

An index was used to compare over- or underrepresentation of minicars on curves with and without spirals for various roadway classifications. The index for each vehicle size was the ratio of the curve accident rate (per unit length of curve) to the tangent accident rate (per unit length of tangent section adjacent to the curve). In general, this index was higher (reflecting an overrepresentation) for minicars on most roadway classifications for curves both with and without spirals. Regression analyses for each roadway system (principal arterials, minor arterials, major collectors and Interstates) showed the greatest overrepresentation for minicars when compared to big cars at the extremes -- curves with either very low or very high degree of curvature. (The models fit the data best for minor arterials and major collectors without spirals and for principal arterials with spirals.)

Sideslope/Embankment/Ditch Bank Design

Literature review. The Washington study indicated that mini cars experience a higher proportion of fatalities and injuries resulting from going over embankments.(6) Woods noted that present ditch bank standards are designed for 4,000 pound (1.81 mg.) vehicles. Crash test results have already indicated that some current designs are not suitable for small vehicles in that they cause these vehicles to overturn. He also noted that 3:1 sideslopes, which are used in many high-level designs, are very questionable with respect to minicars because of the instability of the smaller vehicle on uneven terrain.(3) Viner noted in his study of the FARS data that embankments are one of the six types of fixed objects causing the most fatalities for minicar drivers.(13)

As noted earlier, Glennon, et al. found hazardous roadside design (including steep sideslopes) to be the major discriminator between high accident and low accident curve locations. Their related simulation work indicated that vehicle skidding is very likely for even mild roadside slopes (6:1) and that on unstabilized roadside surfaces, there is a high expectation of rollover. In order to prevent such rollovers, encroachments on the outside of sharp curves require both greater clear zones and flatter slopes than encroachments on tangents. Finally, their economic analyses indicated that, while widening shoulders, rebuilding curves, and repaving may not be cost effective at most rural locations, for moderate traffic volumes, clearing roadsides and flattening slopes may indeed be cost effective and may be the most promising measure to look at.[21]

Deleys and Parada provided more detailed information concerning sideslopes in accidents.[15] As noted by Perchonok, et al., fill sections experience more rollovers than cut sections, and the rollover rate and the number of objects struck increase with the increase in slope steepness. Both rollover rate and object struck rate increase dramatically for sideslopes steeper than 3:1. For both ditch cuts and fills, there appears to be a critical increase in both rollover rate and object struck rate at the 4 to 5 foot (1.2 to 1.5 m) depth level.[23]

Accident analysis results. Analysis of the North Carolina data base indicated that, when compared to either midsize or larger vehicles, the minicars experience relatively higher proportions of single-vehicle accidents involving ditch banks or embankments for most highway types and both urban and rural locations.

The major overinvolvement in rural areas was on secondary roads, and in urban areas the overinvolvement pattern was consistent across all highway types. The major exceptions to this pattern were on all Interstate routes and on US-numbered routes in very rural areas where the proportions across car sizes were approximately equal (perhaps indicating effects of higher design standards).

As has been noted by other authors, this overrepresentation could result from the fact that the minicars are "missing" various fixed objects when they run off the road and are striking the final fixed object remaining -- the ditch bank. It may also be the case, however, that this overrepresentation is due to the fact that when on an embankment or in a ditch bank area, an errant minicar is less likely to be able to recover and avoid being involved in a reportable accident. (This hypothesis is supported to some extent by earlier reported findings of increased rollovers on ditch banks for almost all rural roadway types. Approximately 37 percent of minicar impacts with ditch banks resulted in rollover, a proportion that is 28 percent higher than the rollover rate for midsized cars and is the highest rate for any fixed object.)

In addition, the North Carolina data indicated that the minicars experienced a higher serious and fatal injury rate than larger cars when striking ditch banks and embankments in rural areas ($p < .15$) and suburban areas ($p < .10$). Here, the serious injury rates were significantly higher for crashes involving ditch banks on rural Interstates and urban streets. They were higher for other rural primary roadways and for urban Interstates, but the difference did not lead to statistical significance. As will be discussed in the later section concerning drainage structures, there appear to be additional problems with ditch bank design related to impacts with drainage pipes and culverts, particularly on rural non-Interstate roadways.

Guardrail/Median Barrier/Bridgerail

Literature review. The GAO analysis of New York and Michigan data indicated that, while smaller cars are not overrepresented in total vehicle accidents when compared to registrations, "smaller cars were generally overrepresented in single-vehicle accidents with guardrails and to a lesser degree median barriers."[11] In his discussion of current and potential problems with small cars, Woods noted that 80 percent of the minicompact (less than 2000 lb (0.91 Mg.)) vehicles have bumper midheights of less than 17 inches (432 mm). Because the lower edge of the typical W-beam is 17 1/16 inches (433 mm) above the ground, obvious mismatches will occur which could lead to potentially increased snagging and abrupt changes in velocity. Guardrail ends are cited as another potential problem since crash tests have indicated that both the breakaway cable terminal and the turndown end treatment do not appear to work adequately for many compact-sized vehicles. He also noted that there is evidence of an increase in rollovers of smaller vehicles when they strike concrete median barriers.[3]

In an attempt to develop a methodology to provide the missing linkage between G-forces measured in crash tests and resulting occupant injuries, Ivey combined information from a number of different sources.[24] He then used this methodology to predict differences in predicted injury for various crash angles and crash speeds into rigid, semirigid, and flexible barriers. He noted that there was an expected difference in the injuries in all cases between the small car and the large car and that the predicted probability of occupant injury ranged from a 130 percent increase for impacts into the rigid barrier to a 140 percent increase for impacts into the flexible barriers. Although the greatest difference between small and large cars occurs with the flexible barrier, it is noted that the injuries were down in the nonsevere range. His results would predict fairly large differences in serious injury for smaller vehicles particularly when striking rigid barriers. Viner noted the same potential problems with guard and bridge rails involving snagging of smaller vehicles because of misfit with the barrier, the deformation of the guardrails being struck by small vehicles, and the increased rollover propensity of the smaller vehicle when striking these railings.(13) Many of these potential problems were based on the results of crash tests which had shown that front-wheel snagging on the guardpost is a definite problem with the smaller minivehicles.

Viner then began to examine the overturn performance of the more rigid guardrails and concrete median barriers. Here he cited a number of studies showing that the percent of vehicles overturning is higher for specific designs of concrete median barriers and that the rollover rate was even higher for small vehicles. Using unpublished California data and comparing the number of registered vehicles categorized by vehicle weight in accidents in which rollovers occurred after collisions with New Jersey shaped concrete median barriers, Viner documented this increased rollover propensity for smaller vehicles. He found that while 24 percent of the registered passenger vehicles weighed less than 2250 pounds (1.02 Mg.), 51 percent of the vehicles that overturned weighed less than this amount. It appears that the overturning problem is significant for vehicles that weigh up to approximately 2700 pounds (1.22 Mg.).(13)

Griffin found somewhat different results when looking at accident data. In his analysis of guardrail accidents, Griffin found increased minor and moderate injury for the smaller cars but no increase in serious or fatal injury. Again, as he noted, this is not to indicate that guardrails are not a problem but simply that the serious and fatal injury rates do not differ by car size. Indeed, guardrails produce the third highest serious injury rate of any of the fixed objects, ranking behind culverts and bridge rails.[25]

With respect to bridge railings, Buth provided information on a series of crash tests involving small cars and a variety of existing bridge rails.[26] Testing indicated that all of the railings properly contained and redirected the small cars. However, several of the railings frequently pocketed and/or snagged the smaller vehicles resulting in fairly high deceleration forces to the vehicle. Virtually all of the instances where occupant compartment integrity was not maintained involved the smaller vehicles. In addition, a major damage-causing component was the protruding curbs found in some designs.

These findings of potential problems with bridge rails are in contrast with the one accident-based study conducted.[25] Here Griffin noted no difference in any level of injury between smaller vehicles and larger vehicles striking bridge rails. Again bridge rails are the second leading cause of serious injury among fixed objects, however, there appears to be no difference in the injury experienced by drivers of large cars versus those of small cars.

Accident analysis results. None of the three data sets indicated an overrepresentation of minicar accidents with longitudinal barriers in terms of accident frequency. As noted earlier, the North Carolina data indicated a higher rollover rate for median barrier faces on all roadway classes except Interstates (with too few data on the Interstates to allow such an analysis). Indeed, the Texas data indicated an underrepresentation of minicar guardrail crashes on rural Interstates. However, this could be some indication of differences in exposure with minicars travelling less on the rural Interstates than their proportion of the total population.

One significant finding with respect to longitudinal barriers involves guardrail terminals. Here the North Carolina data allowed us to analyze crashes into "guardrail ends." We found a significantly higher A+K injury rate for minicars. This significantly higher injury rate was consistent over all highway classes in urban and rural areas, but was strongest in rural areas. The rate was most elevated on rural Interstate roadways (although the difference was non-significant, perhaps due to sample size).

Culverts/Drainage Structures

Literature review. In his discussion of smaller cars and highway safety issues, Ivey hypothesizes problems with drainage structures including both open-end culverts on the roadways and longitudinal culverts under driveways. It appears that the driveway culvert problem might be solvable by careful design, but he notes that the terrain surrounding these drainage structures may well present large problems to small cars which are less stable on uneven terrain.(1) Viner, in his analysis of the FARS data, also notes that culverts have a potential problem. Again, culverts are one of the six fixed objects that produce the most fatalities of all types of fixed objects.(13)

In his analysis of Texas accidents, Griffin found no differences between injury to drivers of large and small vehicles involved in culvert accidents. Griffin notes that culverts are perhaps the stiffest of objects struck by the front of the vehicle and produce the highest proportion of injury to the driver. However, there appears to be no differential effects between car sizes.(25)

Accident analysis results. Analysis of North Carolina data indicated problems with the category of fixed objects designated as "catch basins or culverts." Here we found minicars experiencing a slightly higher frequency of accidents with these fixed objects both on the shoulder and in the median. The major overinvolvement in rural areas was found on the NC (primary) routes, whereas in urban areas it was found on Interstates, US (primary) routes, secondary roads, and city streets. In addition, as might be expected from the literature findings, we found a significantly higher serious and fatal injury rate for minicars -- mainly in rural areas. When we examined the data by roadway class, we found that the elevated injury rate was present on primary rural (U.S. and State) roadways but was not present on Interstates.

(It is noted here that the use of this combined code makes it difficult to determine whether the object being struck is a culvert or a true drop-inlet type catch basin. Based on conversations with the N. C. State Highway Patrol, our assumption at this point is that the shoulder-related involvements on rural non-Interstate roadways are primarily impacts with parallel culverts under driveway entrances, while median involvements might primarily be with catch basins of some type.)

Utility and Luminaire Poles

Literature review. In the discussion of accidents in Washington State, the authors noted that small cars experience a high percentage of fatalities and injuries resulting from striking poles.(6) In his analysis of FARS data, Viner indicates that utility poles are the most frequent man-made object struck. He predicts that the shift to smaller vehicles will increase the fatal and serious injury utility pole crashes by approximately 50 percent within the next five years.(13)

Griffin, in his review of Texas accident data, supports these indications of high severity. His data indicates that small car drivers experience significantly higher injury rates than large car drivers when striking both utility poles and luminaire supports. The differences in injury are found at all three injury levels (minor or greater, moderate or greater, and serious or greater). He concludes that the driver of a mini car striking a utility pole is approximately 2.4 times more likely to experience a serious or fatal injury than is the driver of a 3500 pound (1.59 Mg.) car.(25)

Accident analysis results. Analysis of N.C. data indicated that utility poles are indeed the man-made fixed object most often struck (with the exception of ditch banks) for all three car sizes. In minicar single-vehicle crashes involving fixed objects, utility poles are involved 10.7 percent of the time.

While minicars (and midsized cars) overturn more often than large cars in such involvements, the rollover percentages are quite low when compared to other fixed objects (4.9%, 4.8%, and 2.7%, respectively). This lower rollover rate does not, however, result in fewer injuries. As indicated above, the Texas accident data had shown earlier that small car drivers experience significantly higher injury rates in involvements with utility poles and luminaire supports. Analysis of the North Carolina data supported these findings. Here, we found a significantly higher serious and fatal injury rate for the minicar utility pole involvements for both urban and rural locations.

Curbs/Traffic Islands

Literature review. Woods notes that 30 percent of the mini-compacts have less then a 6 in (152 mm) clearance, the height of some curbs and islands.(3) Indeed Griffin's analysis of accident data indicates that drivers of small vehicles experience elevated minor and moderate (but not serious or fatal) injury rates when striking curbs. He further notes that his analysis of accidents involving curbs indicated that the average vehicle striking the curb was much lighter than the average vehicle striking the other appurtenances. This could result from either heavier vehicles jumping the curb and hitting a pole or other appurtenance behind the curb and thus being reported as a "pole accident" rather than a curb accident, or the heavier vehicle being able to recover better from an impact with a curb than a lighter, less stable vehicle (and, thus, not being in a reportable accident).(25) (It may also be the case that lighter vehicles are driven more in urban areas where more curbs exist.) It should also be noted that, of the fixed objects analyzed by Griffin, curbs produce the lowest percentage of serious or fatal injury.

Accident analysis results. Examination of the North Carolina data indicated no frequency differences in terms of minicar overinvolvement for curbs. However, we did find there was an overrepresentation of minicars in terms of the percent striking traffic islands. This overinvolvement was noted to some extent on all classes of rural roads and was significant on NC and secondary routes. In urban areas, the pattern was consistent and significant on all classes of roadways except NC routes, and was present but not significant there. In the Texas data, on the other hand, the analysis indicated that minicars are overrepresented in single-vehicle accidents involving curbs on urban Interstate, urban U.S. and State roads, and urban local roads. It is noted that impacts with rural traffic islands resulted in rollover 33 percent of the time for minicars, 32 percent of the time for midsized cars, and only 7 percent for large cars. This minicar rollover proportion is second only to ditch banks among fixed objects. The North Carolina data indicated no differences in accident severity across car size for traffic island or the curb crashes.

Bridge Piers

Accident analysis results. In analyzing minicar accidents with bridge piers, neither the North Carolina nor the Texas data indicated an overrepresentation in terms of accident frequency. Indeed the Texas data indicated an underrepresentation in terms of minicar frequency on rural Interstates, again perhaps indicating differences in exposure. While the North Carolina data indicated no increased frequencies for minicars, we did, however, find a significantly higher serious and fatal injury rate for the minicar occupants. This was true in both rural and urban areas.

Vehicle-Specific Issues

The problems noted above in both the literature and accident analyses obviously all have a vehicle, a driver and a roadway component in terms of causative factors. Thus far, most of the analyses have been oriented toward looking at the roadway side of the issue. Throughout this discussion, however, it has been apparent that one of the major causes in these accidents is the inherent lesser degree of stability of the minicar as compared to larger vehicles. This was supported even further in the discussions of the Review Panel where vehicle specialists were present.

Some limited additional computer runs were made to further examine these vehicle-specific issues. The major three issues in question here are (1) the possible effects of the yaw instability of minicars, (2) the possible contribution of front-wheel drive as a factor related to the general instability and/or higher rollover propensity of minicars, and (3) the question of whether the origin of the minicar (Japanese, European, or U. S.) affects its rollover potential or crashworthiness.

The first question relates to whether or not any indication of increased yaw instability of minicars as a cause of the increased rollover rates could be found in the accident data. Increased yaw instability would result in the vehicle leaving the road in a nontracking ("non-head-on") condition, and thus might result in fewer frontal and more side impacts in off-road crashes. There is no information on vehicle attitude in the police data files we were working with. Thus, we were forced to look at this question based on the point of impact for vehicles leaving the roadway and striking a fixed object, and comparing these points of impact for various size vehicles. These analyses were first conducted separately for each of the various types of objects and then were conducted with all objects combined.

The computer runs indicated that in rural areas, the minicars experienced a lower proportion of frontal impacts and a higher proportion of right side impacts than did the midsized and larger vehicles when they struck bridge piers and catch basins. In mixed (suburban) areas and in urban areas, the runs indicated that in the accidents with traffic islands and curbs, the minicars experienced substantially lower percentages of frontal impacts and substantially higher percentages of right and left side impacts.

In the final run, the object categories were collapsed to look at the overall point-of-impact trends when any fixed object was struck. Here the findings indicated slightly lower frontal proportions and slightly higher left and right side impact proportions in rural areas. No trends were found in the suburban or urban areas.

The second question involves the potentially higher rollover rates for front-wheel-drive (FWD) minicars as compared to rear-wheel-drive (RWD) mini's and to front-wheel and rear-wheel-drive midsized cars. Here, preliminary runs indicated a FWD effect. To further examine this effect, additional analyses of single-vehicle accidents were conducted in which rollover percentages were calculated for rural, mixed, and urban categories for different types of highways and different speed ranges (with speed being defined as speed prior to accident as estimated by an investigating officer). These analyses indicated that the increased rollover rate for FWD minicars primarily occurs in rural areas on all categories of roadways except Interstates. While the midsized FWD vehicles experience either the same or lower rollover rates than do their RWD companions, the FWD minicars experience higher rollover rates in low speed crashes on secondary roads and in medium and higher speed crashes on both major highways and secondary roads. Findings for the suburban and urban areas were mixed with no real pattern emerging. This same analysis was attempted for non-collision rollovers occurring in the roadway itself to see if differences existed, but sample sizes were found to be inadequate for analysis.

Finally, the question of front-wheel-drive instability was examined further by looking at the condition of the pavement in accidents in rural areas. The question here was whether or not the FWD ran-off-road issue might result from adverse weather and pavement conditions. This analysis was again carried out within three highway types (Interstate, US and NC, and other roadways) and within three speed ranges. When the midsized front-wheel and rear-wheel drive vehicles are compared, it is consistently found that the FWD vehicles have a lower proportion of wet, snowy and icy pavement accidents than their RWD companions and therefore, a higher proportion of dry pavement accidents. The only difference found with the minicar FWD vehicles was on US and NC roads at medium speeds where the FWD minicars experienced a slightly higher proportion of wet, snowy, and icy weather crashes. However, there were no differences in any of the other speed or roadway categories.

The data were then combined into larger categories by first controlling for speed and then for highway class in separate computer runs. Here the findings again indicated absolutely no differential patterns between FWD mini's and FWD midsize cars. Indeed the only hint of a pattern was that the FWD minicars may be experiencing fewer wet, snowy and icy weather accidents than the RWD mini's. Thus it would appear that any elevated ran-off-road or overturn rate related to front-wheel-drive does not appear to be a function of adverse pavement conditions.

The third vehicle-specific question involved whether or not the accident data provided any evidence of a difference in any rollover rate or rollover crashworthiness according to vehicle origin. Three origins were used -- U.S., Japanese, and European. Data on origin was extracted from the Automotive News Market Data Book. U.S.-marketed cars manufactured in a foreign country were coded according to the country of manufacturer. First, in an analysis of the 1981-1983 single-vehicle North Carolina accidents, the proportion of 1971 and later model vehicles overturning was compared by car size and origin within each of eight roadway types (rural and urban Interstates, US and NC highways, and secondary roads and city streets). The results are shown in table 4.

Of interest is the fact that in rural areas, the minicars and midsized cars of U.S. origin are consistently lower than their foreign counterparts in terms of proportion overturning. Not all the differences are statistically significant but some are quite large. The pattern also appears to hold in urban crashes where the proportion overturning is not as high.

Table 4. Proportion of 1971 and later vehicles which roll over in single vehicle accidents by origin of car, highway type, and location (urban/rural).

Origin	Urban I	Urban US	Urban NC	Urban Sec.	Rural I	Rural US	Rural NC	Rural City Street
Minicars								
U.S.	0.18	0.32	0.32	0.42	0.13*	0.13	0.20*	0.13
Japanese	0.32	0.36	0.42	0.46	0.24*	0.19	0.27	0.16
European	0.30	0.35	0.41	0.49	0.16*	0.27	0.19*	0.16
MidSize								
US	0.17	0.25	0.28	0.33	0.13	0.16	0.14	0.09
Japanese	0.20	0.28	0.36	0.41	0.26*	0.19	0.19	0.11
European	0.45*	0.32	0.38	0.43	0.21*	0.27*	0.38*	0.11

*Sample size < 50.

Additional analyses were conducted to see if this pattern was simply the result of comparing newer U.S. minicars to older foreign designs. First, a table of car size and origin by model was prepared to see if obvious biases existed. None did. Sizable samples of US, Japanese and European cars were found in almost all model years since 1971. However, to control for this potential bias, the data were further screened to only include 1978 and later model cars and the runs were repeated. Table 5 below shows the results of this analysis.

Here, because of the additional data screen, the sample sizes are understandably smaller. However, on the rural roadways, the same pattern seems evident with the US minicars and midsized cars experiencing a consistently lower rollover proportion than their foreign counterparts. The two exceptions to this pattern are with the minicars on NC routes and with the midsize cars on

Table 5. Proportion of 1978 and later vehicles which roll over in single vehicle accidents by origin of car, highway type, and location (urban/rural).

	Urban				Rural			
Origin	I	US	NC	Sec.	I	US	NC	City Street
Minicars								
U.S.	0.19	0.31	0.33	0.41	0.18*	0.09*	0.29*	0.15
Japanese	0.27	0.37	0.38	0.42	0.19*	0.19	0.23	0.14
European	0.24*	0.38	0.32	0.48	0.20*	0.33*	0.08*	0.16
MidSize								
US	0.14	0.24	0.27	0.32	0.12	0.15	0.14	0.09
Japanese	0.12	0.28	0.31	0.42	0.32*	0.19	0.13*	0.07
European	0.41*	0.29*	0.37*	0.39	--	0.25*	--	0.11

*Sample size < 50.

Interstates. The pattern is not as consistent in the urban areas, where small sample sizes are more prevalent.

What cannot be answered from these runs is the question concerning the cause of these differences. They may well result from weight differences, wheelbase differences, or even driver-related differences not yet controlled for. The additional runs required to conduct detailed analyses of these factors and to further define the specific causes of these differences are not possible within the time and budget constraints of the current phase.

In the second analysis, we attempted to examine whether or not the vehicle origin resulted in a difference in serious or fatal (A+K) driver injury given a rollover. Here, the results were classified by speed prior to impact and driver belt use, and the proportions of serious or fatal driver injuries were compared by car size and origin. The numerous tables produced indicated little difference between the U.S., Japanese, and European-manufactured cars in terms of injury given that a rollover had occurred for either set of model years. The only hint of a difference where sufficient data existed was in the higher speed crashes (50 mi/h (80 km/h) and higher) where unbelted drivers in Japanese minicars experienced a lower proportion of serious or fatal injury than did the drivers of US or European cars (15%, 18%, and 23%, respectively).

Additional Hypotheses Tested

As noted in the earlier overview of Project Methodology, in addition to problem identification analyses, a number of specific hypotheses were generated from the literature review, discussions among project staff and with the COTR, and discussions with the expert panel. Results of some of the testing done specific to many of these hypotheses (e.g., rollover propensity after striking roadside hardware, front-wheel-drive, origin of manufacturer) have already been covered.

In addition, we attempted to examine the accident data in a number of other hypotheses including the following:

1. Are there differential problems between new small and large vehicles due to driver non-familiarity (i.e., differences in handling, sight distance, etc.). Does front-wheel-drive interact with this?

2. Are there differential problems between small and large cars for drivers who are unfamiliar with the roadway they are on?

3. Are small cars driven more "aggressively"?

4. Are there accident-related differences between mini- and larger cars due to vehicle conspicuity (car color, light configuration or use, or other factors?

5. If small car driver eye height is lower, does this affect eye contact with drivers of higher vehicles (vans, trucks) resulting in higher incidence of crashes?

6. Does the lower/smaller profile of the small car make it more difficult for other drivers to correctly judge gaps or closing speeds? Like the motorcycle, is the small car just not "seen" in certain situations?

7. Are there passing, merging, uphill speed, or other problems related to lower power-to-weight ratios of some small cars?

In the first five cases, the accident data did not provide sufficient detail for meaningful analyses. However, in the latter two cases, an attempt was made to test these hypotheses. It is noted at this point that this testing could not be done in a straightforward manner since, for example, no information exists on the accident report form concerning whether or not the driver misjudged a gap or did not have enough power to successfully cross an intersection. Thus, the testing had to be done in a less direct way by examining related information that should reflect any such minicar problems.

For example, with respect to the question of the smaller profile of the minicar making it more difficult for other drivers to correctly judge gaps or closing speeds, we attempted to analyze gap judgement in two different situations. First, we assumed that the lack of the ability to judge closing speeds or proper gaps might cause the minicar to be struck more often by a vehicle involved in a passing maneuver. That is to say, if the larger vehicle did not judge the gap correctly, it might pull out and attempt to pass and strike an oncoming minicar head-on in the opposing lane more often than would be expected. We queried the North Carolina accident file for passing accidents, but unfortunately found too few motor vehicle head-on passing accidents in three years of data to analyze. Obviously, it was not possible to categorize this small sample by vehicle size or to draw any conclusions.

Our second attempt at analyzing gap judgement problems involved analyzing stop-controlled intersection-related crashes. Here, we attempted to examine whether the small car was the striking vehicle more often than one would expect, i.e., to try to determine if other vehicles pulled out in front of minicars more often than they pulled out in front of larger vehicles. We defined a vehicle "pulling out" as the one with the stop sign-related violation as cited by the investigating officer. We then looked to see if the small cars represented more of the "non-pulling out" vehicles than their percent in the population of two-vehicle accidents (i.e., angle, left-turn-across-traffic and right-turn-across-traffic crashes).

The data indicated very little evidence of a gap judgement problem. In the rural areas, the percent "striking" vehicles which were minicars was approximately the same as the percent of minicars in the two-car accident population. The proportion of "striking" minicars was only very slightly elevated in angle hits. The difference was not even marginally statistically significant. In urban areas, there appeared perhaps to be a hint of a gap judgement problem in the left-turn-across-traffic and angle accidents but the difference from the expected was very small. Thus, in this data we can find no evidence of such a problem.

Next we attempted to examine the question of whether the power-to-weight ratio of the minicars resulted in accident-related problems. We hypothesized that if minicars in general were underpowered enough to cause a problem, the problem might be apparent in the following three situations: (1) passing maneuvers where the minicar would fail to complete the pass and thus strike an opposing vehicle, (2) rear-end collisions on upgrades where the minicar might be traveling slower than the remaining traffic, and (3) intersection collisions where a minicar might enter an intersection from a stop-controlled roadway and fail to clear the intersection or turn either right or left and then be struck in the rear because of its limited acceleration ability.

Unfortunately, as noted above, there were too few passing accidents in the entire three-year file to allow us to examine passing problems by car size. This not only means that there is probably little effect due to car size but also that, even if the problem exists, it may not be of a magnitude that would cause concern.

In terms of accidents on grades, we looked at the proportion of the crashes on grades in which the minicar was struck in the rear and compared this to (1) the rear-end proportion for minicars on flat segments and (2) the proportion of minicars in all two-vehicle nonintersection accidents. Here we find that minicars are struck less often in the rear than might be expected _ just the opposite effect of what one would expect if the hypothesis was true.

In terms of the two intersection analyses, we first discovered that, because of the way the report form was designed, it was not possible to determine whether a vehicle was struck in the rear after pulling out and turning versus being struck in the rear in the intersection proper, or being struck prior to reaching the intersection. Thus, the only analysis open to us was to examine the proportion of minicars cited at stop-controlled intersections for running the stop sign that were involved in angle and cross traffic turning accidents. Again we defined the minicar as being the stop-controlled "pulling out" vehicle by looking at the vehicle that was cited for a stop-sign violation. This analysis showed no difference in the proportion of minicars being struck versus the proportion that would be expected based on their number in the accident population.

It is noted that while these failures to find significant differences in all of these analyses may indeed reflect that the hypotheses have no basis in fact, they may also reflect the fact that the accident data does not allow us to look at such sensitive issues in a direct fashion given the information that is provided on the accident report forms themselves.

Hard-Copy Accident Analysis

The final set of accident analyses was conducted to define a minicar and big car "accident typology", and to gain more insight into the nature of minicar accidents than the computerized data would allow. A detailed analysis of a random sample of 200 hard-copy accident reports from the 1981, 1982 and 1983 North Carolina files was performed. Half of the sample was single-vehicle accidents and half involved more than one vehicle. Half of each of these subsets involved minicars and half involved big cars. All of the accidents were from rural areas and all occurred at nonintersection locations. The analysis involved reading the accident narrative as well as the coded descriptive information to identify the causal patterns or precipitating and predisposing factors most frequently associated with minicar accidents and with big car accidents.

Single-vehicle accidents. The first analysis examined the subset of single-vehicle accidents. As is shown in table 6, minicars are more likely to run off the roadway (90 percent) than are big cars (77 percent) when they are involved in single-vehicle accidents. Single-vehicle accidents that did not involve running off the roadway included collisions with deer, cows and pigs as well as domestic squabbles, felony situations and passengers falling from the vehicle. When minicars do run off the roadway, they are no more likely (57 percent) to do so in curves than are big cars (55 percent). However, when minicars do run off the roadway on a tangent, they are far more likely to roll over (53 percent) than are big cars (11 percent). When big cars run off the roadway on curves they are, however, slightly more likely to roll over (59 percent) than are minicars (48 percent). This slight increase in tendency to roll over on curves does not appear to be related to alcohol involvement in the

Table 6. Categorization of single vehicle accidents by car size, curvature, rollover and alcohol involvement based on hard-copy analysis.

	BIG CARS					MINICARS				
Ran-off-roadway	Yes 77%				No 23%	Yes 90%				No 10%
Curve	Yes 55%		No 45%			Yes 57%		No 43%		
Rollover	Yes 59%	No 41%	Yes 11%	No 89%		Yes 48%	No 52%	Yes 53%	No 47%	
DUI - Yes	23%	22%	0%	13%		36%	21%	10%	10%	
Ran-off-roadway	Yes 77%				No 23%	Yes 90%				No 10%
Curve	Yes 38%		No 62%			Yes 51%		No 49%		
Rollover	Yes 87%	No 13%	Yes 36%	No 64%		Yes 58%	No 42%	Yes 57%	No 43%	
DUI - Yes	23%	0%	22%	13%		36%	10%	23%	10%	

accidents involving big cars. However, in the accidents involving minicars, the highest reported alcohol involvement (36 percent) was found in those occurring on curves and involving rollovers.

Now let us further examine the rollover accidents. The bottom of Table 6 shows that big cars are less likely to roll over (38 percent) than minicars (51 percent) when they run off the roadway on curves and tangent sections combined. However, when big cars do run off the road and roll over, they are far more likely to do so on curves (87 percent) than are minicars (58 percent). Minicars are far more likely to run off the roadway and overturn on straight tangent sections, again perhaps indicating the propensity of minicars to rollover even in more benign situations while the large car requires more severe crash circumstances (the curve) to rollover.

Nonrollover minicar accidents, on the other hand, are more likely to occur on curves (57 percent) than are nonrollover big car accidents (36 percent). Alcohol involvement appears to be higher for accidents occurring on curves for both big cars and minicars regardless of whether or not a rollover occurred.

A more detailed analysis of single-vehicle, ran-off-the-roadway accidents was attempted. The collision dynamics were examined to see if minicars and big cars differ. Big cars and minicars appear to run off the right side and the left side of the roadway with comparable frequency. The major differences involved the sequence in which the vehicle ran off the roadway, back on the roadway, and then overturned. Forty percent of the minicar rollovers on straight roads and 14 percent of the minicar rollovers on curves involved this pattern. None of the big car in the sample ran off the roadway, back on the roadway and then overturned. Why this occurs is not apparent from examining the driver condition or the roadway condition factors listed in the accident reports. In only one accident narrative was the presence of a drop-off or low shoulder mentioned.

Multi-vehicle accidents. The second hard-copy analysis examined the multi-vehicle accidents that were selected. The sample analyzed included only those accidents in which one minicar and one large car were involved (e.g., no accidents involving two minicars striking each other were included). Five causal accident types or accident scenarios were identified. These included:

- Rear-end -- both vehicles traveling in the same direction and one strikes the rear of the other (39% of sample).

- Head-on -- vehicles traveling in the opposite direction and they collide (23% of sample).

- Sideswipe -- both vehicles traveling in the same direction and they contact one another on their sides (14%).

- Angle -- vehicles traveling in directions perpendicular to one another. The front of one vehicle strikes the side of the other vehicle (7%).

- Weird -- an unusual situation involving loose wheels, mechanical defects, domestic problems, "hot pursuit" and other situations not related to vehicle size (17%).

For each multi-vehicle accident, the hard copy was reviewed to see which vehicle (mini or big) was the striking vehicle and which vehicle was the struck vehicle. Because of the way this sample was drawn, if there was no car-size effect, one would expect the minicar (and the large car) to be the striking vehicle 50 percent of the time. Again, these accidents occurred at nonintersection locations.

Thirty-nine percent of the multivehicle accidents were of the "rear-end" type. Since 50 percent involved minicars striking big cars and 50 percent involved big cars striking minicars, there does not appear to be any interaction involving vehicle size for rear end accidents. Angle accidents are far less common (7%) but also show no interaction involving vehicle size. Sideswipe accidents accounted for 14 percent of the multi-vehicle accidents. Although 63 percent of these accidents involved a mini-car striking a big car, no causal patterns were apparent.

Head-on accidents, on the other hand, do appear to show an interaction based on vehicle size. The minicar struck the big car in 62 percent of the head-on accidents. Here the definition of "striking" versus "struck" was made from the full narrative, the diagram, and other indicators such as vehicle being left of center, etc. Seventy-five percent of the head-on crashes where the minicar struck the big car occurred on a curve. Only 17 percent of the accidents where the big car struck the minicar head-on occurred on a curve.

The overinvolvement of minicars on curves is apparently not due to alcohol involvement, weather conditions or lighting conditions. Posted speed limits and the investigating officers estimate of preinvolvement speeds were also examined. Virtually all of the accidents (94 percent) occurred on roadways with a 55 mi/h (89 km/h) posted speed limit. The officers estimate of pre-involvement speed for both the striking vehicle and the struck vehicle does not vary according to vehicle size. Excessive speed was cited as a factor in only one accident when a minicar struck a big car.

Only one difference is readily apparent when comparing head-on accidents by vehicle struck. In 38 percent of the cases where a minicar struck a big car head-on, the minicar had first run off the roadway to the right before coming back on the roadway and crossing left-of-center into the on-coming vehicle. This did not happen in any of the accidents where a big car crossed left-of-center and struck a minicar. It would appear that minicars are often going out of control on curves and are striking on-coming vehicles that "just happen" to be coming into the curve.

Curve-related crashes. The earlier Glennon analysis had defined the "path-overshoot" phenomenon in which drivers often put themselves in a position of having to make a greater steering input than is necessary for the sharpness of the curve being driven. Since minicars may be more responsive than larger cars to steering inputs (and thus may be overcorrected more often), it is possible that the above-noted minicar overrepresentation in head-on crashes on curves may be the result of such overcorrection. For this reason, an additional hard-copy analyses was conducted which concentrated on those accidents in the sample occurring on curves. Of the original sample of 200 accidents, there were 87 that occurred on curves. Some of these involved rear-enders, mechanical failure accidents, "passing" accidents, etc. which were eliminated from this curve-related sample. This left 55 accidents that appeared to be related to the driver (or one of the drivers) having some difficulty "tracking" around the curve. Both single and two vehicle accidents were included. Interestingly enough, the vehicles in these accidents were almost evenly divided between big cars and minicars.

In order to look at the "path-overshoot" phenomenon, several accident scenarios were identified. In negotiating a curve, a driver can either (1) not turn enough (for the unique combination of speed, vehicle characteristics, and available traction existing at the moment), (2) turn too much (oversteer),or (3) turn the wheel to approximately follow the curve path. In the first case (insufficient steering input), the vehicle will fail to negotiate the curve and run off the outside of the roadway on a curve to the left or over the centerline on a curve to the right. In the second case (too much steering input), the vehicle will run off the inside of the curve on a curve to the right and cross the centerline on a curve to the left.

Once the vehicle's course was established as going to either the inside or outside of the curve, a wide variety of additional descriptive scenarios were identified. In the simplest case, the out-of-control vehicle continues out of control and runs off the road. In the situation where the vehicle runs off the road to the left, it must also cross a lane of opposing direction traffic before it can run off the road. So, in about half of the off-roadway to inside of curve and about half of the off-roadway to outside of curve situations, the out-of-control vehicle has the potential for striking another vehicle. The fact that such a collision occurs as often as it does (relative to the chances of there being a car in the opposing lane on low volume two-lane roadways) suggests that oncoming traffic may play some kind of a predisposing factor, perhaps causing the driver to commit an error that ultimately results in a crash.

In addition to the situation where the out-of-control vehicle strikes another vehicle, other scenarios identified and tabulated included various combinations of running off the roadway, staying off the roadway, rolling over off of the pavement and coming back on the roadway and rolling over on the pavement.

Table 7 shows how the 55 curve "tracking" accidents were distributed relative to rollovers and non-rollovers. The most interesting finding is that big cars almost never have tracking failures to the inside of the curve. The one case where it did happen involved the big car crossing the centerline and striking another vehicle. None of the 26 cases involved big cars actually running off the pavement to the inside of the curve. On the other hand, 28 percent (8 of 29) of the total minicar crashes involved the small car either

Table 7. Inside/Outside curve-related crashes by car size, rollovers and non-rollovers (hard-copy analysis).

Accident Scenario	BIG CARS		MINI-CARS	
	R/O	Non R/O	R/O	Non R/O
Vehicle going to INSIDE of Curve	0	4%	13%	13%
Vehicle going to OUTSIDE of Curve	34%	62%	28%	46%
TOTALS	100%		100%	

crossing the center line and striking an oncoming vehicle in the inside lane or running off the road to the inside and failing to recover.

The most common scenarios involve:

- o Big cars running off the roadway to the outside of the curve and staying off the roadway (8 accidents).
- o Big cars going off the roadway to the outside and rolling over (7 accidents).
- o Big cars going off roadway to the outside, coming back on, and going off again (3 accidents).
- o Small cars going off to the outside and staying off (6 accidents).
- o Small cars running off the roadway to the outside and rolling (4 accidents).
- o Small cars going off to the outside, coming on, and going off again and then rolling (4 accidents).
- o Small cars going off to the <u>inside</u> and rolling over (3 accidents). For whatever reason, small cars are rolling whether they go off to the inside (3), off to the outside (4), or whether they are leaving the pavement after having returned (4). This may be a "tripping" phenomenon more than one of vehicle dynamics.

- o The preliminary analysis indicated that drunks also don't roll over any more than non-DWI's. Forty percent of the DWI sample involved rollovers while 45 percent of the non-DWI sample rolled.

In summary, these data are difficult to interpret. The small sample size makes conclusions difficult, as do the many confounding factors present (e.g., driver age differences, shoulder/roadside difference, etc.). The only general findings are that minicars did seem to leave the curve on the inside more often than do the large cars, and may be involved in more complex "recovery" sequences which ultimately end in crashes. There is no overwhelming trend in this small sample leading to the conclusion that minicar oversteer is a major problem in curve accidents.

Prioritization of Critical Accident Subsets/Countermeasures

Most of the aforementioned results were mailed to the expert review panel prior to the panel's one and one-half day meeting. At the meeting, these results were critically discussed in detail. Much of the discussion stemmed from the panelists' research and implementation experiences with the individual accident issues and potential countermeasures. At the end of the meeting, each panel member was asked to propose countermeasures and additional research activities for each of the major areas cited above. These proposals were then combined into a larger master list, with the list being categorized into the nine major headings with both pertinent countermeasures and remaining research issues defined under each of the headings. In total, 56 distinct countermeasures or research issues were generated by the panel for further study (see appendix D).

The listing was then mailed back to each of the non-HSRC workshop attendees to be ranked. Two rankings were requested. First, each member was asked to rank the nine major areas as to its priority for further research/implementation attention. Next, within each of the areas, the attendees were asked to rank the individual countermeasures by "potential benefit", and then by "implementation feasibility." Even though some panel members modified these ranking procedures to some extent, it was possible to then combine the results for study.

While the rating scores allowed for ranking the major areas from first to ninth, the subjectivity of any such ranking methodology and the closeness of the scores of some of the nine areas resulted in four groups of issues, ranging from highest to lowest priority. Here the issues of concern to the panel are:

1. Pavement edge (and shoulder) related issues.

2. Sideslope/embankment/ditch bank issues.
   Horizontal curvature.
   Curb/traffic island-related issues.
   Vehicle parameters related to rollover and handling.

3. Longitudinal barriers.
   Utility poles.
   Culvert/drainage structures.

4. Driver issues.

It is interesting to note that the driver-related issues were felt to be the lowest priority by eight of the nine panel members (quite likely due to the panel's discussion of the difficulties of modifying driver behavior).

It must be noted here that, as expected, the rankings differed considerably among panel members. Such differences were clearly evident between two groups of panel members -- those considered to be "vehicle specialists" and those who are "roadway specialists." Most striking is the difference in group rankings for "vehicle-related issues". Here, the roadway specialists ranked this as the number one area of priority, while the vehicle specialists, who should have more insight into the possibility of modifying the vehicle in a positive fashion, ranked this area as their eighth priority -- higher than only the driver-related issues. (As noted above, the combined ranking places the vehicle-related issues in the middle of the overall rankings.) Vehicle specialists were most interested in the roadside/embankment/ditch bank area. (Indeed this difference in opinion is not of great surprise to the author, since the discussion in many of these meetings of the past two years has centered around the roadway specialist's interest in finding solutions to problems by modifying the vehicle, while the vehicle specialists are more cautious about the potential benefits of such a research strategy.)

In terms of individual countermeasures or issues within each of these major areas, again the rankings varied from individual to individual and group to group. While information on all potential treatments will not be presented, the table below presents the three or four top-ranked countermeasures in each of the higher-ranked areas.

Table 8. Potential countermeasures ranked most beneficial by external review panel.

Pavement/Pavement Edge/Shoulder Design

- Better monitoring of current pavement edge conditions and improved maintenance
- Development of a bevelled pavement edge to aid in recovery from a shoulder encroachment
- Research concerning improved shoulder stabilization

Sideslope/Embankment/Ditch Bank Designs

- Widen shoulders at critical accident locations
- Cover ditches at critical accidents locations

Horizontal Curvature

- Increased clear zone on outside of horizontal curve
- Widen pavement on critical curves
- Use of spirals in all new curve designs

Curb/Traffic Island Design

- Develop a procedure for removal of traffic islands at rural and suburban locations
- Reduce the frequency of curbs in urban locations
- Develop a design for a minicar mountable curb

Vehicle-Related Issues

- Use of passive restraints in all minicars
- Improved compatibility of front-end structures with highway hardware
- Increased enforcement of the 55 mi/h (89 km/h) speed limit
- Study the effects of limiting minicar steering response

- Study the issue of angle-of-attack into roadside hardware

Longitudinal Barriers

- Improved guardrail ends for minicars
- Development of a flat-faced median barrier design
- Study of the smooth-faced (low friction) concept for median barriers

Utility Poles

- Relocate utility poles outside the clear zone
- Relocate utility poles to the inside of horizontal curves
- Development of a lighter utility pole for use at critical locations

Culvert/Drainage Structures

- [a]Elimination of driveway culverts and extension of culverts beyond clearzone
- aExtension of culverts

[a]Equal ranking

For comparison purposes, a separate weighting process was then carried out by the principal investigator to rank critical accident areas. In this ranking, he attempted to include degree of the accident problem in terms of both accident severity and accident frequency and the statistical significance (or near significance) of the results. Here, just as noted earlier, the rollover issue overshadowed most of the other issues. If one assumes that pavement edge and shoulder design are somehow strongly related to rollover frequency (an assumption that cannot be completely verified since the detail in the accident data did not allow us to analyze pavement edge or shoulder design as a specific causative factor), then this ranking (from highest to lowest) based on the analysis results would be:

Shoulder/pavement issues
Curb/traffic islands

Sideslope/embankment/ditch banks
Horizontal curvature
Culvert/drainage structures
Utility poles
Bridge piers
Longitudinal barriers

Finally, in an attempt to correlate these results with related efforts currently in progress at FHWA, the COTR and the FHWA subcontractor coordinating a review of FHWA Project 1S, "Design, Operations, and Corrective Geometrics," forwarded material to HSRC for review. This material contained the results of a separate external panel review of overall research in the geometric design area. It is noted here that Project 1S is not only concerned with minicars but with all vehicles and their relationship to roadway geometrics. The attempt here was to see whether the priorities related to minicar accident subsets and countermeasures parallel the priorities provided by this additional review panel.

Indeed, there were some similarities in the results. Most specifically, the above cited needs for research work in the areas of horizontal curvature and roadside design were also found to be important by the 1S Review Panel. This panel ranked the following three projects in their top group of research needs:

- Guidelines for a critical examination procedure for corrective geometric practices on highway curves.
- Tradeoff between lane width and foreslopes.
- Clear recovery zones.

In the second highest category of research needs, the 1S Panel included a study of "pavement-shoulder interaction," and in their third category of research needs included the need for work on "curb designs for intermediate design speeds." Obviously, while the needs as defined by minicars are somewhat different from those that are defined by the total population of vehicles, there are very definite parallel needs in these major areas.

In general, it would appear that the literature, the accident analyses, and the panel support the idea that the major minicar problem is related to rollovers. This may be due to (1) the instability of the smaller vehicle in abrupt handling situations, (2) the minicar's higher potential for "tripping" on shoulders or pavement edge irregularities, and/or (3) the inability of the vehicle to stay upright (especially in a yawed condition) on some sideslopes and embankment designs currently in use. Thus, these results would indicate that future research should first attempt to determine the specific problems of minicars on various pavement and roadside designs and the treatments that might prevent the vehicle from rolling. Also, given a crash, research is needed to determine what can be done to soften the impact of the minicar with utility poles, longitudinal barriers, and bridge piers.

HVOSM Results

As indicated earlier, the information from the above-described ranking along with the accident analyses and literature review were used to develop topics for HVOSM computer simulation efforts. In this HVOSM effort, a number of the countermeasures and issues raised were examined by project staff, the simulation subcontractor, and the COTR to determine whether simulation prior to the development of full-scale test validation plans would produce additional useful information and make the overall evaluation process more efficient. Potentially, this list included the following:

- Bevelled pavement edge design.
- Shoulder "smoothness".
- Minicar mountable curb.
- Flat-faced median barrier design.
- Smooth (low-friction) faced median barrier design.
- "Lighter" utility poles.
- Alternative drainage ditch designs.
- Alternative roadside slope designs.

In addition, because of the general findings related to the increased propensity of minicar rollover, it was decided to further examine the possibility of limited simulation effort concerning vehicle-related parameters. These runs involved such parameters as the ratio of track width to height of the center of gravity, roll-yaw moment of inertia, suspension characteristics and others.

Based on preliminary review and discussion and on results of some ongoing and recently completed research concerning some of these areas, the decision was made to conduct runs on the following:

> Sideslope related issues -- Recent simulation and field testing by Deleys at CALSPAN had examined the issue of sideslope steepness and design on rollover potential of minicars and larger vehicles.(15) This effort was basically to verify the results of that work using different vehicles.
>
> Traffic Islands -- Because of the high rollover probability when minicars strike traffic islands, particularly in rural areas, and because simulation of various curb designs is possible, a series of runs was made in which mini and larger cars impacted various traffic island designs, including a new design currently used in the State of North Carolina.
>
> Vehicle parameters associated with rollover -- As described above, an attempt was made to better determine those vehicle parameters, in addition to T/2h, which may inherently increase the minicar's rollover potential. This would be exploratory work examining a listing of parameters suggested by past research and the simulation team's knowledge of vehicle dynamics.

In addition to these three areas, a fourth area related to the pavement edge drop issue was also considered by the subcontractor and the project staff as a potential candidate for HVOSM work. However, careful review of the recently conducted field testing involving novice and professional drivers attempting to recover from a tire scrubbing condition clearly indicated that a 45-degree pavement wedge could virtually alleviate the problem of reentry to the highway for the minicar.[27] Since it did not seem that study of differences between, say, a 45-degree wedge and a 30-degree wedge would provide any practical information in terms of the future design of a usable wedge, the decision was made to accept the results of this recently completed work.

Detailed reports of the methodology and results of each of the three HVOSM runs conducted are included in appendix E. Summaries of the results of these runs are as follows:

Sideslope related issues. This effort involved verification of the recent simulation work by Deleys concerning the effect of sideslopes on rollovers for small and large vehicles.[15] McHenry Consultants, Incorporated (MCI) conducted a detailed review of the Deleys report, with emphasis on the tire model used. In a separate effort, MCI had made additional changes to the tire model used by Delays. A series of runs was then conducted comparing the Deleys results with results using this newly modified tire model. The three vehicles simulated included a VW Rabbit (approximately 1800 lb (0.82 Mg)), a Dodge Omni (2138 lb (0.97 Mg)) and a Ford LTD (4450 lb (2.02 Mg)). Ground friction factors used as model inputs were similar to those that Deleys had found to be critical (i.e., to result in rollover for a given vehicle).

In general, the runs indicated that the resulting vehicle dynamics were the same for the revised tire model as for the model used in the Deleys work. The only exception was with the large Ford LTD. Here, while the Deleys work produced no rollovers for friction factors up to 1.6 on a 3:1 slope, the modified HVOSM simulation indicated an LTD rollover on this slope with a nominal friction coefficient of 0.9, a coefficient well within the range of possibility. It appears that this simulated rollover could have resulted from minor differences in tire forces obtainable with the two versions of HVOSM, and these minor differences could have made a difference in the rate at which the vehicle spins out (rather than rolls over) within the program.

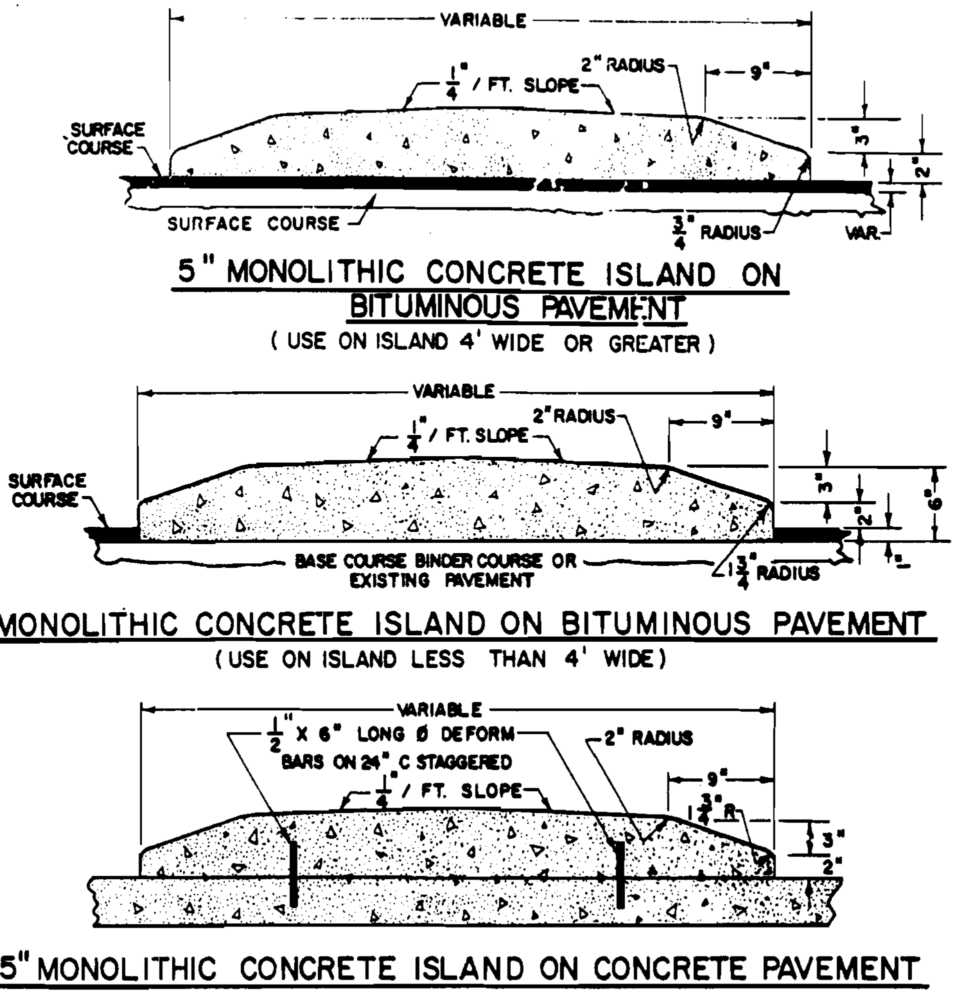
Traffic islands. To further examine the issue of minicar and large car rollover and impacts with traffic islands, simulations were run with both a six inch curb with a 45 degree face (less hazardous than the vertical face found on many traffic islands across the nation) and with a modified face design now in use by the North Carolina Division of Highways. When the minicar (a Honda Civic) struck the curb face in essentially a broadside slide and also in a yawed attitude, the simulation indicated that the minicar rolled at 17 mi/h on a 45 degree face, experienced a near roll on a 30 degree face, and no rollover on a 15 degree face. Tests with the midsize Chevrolet Celebrity showed similar results with the rollover occurring at 20 mi/h (32 km/h) on a 45 degree face. The large car (an LTD) experienced no rollover up to a 60 degree face at any speed. When the face angle and speed were varied to define a "rollover envelope," the simulation indicated that rollover can be produced for small to intermediate vehicles for curb face angles greater than 30 degrees and speeds between 15 and 25 mi/h (24 and 40 km/h).

Several simulation runs were then conducted using a traffic island design currently in place in North Carolina. As shown in the accompanying figure, this design includes two inches of face at 60 degrees, followed by a vertical rise of three inches with a 20 degree face, and the remaining rise at 1 degree to the center of the traffic island. Runs similar to those described above indicated no rollover either for the minicar or the midsize car in comparable situations.

Vehicle parameters associated with rollover. While other accident and HVOSM related efforts have examined issues related to roadway parameters, this specific HVOSM effort was designed to further examine vehicle parameters which might be related to increased rollover propensity. Past theory has suggested that a critical indicator of rollover propensity is the ratio of the half track width to the height of the center of gravity (T/2H). The goal of this effort was to further examine this hypothesis and to search for other parameters which might be related to rollover propensity.

This HVOSM effort involved repeated runs involving eight vehicles ranging in weight from 1699 to 4450 lb (0.77 to 2.02 Mg). While the initial goal was to input a steering maneuver which would put the vehicle in a near-rollover position and to then modify various parameters to determine which were critical, the method had to be modified due to the difficulty of obtaining such a state on a flat area with a normal coefficient of friction. As a substitute, the vehicles were run from the roadway onto a flat, high friction surface and placed in a yawed (nontracking) attitude. The nominal friction value for the test surface was then increased until a rollover occurred. The vehicle parameters were then studied as they changed with this change in critical rollover friction.

The results indicated that while both vehicle weight and T/2H are related to rollover, there are clearly some other vehicle parameters involved. This is most clearly shown by figures 3 and 4 on the following page. Here, vehicle weight and then T/2H values are plotted against the critical friction value



1\4 in/ft = 2 percent
1 in = 25.4 mm

Figure 2. Details of traffic islands used by the North Carolina Department of Transportation.

resulting in rollover. If either weight or T/2H was a perfect indicator of rollover, then one would expect a fairly straight-line relationship with very little variability. However, as can be seen from the figures, there is some variability, with both vehicle weight and T/2H deviating from an increasing slope. More pertinent to this effort, the maximum variability is at the lower weight and T/2H values, values pertinent to smaller vehicles.

In a related set of runs, the center of gravity heights were changed in order to give all vehicles the same basic T/2H value. Simulation runs were then made to see if the critical friction factor remained constant. Results here also indicated that for the higher T/2H values (approximately 1.3) the critical friction coefficient for rollover was a constant function of the static stability factor (T/2h). However, for lower T/2H values of approximately 1.1, there was a great deal of deviation in the friction factors, again denoting the fact that T/2H is certainly not the only predictor of rollover potential.

Additional runs were made involving other vehicle parameters related to roll stiffness, radii of gyration about various axes, and suspension travel. Whereas these analyses indicated a general trend that would explain larger cars having greater resistance to rollover, there does not appear to be any single variable in itself that would indicate why certain vehicles roll at a friction coefficients which are 65 to 70 percent of their static stability factors while others roll at 90 percent of their static stability factors.

Thus, the test runs have indicated that while T/2H is certainly related to rollover propensity, it is not the sole indicator of the vehicle's propensity to roll. There exists an inherent resistance of vehicles to roll which must be a function of certain other vehicle parameters which are yet to be defined.

The results of these HVOSM analyses were then utilized in the development of research plans.

Detailed Research Plans

As noted in the methodology section, based on inputs from a number of sources including the literature review, the expert panel, the author's assessment of the weighted results of the accident analyses, and discussions

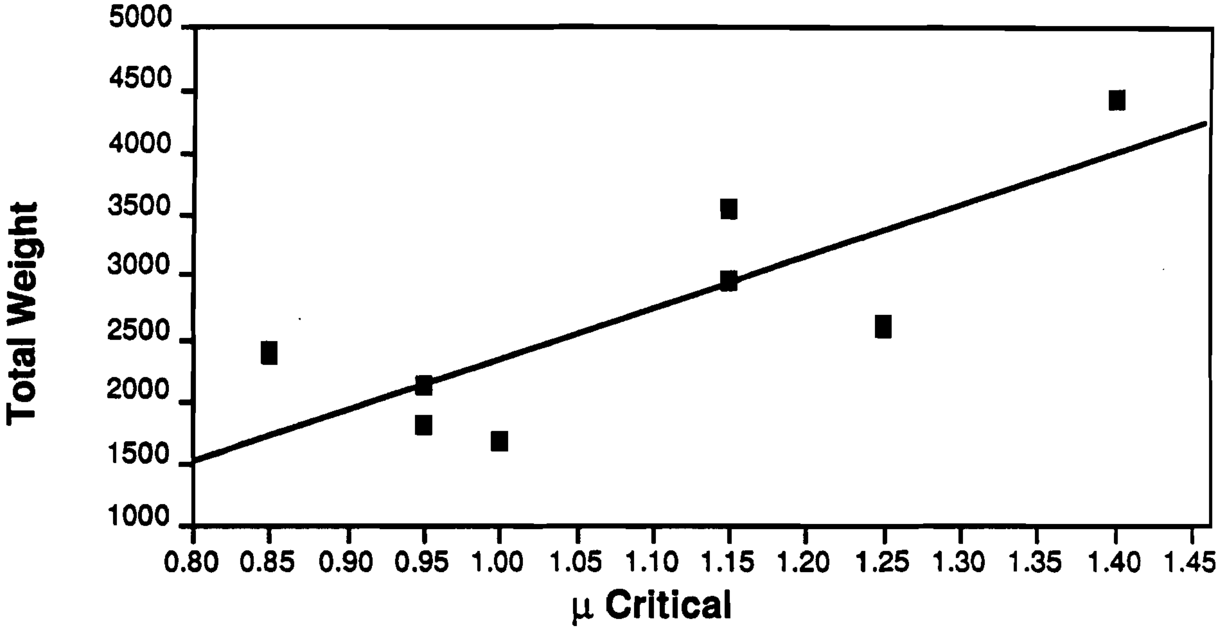


Figure 3. Vehicle weight vs. critical friction factor resulting in rollover.

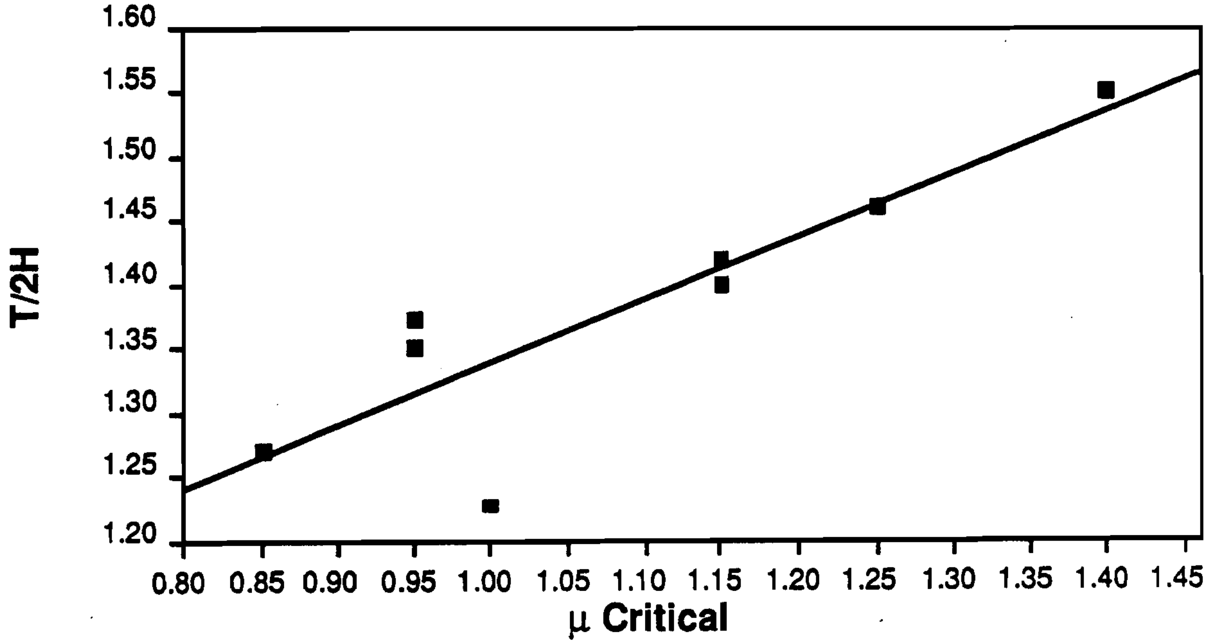


Figure 4. Static stability factor (T/2H) vs. critical friction factor.

with FHWA staff, a priority listing of potential future research areas was developed. This listing includes:

1. Shoulder/sideslope treatments
2. Rural ditch bank designs
3. Pavement edge related research
4. Rural traffic islands
5. Rollover propensity as related to vehicle parameters
6. Horizontal curvature issues
7. Rollover propensity as related to rural catch basins, rural bridge piers, and median barrier faces
8. Utility pole related research

While details of each of these research plans will not be presented here, they can be found in appendix F. For each of the areas, however, a summary of the basic research issue and an overview of the research needs and proposed methodology is presented below.

Minicar involvements on sideslopes. Both the results of the better accident-based studies concerning the effects of steeper sideslopes on the minicar rollover propensity and recent crash tests have indicated that sideslope of 3:1 or steeper continue to produce rollovers for minicars and some larger cars. These steeper sideslopes are found in numerous locations on rural non-Interstate roadways across the nation. Thus, the basic research needs include:

- Better verification of the effects of steeper slopes on minicar accidents and rollovers, while controlling for other contributing factors such as object clutter, shoulder width, vehicle size, etc.

- Definition and study of the feasibility of treatments which could decrease rollover for mini cars on steeper sideslopes.

Further verification of the accident-based findings will involve further analysis of existing State and Federal data related to steeper sideslopes, particularly the data base recently developed by Zegeer, et al.[28] Determination of new low-cost alternatives will be based both on information from research literature, from current State practices, and the inputs of an expert panel to generate ideas. Potential treatments such as changes in slope firmness and friction, changes in shoulder-slope transition design, low cost roadside barriers for lower traffic demands, and shoulder/pavement delineation treatments to prevent roadside encroachments would be studied using simulation and appropriate crash and field testing.

Roadside ditch design in rural areas. A large proportion of single-vehicle crashes for all size vehicles involves the vehicle striking a ditch bank. When these crashes involve minicars, they quite often result in rollover and in more severe injury to minicar occupants. Thus basic research needs include:

- Inventory of current designs in place on non-Interstate rural roadways and determination of problems with these designs.
- Determination of alternative designs aimed at reducing minicar rollover and safely decelerating the vehicle.
- Evaluation and testing of these alternatives.

These research needs will be met by a multifaced effort including many components. The inventory of current designs and problems will be conducted both with questionnaire and field surveys. Accident research based on existing data bases will attempt to better define the accident trade-off issue in which the improvement of rural ditches may lead to increased minicar impacts with more hazardous objects behind the ditches. HVOSM simulation work is proposed for development of ditch bank designs which are both nontraversable and safe -- which might possibly capture the vehicle within the ditch bank and decelerate it at an acceptable rate. Based on this work, alternative designs would be developed by an expert panel and appropriate crash testing and field testing would follow.

Pavement edge drop research. There is some evidence that minicar rollover may be initiated by discontinuities at the pavement edge when the minicar leaves the pavement or when it is attempting to return to the pavement after a roadside encroachment. While recent field tests have developed a pavement wedge which virtually eliminates this reentry problem, there remains the issue of better defining the scope and size of the pavement edge drop problem, defining other alternative treatments, and field tests of those treatments. Thus, the basic research needs include:

- o Better definition of the size, nature and cost of the edge drop problem.

- o The definition and evaluation of alternative edge drop treatments.

The definition of the nature of the edge drop problem will be difficult to determine, and will require innovative accident methodology to extract information from existing accident data bases. Proposed methods here include not only modeling but also the use of an expanded hard copy analysis effort. Alternative treatments range from the earlier mentioned pavement wedge to various shoulder stipulation and pavement issues to innovative edge markings. An attempt should be made to evaluate these alternatives using accident-based research methods. If this is not feasible, then driver behavior-based methods involving such techniques as roadside encroachment counts are proposed.

Rural traffic islands. When compared to larger vehicles, minicars overturn more frequently when striking traffic islands, particularly in rural areas. Research needs include:

- o A re-examination of the basic need for raised channelization, particularly in rural areas.

- o An evaluation of the comparative effects on driver behaviors of raised islands versus painted islands.

- o A better definition of alternative designs for traffic islands which are less likely to result in reportable crashes and/or rollovers for minicars.

- o Crash and field tests of alternative designs.

The examination of the basic need would involve identification and critical review of past studies on which design and channelization standards have been based, a review conducted with the different vehicle sizes in mind. Driver behavior studies aimed at determining differential behavior between painted and raised islands would involve visual or photographic data of traffic behaviors at these types of locations. Additional simulation efforts could be used to further develop workable cross-section designs. If this research continues to show the need for raised islands, and alternative designs can be developed, appropriate crash testing and field studies of these designs would then be conducted.

Rollover propensity as influenced by vehicle parameters. The overinvolvement of minicars in accidents involving overturning has been well documented, as has the increased injury potential of such rollovers. While it is currently hypothesized that this rollover propensity is a result of vehicle size, weight and limited parameters involving height of the center of gravity and track width, there is a need to examine other specific vehicle parameters which might contribute to this rollover overrepresentation. Thus, research needs include:

- Better definition of the possible contribution of front wheel drive as a factor in minicar rollover.
- Better definition of the contribution of country of origin of the minicar (Japanese, European, or U.S.) as a contributing factor in minicar rollover.
- Identification of the relationship between specific vehicle parameters (center of gravity height, suspension characteristics, rollover related moments of inertia, etc.) and the involvement of minicars in rollover accidents.

In attempting to develop information related to the first two issues, accident analysis will be necessary involving both computerized accident files as well as in-depth analysis of hard copy accident reports from State and Federal data files. The work related to the identification of relationships of specific vehicle parameters will involve expanded HVOSM simulation work. Once the critical properties determining rollover propensity have been identified by the HVOSM, test track validation will be necessary.

Horizontal curvature. Minicars are overrepresented in single-vehicle accidents on curves, particularly on non-Interstate roads where poorer geometry exists. Their accident pattern seems to involve some type of loss of control and an inability to correct without either experiencing a single-vehicle accident or returning to the pavement and striking another vehicle. Very few analyses have examined this issue in depth by car size and thus, little is known about the effects of certain geometric factors such as transition sections, spirals, or superelevation on minicar crashes. Thus the basic research needs are:

- The identification of geometric features resulting in minicar overrepresentation on curves.

- The further study of the issue of minicar "head-on striking vehicle" trend in which the minicar is more often the vehicle which crosses the center line and strikes an opposing vehicle.

- Evaluation of treatments to reduce minicar accidents on curves.

It is anticipated that the bulk of this accident-related research will be conducted in a current FHWA research study entitled, "Cost Effective Geometric Improvements for Safety Upgrading of Horizontal Curves". It is anticipated that the methodology to be used will include further modeling efforts, particularly with emphasis on spirals, superelevation and clear roadsides. Additional inputs from HVOSM simulation efforts related to vehicle paths on spirals and other transition sections, and field tests related to innovative delineation attempts may be necessary.

<u>Minicar collisions with specific fixed objects</u>. When compared to larger vehicles, minicars experience a higher rollover rate when colliding with any fixed objects. Impacts with rural bridge piers, rural culverts and catch basins and median barrier faces appear to result in a large rollover overrepresentation for the minicar. Basic research needs include:

- The determination of whether bridge pier-related rollovers produce more injury than nonrollover bridge pier impacts, and if so, the dynamics of the crash and development of appropriate treatments.

- The nature of the catch basin/culvert problem -- whether the object being struck is more often a primary ditch culvert, or a drop inlet or other type catch basin.

- Reconciliation of the results from accident research which indicates rollover problems with median barrier faces and crash tests results indicating no such problems.

Research methodology for all three attempts would involve an expanded analysis of accident report hard copies from both appropriate State and Federal accident files. The hard copy analysis will allow the gathering of more detailed information on collision dynamics and object location and type.

Minicar utility pole crashes. While minicars do not appear to strike utility poles any more often than do larger cars, the severity of such crashes is much greater than for most other fixed objects. While certain breakaway treatments have been developed for large cars, these treatments have not been tested in the field, and preliminary crash testing has indicated problems with small car impacts. Thus, the basic research needs include:

- o Field testing of current breakaway designs.
- o Continue development of minicar treatments.

Field testing of breakaway designs is currently being initiated as demonstration efforts in three states. This field testing will involve detailed accident follow-ups for impacts involving breakaway utility pole designs. The developmental and crash testing effort for better minicar treatments would involve both additional simulation and crash testing of such designs as the Hawkins Breakaway System, the CAM REDIRECTOR (a hybrid crushable ring system), and the Pole Crash Cushion under study at the Texas Transportation Institute.

SUMMARY

The preceding narrative has provided a discussion of the goals, methodology, and results for "Safe Geometric Design for Minicars", a project designed (1) to identify specific accident-related problems that the minicar experiences in our current roadway environment, and (2) to develop research plans which will overcome or lessen these problems. In general, the analyses have indicated that the minicar appears to be a less stable vehicle than its larger counterparts, and that this instability results in increased rollover rates on the pavement and on the roadside. There is some indication that part of this rollover problem may be related to the vehicle either being more often in a yawed condition when it leaves the pavement or being less stable when it reaches the shoulder in such a nontracking attitude. There is also some evidence that front-wheel drive and origin of design may be indicators of some parameters which lead to this higher rollover rate. Roadside and geometric features which result in increased accident or rollover frequency for the minicar as compared to larger vehicles include steeper sideslopes, rural ditches, traffic islands, culvert and other drainage structures, and horizontal curves. While the occupants of the smaller vehicles are more seriously injured in general when a crash occurs, this overrepresentation in injury is even more obvious in crashes with utility poles, bridge piers, and longitudinal barriers.

Opportunities for future research efforts are numerous, including such studies as (1) additional accident analysis and computer simulation to further investigate the causes of (and possible treatments for) the increased vehicle instability, and (2) investigation of modification of current pavement edge and roadside design practices and hardware to make the environment less likely to interact with the minicar in an undesirable manner.

The minicar will continue to represent a sizable part of the vehicle fleet for the foreseeable future. It is hoped that research targeted to the accident-related problems which will arise from this use will enhance the level of safety for the present and future minicar user.

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APPENDIX A

Critical Reviews of the Literature

a. Literature Citation

Altsheular, A., Anderson, M., Jones, D., Roose, D., and Womack, J. The Future of the Automobile. Cambridge, Massachusetts: MIT Press, 1984.

b. Study Description

1. Objectives. The author's objective is to discuss the nature of the changing automobile market and the effects on the world automobile industry. Thus the objectives are much broader than safety issues and indeed are more oriented to the economic issues related to the changes in the automobile industry. Safety is only discussed as one of the many components, particularly as it relates to government regulations and how they will drive innovation in design.

2. Key Elements. Future assessment, automobile economics, automobile trade.

3. Data Collection. Information was collected for international scale through review of literature, interviews with automobile industry leaders, and a series of forms in each of seven key auto-producing nations at which company executives, government leaders and others reviewed, critiqued and discussed prepared papers and related issues.

4. Analysis Method. This book represents the authors interpretations of the data and information collected from the various sources. As such, it is the results of multiple analyses.

5. Results. In discussing the safety aspects of the changing automobile market, the authors note that innovation is usually driven by regulation and by fuel prices rather than by public demand. In terms of safety, they do predict, however, that within the next 10 to 20 years, three significant innovations will occur:

- o A good inexpensive passive occupant protection system for all positions.
- o Antilock brakes for most vehicles.

- Antiskid steering capabilities.

This latter capability would involve a computer operated device to monitor side slip on wheels and to, presumably, change steering inputs as well as braking forces. Obviously, all three of these can have a great effect on the frequency with which roadside objects are struck and on the frequency with which occupants are injured in such collisions.

c. Critical Analysis

Use of the initial analysis checklist is not feasible. However, the scope of the data collection and analysis efforts lend strong support to the findings.

a. Literature Citation

Buth, Eugene. Safer Bridge Railings. Volume I: Summary Report. Austin, Texas: Texas Transportation Institute. (FHWA Contract No. DOT-FH-11-9181). June, 1984.

b. Study Description

1. Objectives. The report describes the results of full-scale vehicle crash tests on five currently in-service bridge railing systems. Design guidelines and performance standards are recommended.

2. Key Elements. Bridge railing, crash tests, impact performance.

3. Data Collection. Crash tests were conducted using instrumented vehicles weighing from 1800 lb (Honda Civic) to 32,000 lb (Intercity Bus) (.82 Mg to 14.51 Mg). Vehicle dynamic performance during impact with the barriers was photographically recorded.

4. Analysis Method. No sophisticated statistical analysis methods were used. The results were presented as descriptions of each of the individual crash tests.

5. Results. For the purposes of this review, the results described will be limited to those relevant to small car safety and existing bridge rails. Six Honda Civics (test weights 1950 to 2150 lb (0.88 to 0.98 Mg)) and seven Chevrolet Vegas (test weight 2770 to 2830 lb (1.26 to 1.28 Mg)) were included as test vehicles in the tests conducted. All of the railings tested properly contained and redirected the smaller cars. However, several of the railings (Colorado Type 5, New Hampshire, North Carolina, and Indiana 5A) frequently pocketed and/or snagged the smaller vehicles. When snagging of the front wheel occurred with the Indiana Type 5A rail, the front wheel underrode the lower rail and snagged on the posts. The New Hampshire barrier tests resulted in a deflated front tire caused by impact with the lower rail and the vehicles subsequently snagging on the next downstream post. Virtually all of the instances where occupant compartment integrity was not maintained involved the smaller vehicles.

The curbs, particularly the protruding curb of the New Hampshire design, were the cause of much damage to the test vehicles. Design recommendations suggest that curbs -- either flush or protruding -- should not be used as part of the bridge railing system. Design recommendations for the size of the vertical opening and post setback distances were also made to minimize or preclude the snagging of the front wheels of the smaller cars.

Evaluation criteria for determining the acceptability of performance of bridge railings are presented. As expected (since none had been designed for the smaller vehicle), virtually all of the existing railings failed to meet the new criteria in the smaller vehicle crash tests.

c. Critical Analysis

1. Authors consider relevant variables? The crash tests were conducted "generally in accordance with procedures recommended in Transportation Research Circular 191". Although this is the generally accepted standard one must wonder if the presence of a human driver, in terms of braking and/or steering inputs, would alter the outcome of the tests.

2. Errors in data collection? None are apparent.

3. Sufficient data detail? Yes.

4. Large enough sample size? A total of 37 crash tests were conducted. Of these, 13 involved smaller vehicles. Although this is too small a sample for statistical purposes, crash tests are very expensive and the results are never the less very useful. Since no two tests were identical the "test-retest" reliability of the procedures was never demonstrated.

5. Statistical assumptions met? None made.

6. Statistical tests? None performed.

7. Correct interpretation? The interpretation of the test results and the recommended guidelines for geometric requirements and collision forces for bridge railing appear to be reasonable. Unfortunately, due to the timing of the initiation of the small-car testing, while tests using both the Honda Civic and the Chevy Vega were made on most of the bridge railing systems tested, no Honda test vehicles were included in the test of the Texas T101 railing (essentially a w-beam reinforced with two tubular steel members mounted on a 27-in (686-mm) steel post). While the Texas railing appeared to be the most effective in most of the larger-car tests, no information could be generated concerning how well the T101 railing would perform with the smaller vehicle.

a. Literature Citation

Rollover Potential of Vehicles on Embankments, Sideslopes and other Roadside Features: Task A Report: Review of the Literature and Accident Data Analysis. FHWA Contract No. DTFH61-83-C-00060. March, 1984.

b. Study Description

1. Objectives. The stated objective of the report was "to determine the general state of knowledge of rollover accidents, particularly with regard to the frequency of occurrence for various classes of vehicles, the severity of such accidents in producing injuries to the vehicle occupants and the identification of possible causative factors related to roadside features encountered by the vehicles as well as conditions at which vehicles depart from the roadway."

2. Key Elements. Roadside features, embankments, sideslopes, rollover accidents, vehicle size.

3. Data Collection. The report reviews data previously presented in past studies of vehicle rollover accidents. Data from NASS, NCSS, FARS, and CPIR are described.

4. Analysis Method. No sophisticated analysis procedures were developed or utilized. The emphasis of the report was to examine the existing data in terms of vehicle classification, rollover accident frequency, vehicle departure conditions, occupant injuries, and roadside features.

5. Results. Because of everchanging definitions of "large" and "small" vehicles in the changing vehicle fleet, the authors initially attempted to better classify vehicle size and weight characteristics as related to rollover potential. Using a MVMA listing of 1980 cars, the authors analyzed various characteristics to look at the correlations between measures. They found that wheelbase and curb weight were highly correlated for both American and foreign cars and that wheelbase, tread width and curb weight were all three highly correlated for American cars. They concluded that any of these measures could be used in analysis of rollover accidents.

All of the various data bases reported that utility vehicles have the highest frequency of rollover accidents. Of particular relevance is the observed systematic decrease in rollover tendencies with an increase in vehicle weight. The curve plotting rollover rate and vehicle weight is essentially curvilinear but flattening out at 3500 lb (1.59 Mg). None of the various vehicle characteristics that were considered (wheelbase, tread width, or vehicle weight) accounted for this flattening when considered separately. The authors hypothesized that perhaps some combination of these factors or perhaps some unknown relevant variables may combine to produce the exaggerated rollover tendencies.

When examining vehicle roadway departure, it was found that 85.7 percent of the rollover accidents involved locked wheel skids (NCSS) while 30.7 percent of all single vehicle accidents involved "nontracking vehicles" (Perchonok, et al., 1978). Further evaluation of the NCSS data found an overinvolvement of lighter cars (≤ 3500 lb (1.59 Mg)) for all of the precrash conditions and particularly for "skidding sideways" and "spinning out of control" which are most likely to induce rollover. (Unlike much of the data reported, this was based on involvement rates, i.e., percent of involvement divided by percent of registrations.) The authors concluded that "It is in fact this mode of losing control that leads the lighter cars to roll over so overwhelmingly more often than heavier cars." Information on departure angle and location was also reported, but this data was not broken down by vehicle size.

Data on impact speed showed that the likelihood of rollover increased with speed prior to impact (CPIR data). However, a study of British cars and trucks showed that more rollovers occurred at the lower speed ranges. (Although it was not mentioned, in all likelihood, the vehicles in the British study were probably lighter.)

Several data sources relating occupant injury frequency and severity to rollover accidents were discussed. In general, it was reported that rollover accidents tend to be more severe than other types of accidents. Only one study (Reinfurt, et al.) considered the role of vehicle size in this general trend.(1) Reinfurt found that serious injury rate decreased with increasing car size. By contrast, the British data reported injury severities in rollovers to be more comparable to the severity of all accidents in the CPIR data than to the rollover accidents (which were the more severe) in the CPIR file. It was hypothesized that this might be due to the role of the lower vehicle speeds reported in the British study. The possible role of vehicle size was not analyzed or discussed.

The authors then further examine roadside features and roadside conditions leading to rollovers. In their study of FARS and NASS data, McGuigan and Bondy noted that, in one-half the rollover cases, there has been a prior impact with an object or roadside feature. They further concluded that when a prior impact occurred, it initiated a rollover in 59 percent of the cases. These authors also noted that the embankment, culvert or ditch was the object struck in 36 percent of the accidents.(2)

Wright and Zador indicated that comparatively small objects were the probable cause of most rollovers. These objects included curbs, edge dropoffs, ditches, and soft soil.(3) Perchonok, et al. present good evidence that fill sections experience more rollovers than ditch/cut sections.(4) For roadway built on a fill, there is an increasing rollover rate with an increase in roadside slope. There is also an increasing number of objects struck with an increase in slope. (It is noted however that very little is known about object exposure or slope exposure in this study.) Conversely, for ditches, there is a decreasing rollover rate with slope down to a three to one slope coupled with an increasing object struck rate. It appears that both the object struck and the rollover rate increased dramatically for slopes steeper than three to one.

For both ditch cuts and fills, there appears to be a critical increase in both the rollover rate and the object struck rate at the four to five foot depth level. That is to say, if a ditch cut or a fill height is greater than four to five feet, the rollover rate increases dramatically.

c. Critical Analysis

1. Authors consider relevant variables? The authors were reporting and interpreting the results of other studies. Their concern was to relate the occurrence of vehicle rollover accidents to roadside features. Their major oversight was to report data that was not based on an appropriate common denominator (i.e., an exposure measure) and to not note that the effect reported may have been due to an exposure effect. Specific instances of this oversight will be described in Section #7 on the following page.

2. Errors in data collection: All data described was previously published. No data collection problems were described. The only "error" in some of the studies described was the failure to express their results as "rates" instead of absolute numbers.

3. Sufficient data detail? Different detail was presented for the expressed purpose. Further cross-tabulations (i.e., by vehicle weight classifications) would have been useful for the current effort.

4. Large enough sample size? The sample sizes reported were sufficient for the conclusions reached. Additional cross-tabulations (i.e., by vehicle size) might have resulted in less than desirable cell totals.

5. Statistical assumptions met? No statistical tests were performed on the data. Only descriptive statistics were presented and the procedures appear to be acceptable.

6. Statistical tests? None performed.

7. Correct interpretation? As indicated in Section #1 above, the only major shortcoming apparent is the lack of exposure data. In some cases this may have led the authors to overlook the role of confounding variables such as vehicle size, roadway type, driver characteristics and other factors that may have influenced the conclusions reached. Several examples of how the authors reported data that failed to consider exposure (i.e., rates) were described in the preceding discussions of "Results". Several additional examples follow:

The discussion of the frequency of rollover accidents was generally presented in terms of rates (per vehicle registration). There was, however, no mention of the role of exposure (by vehicle class) to roadway conditions (i.e. roadway classification) that may affect the role of vehicle rollovers.

The discussion of roadway departure conditions did not consider the possible role of degree of curvature and roadway classification on the departure angle. Since secondary roads tend to have more severe curvatures, this may have been a possible confounding variable. The speed of the vehicle prior to impact should have been presented as a percentage of the posted or design speed of the highway. Possible interrelationships between roadway classification and vehicle size should also have been considered.

The authors reported that rollover accidents tended to be more severe than other types of accidents. Yet in the preceding section of the report, they reported that rollovers also tend to occur at higher speeds. They failed to determine whether the rollovers are more severe because they are high speed accidents or because they are rollovers. Only one of the studies of injury severity (Reinfurt, et al.) considered the role of vehicle size relative to rollover accident injury severity.(1) If smaller cars tend to rollover, one would expect rollover accidents to be more severe.

The discussion of roadside features was particularly weak in terms of potential confounds due to the failure to consider "exposure." For example, Wright and Zador reported that "elongated hazards such as ditches and embankments were found more likely to be present at sites of rollover accidents than at locations of fixed-object crashes."(3) This is not surprising. If a vehicle runs off the road and does not strike a "fixed object" it will invariably run into a ditch or embankment. Ditches or embankments are found on most roadsides.

The discussion of the effect of "fill" vs "ditch" type of road does not mention the possible interaction of either roadway classification or operating speed. The authors did conclude that the reduced likelihood of rolling over on ditch cut roads was due to the general terrain contours associated with these two types of road construction. However, the role of operating speed, vehicle type or roadway width was not mentioned.

d. References

(1) Reinfurt, D.W., Li, L.K., and Popkin, C.L. "Rollover and serious driver injury differences among utility vehicles, pickup trucks, and passenger car groups". Proceedings of the 26th Annual Conference of the American Association for Automotive Medicine. Arlington Heights, Illinois: AAAM, October, 1983.

(2) McGuigan, R. and Bondy, N. A Descriptive Study of Rollover Crashes. Washington, DC: Unpublished NHTSA Report. July, 1980.

(3) Wright, P.H., and Zador, P. A Study of Fatal Rollover Crashes in Georgia. Washington, DC: Insurance Institute For Highway Safety. November, 1980.

(4) Perchonok, K., Ranney, T., Baum, S., Morris, D., and Eppich, J. Hazardous Effects of Highway Features and Roadside Objects. Buffalo, New

York: CALSPAN Field Services, Inc., (Report No. ZR-5564-V-2). September, 1978.

a. Literature Citation

(1) Evans, L. Driver fatalities versus car mass using a new exposure approach. Accident Analysis and Prevention, 16(1), pp. 19-36. 1984.

(2) Evans, L. Driver age, car mass and accident exposure -- A synthesis of available data. Accident Analysis and Prevention. (ln press).

(3) Evans, L. Fatality risk for belted drivers versus car mass. Accident Analysis and Prevention. (In press).

NOTE: All three papers deal with applications of a new approach to estimating exposure in studies concerned with car mass. Thus they are important to this project. As they are related and reasonably similar, they are examined simultaneously.

b. Study Descriptions

1. Objectives. All three papers illustrate the need for considering or adjusting for driver age in making car size (or mass) comparisons. Using data from seven different sources (e.g., NC registered owners; Michigan registered owners; Michigan mileage estimates), empirical relationships are given from which to disaggregate overall exposure information into portions for each of three driver-age groups as a function of car mass.

2. Key elements: exposure, car mass, driver age groups.

3. Data collection. No special data were collected for these studies. Study (1) used FARS data; study (2) utilized registration and overall exposure estimates from North Carolina, Michigan, New York, US, and Canada; and study (3) again used FARS data.

4. Analysis Method. In (1) and (3), the effect of driver age is examined fitting exponential models to the data. Car mass is the independent variable while the ratios

$$\frac{SC}{PED}, \frac{SCC}{MCY}, \frac{TR}{PED}, \text{ and } \frac{CTR}{MCY}$$

within driver age groups constitute the dependent variable where:

SC(m) = no. drivers of cars of mass m killed in single car crashes

CTR(m) = no. drivers of cars of mass m killed in crashes with trucks (GVW $\geq$ 10,000 lb (4.54 Mg))

PED(m) = no. pedestrians killed in crashes with cars of mass m

MCY(m) = no. motorcyclists killed in crashes with cars of mass m

In (2), linear models within driver age groups are fitted (using regression procedures) to the various data sets (e.g., NC accident and mileage data).

5. Results. In (1), the new exposure approach shows that the ratio of people killed (e.g., mass-dependent SC vs mass-independent PED) gives an estimate of how car mass affects the likelihood of a driver fatality. It further implies that the estimate obtained is an estimate of the physical effect of mass, essentially independent of driver behavior. Example result: a driver of a 1,984-lb (900-kg) car is 2.6 times as likely to be killed as a driver of an 3,968-lb (1800-kg) car. Bottom line in (2) is a general procedure for disaggregating exposure data into three driver age groups. The general representation is given by

$$f(i,m) = H_i[1 + G_i(m/900 - 1)] \tag{1}$$

where

$f(i,m)$ = fraction of cars of mass m which are driven by persons in the A_i ($i = 1,2,3$) age category

$$G_i = a_i + 900\, b_i$$

$$H_i = 900\, b_i/G_i \tag{2}$$

with

$$f(i,m) = a_i + b_i m \tag{3}$$

Study (3) extends (1) to data by belt usage. The paper presents the results as graphical and analytical comparisons of fatality likelihood vs car mass for belted and unbelted drivers. For example, a belted driver of a 1,984-lb (900-kg) car is 2.3 times as likely to be killed in a single car crash as is the belted driver in an 3,968-lb (1800-kg) car. The corresponding rate for unbelted drivers is 2.4.

c. Critical Analysis

1. Authors consider relevant variables? Yes, various outcomes by car mass within driver age categories are precisely what is and should be considered.

2. Errors in data collection? The registration data is certainly the most reliable followed by FARS data, then statewide accident data and, least reliably, the distance-of-travel estimates (Michigan, US, and Canada).

3. Sufficient data detail? More than adequate for these studies.

4. Large enough samples? More than adequate in all cases.

5. Statistical assumptions met? The data generally fit the models rather well.

6. Statistical tests? None. Purpose of studies was to develop estimation equations.

7. Correct interpretations? Yes. The combined work represents a considerable advance in accounting for driver age differences with respect to exposure in making car mass comparisons.

a. Literature Citation

Farber, Eugene I. "Driver eye height trends and sight distance on vertical curves," Visibility and Operational Effect of Geometrics. TRR 855. Washington: Transportation Research Board. 1982.

b. Study Description

1. Objectives. The overall objective was to determine if the change in vehicle mix (the addition of smaller cars) is compatible with current highway and vehicle design practices. The purpose of the paper is to analyze the role of driver age height in determining sight distance on hill crests and to determine the sensitivity of sight distance to eye height and other vehicle and highway geometry parameters.

2. Key Elements. Sight distance, driver eye height, minicars.

3. Data Collection. No new data was collected. Objectives were achieved by reanalysis of existing parameters.

4. Analysis Methods. Analysis is limited to recomputation of the standard sight distance equation for different driver eye heights.

5. Results. The results of the analysis indicate that sight distance on hill crests is not very sensitive to the changes in eye heights produced by the downsizing of the current passenger cars. The sensitivity of stopping distance to speed, reaction time, and pavement friction is so great that normal variations in these parameters overwhelms the effect produced by variations in eye height.

c. Critical Analysis

1. Authors consider relevant variable? Standard sight distance equations were used. These equations consider all the relevant, reality-measured parameters.

2. Errors in data collection? No new data were collected.

3. Sufficient data detail? Not applicable.

4. Large enough sample? Not applicable.

5. Statistical assumptions met? Not applicable.

6. Statistical tests? Not applicable.

7. Correct Interpretation? The analytical procedures used and the conclusions reached are well founded. The source for the driver eye height values is not referenced but is in agreement with other values that are available.

a. Literature Citation

Glennon, J.C., Newman, T.R., and Leisch, J.E. Safety and Operational Considerations for Design of Rural Highway Curves. Jack E. Leisch & Associates. Final Report for FHWA Project DOT-FH-11-9575. August, 1983.

b. Study Description

1. Objectives. The research was performed to study the safety and operational characteristics of 2-lane rural highway curves.

2. Key Elements. Single vehicle accidents, run-off-road accidents, 2-lane highways, rural highways, curves, HVOSM, vehicle behavior, simulation.

3. Data Collection. Part of the analysis used existing accident data for selected curve locations and existing HVOSM simulation techniques. Field studies collected new data on driver curve-taking behavior.

4. Analysis Method. Four independent research methodologies were used:

- Multivariate accident analyses.
- Simulation of vehicle/driver operations using HVOSM.
- Field studies of vehicle behavior on highway curves.
- Analytical studies of specific problems involving highway curve operations.

5. Results. The report began with a review of previous research that related accidents to horizontal alignment, superelevation role, curve transition, roadway width, shoulder width, vertical alignment, sight distance, roadside design and traffic volume. The authors correctly noted that much of the previous research often failed to account for variables not being studied, failed to consider appropriate exposure measures, and failed to recognize and evaluate potential interactions among variables. Based on the critical review of the literature a series of 13 general hypotheses on the safety of highway curves was postulated. Four basic research methods were selected to study the hypothesized problems:

- Accident studies.
- Computer simulation.
- Field operational studies.
- Analytical studies.

Accident Studies

A sample of 3304 curve segments and 253 tangent segments in four States was selected to roughly approximate the population of highway curves on main rural 2-lane highways in the United States. There were 13,545 reported accidents on these 0.62-mi (1.0-km) segments for the 3-year analysis period. Analysis of the number and type of accidents on the curve and tangent sections confirmed that curves are substantially more hazardous than tangents. The probability of accident occurrence was found to be about 75 percent greater in curves than on tangents. Single vehicle ROR accidents accounted for 35 percent of the curve accidents, were more likely to be severe, and were more likely to occur during poor environmental (wet/dark) conditions.

An Analysis of Covariance (AOCV) was performed to investigate the incremental accident effects of highway traffic and geometric variables generally available from the State data files. The analysis indicated that degree of curve, length of curve, roadway width and shoulder width, but not ADT were significantly related to accident rate.

A subset of high- and low-accident locations (N = 333) was identified and additional descriptive data (i.e., roadside hazard, curve superelevation, pavement skid resistance) were collected at each location. Discriminant Analysis Procedures found that hazardous roadside design was the greatest contributor to high-accident experience at highway curves. Other less prominent contributors are sharp curvature, narrow shoulders, low pavement, low skid resistance and long curves.

Computer Simulation

The HVOSM computerized mathematical model was used to simulate the dynamic responses of a vehicle traversing a three-dimensional terrain configuration (a curve). A 1971 Dodge Coronet was used as the test vehicle. The test results suggest that an existing highway curve that is underdesigned for the prevailing operating speed can present a severe roadway hazard. The addition of spiral transitions to highway curves dramatically reduces the friction demands of the critical vehicle traversals. Examination of roadside slope characteristics showed that skidding is very likely for even mild roadside slopes (6:1) and that on unstabilized roadside surfaces there is a high expectation of vehicle rollover.

Field Operational Studies

Vehicle speed data were observed on 25 to 30 free-moving vehicles as they traversed 60 curve approaches. A total of 1400 radar-gun speeds were recorded at 4 points entering each curve. The greatest factor in explaining driver behavior was found to be the sharpness of the impending curve. Regression analyses found only a slight difference in speeds for narrow vs wide roadways. Drivers were found to begin adjusting their speeds only as the curve becomes imminent. Curves greater than 6-degrees were shown to produce different speed behavior than milder curves.

The purpose of the final phase of the study was to identify and quantify combinations of geometry which produce variable driver behavior. Vehicle traversal data were collected using a 16 mm motion picture camera from a roadside location at five curve sites. Data on 87 to 150 vehicles were recorded and analyzed from each site. Speed, lateral placement, and vehicle path were obtained from the film. Several concepts in terms of vehicle behavior were noted:

- Drivers tend to overshoot the curve radius, producing a minimum vehicle path radius which is sharper than the highway curve. The tendency to overshoot is, surprisingly, independent of speed.

- Drivers position themselves in advance of the curve to effect a spiral transition.

- The tangent alignment immediately in advance of the curve is a critical range of operation.

- The speed studies and the traversal studies point out the criticality of sharp, underdesigned curves on high-speed highways.

Comparisons were made between the HVOSM simulation data and the field data collected on vehicle curve traversals. In general the findings confirmed the ability of the HVOSM to predict vehicle dynamics across a range of curve conditions. However, the research also demonstrated the need to study actual vehicle behavior in order to assess the validity of the simulations.

Analytical Studies

Analytical studies were performed to address three major research questions. It was determined that, because of the added pavement friction demands created by vehicles during cornering, design braking distances, sight distances and hence design stopping should be greater on highway curves than on tangents. Also, roadside encroachments on the outside of sharp highway curves appear to require both greater clearzone widths and flatter roadside slopes than encroachments on highway tangents. Encroachments in the inside of sharp highway curves may require less clearzone width. The analytical studies also indicated that a "washboard" can have a potentially hazardous effect on a nominally critical vehicle traversal at design speed.

The final section of the report addressed the cost effectiveness of countermeasures to safety problems on curves. The large cost and relatively low effectiveness of widening shoulders, rebuilding curves or repaving indicate that these countermeasures have limited applicability in programs to treat rural highway curves. However, treatment of roadsides, and particularly the clearing of objects from the roadside, holds promise for cost-effectiveness.

Flattening slopes may also be cost-effective for moderate traffic volume levels.

c. Critical Analysis

1. Authors consider relevant variables? In the majority of analyses, most relevant variables were considered. In some of the accident analysis, the authors failed to analyze the data to determine if there were any interactive effects between several potentially interesting variables (i.e., car size, driver age, etc.) and other factors (i.e., accident type, ROR, or accident severity). In the HVOSM experiment a full-sized 1971 Dodge Coronet was used as the test vehicle. Although comparisons were made with field data from actual drivers, it was not noted whether the observed vehicle population had the same handling/vehicle dynamics characteristics, or, since the results appear to "match," whether such characteristics have little effect.

2. Errors in data collection? The vehicle-speed studies were conducted using radar gun speed readings of "free-moving" vehicles. The researchers noted (p. 98) that the field crews voided observations of drivers who were "obviously aware of the study." Although no details were given of the location of the field crew and the radar guns, there is some question as to whether the procedure could be called an "unobtrusive" study of vehicle speeds. The vehicle traversal studies collected speed and lateral placement data from a pickup truck RV parked along the shoulder in the opposite lane from the observed vehicle. Although the researchers note that RV's are relatively commonplace, there might have been some consideration given to the influence that the parked vehicle may have had on driver curve-taking behavior. In addition, the white reflective tape markers placed on the roadway centerline at 25-ft intervals may have had an effect on driver behavior.

3. Sufficient data detail? More than sufficient detail is presented and analyzed.

4. Large enough sample sizes? The accident analyses were based on 13,545 reported accidents, a more than sufficient sample size even for the numerous cross tabulations and subcategories that were examined.

The sample sizes used for the vehicle speed studies (1400 observations at 60 curves) and the vehicle transversal studies (87 to 150 vehicles at each of the sites) appear to be less than adequate. Such samples probably provide sufficient data to describe "normal" driver behavior. However, "normal" drivers do not typically have difficulty negotiating curves. Larger samples would have been useful to more precisely describe the speed profiles and curve-taking behavior of "deviant" drivers.

5. Statistical assumptions met? The authors, very appropriately, inserted a number of caveats throughout the report. For example, they

concluded that degree of curvature and shoulder width appear to have sizable effects on accident rate. They further qualified this summary statement by observing that the effects are subject to potential interactions between variables and "the dubious validity of using regression coefficients as predictors for incremental effects of individual variables". Caveats on the assumptions of normality required for discriminant analysis were also appropriately mentioned.

6. Statistical tests? Statistical tests, where conducted, were apparently appropriate. Where assumptions were made prior to conducting a procedure, the authors generally provided the reader with a summary of the assumptions that were being made. For example, before applying the discriminant analysis to all sites, it was necessary to assure that (1) the discriminant score describes cause/effect relationships (as opposed to correlative ones), and (2) that the relationships between geometric elements and accident rates are continuous. The authors state that the assumptions are "logical and appropriate" and that appears to be the case.

7. Correct interpretation? Apparently the majority of the conclusions reached are appropriate. However, as noted above, there is some concern that the authors may have overlooked some potentially confounding variables (i.e., the role of vehicle size, driver age, etc.) in single vehicle ROR accident frequency and severity. In the analysis of the field data of driver curve speeds, the authors report a significant change for both degree of curvature and approach alignment (= 0.10). In the case of degree of curvature this effect may be an artifact of their curvature categories (1 to 2 degrees, 3 to 4 degrees, greater that 6 degrees). The approach alignment speeds varied from a 4.9 mi/h (7.8 km/h) reduction for mostly tangent and flat curves to 6.1 mi/h (9.8 km/h) for predominantly curvilinear and/or hilly approaches. Although a 1.2 mi/h (1.9 km/h) difference may be statistically significant, there is serious doubt as to whether it is meaningful.

Although the authors suggest that stopping sight distances are "significantly different on curves, there is also some doubt as to whether these significant" differences are meaningful. At 80 mi/h (129 km/h), the curve stopping sight distance is 1120 ft (341 m) versus 1083 ft (330 m) on a tangent section, a difference of only 37 feet (11.3 m) or 3.4 percent.

The AOCV of the accident data is of somewhat limited value because (as the authors freely admit) important variables such as roadside and pavement conditions were not available in the State data files.

The authors mention that one of the most useful aspects of HVOSM simulation is the ability to study dynamic effects of various vehicle types (e.g., trucks and buses) and ranges of vehicle characteristics (e.g., 4-wheel drive). Unfortunately, the examination of these factors was not included in the reported research and some of the conclusions reached may be confounded by these kinds of factors.

In general, however, the research was well designed and produced meaningful results. As is always the case, a larger scale or differently designed study may have produced other useful findings, particularly as related to vehicle size.

a. Literature Citation

Griffin, L.I., III. Probability of Driver Injury Collisions with Roadside Appurtenances as a Function of Passenger Car Curb Weight. Austin, Texas: Texas Transportation Institute, Texas A&M University. October, 1981.

b. Study Description

1. Objective. The author's goal was to study single vehicle crashes involving impacts with various fixed objects and to determine whether the vehicle size differences were related to differences in occupant injury.

2. Key Elements. Small car safety, roadside appurtenances, single vehicle accidents.

3. Data Collection. Griffin used a file of 1980 Texas accident data collected Statewide. The file included 432,940 accidents of which 39,580 were classified as single vehicle accidents involving a vehicle of known curb weight. Of these, 15,536 vehicles struck either highway signs, culverts, utility poles, luminaire supports, curbs, guardrails, or bridge rails.

4. Analysis Method. For each appurtenance, a logistic regression model was developed which predicted the probability of driver injury as a function of the weight of the vehicle. Three classes of driver injury were predicted: serious injury (including fatal and Class A injuries), moderate or greater injury (including fatal, Class A, and Class B injuries) and minor or greater injuries (including all injuries). Thus, a series of 21 regression models (Predicting three levels of injury for each of the seven roadside appurtenances) was developed. These regression plots were then statistically analyzed to determine whether or not vehicle weight caused the slope to be different from zero.

5. Results. Griffin first reviewed other studies of single vehicle ran-off-road accidents and found mixed results. O'Day, et al., had found a higher percentage of occupant injury in small (1500 to 3100 lb (0.68 to 1.41 Mg)) cars.(1) On the other hand, Campbell and Reinfurt and Stewart and Stutts had found very little relationship between car size and driver injury in single vehicle crashes.(2,3) (The reviewer notes that these latter two studies either did not include rollover accidents as part of the sample or used rollover as a controlling factor, thus perhaps eliminating much of the potential difference between cars of various sizes.)

In the current study, as noted above, the analysis examined whether or not smaller car drivers experienced a higher level of injury than larger car drivers when striking the same fixed object. It is noted that the lack of difference would not indicate that the object itself was not hazardous, but simply that the object was no more hazardous for a smaller car driver than a large car driver. The results are summarized in the table below.

In general, for those objects classified by Griffin as "frontal objects" (culverts, signs and utility and luminaire poles) the results were mixed. Culverts, the stiffest of frontal objects, produced no difference by vehicle size. Signs, the least stiff of the frontal objects, again produced no difference by vehicle size. In contrast, analysis of poles and luminaire support crashes indicated that the smaller car drivers were injured more severely than the large car drivers for all types of injury.

For the lateral appurtenances, the analysis of curb accidents and of guardrail accidents indicated increases in minor and moderate injury for the smaller cars and the analysis of bridge rails indicated no difference by

Table 9. Does passenger car curb weight significantly affect the probability of driver injury in single vehicle collisions?

Object Struck	Minor Injury or Greater	Moderate Injury or Greater	Serious Injury or Greater
Highway Signs	No	No	No
Culverts	No	No	No
Utility Poles	Yes	Yes	Yes
Luminaire Poles	Yes	Yes	Yes
Curbs	Yes (=0.10)	Yes	No
Guard Rails	Yes	Yes	No
Bridge Rails	No	No	No

vehicle size. The author also notes that there are interactions between the objects struck and the vehicle sizes which could be leading to some of the differences in results. For example, further analysis of accidents involving curbs indicated that the average vehicle striking the curb was much lighter than the average vehicle striking the other appurtenances. The author explained that this could possibly be caused by two different mechanisms. First, the heavier vehicle may jump the curb and hit a pole or other appurtenance behind the curb, thus being reported as a "pole accident" rather than a curb accident. Second, the heavier vehicle may be able to recover better from an impact with a curb than a lighter, less stable vehicle. (The reviewer also notes that it may be the case that lighter vehicles are driven more in urban areas where more curbs exist.)

In terms of general findings, the author notes that the severity of single vehicle accidents is, as expected, highly dependent upon the object struck. The table below presents the results:

Table 10. Percent of Drivers Injured in Single Vehicle Accidents by Object Struck and Level of Injury

Object Struck	Minor Injury or Greater	Moderate Injury or Greater	Serious Injury or Greater
Curbs	23.37	15.68	3.51
Highway Signs	25.78	17.79	4.14
Utility Poles	44.65	33.51	5.79
Luminaire Poles	40.87	31.97	6.63
Guard Rails	38.36	28.44	7.14
Bridge Rails	38.31	28.31	8.91
Culverts	55.60	45.72	18.91

c. Critical Analysis

1. Author consider relevant variables? As noted by the author, the analyses were very coarse in nature. They were not controlled by any other variables. As he mentioned, variables such as highway class, location (urban, rural), driver age, driver sex, driver violations and belt use would all be examples of variables to be controlled for.

This is particularly true if one is attempting to make a determination (as was done in Table 1) concerning which object might be more hazardous to small or large cars since many of the factors associated with small cars hitting objects have to do with the drivers who are driving the vehicles. On the other hand, when analyses are conducted of the injury potential of fixed objects, it appears that not as much control would be necessary since the exposure here is injury given a crash. However, such potential biases as smaller vehicles being driven at lower speeds and thus hitting objects at lower speeds, smaller vehicles being driven by older drivers who are more susceptible to injury, smaller vehicles being driven by more drinking drivers who are now being shown to be more susceptible to injury, or smaller vehicle drivers wearing fewer belts would clearly have an effect on the outcome of this study. In general, however, given other studies that have examined some of these factors, this analysis does provide a great deal of pertinent preliminary information concerning the question of vehicle size and appurtenance crashes.

2. Errors in data collection? No errors were detected in the data collection.

3. Sufficient data detail? Sufficient detail concerning the data used

was presented. The Texas data includes a great amount of detail which could have augmented the analyses done.

4. Large enough sample? The sample size for this work appears to be very adequate.

5. Statistical assumptions met? The statistical assumptions necessary for logistic regression appear to be met.

6. Statistical tests? The statistical tests used appear to be proper.

7. Correct interpretations? Based on the analyses conducted, the interpretations of the data are correct. As noted by the authors, some of the results and thus some interpretations might well be modified if other variables had been controlled for. Again, however, as a first attempt, this work is very important.

d. References

(1) O'Day, J., Golomg, D.H., and Cooley, P. "A statistical description of large and small car involvement in accidents." Automotive Safety Engineering Seminar Proceedings. Warren, Michigan: General Motors Corporation, June, 1973.

(2) Campbell, B.J. and Reinfurt, D.W. Relationship Between Driver Crash Injury and Passenger Car Weight. Chapel Hill, NC: University of North Carolina Highway Safety Research Center, November, 1973.

(3) Stewart, J.R. and Stutts, J.C. A Categorical Analysis of the Relationship Between Vehicle Weight and Driver Injury in Automobile Accidents. (DOT-HS-4-00897). Chapel Hill, NC: University of North Carolina Highway Safety Research Center, May, 1978.

a. Literature Citation

Griffin, L.I., III. Probability of Overturn in Single Vehicle Accidents as a Function of Road Type and Passenger Car Curb Weight. Austin, Texas: Texas Transportation Institute, Texas A&M University. November, 1981.

b. Study Description

1. Objective. The overall objective was to study the probability (propensity) for a given size passenger car to overturn when involved in a single vehicle ran-off-road type accident, to compare the propensities of various sized cars, and to examine this propensity within highway classes.

2. Key Elements. Small car safety, rollover accidents.

3. Data Collection. Griffin used the 1980 Texas accident data collected by police agencies across the State. These data included 432,940 accident of which 39,580 were classified as single vehicle accidents involving vehicles with known curb weights.

4. Analysis Method. Using the computerized police reported accident data, the author developed standard logistic regression models which predicted the probability of an overturn as a function of vehicle curb weight. A model was developed for each of five highway classes: Interstate roadways, US and State roads, farm to market roads, county roads, and city streets. The slopes of regression lines were then tested to determine whether or not vehicle weight affected the probability of overturn.

5. Results. Griffin reviewed two earlier studies which were related to the high rollover propensity in utility vehicles (Synder, et al. and Reinfurt, et al.).(1,2) He noted that Reinfurt also looked at other passenger cars and found a higher rollover rate in smaller cars. His objective was to expand on this earlier work and to analyze in more detail the propensity of rollover as related to road class.

The results of the analysis of the regression models indicated that lighter vehicles are indeed much more likely to overturn in each road class. The percent of single vehicle collisions in which vehicle overturn ranged from 19.66 percent for county roads down to 3.5 percent for city streets. There was a large difference between the rollover propensity of the largest (5200 lb (2.36 Mg)) car and the smallest (1600 lb (0.73 Mg)) car. For example, the smaller car was eight times more likely to overturn on a county road, 12 times more likely to overturn on an Interstate roadway and 37 times more likely to overturn on city streets. The author noted that the difference on city streets may well result from the fact that city streets are full of small appurtenances such as curbs, drains, traffic islands, etc. which are disadvantageous to the smaller, less stable vehicles.

As the author notes, it is very important for the reader to realize that weight itself may not be directly related to overturn propensity. Indeed, vehicle curb weight is probably only a correlate for the parameters which are of real importance in terms of overturn. Studies of parameters such as track width, suspension geometry, roll moment of inertia, height of the center of gravity, and others must be conducted to determine which of these can be improved to reduce this overturn propensity for the smaller vehicles.

c. Critical Analysis

1. Authors consider relevant variables? In this study of overturns the author used highway type as a controlling variable. Obviously there are other variables which could relate to the propensity for overturn in a given single vehicle accident. These would include such items as speed of the vehicle, pavement edge drop, shoulder type, sideslope or the nature of roadside ditches or slide slopes, and others. However, to some extent, the use of road type does control for these variables. Indeed, the fact that the findings are so consistent across the roadway classes and, in particular, that the data from Interstate roadways reflects a fairly large magnitude of difference for the small and large vehicles would indicate that the results are sound. Coupled with the preceding studies, there appears to be strong evidence that small cars overturn at a higher rate in single vehicle accidents than do larger cars.

2. Errors in data collection? None.

3. Sufficient data detail? The description of the data used was sufficient for the reviewer. In addition, the detail presented in the data appear to be sufficient for the analyses conducted.

4. Large enough sample? Sample sizes used in this work appear to be of sufficient size. This is verified by the fact that in all cases the differences in slope were shown to be statistically significant.

5. Statistical assumptions met? Necessary assumptions for the logistic regression models development procedure were met.

6. Statistical tests? Statistical tests used were appropriate.

7. Correct interpretations? As indicated above, while there might potentially be some minor bias not controlled for in this study, the consistency of the findings and the interpretations of the data would lead one to believe that the results are both scientifically sound and very important.

d. References

(1) Snyder, R.G., McDole, T.L., Ladd, W.M. and Minahan. On-road Crash Experience of Utility Vehicles. Ann Arbor: The University of Michigan Highway Safety Research Institute, February, 1980.

(2) Reinfurt, D.W., Li, L.K., Popkin, C.L., O'Neill, B., Burchman, P.F., and Wells, J.K. A Comparison of the Crash Experience of Utility Vehicles, Pickup Trucks and Passenger Cars. Washington, D.C.: Insurance Institute for Highway Safety, September, 1981.

a. Literature Citation

Ivey, D.L. Predicting the probability of injury during highway collisions: subcompacts vs. standard-size vehicles. Proceedings of the 3rd International Congress on Automotive Safety, Volume II. Washington, DC: US DOT, pp. 41-1 through 41-35. July, 1974.

b. Study Description

1. Objectives. The authors' objective was to combine data from various sources in order to predict the difference in expected injury when subcompacts and Big 3 vehicles hit roadside barriers.

2. Key Elements. Roadside accidents, vehicle size, barriers, guardrails, bridge rails.

3. Data Collection. Three different types of data were used by the author in this study. All were extracted from studies done earlier. First, data based on studies by Michaelski (1) and Olson (2) concerned a prediction of the probability of occupant injury based on the g-forces to the vehicle. This work was done by comparing vehicles in crash tests with known g-forces to pictures of damaged vehicles in real world crashes with known injury. Second, data concerning the tolerable level of g-forces for belted and unbelted occupants in automobile collisions were extracted from prior work by Graham (3), Weaver (4) and Hyde (5). Finally data were extracted from a study by Campbell (6) which depicted driver injury as a function of car size in real world accidents. These data made it possible to extract specific information on injury to occupants in both the subcompact class cars and in the large cars.

4. Analysis Method. Using the past work of Olson, Michaelski et al. concerning automobile g-forces and resultant probability of injury, coupled with theoretical work by Hyde, Graham and Weaver concerning the g-forces which are tolerable to human occupants, the author determined an equation based on Weaver's crash test severity index which could output the probability of injury for an average vehicle. He then used Campbell's real world accident data to extrapolate these results to both subcompact cars and to larger cars based on differences in injury in the real world for these two classes of cars. G-force data was extracted from various crash tests conducted by Texas Transportation Institute and other FHWA subcontractors. Then, using an iterative procedure, repeated runs were made to predict the difference in predicted injury for various crash angles and crash speeds into rigid, semirigid, and flexible barriers.

5. Results. Based on his methodology, the author found that differences in the predicted probability of occupant injury between the smaller vehicle and larger vehicle ranged from a 130 percent increase for impacts into rigid barriers to a 240 percent increase for impacts into flexible barriers. It should be noted that although the greatest difference between the small and large car occurred with the flexible barrier, because of the nature of the

barrier, the injuries were down in the nonsevere range. This work is of particular interest since some of the real world accident studies have not shown any difference in car size for single vehicle and ran-off-road type crashes. This theoretical work, if true, would indicate that not only does a difference exists, but that it is a fairly large and significant difference when vehicles strike guard rails or bridge rails.

c. Critical Analysis

1. Authors consider relevant variables? As noted by the author, there is currently no good existing methodology which links the results of crash tests to the probability of real world accident injury. This attempt was to develop such a methodology based on information existing at that time (1974) from studies conducted by others. Formulas used in this methodology appear reasonable. However, there is no way to verify whether or not the predictions produced are accurate. Indeed, other methodologies and other formulas which would also appear logical might also be used. (One such substitute was hypothesized by the reviewer and resulted in quite different predicted injuries.) As noted by the author, the basic point is not the magnitude of the difference in injury, but that his methodology would predict that such differences would exist. It is interesting to note that this work would predict some differences in serious injury for rigid barriers whereas the real world accident work by Griffin (1980a) reviewed later found no such severe injury differences by car size for all barriers combined.

2. Errors in data collection? Because the data was collected from other studies, it was all that was available to the author.

3. Sufficient data detail? The author presented a sufficient amount of detail describing the data. However, as noted, there still remains some question as to whether the detail present in the data was sufficient for these analysis purposes. The earlier work done by Olson and Michaelski was based on various small sample sizes of pictures and was not meant to include a wide range of either crash test severities or injuries. Campbell's work was primarily based on a sample of small cars which are different in construction, handling, and probably crash capabilities and characteristics from the present fleet of small passenger cars. Finally, the g-force tolerance work by Graham, Weaver, and Hyde is to a great extent theoretical and, at present, still unverified.

4. Large enough sample? As indicated above, sample size for Michaelski's work is somewhat small to be one of the main ingredients to a new methodology. Unfortunately it is all that existed.

5. Statistical assumptions met? Since no statistical tests were carried out, no assumptions were made.

6. Statistical tests? Again no statistical tests were used other than a simple formulation of the data to predict g-forces.

7. Correct interpretations? As stated, the methodology proposed by the author and thus the interpretations of the data appear correct. However there are biases noted above which may make this methodology less accurate (or more accurate) than a host of other methodologies. There is a great need for additional data to verify the various parts of the methodology before the magnitude of differences can be felt to be well documented. The interesting point, however, is that the author has attempted to do something that has been needed for years _ to develop a link between vehicle crash tests with roadside obstacles and the ultimate probability of injury for the vehicle occupants in the real world. The need still exists in 1986.

d. References

(1) Michalski, C.S. "Model vehicle damage scale: A performance test". Traffic Safety. 12(2), June, 1968.

(2) Olson, R.M., Post, E.R. and McFarland, W.F. Tentative Service Requirements for Bridge Rail Systems. NCHRP Report No. 86. Washington, D.C.: Highway Research Board, 1970.

(3) Graham, M.D., Burnett, W.C., Gibson, J.L. and Freer, R.H. "New highway barriers: The practical application of theoretical design". Highway Research Bulletin 174. Washington, D.C.: Highway Research Board, 1967, pp. 88-189.

(4) Weaver, G.D. The Relationship of Side Slope Design to Highway Safety. (NCHRP Project 20-7). College Station, Texas: Texas Transportation Institute, May, 1970.

(5) Hyde, A.S. Biodynamics and Crashworthiness of Vehicle Structures. (Wyle Laboratories Report WR 68-3, Volume III of V). March, 1968.

(6) Campbell, B.J. "Safety, small cars and the gasoline shortage". Highway Safety. 7(10), January, 1974.

a. Literature Citation

Ivey, D.L. "Smaller cars and highway safety," Texas Transportation Researcher. 17(2), pp. 4-8. April, 1981.

b. Study Description

1. Objectives. This article is a short review of other work that has been done both by TTI and other research agencies. The overall goal is to discuss the effects of the changing vehicle fleet on roadside appurtenance crashes.

2. Key Elements. Roadside safety, roadside accident research, guardrails, bridge rails.

3. Data Collection. The data discussed in this paper is data which has been presented in other studies. These studies include an earlier study by Ivey in which a methodology was developed to predict the probability of driver injury for accidents involving bridge and guardrails with different sized vehicles and a study by Wootan analyzing the predictive shift to a large number of subcompacts by 1990.(1,2)

4. Analysis Method. As indicated above, this article is simply a review of other work.

5. Results. As indicated in the Wootan study, there is a large predicted shift to subcompact vehicles by 1990.(2) It is estimated that the percent of subcompacts in the vehicle fleet will increase from 18 percent to 44 percent. There will be a related increase in minicars but not to as great an extent, with an increase from 4 to 8 percent. Full-sized vehicles will decrease from the 1980 level of 26 percent of the fleet to approximately 2 percent in 1990. In addition, there will be a shift to more and heavier trucks, with the truck population increasing from 17 to 34 percent of the total vehicle population.

Using this background information, Ivey then cites his own earlier work in which he developed a methodology for predicting the probability of driver injury for various appurtenance-related accidents that indicated that in collisions with semiflexible and rigid rails (both guardrails and bridge rails) subcompacts are approximately 2 times as likely to produce injury to the occupants as are large, "Big 3" cars.(1) The smaller vehicles are particularly troublesome in collisions with the rigid rails where the results indicated a probability of severe injury for occupants very close to 1.

Ivey then notes other problems which may arise from this shift to smaller vehicles. These include problems with small sign supports which will not yield when struck by subcompacts; problems with concrete median barriers where compact cars have been shown to overturn more often and thus produce a higher probability of injury; breakaway cable terminals which are too stiff to perform adequately when struck by many compacts; turn down guardrail end treatments in which the current design is too stiff for the minicompacts; concerns with older, more open bridge rails where there is the possibility of snagging of front wheel drive vehicle axles since the guardrail is higher than the tire, (however, the author notes here that this has not yet been demonstrated to be significant to passenger survivability); and problems with drainage structures, including both open end culvert under roadways and longitudinal culverts under driveways. The driveway culvert problem appears to be solvable by careful design, but the terrain surrounding these drainage structures may well present large problems to the small car which is less stable on uneven terrain. Ivey closes by noting that many of these problems can be solved by the design engineer, and indeed some designs have already been proposed. However, very few of these designs have been tested in the real world. He also notes that these designs will lead to higher costs and that "the public is apparently more interested in patching potholes than in making functional crash cushions accommodate very small cars."

c. Critical Analysis

Because the study was a review of other studies, the critical analysis checklist will not be used.

d. References

(1) Ivey, D.L. "Predicting the probability of injury during highway collisions: subcompacts vs. standard-size vehicles," Proceedings of the 3rd International Congress on Automotive Safety, Volume II. Washington, DC: US DOT. July, 1974, pp. 41-1 through 41-35.

(2) Wootan, C.V. The Changing Vehicle Mix and Its Implications. A presentation at the Texas Institute of Traffic Engineers, February 1, 1980, El Paso, Texas.

a. Literature Citation

Joksch, H.C., and Thoren, S. Car size and Occupant Fatality Risk, Adjusted for Differences in Drivers and Driving Conditions. Hartford, Connecticut: The Center for Environment and Man, Inc. January, 1984.

b. Study Description

1. Objective. The objective of this study was to determine the relative risk of fatality in collisions involving cars of various sizes while controlling for other factors which could affect the risk.

2. Key Elements. Car size, fatality risk.

3. Data Collection. The accident data used in the study were extracted from the Fatal Accident Reporting System (FARS) data files and included 1979 to 1983 model cars which were involved in fatal accidents in the either 1981 or 1982. Because the final calculated rates were reduced in terms of rates per registered vehicles, data from monthly sales data published by the Motor Vehicles Manufacturer's Association were used to estimate the total fleet size within the U.S. by make/model and year. Using this data, the vehicles were categorized into six groups: small subcompact, large subcompact, small compact, large compact, intermediate, and large cars. (It was noted in the study that because these are slightly older cars, the 1984 fleet definitions would be somewhat different with, for example, 1981 to 1982 intermediate cars now being classified as full-sized.) The data used to control for the various factors which the author felt should affect fatality risk was vehicle miles of travel data extracted from the 1977 Nationwide Personal Transportation Study (NPTS) and from a later study by Comsis Corporation based on NASS and NPTS data.

4. Analysis Method. As noted above, the author's objective was to produce fatality rates per 10,000 registered cars adjusted by a number of variables which could affect fatality risk. The variables used in this paper for adjustment variables include driver age and sex, the time of day, day of week, highway class and state of operation. The adjustment methodology involved using the VMT data to calculate a series of ratios which specified relative travel by any given driver population/roadway circumstance (e.g., young male Virginia drivers on Interstate roadways at 2 to 3 a.m. on Sunday morning). These relative ratios were then used to adjust the number of fatalities to equalize exposure.

5. Results. The analysis of the data using the adjusted rates showed some interesting results. As is consistent with other work, the analyses of car size in car-versus-car collisions indicated that both car weight and wheelbase has an effect on the driver death rate, with the driver of a small subcompact being approximately five times more likely to be killed per 10,000 car years as the driver of a larger car.

In contrast, the findings for single vehicle accidents were somewhat different. Here the analysis indicated that there were large differences between the driver death rate for the smallest subcompact category and the large car category. However, the rates did not decrease uniformly. Instead the data indicated that the small and large subcompact vehicles had a higher death rate than did the other four categories of vehicles, all of which were at the same level. Thus the small compact, large compact, intermediate cars, and large cars showed approximately the same adjusted death rate. The authors point out that the analyses indicate that car weight was not nearly as important a variable in single vehicle crashes as was car wheelbase, and that increasing wheelbase produced a lower death rate only up to a length of approximately 105 in (2.67 m). (This 105-in (2.67-m) wheelbase is approximately the wheelbase of a small compact vehicle.) Thus, the analysis indicated that whereas subcompacts were more dangerous in single vehicle crashes, increases in wheelbase above 105 in (2.67 m) does not produce a beneficial effect.

Also of interest in this current work is the fact that the percent of younger drivers decreased as wheelbase increases and that the percent of older drivers increases. Thus, its apparent that these factors should indeed be taken into account in any study of car size versus roadside hazard.

c. Critical Analysis

1. Authors consider relevant variables? As noted above, the authors of this study attempted to consider as many of the relevant control variables as possible. It appears that most of the major ones were accounted for in the analysis. As noted by the authors, because the vehicle miles of travel data had to be based on 1977 figures, if the relative miles of travel for the various risk groups have changed substantially since 1977, then the results would be biased to some extent.

2. Errors in data collection? As best can be determined from the study there were no errors in data collection. Because the authors used data from other sources, any errors inherent there would be present here.

3. Sufficient data detail? The data used in the study appear to be sufficiently detailed to carry out the analysis conducted and the description of the data used was adequate for the reviewer to understand the process followed.

4. Large enough sample? Sample sizes used appear to be adequate in all cases.

5. Statistical assumptions met? As can be determined, no statistical tests were run. There were some basic assumptions that had to be met due to the methodology used in producing the adjustment factors. It appears that these assumptions were justifiable.

6. Statistical tests? As best can be determined, no statistical tests were run. It is difficult to tell whether or not the decreases indicated in the graphs presented in the paper were indeed statistically significant or nonsignificant.

7. Correct interpretations? Based on the analyses conducted in the paper, it appears that the authors have correctly interpreted the findings.

a. Literature Citation

Jones, I.S. The Effect of Vehicle Characteristics on Road Accidents. Oxford: Pergamon Press, LTD., 1976.

b. Study Description

1. Objectives. The objective of the study is to investigate whether it is possible to relate car characteristics which define handling and stability with the appropriate accident rates.

2. Key Elements. Vehicle characteristics, accidents.

3. Data Collection. Existing accident data from TRRL and Britax, vehicle-mileage survey data for the greater London Council and vehicle handling data from several manufacturers were analyzed. A survey of 1200 vehicle odometer readings was conducted to determine exposure by model.

4. Analysis Method. Multiple regression analysis was used to investigate the effect of vehicle characteristics on accident causation.

5. Results. The first chapter examined existing accident data to determine how vehicle characteristics may contribute to accident causation. The effect of accident type, speed, skidding, occupancy, type of car, number of vehicles involved, loss of control, and tire failure were examined.

The second chapter developed an exposure measure for various models of cars. Odometer readings for vehicles parked on the street and in free car parks were recorded. (The author admits that this procedure may underrepresent motorists who park in garages and use their cars very little during the week.) Data was collected in 12 separate areas of London to ensure geographical/demographic representation. Projections of total mileage traveled by model of car were developed.

The third chapter analyzed accident rates by make and model of car, comparing the frequency of the different accident types (head-on, single-vehicle, etc.) by model of car with the corresponding exposure measure (mileage traveled). The analysis indicated that, although there is a very strong correlation, the variation in number of accidents between models is not completely explained by variation in vehicle travel. Other factors are especially important in single-vehicle accidents, including age and sex of the driver and variation in vehicle characteristics. Having established the dependency of accident notes on age and sex of driver, the author uses a "normalizing factor" to represent the number of accidents expected regardless of driver age or sex.

The fourth chapter establishes measures of handling and stability for the various models of cars. Vehicle design parameters examined include; weight, weight distribution, power to weight ratio, ratio of load carried to total weight, wheelbase, track and center of gravity height. He notes that vehicle response parameters are more likely to be more closely related to loss of control than vehicle design parameters, unfortunately they are far more difficult to quantify, especially by make/model. The following response parameters were considered; steady-state response, understeer with respect to speed, understeer with respect to steering angle, the "Consumers Association's handling procedure," static margin, slip/steer gradient, transient response, roll stiffness imbalance, subjective evaluations, braking instability, overturning as a result of skidding, and overturning as a result of striking an object.

The final chapter relates the various accident rates for the different models of cars to the measures of handling and stability derived in the preceding chapter. Normalized accident rates for the various models were plotted against vehicle characteristics, regression lines were fitted by least squares and the correlation coefficients calculated. The "r" for weight, wheelbase, load carried/total weight, and power-to-weight ratio are significant for single vehicle accidents. The strongest positive correlation (0.811) was with weight while the power-to-weight correlation was negative (accident rate decreases as power-to-weight ratio increases). The plots for center of gravity height/track and weight distribution are not significant.

For car-versus-car accidents, weight, wheelbase and load carried/total weight all show a significant correlation with accident rate. Weight distribution, the ratio of center of gravity height/track (CGH/track), and power-to-weight ratio are not significant. All of the design parameters which show any significant correlation with accident rate are related to the size of the car.

Of the vehicle stability parameters examined, minimum velocity for overturning and height/track and CGH/track indicate increased proneness to overturning in rural areas. Minimum velocity for overturning is the stronger measure. Neither parameter affects proneness to overturn in urban areas.

c. <u>Critical Analysis</u>

1. <u>Authors consider relevant variables?</u> The author considered a great number of relevant variables, some of which were very sophisticated. However, he may have overlooked some potential interactions due to relatively unsophisticated factors. For example, a chi-square test indicated that the likelihood of overturning after skidding is higher in dry or icy conditions than in wet conditions (.05 level). Subsequent analyses of make/model effects did not consider any potential interaction between environmental and roadway factors and the make/model effects reported.

<u>2. Errors in data collection?</u> The field data collection of estimated total annual mileage was done at two different times. Analysis of variance comparisons between the two samples found no significant differences, and the

samples were combined. This suggests that, if there were any errors in the data collection procedure, they were at least systematic.

3. Sufficient data detail? Some vehicle response information was not available for all of the make/model combinations being considered but this did not have an adverse effect on the analysis and conclusions.

4. Large enough sample? The accident data base consisting of a 1969 and 1970 combined national sample of over 200,000 accidents was large enough. The exposure data were based on two surveys of 499 and 454 vehicles. The author indicated that a sample of 300 was sufficient to define the average annual vehicle travel within ±500 mi (±800 km) with a 90 percent confidence level. However, since there were 15 vehicle models being considered, the within cell sample sizes vary considerably and eight of the projected control mileage figures are based on 20 or less surveyed vehicles. The author is aware of this potential problem and presents a margin of error figure for a 95 percent confidence level.

5. Statistical assumptions met? Yes. One assumption, however, is somewhat bothersome. Jones assumed that the effect of driver age is independent of the model of car that is driven. This was done so that he could apply the "normalizing factors" to each model of car when the accidents were enclosed by age of driver. It is possible (but not proven) that, for example, a young driver from a high socioeconomic strata may be more likely to crash his family's deluxe model than a young driver from a lower strata is to crash his family's base model econocar due to difference in the value systems of the two families.

6. Statistical tests? Appropriate statistical tests were apparently used for each analysis step. The stepwise regression vs mean age, sex and handling characteristics provide a clear indication of the role of operator and vehicle characteristics.

7. Correct interpretations? The interpretation of the data are apparently correct. The author, quite correctly, does not input great importance to relatively small effects (10 to 15 percent of the variation) that were uncovered in the stepwise regression analysis.

a. Literature Citation

Kuroda, K., Maleck, T., and Taylor, W. Impact of Vehicle Size on Highway Safety. Lansing, Michigan: Michigan State University, January, 1985.

b. Study Description

1. Objectives. The purpose of the study was to investigate the relationship between automobile size, highway geometry, and traffic accidents. Curb weight was selected as the parameter to define vehicle size.

2. Key Elements. Vehicle size, single vehicle accidents, rollover accidents, slippery pavement accidents, rural road accidents.

3. Data Collection. The study results are based on police reported accidents that occurred in Michigan in 1982. Only accidents that occurred on either the Interstate system or on the Michigan Truckline system were analyzed. A total of 51,740 accidents were included.

4. Analysis Method. The study used a surrogate for exposure that was based on two hypotheses:

(1) The likelihood of an automobile being an object (the second vehicle) of an accident is proportional to its exposure"

(2) "The likelihood of an automobile being an object of an accident is equal if the exposure is the same."

The authors claimed that the hypotheses were "consistently supported by data and the surrogate exposure approach is found to be a useful tool for the quantification of exposure."

Unfortunately, because this paper was a summary paper of what was a very extensive full report, very few details were presented concerning exactly how the exposure surrogate was used to produce an expected number of accidents for a given weight class and given type of roadway geometry. Subsequent conversations with one of the authors indicated the following procedure. The measure for exposure was derived using multicar (two vehicle) accidents for the accident subclass of interest (e.g., rural, midblock accidents on 10-ft lanes). The actual measure was then calculated by dividing the number of not-at-fault vehicles in the weight class in question by the total number of not-at-fault vehicles in the accidents. Multiplying this ratio by the total accidents in the subclass of interest produce an expected number of accidents for the weight class. The actual observed number of such accidents was then compared to this expected number. It should be noted here that the expected number of accidents is based on the number of vehicles in a given weight class which was struck in multivehicle type collisions. The observed number of accidents, however, may include both multivehicle collisions and single-vehicle collisions. Thus, the implied assumption being made is that the surrogate based on not-at-fault vehicles in multicar crashes holds true for single vehicle crashes also.

It should also be noted that, using this methodology, if a given vehicle class (say minicars) indicates an overrepresentation of accidents (i.e., a ratio of observed to expected greater than one), then a separate vehicle class will, by definition, have a lower than expected number of accidents. Thus, even though all vehicles may have problems with narrow lane widths, the results of this methodology would indicate that some vehicle classes are overrepresented and others are underrepresented, since the comparison is always between vehicles rather than between geometric features.

5. Results. Small cars were found to have a unique risk of accident involvement and were found to be more likely to be involved in accidents in the following conditions:

- Single vehicle accidents.
- Overturned vehicle accidents.
- On icy or snowy highway surfaces.
- At midblocks.
- In rural areas.

Large automobiles were found to be more likely to be involved in accidents under the following conditions:

- Accidents with pedestrians.
- Accidents with parked vehicles.
- Accidents with other vehicles.
- At intersections.
- In urban areas.

In rural areas small vehicles were found to be more likely to be involved in an accident at the following geometric features:

- Midblocks.
- 2-lane 2-way highway.
- No passing zones.

Drivers of small vehicles were also found to be more likely to be injured if they are in the vehicle being hit.

c. Critical Analysis

1. Authors consider relevant variables? The value of this report depends on whether the authors' exposure surrogate is a tenable one. The assumption here is that a study of not-at-fault vehicles gives a good indication of the number of vehicles of a given weight class which are on the roadway under certain conditions of roadway geometry. Some past studies of such "induced exposure" have indicated that induced exposure does not match very well with actual calculation of exposure in terms of vehicle travel. However, in certain cases, it appears that induced exposure is a viable option. It appears that the methodology used here involves dividing induced exposure up into small subsets may well be the best method available. The real issue of whether or not this is a viable exposure technique revolves around the question of whether there are cases in which small cars will not get hit as often (in relation to other size vehicles) as they are exposed in the true driving population. If small cars are the not-at-fault vehicles less than they should be, then the expected measures will to be too low and the observed-over-expected ratio will give an erroneous overinvolvement. If one were to assume, for example, that small cars handle better and thus are not hit as often or, because of their size, are not struck as often as larger vehicles, then this methodology would include some bias.

There is a secondary issue, however, that appears to be even more important to deciding the value of the results shown to the current minicar project. This has to do with the fact that even if this exposure measure is valid, there remain other variables which should be controlled for. The results of these analyses have basically been used to show that the vehicle itself is "the problem" when indeed the problem could be the driver of the vehicle. The authors did not control for any other driver variables. Past work has indicated that induced exposure results in more bias when used with single vehicle crashes, particularly with crashes involving the younger driver. The not-at-fault vehicle less often has a younger driver than does the single vehicle crash. This may be a function of the exposure measure or simply may be a function of the fact that younger drivers get in single vehicle accidents more often. If there is then a chance that small cars are driven more often by young drivers, then the results that are found in this paper relative to small cars may indeed be related to the age of the driver rather than the car size itself.

2. Errors in data collection? The authors used existing Michigan State accident records, the Highway Master Data, and INDICATOR 83 to decode the VIN's. No errors in collection or analysis were apparent.

3. Sufficient data detail? Virtually all relevant data elements (and some irrelevant ones) from the police accident reports were available.

4. Large enough sample size? The 51,740 accidents included in the data base is clearly adequate for those comparisons made using the major variable (vehicle size) across all accidents. However, as noted above, the expected values are calculated on the basis of not-at-fault vehicles in a given subset of accidents. Because sample sizes were not shown in the paper, it is difficult to tell whether or not the expected values for certain low-frequency subsets are indeed stable enough to produce a usable expected measure. Again, if the expected measures are erroneous, then this would very clearly effect the conclusions that are drawn.

5. Statistical assumptions met? Most of the results were presented graphically as plots of Actual/Expected proportions by vehicle curb weight. Where statistical tests were made, apparently the appropriate assumptions were met.

6. Statistical Tests? Limited statistical testing was done. See #5 above.

7. Correct interpretation? Whether or not the conclusions are based on a "correct interpretation" of the data is directly related to the validity of the surrogate that was used for exposure. As discussed above, it appears that the authors have done as good a job as possible using the surrogate measure they chose to use. Indeed in some cases this surrogate measure would appear to be a very logical way of trying to determine a very hard to define variable _ exposure by weight class. However, there remain some questions of whether or not this surrogate measure based on two vehicle crashes holds for single vehicle crashes and, secondly, whether or not the use of the measure without controlling for driver age or other driver-related variables can indeed produce results which are specific to vehicle weight itself. For example, results shown in the paper which may, in fact, be real but which are questionable based on logical considerations of vehicle design include the fact that smaller vehicles are very much overrepresented as compared to larger vehicles on both 10- and 12-ft (3.0- and 3.7-m) lanes and for all levels of shoulder widths. Logically, it would appear that a smaller vehicle might indeed have an easier time on narrower lanes than does a larger vehicle. However, this is not the case based on the results presented. In terms of shoulder width, it is interesting that the smaller vehicles are overrepresented on all three categories of shoulder width and indeed experience more of an overrepresentation (although not statistically significant) for 12-ft (3.7-m) shoulders which would usually only be found on Interstates. These results would lead one to believe that what is being measured here is to some extent driver factors rather than vehicle design factors exclusively.

In summary, it appears that the authors have made a valiant attempt at defining exposure by vehicle size in a situation where traditional exposure measures are not collected. It appears that the measures used are quite logical at least as they pertain to multivehicle crashes by car mass. There remain some questions of whether the measure is valid for single vehicle crashes and also questions involving whether or not the results are more related to driver differences between vehicles rather than vehicle differences themselves.

a. Literature Citation

Landwehr, D.A. Safety and Small Cars. Environmental Activities Publication No. 9028. Warren, Michigan: General Motors Corporation, January, 1982.

b. Study Description

1. Objectives. The author's objective was to discuss the effects of fleet resizing on overall safety of the roadway.

2. Key Elements. Small car safety, car design, safety testing, seat belts

3. Data Collection. The author uses data from other studies, primarily NHTSA and FARS data, in supporting some points. He also extracts data from another study related to the relative risk of various threats to life.

4. Analysis Method. As noted above, no new analyses are done.

5. Results. Using data presented by other authors, the author concludes that shifting to small cars will only reduce life expectancy by an average of 0.2 years for small car owners. This small drop in average life expectancy is compared to a decrease in life expectancy of 6.5 years for smoking, and lesser decreases (although greater than the decrease for the small car) for other significant life style changes. The author presents no discussion of the data from which these conclusions were drawn.

He then goes on to discuss General Motor's test procedures and other methods used by General Motors to improve safety. In much of the article, the authors are clearly stressing the need for small car operators to wear seat belts. Indeed his overall summary point is that better design will make the newer small cars safer than they have been in the past. However, they will still be inherently less safe than large cars and thus owners should wear occupant protective systems at all times.

c. Critical Analysis

As indicated above, the study did not present any information concerning where the data or the conclusions came from other than citations to other studies. Thus, it is not possible to conclude whether the data were properly analyzed.

a. Literature Citation

Small Car Safety: An Issue That Needs Further Evaluation. Washington, DC: U.S. General Accounting Office. April, 1982.

b. Study Description

1. Objectives. The General Accounting Office (GAO) conducted a review of the safety of small cars because "vehicle and highway safety experts and the general public have expressed concern over smaller car safety and because of disagreements over alleged safety problems." The results of this review were presented as recommendations for the Secretary of Transportation.

2. Key Elements. Vehicle size, accident involvement, injury severity, single vehicle accidents, roadside features.

3. Data Collection. No new data was collected. GAO reviewed numerous research studies as well as analyzed accident data gathered from New York, Michigan as well as NHTSA's NASS, NCSS and FARS file.

4. Analysis Method. No sophisticated analysis procedures were used. The report attempts to describe the involvement of smaller cars in various types of accidents. Most of the results are presented as tabulation of accident involvement by car size. The only control for vehicle exposure involved comparing accident-involvement to percent of registered vehicles in the fleet.

5. Results. Many of the studies reviewed agreed with GAO analysis of New York and Michigan data in indicating that smaller cars are not overrepresented in total vehicle accidents when compared to the number of smaller cars registered. They did find, however, that "smaller cars were generally overrepresented in single-vehicle accidents with guardrails and, to a lesser degree, median barriers." (Summary page ii) The analysis of FARS data, Michigan data and NCSS data on towaway accidents involving utility poles indicated no trends regarding vehicle weight and occupant injury.

GAO examined the hypothesis that smaller cars are getting progressively safer each model year. They found that newer cars (1975 to 1980) had a lower role of serious and fatal injuries for accidents involving poles and guardrails. However, in the total single vehicle accidents the New York data established no relationship between car age and injury severity.

The various data sources examined did not agree on whether occupant injury was greater in small car collisions with roadside barriers, utility and light poles and median barriers.

GAO concluded that little research has been done involving all smaller car issues. They recommend that DOT analyze real-world accident data, especially if it relates to single vehicle accidents to determine what smaller car safety problems exist. GAO suggested that DOT use one or more of the following three techniques:

- o Organize a task force.
- o Develop a special studies program for NASS.
- o Develop a program to use accident data from several States.

c. Critical Analysis

1. Authors consider relevant variables? All of the accident "rate" comparisons presented were based on vehicle registration data. In fact, GAO never actually talked about "accident rates." All of the tables presented columns of "percent of fleet" and "percent of accidents." They left it up to the leader to interpret whether the differences shown were "real differences" in accident rates. GAO acknowledged that registration data is "only one method of determining whether cars in lighter weight classes have more accidents than those of heavier weight classes." They indicate that vehicle miles traveled is another measure of comparison but that such data is not generally available by weight class. They do admit that, "different measures could result in findings different from ours." However, they continued, NY DOT and NCSS officials "agree that using registration data is an acceptable measure for studying smaller car safety." We note, however, that such variables as driver age, urban/rural travel patterns, and other trip pattern indicators which could greatly influence these conclusions were not examined in the study, making these findings somewhat questionable.

2. Errors in data collection. Since no new data was collected, there was no chance for data collection errors. NY DOT indicated that they checked some of the tabulations and found them to be accurate.

3. Sufficient data detail? Sufficient detail was presented for the purposes intended.

4. Large enough sample size? The New York data consisted of over 225,000 accidents for each of three years. The size of the Michigan data base was never specified but is presumably equally adequate. However, some of the cross-tabs were based on smaller subsets (i.e., 424 median barrier accidents) and many of the resulting cells contained relatively few (i.e., 25) accidents.

5. Statistical assumptions met? No statistical tests were made. Only descriptive, percent of fleet/percent of accident statistics were presented.

6. Statistical test? Although no statistical tests were conducted the percentage figures presented were very frequently interpreted as if they represented both significant and meaningful differences. Often a one or two percentage difference was used as the basis for a relatively broad and far-reaching conclusion.

7. Correct interpretation? Although GAO may have reached a reasonable and proper final conclusion (i.e., more study of the small car safety problem is needed), they did so through some very questionable analyses and findings. The use of registration data as the only exposure measure is a critical flaw. Although they admit "other factors such as driver error, driver age, age of car, speed, and the time of day can influence accident rates" they proceed with their analysis without further mentioning the potential impact of these and other potentially confounding variables.

GAO also seemed to pick out those elements of the data that best proved their point. For example, in the Summary Digest, they state that "smaller cars were generally overrepresented in single vehicle accidents with guardrails and, to a lesser degree, median barriers" (page ii). In the actual text of the report, they concluded "the ... data showed no definite relationship between injuries and smaller car accidents with guardrails" (p. 21, emphasis added). Examination of the raw percentage data shows that these conclusions are based on relatively small (i.e., 1.2 percent) differences between percent of fleet and percent of accidents. The most interesting fact, that the effect is more bimodal than linear, was not even mentioned. Midsized cars (2500 to 2999 lbs (1.13 to 1.36 Mg)) are actually more involved in guardrail accidents than the smaller ones.

One of the Appendices to the report presented DOT's comments on the GAO draft report. The NHTSA developed responses did make several good points:

> "Unfortunately the GAO has a naive faith in the quality of the data they used for their cursory analysis of small car safety ... Generally there are serious problems with State accident data and with all exposure data." However, only a few of NHTSA's many detailed comments criticized the "statistical validity" of the report. Apparently NCSS officials actually approved of the methodology before GAO issued the draft report. The problems associated with a "percent of fleet" based evaluation should have been made apparent at that time.

a. Literature Citation

Small Car Safety Technology: Hearings before the House Subcommittee on Transportation, Aviation and Materials. Washington, D.C.: Government Printing Office, 1983.

b. Study Description

1. Objectives. The stated objective of the Hearings was to review small car safety technology.

2. Key Elements. Minicars, vehicle characteristics, roadside hardware, RSV's, seat belts, air bags.

3. Data Collection. No new data collection is described.

4. Analysis Method. No analysis procedures are described.

5. Results. In spite of the stated objective of the Hearings, they are in fact primarily characterized by criticism of the current NHTSA programs. The major emphasis is on what NHTSA is not doing to improve highway safety in general, and small car safety in particular. There are, however, a number of specific points that were made that are relevant. These will be described in this section:

- GAO Report: A brief summary of the 1982 GAO Report, "Small Car Safety. An Issue That Needs Further Evaluation," is presented. The report criticizes NHTSA/NASS for failure to capture small car relevant variables. The NHTSA reply to the GAO report is included.

- William Haddon, IIHS. Small cars, especially small Japanese cars are less safe.

- "Reagan on the Road: The crash of the U.S. Auto Safety Program." (September 1982). This report by Public Citizen (viz Joan Claybrook) details the failures of Ray Peck of NHTSA to fulfill the Congressional mandated emphasis on safety belts, 55 limit, air cushion restraints, etc. with very little information on small cars. Ms. Claybrook concludes, "they have made NHTSA what I call a wholly owned subsidiary of the Detroit manufacturers"

- David Martin, GM. Increase risk of injury and fatality in small cars is not associated with driver age. He discusses GM computer design for increased crashworthiness. Belt usage in small cars (Chevettes, Rabbits) is 3 to 5 time average. A restrained small car occupant is as safe as an unrestrained large car occupant.

- Betsy Ancker-Johns. "Advancing Vehicle Safety through Industry/Government Cooperation," explains the new climate between regulator and regulatee in accident research, crashworthiness, side impact research, seat belt use motivation. Nothing relevant to small cars is presented.

- Donald Friedman. Comments on RVS's and airbags.

- Michael Finkelstein, NHTSA Associate Administrator.

  - Forecasts a 10,000 increase in fatalities by 1990 due to small cars.

  - "As the domestic fleet becomes a small car fleet, the problems of passenger car safety becomes a problem of small car safety" (p. 300).

- Ray Peck, NHTSA Administrator.

  - Small car belt usage is 18 percent versus 7 percent for large cars and 10 or 11 percent for the whole fleet.

  - Provided NHTSA resource collection plan, i.e., alcohol, RSV's, belts, child restraint and belt incentive programs. Mr. Peck's prepared statements did not address the GAO criticisms, Ms. Claybrook's comments, or other criticisms.

c. <u>Critical Analysis</u>

The nature of the document precludes a critical analyses.

a. Literature Citation

Transportation Research Board. Mini and microautomobile forum: Overview and potential problems. TRB Circular No. 264. Washington, D.C.: Transportation Research Board, September, 1983.

b. Study Description

1. Objectives. The circular contains a series of presentations on the effect of the downsizing of the automobile in relation to highway safety.

2. Key Elements. downsizing, minicars.

3. Data Collection. The circular provides an excellent summary of the views of several prominent highway safety specialists on the potential safety impacts of mini- and microcars. No "new" data is presented.

4. Analysis Method. Since the circular is not a research report per se, no analyses procedures were described in detail. The relevant comments on analysis methods will be included below in the discussion of each presentation.

5. Results.
"Economic Considerations." Charles Lave.
Based on an economic model using operating costs and initial purchase price, a total market share of 60 percent for subcompacts and mini was projected. Minis (like the Honda Civic) would take about 40 percent of the market all by themselves.

"Potential Usage" Kenneth Orski.
Rather than discuss potential uses of mini's, Mr. Orski discussed minimal performance and design standards but did not include safety as a factor. His personal opinion is that safety is not an important consideration.

"The Market Potential for Micro-Mini Cars in the United States," John Hemphill.
Results of the Automotive Consumer Profile (ACP), a national representative survey of 5,000 American drivers indicate that fuel economy is important and safety relatively unimportant to new car buyers. The ACP predicts 6 to 9 percent of car sales by 1985 will be micro-mini's (wheelbase 76 to 90 in (1.6 to 2.3 m), length 123 to 139 in (3.1 to 3.5 m), weight 1200 to 1650 lb (0.54 to 0.75 Mg), engine 550 to 1250 cc (5.5 to 12.5 l) displacement).

"Design Notes for a Safer Half Megagram Automobile." Dr. Carl Clark.
This paper describes several existing micros including the Suzuki Alto, the Dihatsu Cuore, the Commut-a-car and the HM enclosed motorcycle. The crashworthiness of such vehicles is described.

"Potential Impact of the Microvehicle on Roadway Facilities" Donald L. Woods and Hayes E. Ross.

Woods and Ross describe the potential impact of microvehicles (126 in (3.2 m) long, 55 in (1.4 m) wide, 53 in (1.3 m) high, 81.5-in (2.1-m) wheelbase and 1200 lb (0.54 Mg) weight) on highway design. The following topics were addressed:

- Stopping Sight Distance. Since driver eye height of a micro would be only 0.6 inches lower than mini, existing criterion are adequate.

- Passing Sight Distance. From a driver eye height standpoint, passing sight distance standards are adequate. However, there is concern about acceleration characteristics and visibility of restrictive pavement markings.

- Lane Widths. Could be as narrow as 7 ft (2.1 m).

- Parking Stall Dimensions. Could be 8 ft. by 10 ft (2.4 by 3.0 m).

- Sign and Luminaire Supports. Current AASHTO criteria would produce a velocity change of 13.7 mi/h (22.0 km/h) when struck by a 1200 lb (0.54 Mg) vehicle. This is about twice the recommended limit. In addition, there is an increased hazard due to the greater tendency for microvehicles to rollover after impact with sign supports. Smaller vehicles tend to "spin out and in some cases roll over violently if the impact is off-center."

- Longitudinal Barriers. Impacts with W-beam and rigid barriers result in higher than recommended lateral acceleration values. Also, there is an increased propensity for rollover for smaller vehicles striking concrete safety shape barriers. The geometry of other longitudinal barriers is a concern as smaller cars may submarine under the barrier and snag the posts.

- Crash Cushions. A crash cushion that is safe for a 2250 lb (1.02 Mg) vehicle results in unacceptable deceleration levels for microvehicles. Most commercially available cushions could be adopted and a redesign is presented.

- Driver Visibility. New AASHTO standards for driver eye height should satisfy the needs of microvehicles.

"Operator and Safety Problems," James O'Day.
Accident rates would be about the same as for larger cars but the serious injury and fatality rate would be much higher. The author discusses the possibility of separate facilities for micros.

"Laws, Standards and Liability," Andrew Hricko
This paper discusses legal ramifications of microvehicles relative to the manufacturer and the traffic engineer who maintains the driving environment.

c. Critical Analysis

The majority of these papers consisted of "experts" providing their opinion on the potential impact of microvehicles on highway safety. Hence, it is not really appropriate to provide a critical review of this reference.

a. Literature Citation

Transportation Research Board Committee on Sociotechnical Systems. Enhancing Highway Safety through Engineering Management in an Age of Limited Resources. Final Report of a Conference. Washington, D.C.: The Board, November, 1981.

b. Study Description

1. Objectives. The proceedings of a conference are presented. The conference was structured into five workshops that addressed highway operations, maintenance, upgrading and rehabilitation, construction and reconstruction, and program administration. Discussions related only to the safety aspects of the highway and street environment including engineering and design; they were concerned only indirectly with other aspects of safety such as shifts in vehicle size and mix, driver skills, or vehicle design. These, of course, enter into the highway management program as special problems requiring special attention, but they are not the direct responsibility of those agencies.

2. Key Elements. Minicars, roadside appurtenances, sight distance, vehicle characteristics.

3. Data Collection. No new data collection was conducted.

4. Analysis Method. No analysis was done.

5. Results. Although research results, in the traditional sense, are not described, there were a number of comments or statements made that are relevant. These comments will be presented in this section.

Jarvis D. Michie, as a moderator of plenary session on the roadway, noted that a critical roadside safety problem is being imposed by the emerging number of car weighing less than 2,250 lb (1.02 Mg), the percentage of which is projected to increase to 52 percent by 1990. Because this trend to small cars was not anticipated by the highway community or domestic automobile manufacturers until as late as five years ago, and because it takes five to ten years to develop and begin to implement new roadside hardware, it is not surprising that most of the existing hardware were not designed to perform well with the small car. Specific problems that have been documented in either crash test or by accident statistics involved snagging of small cars with standard guardrails, increased small car rollover incidents after collision with concrete safety shape median barriers, and poorer vehicle trajectories in crash test involving small cars with breakaway signs, luminaire supports, and guardrail terminals. Michie goes on to note that although FHWA has been concerned with the emerging problems of a small car for several years and has developed hardware to perform with the small and large vehicle, a number of problems still require additional research and development. These include guardrail terminals, crash cushions, and breakaway supports for small and large signs and luminaries. In contrast, the author notes that this change to small vehicles may have some safety benefits. For example, narrower cars have the same effect as widening highway lanes, and the increasing trend to smaller vehicles may lead to decreasing the number of accidents between vehicles of greatly disparate size. While driver eye height has not been shown to be a serious problem even with the newer lower profile cars, it appears to the author that the engineer must consider this factor in such aspects of future highway design as the selection of speed signs and the lengths of no passing zones. In summary, he concludes that the major problems will be with the roadside appurtenances. It is of interest to note that his opinion is "... in some cases, the engineering limit of breakaway technology may be approaching, and it may be physically impossible to develop suitable hardware."

In a second plenary session concerning vehicle changes in the future, David E. Martin of General Motors notes the need for automobile engineers to communicate the results of their studies and design trends to highway engineers in order to insure future compatibility. In reviewing an earlier paper prepared by Marlowe Ladd of General Motors, Martin notes that the following trends are predicted:

- A decrease in vehicle weight.
- A decrease in car length.
- A narrowing of passenger car wheelbase.
- Little change in thread width.
- Little change in overall vehicle heights.
- Little change in driver eye height.

Martin concludes by noting that it is becoming particularly critical for automobile and highway engineers to work together since the vehicle/highway compatibility problem is of increasing importance. He notes that, just like the highway, any proposed changes to the vehicle fleet to improve the situation would be of a long term nature, in that it takes approximately 10 years to replace a vehicle fleet.

c. Critical Analysis

The nature of the presentations in this document precludes a critical analysis.

a. Literature Citation

Viner, J.G. Implications of small cars on roadside safety. Proceedings of the 27th. Annual Meeting of the American Association of Automotive Medicine: Arlington Heights, Illinois: The Association, October, 1983.

b. Study Description

1. Objectives. The overall objective of this study is to define the specific problems which are anticipated to arise with the shift to smaller vehicles and with their inevitable crashes due to the roadside fixed objects.

2. Key Elements.Small car safety, roadside appurtenances, vehicle downsizing.

3. Data Collection. This study represents an excellent review of other studies in the area. In addition, in order to more clearly represent the scope of the problem, the author has used 1981 FARS data to depict the size of the ran-off-road/roadside crash problem as compared to multivehicle and other types of crashes and to define the objects which appear to be most hazardous in terms of fatalities.

The author also uses vehicle weight data from Texas and California as a form of "exposure" data with which to more clearly define situations in which small cars are and will be overrepresented in accidents.

4. Analysis Method. Using the FARS data, Viner indicates that striking a roadway feature was shown to be the "most harmful event" in 35 to 37 percent of all fatalities. Then, by categorizing the single vehicle accidents according to the object struck, he produced a table ranking objects struck from most to least hazardous in terms of both number and proportion of fatalities on the Interstate system and all roads.

5. Results. Using the tables presented, the author noted that overturning accidents are the most hazardous of the single vehicle type accidents. Of the fixed objects which can be struck, the ones producing the most fatalities are trees, utility poles, embankments, culverts, ditches and guardrails. Viner goes on to use the Texas weight data to show that the lighter cars are slightly overrepresented in total accidents (as compared to the number of registered vehicles within the State) and are even more overrepresented in both fatal and incapacitated injury accidents (as compared to the weights of vehicles in all accidents). Based on this, he anticipates the following specific problems:

- Overturning. Overturning is the leading cause of roadside fatalities. Viner cites Griffin who (1) indicated a strongrelationship between the curb weight of the vehicle and the probability of overturn, and then uses results from a second study by Griffin (2) combined with NASS data to show that when overturning occurs, the accident is much more dangerous in terms of subsequent occupant injury than a non-overturning collision. More specifically, Griffin found that the fatal rate in overturning accidents is 1.9 times higher than the rate in nonoverturning accidents. According to the NASS data, this same fatal rate is 5.7 times higher than the non-overturning rate. However, using data provided by Griffin, Viner also found that given an overturn, there is no difference in injury by car weight. This would imply that any increase in fatalities and serious injuries that would result from a shift to small cars will result more from an increase in overturns than from an increase in injury per overturn.

Finally, using California weight/registration data, Viner predicts that a shift to the predicted 1985 sales fleet would result in a car weight distribution which would increase overturn accidents on the Interstate 1.6 times and fatalities and incapacitating injury accidents by a factor of 3.0.

- Utility poles. Utility poles are the most frequent man-made objects struck. (It is interesting to note that trees are struck more frequently than utility poles, but are not discussed in this article.) In the discussion of utility poles, Viner again cites Griffin (2), who notes that the probability of injury increases as vehicle weight decreases. More specifically, whereas the probability of a fatal or serious injury is 0.05 per crash for a 3500 lb (1.59 Mg) car striking a utility pole, the same probability of serious or fatal injury is 0.12 for a 2000-lb (0.91-Mg) vehicle. Using these data, and the weight data cited above, Viner predicts that the shift to the smaller vehicles would increase the fatal and injury utility pole crashes by approximately 50 percent within the next five years.

- Traffic railings. Potential problems with guard and bridge rails include snagging problems, the deformation (or lack thereof) of rails being struck by small vehicles, and the increase rollover propensity of smaller vehicles when striking traffic railings. In terms of snagging, crash tests conducted by various FHWA contractors have shown that front wheel snagging on the post is a definite problem with the smaller minivehicles. It is interesting to note, however, that Griffin found no accident-based serious injury differences by car size when examining guardrails. He did find some differences in minor injuries. In addition, Griffin found no differences in any injury by vehicle size for crashes in which cars struck bridge railings.

  In terms of the overturn performance of the more rigid guardrails, Viner cites a number of other studies showing that the percent of vehicles overturning is higher for specific designs of concrete median barriers. Bronstad, et al. (3) have indicated that data collected in the State of California showed increased frequency of rollover for all vehicle sizes striking a concrete media barrier as compared to either cable barriers or metal beam barriers. They note that the rollover rate is even higher for small vehicles. Using later, unpublished, California data, Viner then compares the number of registered vehicles categorized by weight to vehicle weight in accidents in which rollovers occurred after collisions with the New Jersey shaped concrete median barrier. The data indicated that smaller vehicles are much more likely to overturn when striking these concrete median barriers. For example, while 24 percent of the passenger vehicle registrations weighed less than 2250 lb (1.02 Mg), 51 percent of the vehicles that overturned weighed less than this amount. It appears that the overturning problem is significant for vehicles that weigh up to approximately 2700 lb (1.22 Mg).

- Signs and Luminaire Supports. Finally, in a discussion concerning problems involving signs and luminaire supports, Viner indicates that a major problem is that the accident researcher cannot distinguish breakaway from nonbreakaway supports in the FARS or NASS data. Thus, there is very little accident data to work with. Griffin indicated no injury differences for sign collision based on car weight.(2) The outcome was equally severe for all car weights. In contrast, crash tests conducted by FHWA contractors have shown that off center hits are a problem for the smaller vehicles, often resulting in rollover or violent vehicle trajectories and occupant forces. Thus, the crash test in this case are somewhat at odds with what has been seen so far in the real world accident data.

c. Critical Analysis

1. Authors consider relevant variables? In terms of the problem analysis/identification analyses, the most relevant variable not taken into account is the variable of exposure or opportunity to crash. As noted by the author, there is very little available exposure data to draw clear conclusions on which are the most hazardous obstacles. For example, Viner has simply used the distribution of fatalities by fixed object in his problem analysis work. There is no measure of how often various size cars are exposed to the various type of hazard, and thus no rate defining how often the objects are struck per unit of exposure. Thus, there is no way of conducting some of this problem analysis very "cleanly". However, it is clear that the overall fatality and serious injury figures presented do give some indication of the objects that are producing the highest accident costs.

In terms of the analyses related to such factors as rollover propensity by vehicle weight, variables which have not been controlled for include variables which are associated with drivers and with differential impact conditions. Such variables include driver age, driver sobriety, weather, vehicle speeds prior to the impact, etc. Because of the size of the data sample, the assumption that all of these variables differ equally with car weight may be valid. However, there is still some question as to whether one is measuring the propensity of the driver to run off the road, strike a fixed object, and overturn rather than some quality related to small car stability or handling.

2. Errors in data collection? The author used the FARS and NASS files in their entirety and thus the collection procedures used for them is inherently used here. These collection procedures appear valid, given the fact that the FARS data is (and always will be) a representation of "failures" in the system. The data cannot give one an indication of the true safety of the system since the entire range of injuries is not included.

In terms of the concrete median barrier data, the author used unpublished data drawn from police accident reports identified by California DOT researchers. There is no way of assessing how complete this data collection effort was whether or not there were biases in the data.

3. Sufficient data detail? The details in the data did not allow for control of other variables. In addition, the author did not describe the vehicle rollover data or the related collection procedure.

4. Large enough sample? For the purpose that it is involved, it appears that the sample sizes used were adequate.

5. Statistical assumptions met? No statistical tests were run on any of the analyses conducted independently of other studies. Therefore, there were no implied underlying assumptions.

6. Statistical tests? No statistical tests were run and thus none could be reviewed. Because of length limitations imposed by the publisher, the hard data could not be presented and thus the reviewers were unable to analyze the frequency data independently.

7. Correct interpretations? Given the qualifications stated above, it appears that the interpretation of the data are substantially correct. Again, some caution is necessary since very few controls were used and the exposure data used is by no means a true measure of opportunity to crash.

d. References

(1) Griffin, L.I., III. Probability of Overturn in Single-Vehicle Accidents as a Function of Road Type and Passenger Car Curb Weight. Austin, Texas: Texas Transportation Institute, Texas A&M University. November, 1981.

(2) Griffin, L.I., III. Probability of Driver Injury In Collisions with Roadside Appurtenances as a Function of Passenger Car Curbweight.

Austin, Texas: Texas Transportation Institute, Texas A&M University. October, 1981.

(3) Bronstad, M.E., Calcote, L.R. & Kimball, C.E.,Jr. Concrete Median Barrier Research. Research Report No. FHWA-RD-77-4, Volume 2. Washington, D.C.: Federal Highway Administration, March, 1976.

a. Literature Citation

Washington State Department of Transportation, Public Transportation and Planning Division. Small Car Accident Experience in Washington State. Olympia, Washington: The State, January, 1983.

b. Study Description

1. Objective. The overall objective of this study was to evaluate the effects on safety of increases in the number of smaller cars on the highways.

2. Key Elements. Small car safety, crash severity, registration crash rates.

3. Data Collection. Statewide police-reported crash data for the period 1973 to 1979 along with registration and crash data for 1980 are examined in this study. There were a total of 768,356 cars in crashes in the 1973 to 1979 period while, in 1980, there were 2,050,000 cars registered in the State and a total of 106,504 cars in crashes.

4. Analysis Method. First, passenger car categories were defined by weight as follows:

Subcompact -	less than 2401 lb (1.09 Mg)
Compact -	2401 to 3000 lb (1.09 to 1.36 Mg)
Intermediate -	3001 to 3600 lb (1.36 to 1.63 Mg)
Large -	greater than 3600 lb (1.63 Mg)

For the 1973 to 1979 period, statistics are provided by car size and individual accident year for all accidents, for injury accidents and for fatal accidents. Regression plots by crash year are presented for each level of crash severity and an accident severity index is presented. Motor vehicle registration and accident data for 1980 is used to provide various registration crash rates by car size. In addition, percentage distributions within car size are given for the following variables: roadway surface condition (e.g., dry, wet); roadway character (e.g., straight and level alignment); collision type (e.g., rear-end, left turn); and object struck (e.g., guardrail, tree or stump, bridge rail).

5. Results. The study concludes that smaller automobiles are experiencing increased numbers of accidents along with the following:

- A higher percentage of fatal and injury accidents.
- A greater proportion of accidents on wet, snowy, and icy roadways, and on horizontal and vertical curves.
- A high frequency of overturning and rear-end collisions.

o A high percentage of fatalities and injuries resulting from striking poles and going over an embankment.

c. Critical Analysis

1. Authors consider relevant variables? With respect to exposure or denominator data so necessary in the problem identification area, the authors appear to do the best that they could with that which was available __ registration data. Based on crashes per 1000 registered vehicles, the rate increases as car size increases as has been found in some other recent work. However, driver age is NOT accounted for. This is most important as the smaller cars are generally driven by younger drivers who have much more than their share of accidents.

The study is basically a descriptive study. There is no attempt to control for important variables such as driver age, sobriety, vehicle damage, speeds, rural-urban, etc. Without this attempt, it remains unclear whether the evident high frequency of overturning and rear-end collisions is a function of car size or more so a function of driver and environmental (e.g., differential rural-urban usage) characteristics.

2. Errors in data collection? As this is motor vehicle registration data and police-reported accident data, the quality of the data should be comparable to that in many other States which is quite adequate. Perhaps the main area of concern might be the make and model (e.g., Chevrolet Citation) designations from which car sizes were determined. However, if this information came from the vehicle registration card, this concern would be minimized. (There is no way to determine from whence the make/model information was derived.)

3. Sufficient data detail? The data (frequency of accidents, accident severity) presented in this study on car size, accident year, vehicle type, roadway surface condition, roadway character, collision type and object struck were adequately described and sufficient for the descriptive analysis that was undertaken. It would not have been adequate for a more complete analysis that controlled for other important variables.

4. Large enough samples? On average, the approximately 105,000 cars in crashes annually should be more than adequate. Likewise for the 2,050,000 registered cars.

5. Statistical assumptions met? Almost no statistical tests were run other than a z-test for differences in proportions between car sizes with respect to roadway surface conditions, roadway character, collision type and object struck. These appear appropriate for the situation.

6. Statistical tests? Z-tests (see #5) for differences in proportions. The results of these tests are somewhat obscured by the text.

7. Correct interpretations? As there were no attempts to control for important variables such as driver age, rural-urban location, etc., it would seem that the conclusions reached are, at best, preliminary.

a. Literature Citation

Woods, Donald L. "Small car impacts on highway design," ITE Journal, 53(4). Washington, DC: Institute of Transportation Engineers, April, 1983, pp. 20-24.

b. Study Description

1. Objectives. This article reviews the shift in the size of the vehicle population and discusses the possible problems which may result from this shift.

2. Key Elements. Vehicle fleet changes, small car safety, appurtenances.

3. Data Collection. No new data were identified as having been collected in this study. It is simply a review of the results and findings from work conducted by the author himself.

4. Analysis Method. Again no new data were collected and no analysis conducted. This is simply a review of other information and results.

5. Results. The author notes that changes in vehicle weights and sizes have had "dramatic" effects on certain design parameters including eye height, bumper height, vehicle length and width, turning radius, acceleration ability, braking ability, and vehicle stability. At the same time that these changes are taking place, roadway design standards have not changed. He then goes on to discuss the specific changes that have occurred in these parameters.

While engine size has been reduced dramatically, he notes that there will not be a dramatic change in acceleration ability due to the decrease in weight coupled with the engine reduction. Total length of the vehicle should decrease from a current (1983) level of 15.8 ft (4.8 m) to 13.7 ft (4.2 m) by 1990. He then goes on to present some hypothesized problems which may arise. (It is noted that no data is presented to support these findings in this paper.) First, differential pavement levels between the lane and shoulders may become more critical to smaller vehicles. Second, pavement cracks and deterioration may be more critical to smaller vehicle stability. Third, superelevation transitions appear to be more critical to smaller vehicles. Fourth, friction, both stopping and turning, will be more critical in the lighter rear-drive vehicles since these vehicles are less stable on wet pavement.

He then cites a specific problem which he sees as needing immediate changes in standards for roadside appurtenances: (1) Bumper heights -- 80 percent of the minicompacts (less than 2000 lb (0.91 Mg) have bumper midheights of less than 17 in (432 mm). The lower edge of a typical w-beam is 17-1/16 in (433 m) above the ground when mounted on a guard post. Obviously mismatches will occur leading to potentially increased snagging and abrupt changes in velocity. (2) Shoulder, curb and other roadway clearance -- 30 percent of the minicompacts have less than the old 6-in (150 mm) clearance standard. (3)

Guardrail end treatments -- both the breakaway cable terminal and the turn down end treatment, used on the ends of many guardrails across the nations, do not appear to work adequately for the minicompact size vehicles. (4) Median barriers -- there is a documented increase in rollovers of smaller vehicles when they strike concrete median barriers. He goes further to note that this is not just a median barrier problem, but a general trend to rollovers after impact with any obstacle, on roadside slopes, or with other vehicles. (5) Crash cushions -- there is a need to change both the standards and the design of crash cushions to allow them to handle 1200-lb (0.54-Mg) vehicles and the author says this is currently feasible within the technology available. (6) Sign supports -- existing small sign supports on most of the highways, even Interstates, do not yield or break away when struck by a smaller vehicle, leading to snagging overturns, and severe velocity changes in many cases. (7) Ditchbanks -- the present ditch slope designs are for 4000-lb (1.81 Mg) vehicles. Crash tests have shown that they are not suitable for the smaller vehicles which have a greater tendency to overturn. (8) Sideslopes -- the use of 3 to 1 sideslopes, currently used in many high level roadway designs, is very much open to question because of the greater instability associated with the smaller vehicles when traveling on uneven off-road terrain. (9) "Delicate" hardware -- because smaller vehicles will require the more "delicate" hardware there will be a great deal more maintenance required after crashes. In contrast, there is no foreseen increase in maintenance budgets to be used for fixing hardware and thus concludes that "every effort should be made in highway design to minimize the need for highway hardware."

c. Critical Analysis

Because this is a review of other studies, the 7-point critical analysis checklist will not be used. However, it is noted that very little data were presented to support many of the potential problems cited above.

a. Literature Citation

Zador, P., Stein, H., Hall, J., and Wright, P. Superelevation and Roadway Geometry: Deficiency at Crash Sites and on Grades (Abridgement). Washington, DC: Insurance Institute for Highway Safety. January, 1985.

b. Study Description

1. Objectives. Engineering survey data from rural primary roads were analyzed to determine the effect of grade on superelevation after adjustment for curvature. The adjusted data were then analyzed to determine the effect of superelevation on crashes.

2. Key Elements. Roadway geometry, grade, superelevation, curvature, rollover accidents.

3. Data Collection. Engineering survey data were collected at locations centered on a reference point where a fatal vehicle rollover accident had occurred, at comparison locations one mile upstream from the crash site and at a stratified random sample of 300 sites. Ten curvature and superelevation and 11 gradient measurements were collected along a 100-ft (30.5-m) section of roadway centered on the crash or comparison site. At the random sites, measurements were taken 50 ft. (15.2 m) before and after the reference points.

4. Analysis Method. The basic unit for statistical analysis were roadway sections 100 ft. in length described by one measurement of superelevation rate and curvature and two measurements of vehicle alignment. Regression analysis was used to study the effects of grade and section type on the linear relationship between superelevation rate and curvature, and to study differences between crash sites and comparison sites in terms of superelevation, curvature, and grade.

5. Results. The superelevation on uphill (+2.5 percent) and downhill (-2.5 percent) sections was found to be deficient relative to curves on flat road sections. The authors concluded that "because the results were based on comparisons between the linear regression estimates of superelevation rates as functions of curvature, the deficiency in superelevation cannot be due to curvature differences between flat road sections and those with grade" (page 7). The results were found to hold for various parameters including State, road class and section type. The relationship was not significant for all of the comparisons made. However, in all cases with significant differences, the sections with uphill or downhill grades were deficient in superelevation.

The superelevation rates at crash sections were also found to be deficient compared to those at comparisons sections. Again, the analysis was adjusted for curvature and thus the deficiency appears to not be the effect of increased curvature at the crash sites. This finding was generally valid regardless of State, road class, or grade.

c. Critical Analysis

1. Authors consider relevant variables? Because this was an abridgment of a more detailed study, it is sometimes difficult to determine why certain steps were taken by the authors. For example, the authors eliminated from the analyses sections that (1) were straight, (2) had "excessive" curvature, or (3) had large increases in curvature relative to adjacent sections (curve transitions). Presumably this was done to ensure that the crash sites which were on curves were being compared to other curve sections, and also to provide a "cleaner" sample by eliminating transitions and excessive curve sections. As the authors note, a number of roadway characteristics such as pavement type and condition, maximum superelevation rate, design speed, pavement width, roadside feature, and others would clearly be related to the occurrence of single vehicle crashes on curves. These factors were not considered in this paper. The authors attempted to control for such factors since approximately three-quarters of the comparison sections were located on the same roads one mile upstream from the crash sites. However, fatal accident sites often contain several deficient features which in combination may contribute to a severe accident occurrence. For example, a horizontal curve site with a fatal accident may have lower skid resistance, one or more large trees near the roadway edge, a greater shoulder edge dropoff, and/or other deficiencies in addition to less superelevation, when compared to a curve one mile downstream. Thus, although adequate superelevation may indeed be necessary for safe curve design, the analysis attributes to superelevation deficiency alone, while ignoring all of the other possible causes.

2. Errors in data collection. While not stated in the paper, telephone conversations with the authors indicated that the crash-related engineering survey data was collected along a 100-ft (30.5-m) section centered on the point at which the vehicle left the pavement. This judgement was based on a visit to the accident site after being alerted by investigating police agencies. Thus, there is the possibility that the wrong "point of accident" was chosen, and that the data collected could be somewhat erroneous. However, if care was taken in identifying and ascertaining where the accident sequence began, the characteristics could well have stayed consistent enough so that any errors here are small.

3. Sufficient data detail? Curvature and gradient measurements were collected every 10 ft (3.5 m) along a 100-ft (30.5-m) segment for the crash and comparison sites. In some respects this may represent a case of "overprecision" of data detail if, indeed, there was some question as to whether the accident actually occurred here. However, as stated above, in general the data collected appear to be quite adequate for the analysis conducted later.

4. Large enough sample size? After eliminating various sections from the analysis (see #1 above), 521 crash sites and 513 comparison sites remained.

Regression analysis by State (2) and roadway type (2) resulted in cell sizes ranging from 31 to 117, apparently sufficient. Unfortunately cell sizes for most of the smaller subcategories were not stated in this version of the paper. In one instance where the results were not consistent with the overall conclusions (i.e., an excess of superelevation) it was noted that there were only 22 sections with uphill vertical alignment.

5. Statistical assumptions met? Obviously superelevation and curvature are closely related. The authors stated that they made an "adjustment" for curvature using the regression procedures. Obviously, an improper "adjustment" could leave a residual curvature effect that could have confounded the results.

6. Statistical tests? Linear multivariate logistic regression analysis using the SAS general linear model procedure was done.

7. Correct interpretation? The authors found that, after controlling for curvature, sections with grade had less superelevation than flat sections. After adjusting for both curvature and grade crash locations were found to have less superelevation than comparison sections. Thus, they conclude, "inadequate superelevation presents a risk that should be eliminated from the roadway system." If, in fact, none of the previously mentioned concerns related to accident location or control over curvature or other variables have adversely affected the outcome of the analysis then the conclusions appear appropriate. Another critical question remaining in terms of conclusions relates to the fact that correlation does not necessarily mean causation. While it appears very logical, the fact that superelevation deficiencies are associated with accident location does not necessarily mean that the relationship between superelevation deficiencies and accidents is a causative one. If this relationship were there but were not causative, then improving superelevation alone may not result in a safety improvement.

This study clearly points out the fact that superelevation on downgrade curve sections is deficient as compared to similar curves on flat or uphill sections. This is definitely a concern based on the need for superelevation, particularly as it relates to speeds of vehicles on the downgrade highway sections. One might also argue that logically the adequacy of superelevation may be important as to whether a vehicle runs off a horizontal curve, but the severity of a resulting accident is largely a function of the roadside condition (i.e., what is struck and whether the vehicle rolls over), the vehicle characteristics (i.e., small car versus large car), the use of safety belts by the passengers, the general health of vehicle occupants, the vehicle speed on impact, among other factors. Thus, a more appropriate accident measure may be the rate of run-off-road accidents (or rate of injury + fatal run-off-road accidents) for determining the influence of superelevation on curve accidents.

APPENDIX B

Accident Data

North Carolina, Texas and the State of Washington provided the accident data analyzed in this study. These three States provide a broad geographical distribution and have similar uniform Statewide reporting procedures and known quality accident data. In each, accident data was examined for calendar years 1981, 1982 and 1983. For uniformity across States, only cars produced after 1970 were utilized in the analyses. By so doing, the possible car age effect has been reduced considerably as the VW Beetle dominated the minicar scene in the 1960's.

For each of the three States, there was a valid procedure for categorizing cars as minicars (that is, less than 2204 lb (1.0 Mg)) vs. midsized cars (2204 to 3000 lb (1.0 to 1.36 Mg)) and big cars (over 3000 lb (1.36 Mg)). In North Carolina, this was done using the vehicle identification number (VIN) and a VIN-decoding program provided by R. L. Polk. In Texas, an existing program converts the officer's make/model and year into vehicle weight groups. For the State of Washington, we utilized the officer's make/model and year along with the Texas designation for weights to provide the study weight groups.

Each of the State data bases had a host of variables which were important to examine and which were similar from State to State. These included day of week, investigating agency, road feature, road characteristics, curve information, roadway class, road surface, road condition, light condition, weather, crash type or means of involvement, estimated speed, whether or not the vehicle rolled over, object struck (according to a detailed breakdown), region of impact on the vehicle, and certain driver characteristics such as age and sex, belt use, intoxication and violations.

In addition, there was a capability in each State to link the accident data with certain features and characteristics of the roadway. These included the ability to examine such variables as surface type and total surface width, median type and width, shoulder type and width, ADT, terrain, functional type, etc. In North Carolina, this linking was done through the Merge system with automatically merges highway and accident data. For Washington, the 7000 mi (11,300 km) of State-maintained roads have a special road inventory file including variables such as terrain surface type, shoulder width and type, and median width and type, along with an intersection inventory file which includes variables such as roadway features, traffic control type, and interchange type. In addition, and most importantly, Washington has detailed horizontal and vertical curvature information on a third highway file that was critical to this study. Texas routinely links accident with roadway data to provide information such as accidents by highway surface width and type, shoulder type, ADT, percent trucks, etc. Thus, each of the three States had a mechanism for simultaneously looking at accident and roadway geometrics data.

The final data base consisted of 486,695 relevant crashes in North Carolina, 221,318 crashes in Washington, and 866,011 crashes in Texas.

APPENDIX C

Analysis Procedures

The data analyses were aimed at both problem identification and testing various hypotheses involving minicar crashes. These analyses involved:

- o Identifying factors associated with minicar accidents; i.e., being able to describe minicar accidents in terms of driver characteristics, accident type, roadway and environmental characteristics.

- o Identifying certain accident types such as rollovers where minicars appear to have special problems; then developing a series of models to determine variables along with car size which account for the elevated rollover properties.

- o Examining crash severity differences for minicars vs. larger cars through driver injury (A+K and any injury) as the response variable.

Procedures included analyses utilizing descriptive statistics, variable selection, categorical data modeling, logistic regression, and specialized procedures for examining the various hypotheses such as was done in examining minicar vs. large car accidents on curves (by degree of curvature) using the curvature file from Washington.

The descriptive analyses mainly compared minicar crash distributions vs. those of midsize and large cars for a host of accident and geometric variables in each of the three States.

For each geometric feature analyzed relative to its role in accidents for cars of different sizes, it is necessary to generate a collection of control variables to include in the analysis. This variable selection was carried out using a stepwise procedure (see reference 1) for selecting independent categorical predictor variables relative to a given response variable (e.g., proportion of minicar crashes resulting in rollovers). This procedure is analogous to forward stepwise regression in that it results in the selection of a set of variables which is in some sense "optimal" (as determined by a series of higher order Chi-square tests) in accounting for the most variation in the response variable. For example, in North Carolina, the variables selected included rollover/no rollover, object struck, means of involvement, curvature, terrain (e.g., rollover), and shoulder type and width.

Having identified the set of the most important explanatory variables, a series of regression models for categorical data (see, for example, reference 2) were fit to the data to examine the three areas cited at the beginning of this section. Models were fit separately for single vehicle crashes and for multivehicle crashes for minicars vs. nonminicars (i.e., midsize and large cars) and for minicars vs. large cars. The FUNCAT procedure in SAS generated these variables categorical regression models.

A supplementary analysis utilized logistic regression which is optimal in situations where there is a combination of continuous and discrete variables as is the case here. Logistic regression was used to examine minicar crashes on curves utilizing the North Carolina accident data.

The specialized procedures such as that used in examining potential problems of minicars on curved roadways in Washington are generally described in the text of this report as they are being utilized.

As expected at the outset of this study, there is a dearth of good detailed exposure information by car size. Although available, vehicle registration was deemed inadequate since merely the registering of a vehicle does not imply any level of subsequent exposure to accidents. For the most part, over- and underrepresentation in crashes by car size is determine from a conditional argument. That is, given the set of crashes for minicars vs. large cars, what relative percentages result in rollovers? in striking utility poles? occur on curves? etc.

REFERENCES

(1) Higgins, J.F. and Koch, G.G. "Variable selection and generalized Chi-square analysis of categorical data applied to the large cross-sectional occupational health survey," International Statistical Review, 45(1), 1977, pp. 51-62.

(2) Lacey, J.H., Stewart, J.R., and Council, F.M. Techniques for Predicting High-Risk Drivers for Alcohol Countermeasures. Volume I - Technical Report. (DOT-HS-5-01250). Chapel Hill: University of North Carolina Highway Safety Research Center. 1979.

APPENDIX D

Treatments Proposed by the Review Panel

The following treatments and critical accident research issues were proposed by the expert panel following the initial literature review and accident analyses efforts. The treatment/issues are group into nine basic areas. No priority is suggested by the order of listing.

Horizontal and Vertical Curvature

- Widen pavement on curves
- Use spirals in all new designs
- Widen shoulder/increase clearzone on outside of curve
- Re-examine and modify superelevation standards for minicars
- "Michie shoulder design" -- on the outside of curve, superelevate shoulder at 8:1 slope with guardrail at top
- Use variable-spaced transverse pavement markings prior to curve to reduce speeds
- Paint pavement in advance of curve to produce definite visual hazard (i.e., make curve appear worse than it is
- Examine whether delineation helps or hinders

Curbs/Traffic Islands

- Reduce frequency of curbs/traffic islands in new designs, particularly in suburban and rural areas
- Redesign drop inlets to reduce height
- Reduce effects of repaving near curb inlets (i.e., remove "dip" in pavement)
- Change design of curb face to make it mountable for minicars
- Develop a strategy for removal of traffic islands (i.e., which ones, how to remove)

Sideslope/Embankments/Ditch Banks

- Limit embankment heights to less than 5 ft (1.5 m) within expanded clear zones
- Compare cost-benefits of improved longitudinal barrier to less hazardous sideslope designs
- Widen unpaved shoulders
- Place drainage ditches underground (piped) at critical "run-off-road" locations

- Build "recovery terraces" into sideslopes (with or without arrestor beds)

Longitudinal Barriers

- Explore the flat wall concept for median barriers
- Examine a "staged rail" concept -- a flat wall behind a w-beam on a spring
- Increase CMB height to $\pm$50 in ($\pm$1.3 m)
- Evaluate smooth (lower friction) barrier faces
- Use Thrie-beam or rub rail instead of w-section
- In longitudinal barrier tests, use higher attack angles and a yawing vehicle in the minicar tests
- Redesign guardrail ends to reduce rollover for minicars

Culvert/Drainage Structures

- Eliminate parallel (driveway) culverts through use of "drive-through-ditch" designs
- Extend transverse culvert ends beyond the 30-foot (9.1-m) clearzone

Utility Poles/Luminaire Supports

- Reduce maximum height of concrete base to 4 inches
- Design and employ lighter poles (fiber glass, plastic) at critical locations
- Protect poles with crash cushions or longitudinal barriers in critical locations
- Relocate utility poles to the inside of curves
- Relocate utility poles beyond the 30-ft (9.1-m) clearzone

Pavement and Pavement Edge

- Develop and utilize a bevelled pavement edge design (i.e., a "wedge" at the EOP)
- Resurface pavement to increase skid number to reduce minicar run-off-road accidents
- Resurface pavement to decrease number of discontinuities to reduce minicar run-off-road accidents
- Implement stricter enforcement of pavement edge standards
- Develop and utilize better methods for stabilizing shoulders to prevent erosion and deterioration

Driver Improvements

- Since current driver training has a low probability of success, teach separation from hazardous situations rather than recovery from such situations
- Determine whether European single vehicle accident rates

are different from US rates, and if so, determine driver differences. Develop education programs to retrain US drivers to European techniques

Vehicle Improvements

- Change weight distribution to improve yaw stability
- Reduce weight with no change in vehicle size parameters (i.e., wheelbase, track width, etc.)
- Continue 55 limit with strict enforcement to reduce minicar speeds
- Design (and require) vehicle bumper stiffness to ensure activation of breakaway mechanisms in poles, barrier ends, etc.
- Limit steering response for minicars
- Develop computer limits/inputs to braking and steering
- Improve crashworthiness of the front-wheel structure for improved interaction with barriers
- Improve suspension properties
- Increase wheel size (while keeping center of gravity low)
- Determine why the minicar "angle of attack" seems to be more acute, and correct the deficiency
- Lower the c.g. through innovative placement (relocation) of vehicle weight
- Since the radius of gyration appears to be an important parameter, develop methods for increasing it
- Increase availability of passive restraints in minicars

APPENDIX E

Details of the HVOSM Runs

Vehicle Inputs/Validation Runs

Simulation Input Setup

Three new vehicles were set up in HVOSM input format for use in the project. HVOSM datasets were created for a 1978 Dodge Omni, a 1978 Chevrolet Malibu and a 1982 Chevrolet Celebrity. Partial definitions of each of the vehicles' weights, moments of inertia, center of gravity locations and suspension spring rates were received by MCI from HSRC, who obtained them from General Motors. The information received was supplemented by data from similar vehicles and tires that had been previously measured (e.g., refs. 1,2) and approximate representations of the vehicles were created in the HVOSM input data format. Figures 5 through 8 are the HVOSM-86 input data decks for each of the three vehicles.

Other vehicle data sets (Figures 9-12) activated for use in the project, which were assembled from various references, are:

Vehicle	Reference Source
1979 VW Rabbit	3
1976 Ford LTD	3
1971 Vega Sprint Coupe	4
1978 Honda Civic	5

Table 11 gives a summary of pertinent vehicle parameters for all the simulated vehicle datasets used in the project.

Table 11. Summary of Simulated Vehicle Data and Reference Sources

Ref	Vehicle	Drive Type	Total Wgt lbs	WB in	H Total Vehicle CG Hgt in	T Track Width in.	T/2H
3	1979 VW Rabbit	F	1800	94.5	19.69	54	1.37
3	1979 VW Rabbit	F	2410	94.5	21.3	54	1.27
3	1976 Ford LTD	R	4450	121.0	20.66	64.2	1.55
–	1978 Dodge Omni	F	2138	97.0	20.41	55.3	1.35
–	1978 Chevvy Malibu	R	3580	108.0	20.74	58.15	1.40
–	1982 Chevy Celebrity	F	2974	105.0	20.31	57.85	1.42
4	1971 Vega	R	2639	97.0	18.76	54.6	1.46
5	1978 Honda Civic	F	1699	86.25	20.98	51.5	1.23

SI Equivalents:
1 in. = 25.4 mm
1lb = 0.45 kg

```
STEP-STEER TEST RUN                                                                     0 100
0.0       4.0       0.01      0.050     70.       2.5       2.5       0.0               0 101
1.0                                               0.002                                 0 102
1.0                                                                                     0 103
0.0       1.0       1.0       0.0       0.0       0.0       0.0       1.0               0 104
1978 DODGE OMNI                                                                         0 200
5.28      0.329     0.316     2699.     12435.    13382.    389.                        0 201
35.4      58.6      55.5      55.1                                                      0 202
0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0               0 203
82.       300.      600.      300.      600.      0.50      -1.80     2.50              0 204
62.       300.      600.      300.      600.      0.50      -2.0      2.75              0 205
6.08      15.       0.1       3.58      15.       0.1                                   0 206
90115.    128471.   0.0       0.0       0.0       0.0       0.0                         0 207
-5.0      5.0       1.0       1.0       0.0                                             0 209
-0.08     -0.33     -0.50     -0.50     -0.17     0.33      0.83      1.83      2.58    1 209
3.50      5.0                                                                           2 209
0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0     3 209
0.0       0.0                                                                           4 209
-0.65     -0.30     -0.10     0.05      0.05      0.0       -0.20     -0.45     -0.80   5 209
-1.25     -1.85                                                                         6 209
GOODYEAR POLYSTEEL RADIAL P155/80R13                                                    0 300
1.0       1.0       1.        1.0       6.0       0.25                1.0               0 301
1099.     5.0       10.       2542.     9.91      2366.     0.687     -8184.    0.75    1 301
0.80                                    11.313                                          0 302
                                                                                        0 303
1.03      -4.167-5-4.340-8400.          1600.                                           1 303
STEP STEER 6 0.20 SEC                                                                   0 400
0.18      0.26      0.01      1.0       1.0       0.0                                   0 401
0.0       0.0       0.0       4.5       4.5       4.5       4.5       4.5       4.5     1 401
0.0       0.0       0.0       -30.      -60.      -90.      -120.     -120.     -120.   2 401
 45 MPH                                                                                 0 600
0.0       0.0       0.0       0.0       0.0       0.0       0.0                         0 601
0.0       0.0       -21.6     792.0     0.0       0.0                                   0 602
0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0               0 603
                                                                                        09999
```

Fig. 5 HVOSM-86 Input Dataset for 1978 Dodge Omni

```
HVOSM-RD2, 1986 UPDATE INPUTS                                                           0 100
0.0       4.00      0.010     0.050     70.0      0.0       0.0                         0 101
0         0                                                                             0 102
         1                                                                              0 103
0.0       0.0       0.0       0.0       0.0       0.0       0.0       1.0       0.0     0 104
1978 CHEVY MALIBU                                                                       0 200
8.32      0.51      0.82      4726.     29500.    30872.    -487.     550.0             0 201
50.       58.       58.5      57.8      0.0       47.0                                  0 202
0.0       0.0       0.0       0.0       0.0       0.0       9.91      9.868             0 203
101.      300.      600.      300.      600.      0.50      -2.54     3.28              0 204
123.      300.      600.      300.      600.      0.50      -2.80     3.87              0 205
6.85      40.0      0.10      7.48      35.0      0.10                                  0 206
270678.   0.0       0.0                                                                 0 207
-3.0      3.0       1.0                                                                 0 209
-0.43     -0.95     -1.22     -1.26     -0.98     -0.41     0.0                         1 209
GOODYEAR P19575R14                                                                      0 300
1.0       1.0       1.0       1.0       6.0       0.25                1.0               0 301
1250.     3.0       10.       2701.     10.1      2533.     1.30      4591.     0.75    1 301
0.80                                    12.94                                           0 302
                                                                                        0 303
1.23      -.3300-30.7590-7400.          1600.                                           1 303
STEP STEER 6 0.20 SEC                                                                   0 400
0.18      0.26      0.01      1.0       0.0       1.0                                   0 401
0.0       0.0       0.0       4.5       4.5       4.5       4.5       4.5       4.5     1 401
0.0       0.0       0.0       -45.      -90.      -135.     -180.     -180.     -180.   2 401
                                                                                        0 500
 45 MPH                                                                                 0 600
0.0       0.0       0.0       0.0       0.0       0.0                                   0 601
0.0       0.0       -22.08    792.0     0.0       0.0                                   0 602
0.0       0.0       0.0       0.0       0.0       0.0                                   0 603
                                                                                        09999
```

Fig. 6 HVOSM-86 Input Dataset for 1978 Chevy Malibu

Note: HVOSM input data and descriptions are not provided in equivalent SI (metric) units since the HVOSM is not presently written to accept SI units.

```
HVOSM-RD2 ,1986 UPDATE INPUTS                                                                0 100
0.0       4.0       0.01      0.050     70.       2.5       2.5       0.0                    0 101
0.0                                               0.010                                      0 102
1.0                                                                                          0 103
0.0       1.0       1.0       0.0       0.0       0.0       0.0       1.0                    0 104
1982 CHEVY CELEBRITY                                                                         0 200
6.76      0.51      0.82      3699.     20578.    22251.    168.      250.                   0 201
37.8      67.1      58.7      57.       1.31      40.                                        0 202
0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0                    0 203
100.      300.      600.      300.      600.      0.50      -2.0      2.20                   0 204
87.       300.      600.      300.      600.      0.50      -2.4      2.50                   0 205
2.        37.       0.10      2.        58.       0.10                                       0 206
161201.   25755.    0.0       0.0       0.0       0.0       0.0                              0 207
-5.0      5.0       1.0       0.0       0.0                                                  0 209
-0.08     -0.33     -0.50     -0.50     -0.17     0.33      0.83      1.83      2.58         1 209
3.50      5.0                                                                                2 209
GENERAL DUAL STEEL III,P195/75R14                                                            0 300
1.0       1.0       1.        1.0       6.0       0.25                1.0                    0 301
1297.     3.0       10.       2113.     8.91      3771.     0.555     -8680.    0.75         1 301
0.80                                    12.50                                                0 302
                                                                                             0 303
1.151     -2.500-44.3100-8400.          1600.                                                1 303
STEP STEER @ 0.20 SEC                                                                        0 400
0.18      0.26      0.01      1.0       1.0       0.0                                        0 401
0.0       0.0       0.0       4.5       4.5       4.5       4.5       4.5       4.5          1 401
0.0       0.0       0.0       -40.      -80.      -120.     -160.     -160.     -160.        2 401
AMU = 1.00                                                                                   0 500
-10000.   10000.    20000.    -10000.   10000.    20000.                                     0 501
0.0       0.0                                                                                1 501
0.0       0.0                                                                                2 501
1.25                                                                                         0 506
 45 MPH                                                                                      0 600
0.0       0.0       0.0       0.0       0.0       0.0       0.0                              0 601
0.0       0.0       -21.8     792.0     0.0       0.0                                        0 602
0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0                    0 603
                                                                                             09999
```

Fig. 7 HVOSM-86 Input Dataset for 1982 Chevrolet Celebrity

```
STEP STEER TEST                                                                              0 100
0.0       4.00      0.010     0.050     70.       2.5       2.5       0.0                    0 101
1.0                                               0.002                                      0 102
1.0                                                                                          0 103
0.0       0.0       0.0       0.0       0.0       0.0       0.0       1.0                    0 104
1979 VW RABBIT 2 DOOR,2410 LB                                                                0 200
5.593     0.3287    0.3157    2600.     8850.     10400.    0.0                              0 201
31.49     63.01     54.5      53.5                                                           0 202
0.0       0.0       0.0       0.0       0.0       0.0       11.893    11.563                 0 203
85.       303.      902.      2916.     134265.   0.65      -1.62     2.88                   0 204
73.       150.      37.       1029.     23210.    0.65      -2.91     3.59                   0 205
.08       15.       0.1       3.58      15.       0.1                                        0 206
.0        84750.    0.0       0.0       0.0       0.0       0.0                              0 207
00.       5000.     0.349     500000.   0.05      0.75                                       0 208
-5.0      5.0       1.0       1.0       0.0                                                  0 209
-0.08     -0.33     -0.50     -0.50     -0.17     0.33      0.83      1.83      2.58         1 209
3.50      5.0                                                                                2 209
0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0          3 209
0.0       0.0                                                                                4 209
-0.65     -0.30     -0.10     0.05      0.05      0.0       -0.20     -0.45     -0.80        5 209
-1.25     -1.85                                                                              6 209
GOODYEAR POLYSTEEL RADIAL P155/80R13                                                         0 300
1.0       1.0       1.        1.0       6.0       0.25                1.0                    0 301
1099.     5.0       10.       2542.     9.91      2366.     0.687     -8184.    0.75         1 301
0.80                                    11.313                                               0 302
                                                                                             0 303
1.03      -4.167-5-4.340-80.80                                                               1 303
STEP STEER @ 0.20 SEC                                                                        0 400
0.18      0.26      0.01      1.0       1.0       0.0                                        0 401
0.        0.        0.        4.5       4.5       4.5       4.5       4.5       4.5          1 401
0.0       0.0       0.0       -30.      -60.      -90.      -120.     -120.     -120.        2 401
                                                                                             0 500
 45 MPH                                                                                      0 600
0.0       0.0       0.0       0.0       0.0       0.0       0.0                              0 601
0.0       0.0       -22.492   792.0     0.0       0.0                                        0 602
0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0                    0 603
                                                                                             09999
```

Fig. 8 HVOSM-86 Input Dataset for 2400-lb. 1979 VW Rabbit

```
STEP STEER TEST                                                                           0 100
0.0       4.00      0.010     0.050     70.       2.5       2.5       0.0                 0 101
1.0                                               0.002                                   0 102
1.0                                                                                       0 103
0.0       0.0       0.0       0.0       0.0       0.0       0.0       1.0                 0 104
1979 VW RABBIT 2 DOOR,1800 LB                                                             0 200
4.014     0.3287    0.3157    1932.     7231.     7976.     0.0                           0 201
32.7      61.80     54.5      53.5                                                        0 202
0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0                 0 203
85.       303.      902.      2916.     134265.   0.65      -1.62     2.88                0 204
73.       150.      37.       1029.     23210.    0.65      -2.91     3.59                0 205
6.08      15.       0.1       3.58      15.       0.1                                     0 206
0.0       84750.    0.0       0.0       0.0       0.0       0.0                           0 207
300.      5000.     0.349     500000.   0.05      0.75                                    0 208
-5.0      5.0       1.0       1.0       0.0                                               0 209
-0.08     -0.33     -0.50     -0.50     -0.17     0.33      0.83      1.83      2.58      1 209
3.50      5.0                                                                             2 209
0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0       3 209
0.0       0.0                                                                             4 209
-0.65     -0.30     -0.10     0.05      0.05      0.0       -0.20     -0.45     -0.80     5 209
-1.25     -1.85                                                                           6 209
GOODYEAR POLYSTEEL RADIAL P155/80R13                                                      0 300
1.0       1.0       1.        1.0       6.0       0.25                1.0                 0 301
1099.     5.0       10.       2542.     9.91      2366.     0.687     -8184.    0.75      1 301
0.80                                    11.313                                            0 302
                                                                                          0 303
1.03      -4.167-5-4.340-8400.          1600.                                             1 303
STEP STEER @ 0.20 SEC                                                                     0 400
0.18      0.26      0.01      1.0       1.0       0.0                                     0 401
0.        0.        0.        4.5       4.5       4.5       4.5       4.5       4.5       1 401
0.0       0.0       0.0       -30.      -60.      -90.      -120.     -120.     -120.     2 401
                                                                                          0 500
 45 MPH                                                                                   0 600
0.0       0.0       0.0       0.0       0.0       0.0       0.0                           0 601
0.0       0.0       -21.1     792.0     0.0       0.0                                     0 602
0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0                 0 603
                                                                                          09999
```

Fig. 9 HVOSM-86 Input Dataset for 1800-lb. 1979 VW Rabbit

```
 VOSM-RD2,1986 UPDATE                                                                     0 100
3.0       4.0       0.01      0.050     70.       0.        0.        0.00                0 101
0.0       0.0       0.0       0.0       0.0       0.0010                                  0 102
     1                                                                                    0 103
0.        1.        1.        0.        0.        0.        0.        1.        0.0       0 104
1976 FORD LTD, 4450 LB                                                                    0 200
9.860     0.635     1.022     5000.     31000.    35000.    0.0       750.                0 201
52.10     68.90     64.10     64.30     0.0       45.50                                   0 202
0.0       0.0       0.0       0.0       0.0       0.0       10.80     10.66               0 203
120.      189.      600.      588.      600.      0.650     -3.0      3.0                 0 204
115.      324.      600.      864.      600.      0.65      -3.50     4.0                 0 205
6.85      160.      0.10      7.48      55.0      0.10                                    0 206
230000.   0.0       0.033                                                                 0 207
                    0.559                                                                 0 208
-3.0      3.0       1.0                                                                   0 209
-0.43     -0.95     -1.22     -1.26     -0.98     -0.41     0.0                           1 209
HR78-15,GOODYEAR STEELGUARD RADIALS                                                       0 300
1.0       1.0       1.0       1.0       6.0       0.25                1.0                 0 301
1360.     6.0       10.       1564.     14.5      2721.     -.18      654.      0.75      1 301
0.80                                    13.98                                             0 302
                                                                                          0 303
1.33      -.5220-31.4700-70.75                                                            1 303
STEP STEER @ 0.20 SEC                                                                     0 400
0.18      0.26      0.01      1.0       0.0       1.0                                     0 401
0.0       0.0       0.0       4.5       4.5       4.5       4.5       4.5       4.5       1 401
0.0       0.0       0.0       -55.      -110.     -165.     -220.     -220.     -220.     2 401
                                                                                          0 500
-10000.   10000.    20000.    -10000.   10000.    20000.                                  0 501
0.0       0.0                                                                             1 501
0.0       0.0                                                                             2 501
1.07                                                                                      0 506
45 MPH                                                                                    0 600
0.0       0.0       0.0       0.0       0.0       0.0       0.0                           0 601
0.0       0.0       -22.22    792.                                                        0 602
0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0                 0 603
                                                                                          09999
```

Fig. 10 HVOSM-86 Input Dataset for 1976 Ford LTD

```
HVOSM-RD2,1986 UPDATE                                                                0 100
0.0       4.0       0.010     0.050     70.       30.       0.20                   0 101
0.0       0.0                            0.0       .002                            0 102
1.                                                                                 0 103
1.        1.        0.        0.        0.        0.        0.        1.           0 104
1971 VEGA SPORT COUPE                                                              0 200
5.831     0.424     0.575     2000.     12000.    15600.    -100.     250.0        0 201
43.87     53.13     55.1      54.1      1.31      38.0                             0 202
0.0       0.0       0.0       0.0       0.0       0.0       8.58      7.21         0 203
96.       156.8     283.      824.4     313.      0.5       -2.2      3.84         0 204
121.      156.8     283.      824.4     313.      0.5       -2.2      4.84         0 205
2.0       37.       0.01      2.0       58.       0.01                             0 206
0.0       11690.    -.01                                                           0 207
300.      1000.     0.559     100000.   0.345     1.50                             0 208
-4.0      4.0       1.0                                                            0 209
-4.75     -3.08     -1.75     -.73      0.0       0.48      0.65      0.78      0.83   1 209
32.       17.6      0.46      1.0       1500.     90.                              0 215
76.       30.       0.        76.       -30.      0.        76.       30.       6.     0 216
76.       -30.      6.        70.       29.       -12.      70.       0.        -12.   1 216
70.       -29.      -12.      64.       30.       10.       64.       -30.      10.    2 216
24.       28.       -18.      24.       -28.      -18.      6.        22.       -32.   3 216
6.        0.        -32.      6.        -22.      -32.      -14.      29.       -18.   4 216
-14.      -29.      -18.      -44.      22.       -30.      -44.      -22.      -30.   5 216
-18.      22.       -32.      -18.      -22.      -32.      -82.      28.       -16.   6 216
-82.      -28.      -16.      -86.      30.       -2.       -86.      -30.      -2.    7 216
-86.      30.       4.        -86.      -30.      4.        -78.      30.       8.     8 216
-78.      -30.      8.        30.       30.       12.       30.       -30.      12.    9 216
32.       30.       12.       32.       -30.      12.                             10 216
                                                                                   0 300
1.0       1.0       1.0       1.0       6.0       0.25                             0 301
1240.     5.        5.        3625.     7.711     2344.     1.55      5500.     0.75   1 301
0.80                                    11.83                                      0 302
STEP STEER @ 0.20 SEC                                                              0 400
0.18      0.26      0.01      1.0       0.0       1.0                              0 401
0.0       0.0       0.0       4.5       4.5       4.5       4.5       4.5       4.5    1 401
0.0       0.0       0.0       -32.5     -65.      -97.5     -130.     -130.     -130.  2 401
 45 MPH                                                                            0 600
0.0       0.0       0.0       0.0       0.0       0.0       0.0                      0 601
0.0       0.0       -19.89    792.      0.0       0.0                                0 602
0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0            0 603
                                                                                   09999
```

Fig. 11 HVOSM-86 Input Dataset for 1971 Vega

```
STEP STEER MANEUVER                                                                0 100
0.0       4.00      0.010     0.050     70.0      0.0       0.0                      0 101
0         0                                                                        0 102
     1                                                                             0 103
0.0       0.0       0.0       0.0       0.0       0.0       0.0       1.0       0.0    0 104
1978 HONDA CIVIC                                                                   0 200
3.579     0.462     0.356     1569.     7107.     5013.     0.0       108.         0 201
31.75     54.50     51.5      51.5      0.0       42.0                             0 202
0.0       0.0       0.0       0.0       0.0       0.0       13.27     12.71        0 203
133.      330.      608.      330.      608.      0.86      -1.35     2.35         0 204
134.9     189.      225.      189.      225.      0.84      -2.39     3.50         0 205
2.68      58.       0.10      2.50      97.       0.10                             0 206
11700.    30900.    0.0                                                            0 207
                    0.559                                                          0 208
-3.0      3.0       0.50                                                           0 209
-1.50     -1.38     -1.25     -1.13     -1.0      -.63      -.38      0.0       0.63   1 209
1.00      1.45      1.75      2.13                                                 2 209
-5.       5.0       0.50                                                           0 210
0.1079    0.1053    0.1030    0.1011    0.0994    0.0981    0.0971    0.0964    0.0959 1 210
0.0958    0.0960    0.0965    0.0973    0.0984    0.0998    0.1015    0.1035    0.1058 2 210
0.1085    0.1114    0.1147                                                         3 210
-5.0      5.0       5.0                                                            0 211
0.0920    0.0920    0.0920                                                         1 211
MI 155 SR12                                                                        0 300
1.0       1.0       1.0       1.0       6.0       0.25                1.0          0 301
800.      2.50      8.0       1256.8    13.24     1829.19 0.533       -31246.71.0  1 301
0.80                                    10.875                                     0 302
                                                                                   0 303
1.0653    -3.926-41.3843-7 0.80                                                    1 303
STEP-STEER INPUT@0.20 SEC                                                          0 400
0.18      0.26      0.01      1.0       1.0       0.0                              0 401
0.0       0.0       0.0       4.5       4.5       4.5       4.5       4.5       4.5    1 401
0.0       0.0       0.0       -25.      -50.      -75.      -100.     -100.     -100.  2 401
45 MPH                                                                             0 600
0.0       0.0       0.0       0.0       0.0       0.0                              0 601
0.0       0.0       -23.40    792.      0.0       0.0                              0 602
0.0       0.0       0.0       0.0       0.0       0.0                              0 603
                                                                                   09999
```

Fig. 12 HVOSM-86 Input Dataset for 1978 Honda Civic

Modification to the HVOSM Tire Model

As part of this research effort and continuing developments by MCI aimed at refining the HVOSM, several modifications to the HVOSM tire model have been implemented. The modifications include:

Further refinements of the overloaded tire side-force calculation procedures.

Variation of the coefficient of friction of the side force as a function of tire load.

Further Refinements of the Overloaded Tire Side-force Calculation Procedures

The original form of the HVOSM tire model (e.g., Ref. 6) can fail to produce full saturation of the tire side forces under conditions of a broadside slide at extreme tire overload. This deficiency results from the fact that the cornering stiffness for small slip angles can be substantially reduced as the tire loading is increased (see parabolic relationship, p. 112, Ref. 6) and the combination of changes produces a situation in which the nondimensional slip angle variable, ß, may not reach its saturation value of 3.0 at slip angles as large as 90° (see Figure 4.8 of Ref. 6). Clearly, this shortcoming in the tire model has significant effects on the ability of HVOSM to predict vehicle rollover. The leading tires in a side slip motion tend to become overloaded as the condition of rollover is approached, and the inability of the leading tires to produce full-saturation side forces can prevent the achievement of a simulated rollover.

While definitive data for tire properties under conditions of extreme overload and large slip angles have not been found to date, an examination of available measures of the side force properties of underinflated tires (e.g., Figure 13 from Ref. 7) indicates that the side force increases at an increasing rate, as a function of slip angle, at large tire loads. In other words, the plot of side force vs slip angle becomes concave upward rather than concave downward in the range of 0 to 16 degrees of slip angle. If it is assumed that saturation ultimately occurs at slip angles beyond the available 16 degree range, the plot must make a transition to become concave downward somewhere in the range between 16 degrees and full saturation.

From extrapolation of the tire plot for the 8 psi (55 kPa) underinflated tire data plot, it appears that full saturation would occur for the underinflated tire in the range of 35 to 40 degrees of slip angle under the conditions of 1400 lbs (6.2 KN) of tire loading (see Fig. 14).

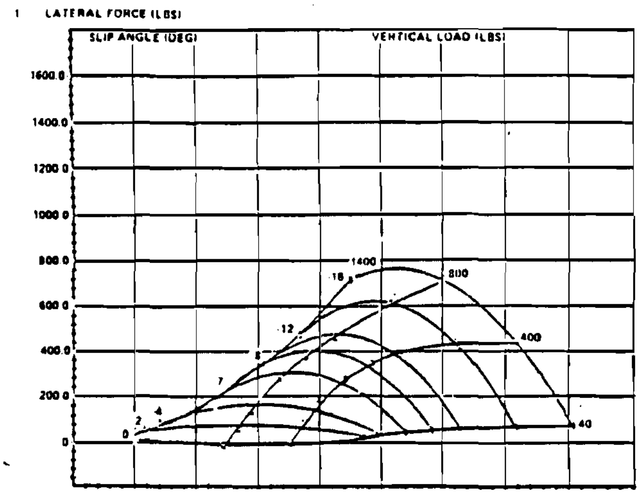
If the extrapolated tire data plot (Figure 14) is converted to a nondimensional diagram (i.e., in format of Ref. 6, p. 117), the observed value of $\bar{\beta}$ at which saturation occurs for an underinflated tire is equal to approximately 0.80 rather than 3.0 for a normally inflated tire (see Fig. 15).

The conversion of the relationship for $\bar{\beta}$ for the underinflated and/or overloaded tire proceeds as follows:

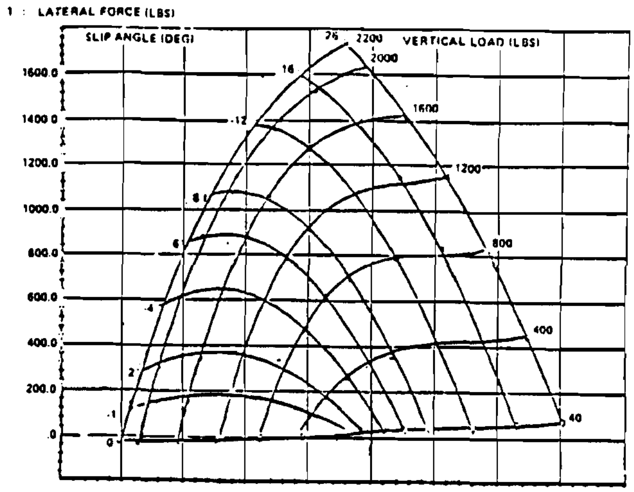
from Figures 13 and 14,

$$F'_{S_i} \cong K_\alpha + A\,\alpha^3 \qquad (4)$$

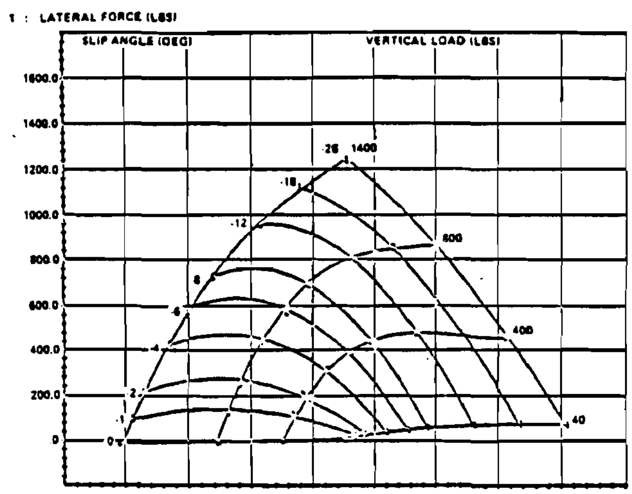
nondimensionally:



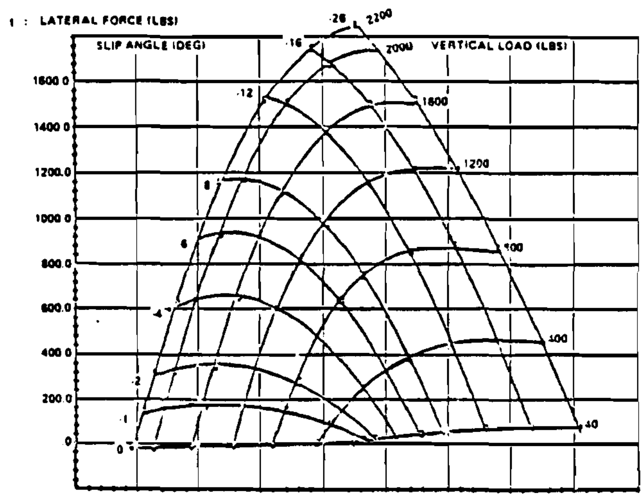
CARPET PLOT OF LATERAL FORCE vs SLIP ANGLE AND VERTICAL LOAD
RUN NO 072 30 mph R.S.
DRY ROADWAY 8 psi T.I.P.



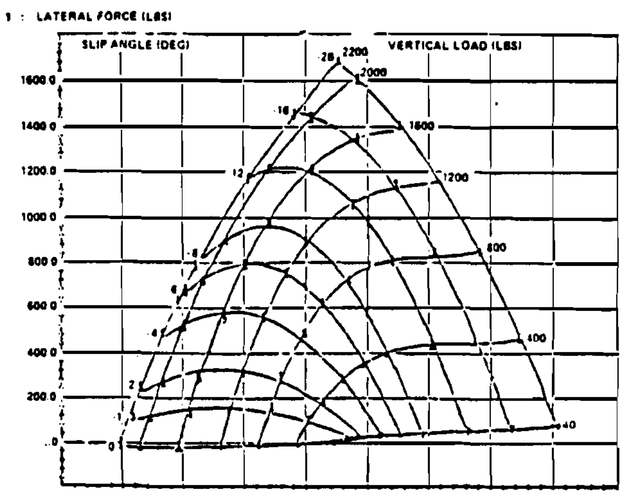
CARPET PLOT OF LATERAL FORCE vs SLIP ANGLE AND VERTICAL LOAD
RUN NO 045 30 mph R.S.
DRY ROADWAY 28 psi T.I.P.



CARPET PLOT OF LATERAL FORCE vs SLIP ANGLE AND VERTICAL LOAD
RUN NO 071 30 mph R.S.
DRY ROADWAY 16 psi T.I.P.



CARPET PLOT OF LATERAL FORCE vs SLIP ANGLE AND VERTICAL LOAD
RUN NO 048 30 mph R.S.
DRY ROADWAY 32 psi T.I.P.



CARPET PLOT OF LATERAL FORCE vs SLIP ANGLE AND VERTICAL LOAD
RUN NO 047 30 mph R.S.
DRY ROADWAY 24 psi T.I.P.

Fig. 13 Side force properties of a tire inflated from 8 to 32 psi (55-250 kPa), from Reference 7

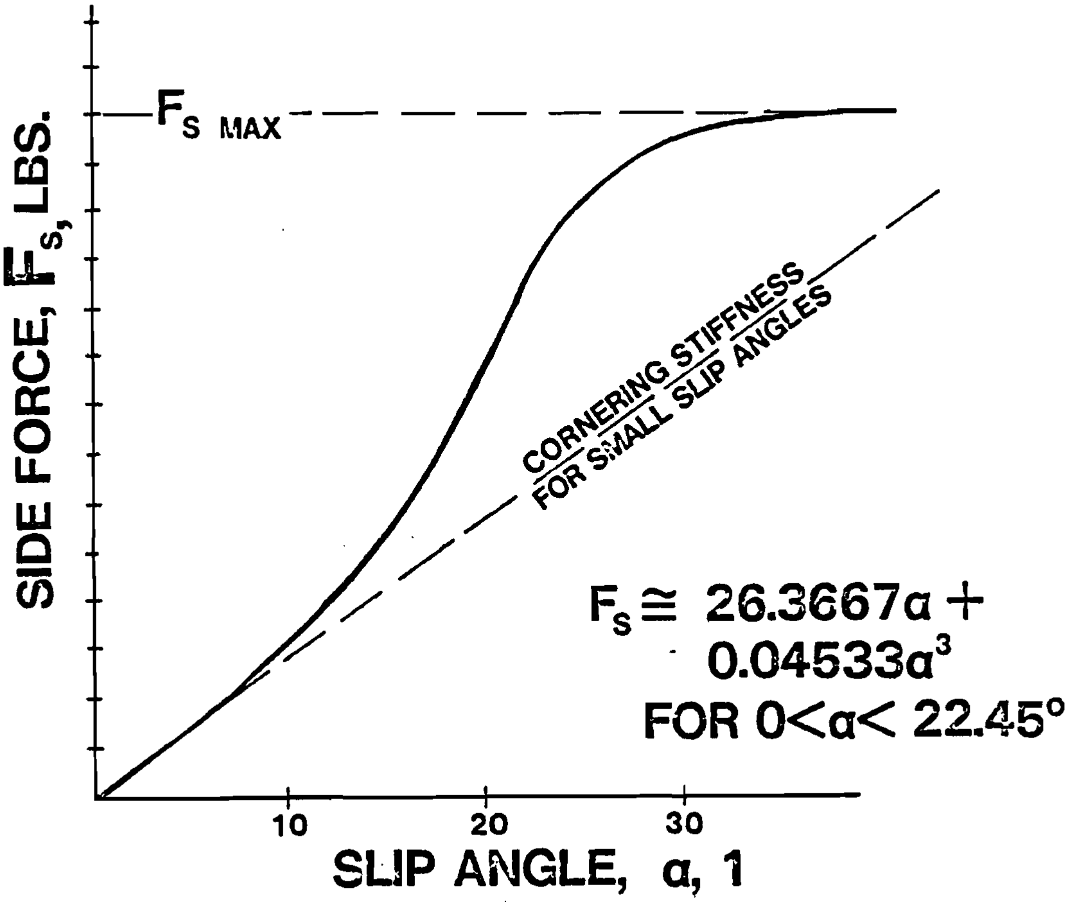


Fig. 14 Extrapolated tire data for 1400 lb, 8 psi (6.2 kN, 55 kPa)

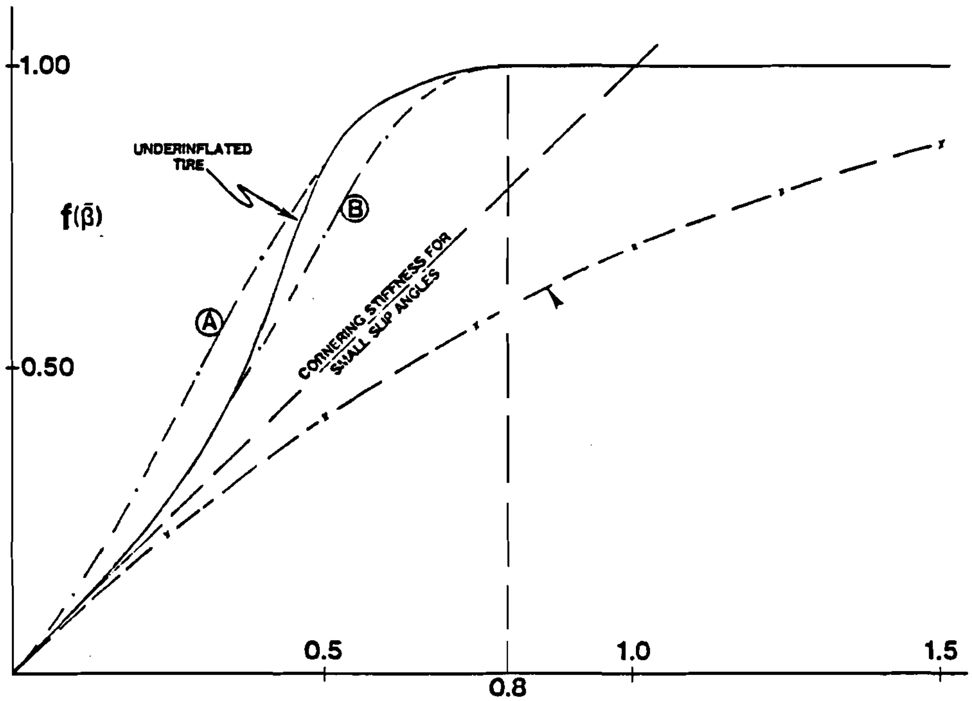


Fig. 15 Non-dimensional tire side-force curve

$$\frac{F'_{S_i}}{(F_{S_i})_{max}} = \frac{K\alpha}{(F_{S_i})_{max}} + \frac{A\,\alpha^3}{(F_{S_i})_{max}} \tag{5}$$

Now since

$$\frac{K\,\alpha}{(F_{S_i})_{max}} = \bar{\beta} \tag{6}$$

Then

$$\alpha = \frac{\bar{\beta}(F_{S_i})_{max}}{K} \tag{7}$$

and

$$\alpha^3 = \frac{\bar{\beta}^3 (F_{S_i})^3_{max}}{K^3} \tag{8}$$

Therefore, equation (2) can be written as:

$$\frac{F'_{S_i}}{(F_{S_i})_{max}} = \bar{\beta}'' = \bar{\beta} + \frac{A\,\bar{\beta}^3 (F_{S_i})^2_{max}}{K^3} \tag{9}$$

and if we let

$$\Gamma = \frac{A(F_{S_i})^2_{max}}{K^3} \tag{10}$$

then

$$\bar{\beta}'' = \bar{\beta} + \Gamma\,\bar{\beta}^3 \tag{11}$$

To insure full saturation of side forces for the underinflated/overloaded tire at 40° of sideslip:

$$\bar{\beta}' = 3.0 \text{ at } \alpha = 40° = 0.69813 \text{ Radians} \tag{12}$$

Substituting in equation (11):

$$3.0 = \frac{K(.69813)}{(F_{S_i})_{max}} + \frac{A(.34026)}{(F_{S_i})_{max}} \tag{13}$$

and

$$A = 8.81678\,(F_{S_i})_{max} - 2.05175K \tag{14}$$

For the tire overload situation, logic was added to TIRFRC to make adjustments to ß per the above to insure full saturation of the side forces by 40° sideslip.

Test run simulations which compare the response characteristics of the HVOSM-84 and the HVOSM-86 with full-scale tests indicate that the revisions related to the overloaded tire situation result in very minor changes in the simulated results. This was expected due to the short duration of tire overload, if any, in most of the simulation comparisons with full scale tests. The potential benefits may be realized when future comparisons are made with full scale tests which have more extensive tire overload situations.

Variation of the Coefficient of Friction of the Side Force as a Function of Tire Load

Early development of the HVOSM tire model included three coefficients, A5, A6, A7, which describe second order variations of the effective coefficient of friction for side forces as a function of the vertical load (Figure 16, from Ref. 8, Appendix III). The variation of the maximum side force friction coefficient has been observed in full scale testing and the calculation of the three coefficients describing the parabolic variation is a standard output of the TIRF scan of tire properties (e.g., refs. 1,2).

The variation of the side force friction coefficient was not included in the final assembly of all the previous HVOSM work documented by Segal (ref. 9) which resulted in the HVOSM-76 RD2 and VD2 versions. Therefore, the three coefficients describing the variation of side force friction coefficient with vertical load were re-installed into the HVOSM RD2 tire model (herein called HVOSM-86 to differentiate it from the 76 and 84 versions). The net effect of the variation of side force friction coefficient may not be dramatic; however, the inclusion of it in the tire model should ultimately produce improved correlation with full-scale tests.

The new inputs to the HVOSM describing the variation of the side force friction coefficient for each tire dataset are the coefficients A5 through A7, as well as the ranges of loads at which the full-scale tire test data were measured, FRMIN to FRMAX. The reason for the inclusion of the maximum and minimum ranges of test measurements was to alleviate initial implementation problems found with the parabolic fits where they were found to reverse or produce unreasonable results for some values of tire loads outside the ranges measured. The program logic was modified to set the values for the side force friction coefficient to the corresponding boundary values for tire loads outside the ranges measured.

Figure 17 is a carpet plot comparison with full scale test measurements of the effects of the inclusion of the variation of the tire side force friction coefficient with the tire vertical load (HVOSM-86) with the HVOSM-84. The comparison does not reveal a dramatic change from the fit produced by DeLeys (ref. 3); however, it should be noted:

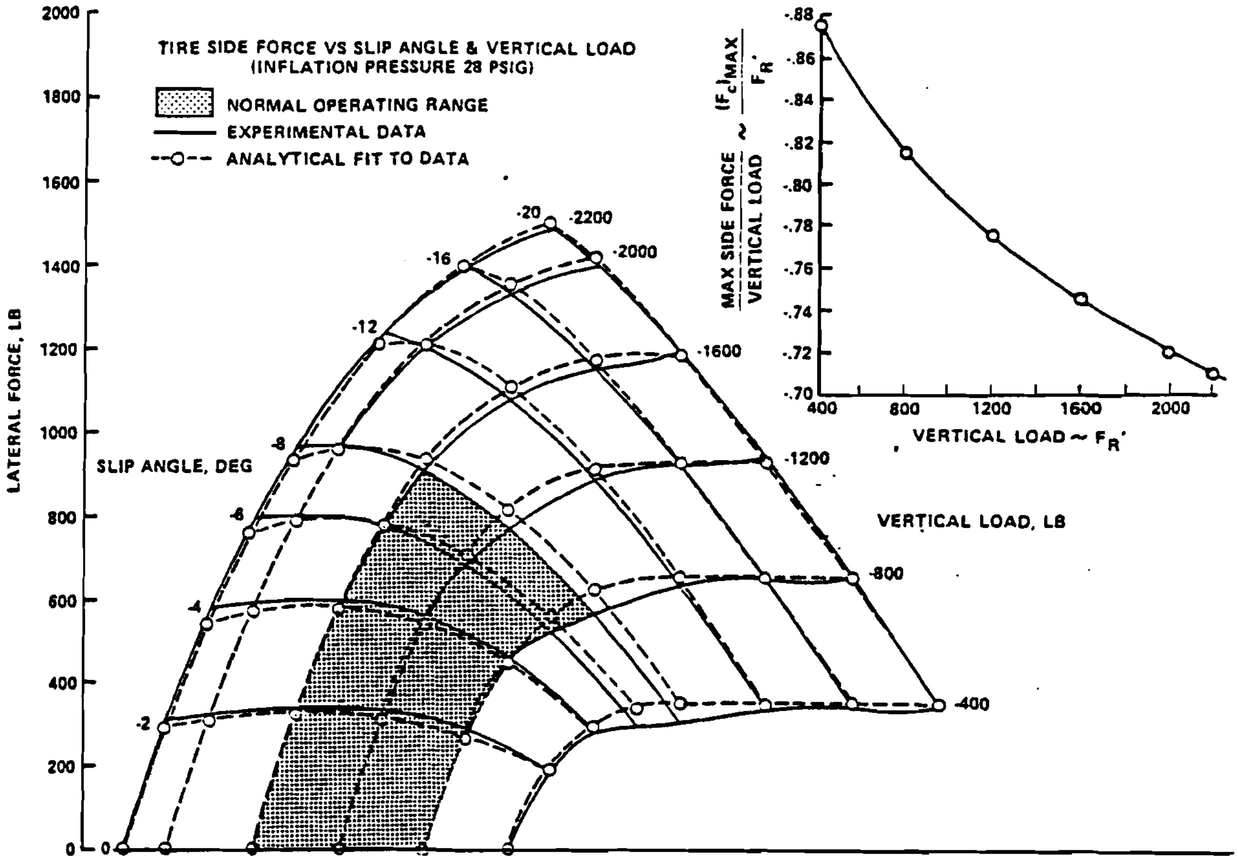


Fig. 16 HVOSM tire model properties from Ref. 4

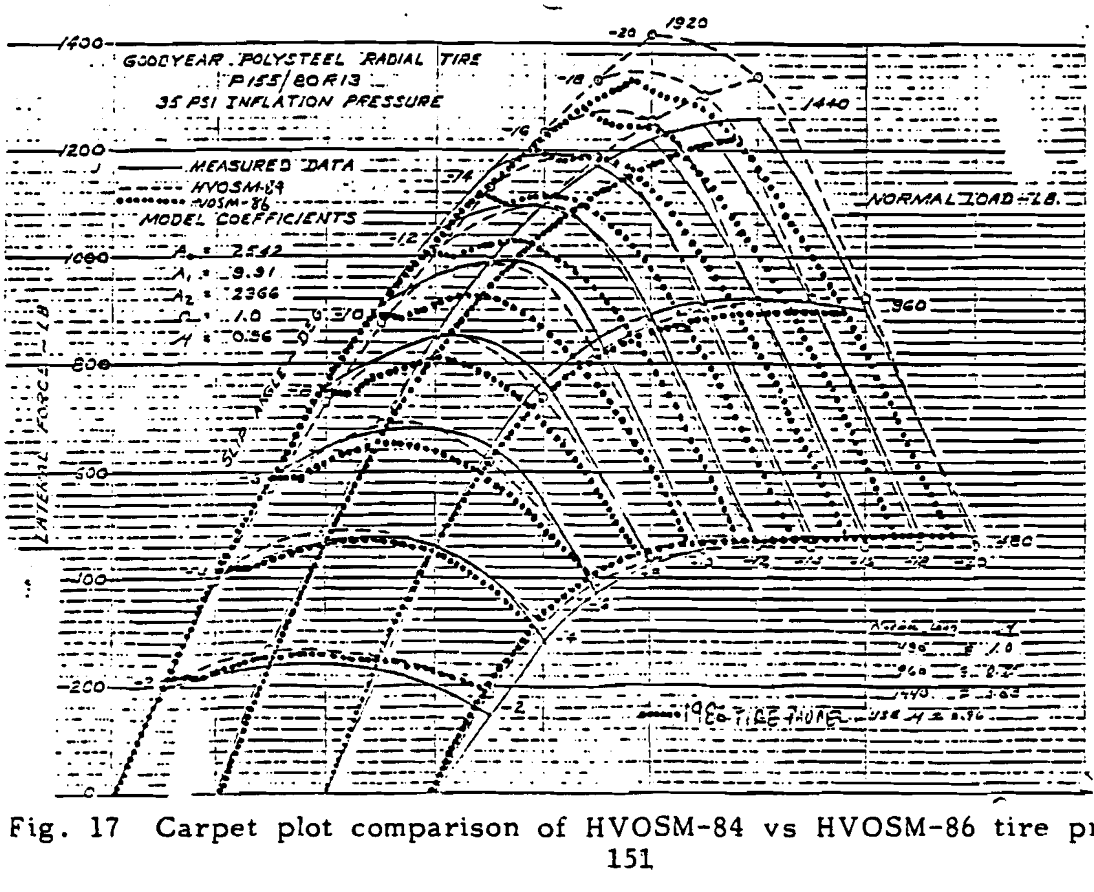


Fig. 17 Carpet plot comparison of HVOSM-84 vs HVOSM-86 tire properties

(1) DeLeys used a nominal friction coefficient of .96 for the comparison whereas the tire tests were performed on a surface with a skidpad number of approximately 80. The HVOSM-86 carpet plot was produced with a nominal friction coefficient of .80.

(2) The values calculated and used by DeLeys for the side force cornering stiffness coefficients were used for the HVOSM-86 comparison. The combination of the inclusion of A5-A7 and the changes documented in section 2.1 may warrant further refinement of the fits.

Validation/Comparison with Full Scale Test Results

The validation runs performed by DeLeys (ref. 3) with HVOSM-84 were rerun with the HVOSM-86 simulation program to verify and compare the results of the two versions of the programs with the full scale test results.

Two tests on paved surfaces were simulated: the sinusoidal steer and the combined steer and braking test.

The results of the comparison reveal the revised HVOSM-86 behaves in a similar fashion to the HVOSM-84 validation runs performed by DeLeys.

The lack of an appreciable improvement in the correlation of the HVOSM-86 vs the HVOSM-84 can be explained by the probable overwhelming contribution of the suspension stop characteristics over the minor changes in the resulting tire forces. The HVOSM input dataset for the 1979 VW Rabbit used in the full scale tests was obtained from Ensco (ref. 10) and modified to accommodate changes made in weights, etc., by DeLeys for use in the full scale validation runs. The HVOSM input parameters received from Ensco for some of the suspension properties (i.e., suspension stop coefficients and percent of energy feedback) are questionable. The values of some of the parameters are extremely large (by order »100 times values ever used before) and could produce unrealistically large forces when the suspension stops are contacted which probably produce some digital integration solution instability and result in the somewhat oscillatory behavior of the simulated pitch and roll responses which are not present in the full scale tests.

However, the resulting simulated behavior still produces an adequate comparison and correlation with the full scale test results so no further investigation of the effects of minor revisions of the inputs were pursued within the present contract. It is recommended that an attempt should be made to further enhance the correlation of the HVOSM with the Calspan measured full scale test results by refining the definition of the suspension properties of the vehicle to be more reasonable and within the limits of a finite time-step digital integration.

Cross-Section Design for Rural Traffic Islands

The goal of this task was to determine a traffic island and section design which will not trip and roll a mini-car striking the island in a yawed attitude. The basic approach of the investigation was to look generally at various traffic island/curb configurations to determine which variables will most likely reduce the probability of a vehicle tripping and rolling over when striking the curb in a yawed attitude.

When a vehicle strikes a curb in a yawed attitude the lateral velocity of the wheels is diminished or stopped as a result of the curb impact and an angular disturbance is imparted to the vehicle such that it rotates about the wheel contact point. A rollover can occur when the angular disturbance in roll is sufficiently large. A rollover will not occur if either the vehicle velocity is insufficient to lift the center of gravity over the wheel contact point, or the velocity is great enough that the wheel mounts the curb and the subsequent vertical load which results from the mount is sufficient to oppose the angular disturbance produced by the curb contact.

A relationship for predicting the minimum speed to produce a rollover when a vehicle encounters a vertical faced curb from (refs. 11,12) is as follows:

$$V = 1.58\sqrt{\left(\frac{k^2 + Z_A^2 + y_A^2}{Z_A^2}\right)(l - Z_A)} \quad \text{Miles/Hour}$$

where

$$l = \sqrt{Z_A^2 + y_A^2} \quad \text{or} \quad (h_c + y_s) \qquad \text{whichever is larger}$$

The definitions of each of the variables are contained in Figure 18.

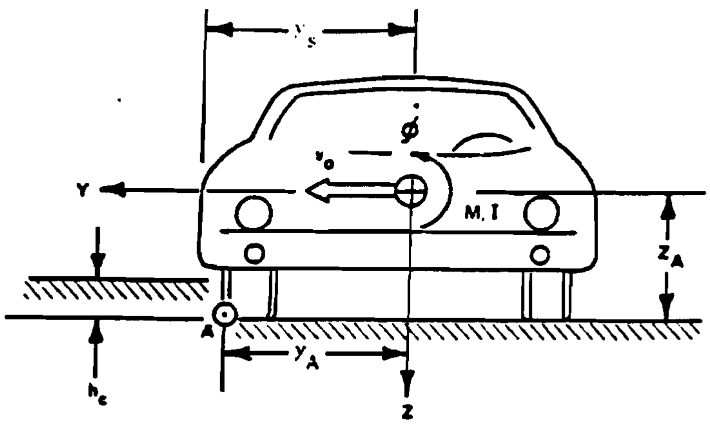


Fig. 18 Rollover Model for Angular Momentum Analysis

M	=	Total mass of vehicle, lb-sec^2/inch
k^2	=	Radius of gyration squared for complete vehicle in roll, in^2
I	=	Mk^2 = Moment of inertia of complete vehicle in roll about the center of gravity, lb–sec^2–in
I_A	=	$M(k^2 + Z_A{}^2 + Y_A{}^2)$ = Moment of inertia of complete vehicle in roll about point A, lb–sec^2–in
Z_A, y_A	=	Coordinates of point A in body-fixed coordinate system with origin at complete-vehicle center of gravity, inches
ϕ	=	Angular velocity of vehicle in roll, rad/sec
V_o	=	Lateral velocity of vehicle at the time of initial contact with point A, inches/sec
y_s	=	One half of overall width of vehicle, inches
h_c	=	Height of curb, inches
p_y, p_z	=	Impulses in the y and z directions of the body-fixed coordinate system, lb–sec
l	=	Maximum elevation of the complete-vehicle center of gravity, inches

For each of the vehicles used in the simulation analysis, the minimum velocity to trip was calculated and the related variables are presented in Table 12.

Table 12. Calculated Minimum Velocity to Produce Rollover for a Vehicle Encountering a Vertical Faced Curb

Vehicle	Z_{CG} in	TR/2	K^2 in^2	l in	V_{min} MPH
1978 Honda Civic	20.98	25.75	455	33.21	8.75
1800-lb 79 VW Rabbit	19.68	27.00	532	33.42	12.1
1978 Dodge Omni	20.41	27.7	632	34.40	12.34
2410-lb 79 VW Rabbit	21.30	27.0	541	34.4	11.15
1971 Chevy Vega	18.76	27.3	376	33.12	10.57
1982 Chevy Celebrity	20.31	28.93	625	35.35	13.06
1978 Chevy Malibu	20.74	29.10	666	35.73	13.00
1976 Ford LTD	20.66	32.10	567	38.20	14.41

SI Equivalents:
1 in = 25.4 mm
1 in^2 = 645 mm^2
1 mph = 1.61 km/h

Since all of the parameters correspond to the total vehicle, an approximate conversion of sprung mass parameters from values for the total vehicle was required.

The curb face angle required to produce rollover of a vehicle which strikes it in a yawed orientation must be above a minimum angle such that the resultant tire forces produced perpendicular to it will pass below the vehicle center of gravity and produce a roll moment. Dynamically, the forces produced and their relationship to the vehicle CG as the tires contact the curb are affected by the tire/ground friction coefficient and the dynamic change in the vehicle geometry, i.e., tread change, suspension geometry and vehicle roll angle. Therefore, the first item investigated was the minimum curb face angle that will produce a rollover.

A study by Segal and Griffith (14) to assess the validity of the HVOSM for the simulation of curb impacts found that the HVOSM-RD2 1976 version predicted responses that appear generally in good agreement with test results with curb faces such as the 45° Type E, while they recommended that it should not be used to simulate low angle encroachment conditions with steeply faced curbs (such as Types C and X).

Subsequent modifications to the HVOSM curb impact routine implemented as part of an investigation of pavement/shoulder dropoffs (15) and documented by DeLeys et al. (3) have the potential of improved correlation with the steeper faced curbs by the inclusion of sidewall springs to interact with the vertical curb forces. However, the additional costs associated with the use of the sidewall spring model and the use of curb face angles of 45 degrees or less for the runs made the use of the revised modifications not cost effective in the present research.

The first series of test runs performed were the Initial Curb Face Angle Check runs. These runs were simulations of lateral slides into six-inch curbs with varying curb face angles from 15 to 45 degrees. The three vehicles tested were the 1699-lb (.77 Mg) Honda Civic, the 2974-lb (1.34 Mg) Chevy Celebrity and the 4450-lb (2.02 Mg) Ford LTD. All vehicles were run into the curbs at a 10-degree heading and a 80-degree sideslip with respect to the curb such that the simulated vehicle test speed was entirely perpendicular to the curb.

The results of the initial curb face angle test runs, which are presented in Table 13 and selected time history plots in THPLOT* Figures 19 through 22, indicate that for curb face angles greater than 30 degrees a rollover can be produced when a small to intermediate vehicle contacts the curb with a sufficient minimum speed to produce the rollover. No simulated rollovers were produced with the large vehicle. There also appears to be a maximum lateral speed above which the duration of the impulse produced by the contact with the curb is insufficient to produce a rollover.

The next phase of the investigation was to determine if the simulated vehicles behave similarly for lateral slide contacts with an island-type configuration like the NC design where the six-inch curb height is divided into three tiers. For the NC design the first tier is a near vertical 2-in (51 mm) rise followed by a second tier which is approximately a 20° angle with a 3-in (76 mm) rise, while the final tier is at approximately 1°-2°. The net effect of this configuration for a 6-in (152 mm) curb as compared with the simple angled face was determined.

*Note: Figures preceded by THPLOT are contained in the final section of this report entitled Time-History Plots.

Table 13. Summary of Results of Initial Curb Face Angle Check Runs

Vehicle	Curb Face Angle Deg	Lateral Speed MPH	
1978 Honda Civic	45	17	Rollover
	30	17	Borderline (@ .5 sec 27° ϕ, P=60°/sec)
	15	17	No roll
1978 Honda Civic	30	25	No
	45	25	No
	60	25	No
Chevy Celebrity	30	20	No
Chevy Celebrity	45	20	Rollover
Ford LTD	45	22	No
Ford LTD	60	22	No

SI Equivalents:
1 mph = 1.61 km/h

The first two test runs of the NC traffic island were the Honda and the Celebrity at 17.5 mi/h and 20 mi/h (28 and 32 km/h), respectively. Neither vehicle rolled as a result of the curb impact; therefore, two further test runs were performed with a doubling of the angle of the second tier of the NC traffic island design from 20 degrees to 40 degrees.

Both the Honda and the Celebrity rolled upon impact with the variation NC traffic island design. THPLOT Figures 23 through 24 illustrate the time history response of the Honda Civic to the original NC traffic island design and the variation of the NC traffic island design. These test runs support the previously drawn conclusion that a small to intermediate vehicle impacting on a curb with a face angle greater than 30 degrees in a yawed attitude may roll over.

The next series of test runs were performed with the Honda and Celebrity wherein the velocity of the vehicle striking the curb was varied to determine the maximum and minimum velocities at which each vehicle would roll for a lateral slide on a 45-degree, 6-in height curb. The 1700-lb (.77 Mg) Honda Civic and the 2980-lb (1.35 Mg) Chevy Celebrity were simulated for this series.

The results of the velocity variations of the lateral slide into a 45-degree curb face are presented in Table 14 and indicate that the Honda will roll for speeds greater than 12 mi/h (19 km/h) and less than 25 mi/h (40 km/h) while the Celebrity will roll for speeds 13 mi/h (21 km/h) or greater and less than 25 mi/h (40 km/h).

Table 14. Lateral Slide Test Runs into 6" Height, 45° Face Angle Curb

Vehicle	Run #	Speed	
Honda	WO2S1A2	9 MPH	No roll, @ .37 sec, 8.7° peak roll
	WO2S1A4	11 MPH	No roll, @ .5 sec, 16.4° peak roll
	WO2S1A5	12 MPH	No roll, @ .7 sec, 34° peak roll
	WO2S1A3	13.3 MPH	Roll
	WO2S1A6	20 MPH	Roll
		25 MPH	No roll
Celebrity	WO2S2B4	13 MPH	No roll
	WO2S2B3	15 MPH	Roll
	WO2S2B2	17 MPH	Roll
	WO2S2B5	25 MPH	No roll
	WO2S2B6	30 MPH	No roll

SI Equivalents:
1 in = 25.4 mm
1 mph = 1.61 km/h

In summary, the results of the curb face angle tests on the six-inch curbs with face angles varying from 15 to 45 degrees indicate that for a lateral slide into the curb face that a rollover can be produced for small to intermediate vehicles for curb face angles greater than 30 degrees and speeds perpendicular to the curb in the range of 15 to 25 mi/h (24 to 40 km/h).

Results of tests on Traffic Island such as the NC Design are consistent with the results for the curb face angle tests. The effects of the 2-in (51 mm) 60° face preceding the 20° curb face on the NC Traffic Island appear to have a negligible effect on the probability of a vehicle rolling over when impacting the curb.

Vehicle Parameters Critical to Rollover

The objective of this phase of the research project was to define a maneuver that puts a vehicle into a "near-rollover" condition and to then vary several parameters of the vehicle to determine which are most effective in reducing or preventing the "near-rollover" condition.

The initial approach was to try to achieve a "near-rollover" condition with a double steer reversal-type maneuver. Through timing of the steer reversal, it was hoped that an amplification of the yaw and roll responses could be produced and thereby a subsequent rollover condition achieved.

Initial setup runs were performed with a sample steer to the left to determine where the maximum response was achieved. A second run was performed reversing the steer at or near the point of maximum angular velocity response and again determining when the maximum response to the second steer input was achieved. A third reversal was then initiated at or near the peak response to the second reversal with the objective of initiating a roll response. THPLOT Figure 25 is a sample time history plot of the simulated vehicle response to a double-steer reversal. Several variations of the timing, extent and number of steer reversals were attempted; however, a rollover response was not readily achieved on surfaces with a nominal friction coefficient using this form of open-loop steer input.

Since difficulty was encountered in achieving a "near-rollover" maneuver with simple steer, an alternative approach to determining critical rollover parameters was investigated. Some of the runs from the sideslope investigation in this project wherein a rollover was achieved were repeated with a variation of parameters to determine which, if any, were most effective in preventing the rollovers.

The series consisted of a rerun of the critical sideslope runs with variations of vehicle parameters. Variables investigated were:

(1) I_X – Moment of inertia in roll (how much of a change would prevent roll?)

(2) Suspension Travel – Would an increase or decrease prevent rollover?

(3) I_{XZ} – Roll-Yaw Product

Table 15 gives a summary of the results from the variation of parameters on the critical sideslope runs. The variation of parameters did not prevent rollover for any of the runs although it did delay the onset of rollover in a number of the runs. Review of the simulation runs indicates that the overwhelming influence of the tire/soil sinkage forces cannot be easily overcome by a variation of parameters.

Step-Steer Maneuver

Initial baseline simulation runs of rapid steer inputs to several vehicles were performed to test different rates and extents of steer input. The results confirmed the observation of Reference 16 that the vehicle peak responses were a function of the extent of steer rather than the rate at which the steer was input. Therefore, calibration runs of a step steer input were performed with a nearly instantaneous input of steer to determine the characteristic responses of the various vehicles to be used for the current project.

The step-steer simulation test conditions were as follows:

Speed = 45 mi/h (72 km/h)
Nominal μ = 0.80
Steer input = 4.5 deg. at front wheels
applied at T = 0.20 of simulation run
10% engine braking also initiated

A summary of the step-steer input response characteristics of each of the 8 simulated vehicles is contained in Table 16 and their corresponding time-history response plots are contained in THPLOT Figures 26 through 33.

Flat Surface Rollover Tests

A series of runs was performed to determine the minimum friction coefficient required to roll the various vehicles on a flat surface. The series was modeled after the critical ground friction

Table 15. Test Matrix of Variation of Parameters on Critical Sideslope Runs

Vehicle	Run	Variable Tested	45° Roll Time sec.	45° Roll P deg/sec	90° Roll Time sec.	90° Roll P Deg/sec.
Honda	TS#12BB	BASELINE	1.40	45.3	1.99	90.4
	WO5S1A	I_{XZ} = −250	1.40	47.9	1.92	90.3
	WO5S1B	I_{XZ} = +250	1.40	45.2	2.04	138.4
	WO5S1BB	I_{XZ} = +500	1.40	42.0	2.15	131.1
	WO5S1C	I_X = 3900 (+150%)	1.40	51.3	1.88	146.0
	WO5S1D	I_Z = 15600 (+150%)	1.40	56.0	1.85	135.0
Omni	TST#12CC	BASELINE	1.50	33.7	2.17	127.0
	WO5S2A	I_{XZ} = +778	1.55	29.7	2.31	109.4
	WO5S2B	I_X = 4049 (+200%)	1.40	52.5	1.86	149.0
	WO5S2C	I_Z = 26764 (+200%)	1.50	43.4	2.02	130.0

Table 16. Summary of Step-Steer Maneuver Responses

Drive Type	Vehicle	Weight lbs	Roll Max Degrees	Ay Max G Units	$\dot{\chi}_{Max}$ Deg/Sec
F	Civic	1699	−5.07	.863	58.5
F	Rabbit2	1800	−5.55	.871	31.0
F	Omni	2138	−3.24	.772	25.3
F	Rabbit1	2410	−6.31	.763	25.9
R	Vega	2639	−6.34	.803	72.2
F	Celebrity	2974	−4.61	.690	22.5
R	Malibu	3580	−5.77	.786	60.0
R	LTD	4450	−5.72	.632	20.5

Step-Steer: @ Time = 0.20 sec
4.5 Deg at Front Wheels
10% Engine Braking
Nominal μ = .80
Speed = 45 MPH

SI Equivalents:
1 lb = 0.435 kg
1 mph = 1.61 km/h

coefficient on sideslopes study performed by DeLeys (Ref. 3) for his sideslipping departure with starting conditions as follows:

Speed	=	45 mi/h
Path Angle	=	25 degrees
Sideslip Angle	=	30 degrees

The vehicle was run across an 8-foot shoulder ($\mu = .55$) onto a high friction surface. The nominal values for the high friction surface were increased until a rollover was achieved. A summary of the results for the various vehicles is presented in Table 17.

Table 17. Comparison of Critical Friction Coefficients in Flat Surface Rollover Maneuver

Vehicle	Total Weight (lb)	Mass (kg)	$\mu_{critical}$
Civic	1699	770	1.00
Rabbit2	1800	816	0.95
Omni	2138	969	0.95
Rabbit1	2410	1093	0.85
Vega	2639	1197	1.25
Celebrity	2974	1349	1.15
Malibu	3580	1624	1.15
LTD	4450	2018	1.40

Examination of the results of the initial flat surface rollover test runs reveals that the minimum friction coefficient required to roll over the individual VW Rabbits was less for the heavier vehicle (i.e., 0.85 for 2400-lb (1.09 Mg) Rabbit, 0.95 for 1800-lb (0.82 Mg) Rabbit). This observation correlates with the results of the critical ground friction coefficient on sideslopes runs performed by DeLeys for the two Rabbits (i.e., 0.80 for 2400-lb (1.09 Mg) Rabbit, 1.05 for the 1800-lb (0.82 Mg) Rabbit). DeLeys attributed the differences in the results for the two vehicles primarily to the differences in their static stability factors (i.e., T/2H = 1.27 for the 2400-lb (1.09 Mg) vehicle, 1.37 for the 1800-lb (0.82 Mg) vehicle).

A set of test runs was run with the two vehicles wherein the values for the static stability factor (i.e., T/2H) were reversed by changing the center of gravity heights. The results of this test are presented in Table 18 and time history plot comparison is in THPLOT Figures 34 through 37.

The test runs indicate that the critical values of friction coefficient required to roll over the two vehicles, which are identical except for their weights and moments of inertia, are related to their static stability factors, T/2H. Determining how this relationship between the critical friction coefficient and T/2H varies among vehicles would appear to be of critical importance to determining what other factors influence the resistance of a vehicle to rollover.

Table 18. Comparison of Critical Friction Coefficient Required to Roll Over 1979 VW Rabbit with T/2H

Vehicle	T/2H	Flat Surface $\mu_{CRITICAL}$	% μ_{CRIT}/T/2H	5:1 Slope $\mu_{CRITICAL}$	% μ_{CRIT}/T/2H
STD 1800 lb	1.37	0.95	69%	1.05	77%
MOD 1800 lb	1.27	0.90	71%	–	–
STD 2400 lb	1.27	0.85	67%	0.80	63%
MOD 2400 lb	1.37	0.95	69%	–	–

Table 19 presents the results of the critical friction coefficient tests and the corresponding relationships between the minimum friction coefficient required and the static stability factor.

It may be seen in Table 19 that the static stability factor (T/2H) is not a consistent indicator of the minimum friction coefficient required to roll a vehicle on a flat surface. The value of μ-critical can be observed to vary from 67% up to 90% of the static stability factor. The question that arises is, what other vehicle parameters affect the relationship between the two variables? A first guess would be that some parameters such as the moments of inertia, the suspension properties or the tire properties alter the amount of dynamic change in the vehicle stability factor. The tests with the two Rabbits (i.e., Table 18) seem to indicate that the relationship between the minimum friction coefficient required to roll over the vehicle on a flat surface vs the static stability factor is approximately independent of the weight (note μ-critical approx. average of 69% of T/2H for both vehicles).

The next phase of the project was an investigation of the vehicle parameter(s) that affect the value of friction coefficient required to roll a vehicle with a given static stability factor.

A series of runs was performed to determine if the relationship between the critical friction coefficient for rollover and the static stability factor is a constant for each vehicle or if it varies with the magnitude of the static stability factor. The first phase of the test series was to vary the center of gravity height for some vehicles to make them all have the same static stability factor and to then determine each of their critical friction coefficients for rollover to see if there is a relationship between the static stability factor and the critical friction coefficient for each vehicle.

Table 20 and THPLOT Figures 38 through 41 present the results of the test run series. For static stability factors of 1.30, the results support the original findings that the critical friction coefficient for rollover is a constant function of the static stability factor. The minor variations of the percentages (i.e., ±5%) are consistent with the .05 step size increments of the friction coefficient at which the tests were run.

Table 19. Relationship between Flat Surface $\mu_{CRITICAL}$ and Static Stability Factor (T/2H)

Vehicle	Total Weight (lb)	Mass (kg)	Flat Surface $\mu_{CRITICAL}$	T/2H	μ_{CRIT}/T/2H %
Ordered with respect to T/2H:					
Civic	1699	770	1.00	1.23	81%
Rabbit1	2410	1093	0.85	1.27	67%
Omni	2138	969	0.95	1.35	70%
Rabbit2	1800	816	0.95	1.37	69%
Malibu	3580	1624	1.15	1.40	82%
Celebrity	2974	1349	1.15	1.42	81%
Vega	2639	1197	1.25	1.46	86%
LTD	4450	2018	1.40	1.55	90%
Ordered with respect to $\mu_{CRITICAL}$:					
Rabbit1	2410	1093	0.85	1.27	67%
Omni	2138	969	0.95	1.35	70%
Rabbit2	1800	816	0.95	1.37	69%
Civic	1699	770	1.00	1.23	81%
Malibu	3580	1624	1.15	1.40	82%
Celebrity	2974	1349	1.15	1.42	81%
Vega	2639	1197	1.25	1.46	86%
LTD	4450	2018	1.40	1.55	90%

Table 20. Comparison of Critical Friction Coefficients for Rollovers for Various Vehicles Modified to Have Identical Static Stability Factors

Vehicle	Modified Sprung Mass CG Height (in)	Modified Sprung Mass CG Height (mm)	Static Stability Factor (T/2H)	Critical Rollover μ	% of $\mu_{CRITICAL}$/T/2H For T/2H = 1.30	% of $\mu_{CRITICAL}$/T/2H For Original T/2H
Honda	−21.97	−558	1.30	1.10	85%	81%
Celebrity	−24.12	−613	1.30	1.00	77%	81%
LTD	−24.70	−627	1.30	1.17	90%	90%
Vega	−22.52	−572	1.30	1.05	81%	86%

The test runs reveal that the static stability factor (T/2H) of a vehicle in itself is not a reliable indication of a vehicle's propensity to roll over. It has been found that through a combination of vehicle properties there exists an inherent resistance of a vehicle to roll which is related to the vehicle stability factor but which is substantially modified by other vehicle parameters.

The vehicle properties which intuitively would most likely affect the vehicle's resistance to rollover are the suspension properties, moments of inertia (primarily roll), vehicle dynamic response characteristics and the vehicle weight and stiffness distribution. Unfortunately, the properties for the vehicles simulated as part of this project include either approximations required due to incomplete measurement information (i.e., LTD, Omni, Celebrity, Malibu, Honda) or somewhat questionable inputs based on measurements (i.e., the Rabbits) which require additional review.

The lack of a detailed definition of the properties of each vehicle undermines any definitive conclusions with respect to identification of specific vehicle characteristics which affect the overall vehicle resistance to rollover.

It is recommended that a detailed definition and validation of several vehicles should be produced which are representative of the vehicle population so that specific suspension properties which affect vehicle rollover response can be further identified.

Sideslope Issues

As part of the performance of Work Order No. 4, several of the HVOSM simulations performed as part of the recent Calspan study (ref. 3) were re-run on an IBM mainframe to verify the results obtained by Calspan. The Calspan simulation work was performed with a version of the HVOSM received from McHenry Consultants, Inc. (MCI) and modified by Calspan to run on a PIXEL mini-computer. Some additional minor revisions of the code received from MCI were also installed on the mini-computer version by Calspan during the performance of their research effort. The mainframe version of HVOSM (herein referred to as HVOSM-84) was then subsequently modified by Calspan to be consistent with their mini-computer version. Calspan did not perform any verification tests of the final mainframe version of HVOSM (they did perform checks of the original "as received" version); therefore, the first phase was to obtain and re-compile the HVOSM-84 as modified by Calspan. Some of the simulations from the Calspan project were then re-run to verify the compatibility of results between the mini and mainframe versions of the program. Some minor discrepancies between the mini and mainframe versions were discovered and subsequently revised to make the results obtained between the two versions identical.

The next phase of the project was to determine the effects of the modifications of the HVOSM tire model installed as part of this project (i.e., Work Order No. 2). Identical simulation inputs were tested on both HVOSM-84 (HVOSM per the Calspan research, ref. 3) and HVOSM-86 (HVOSM as modified per of this project), to determine the effects of the changes on the results of the Calspan work.

Several of the runs of Calspan's Threshold of Ground Friction Coefficient for Rollover Simulations were re-run using both HVOSM-84 and HVOSM-86. Table 21 presents a summary of the results of the comparison of the two versions of the program as well as results obtained with different vehicles on the 3:1 sideslope. Some sample time history plots of the results are contained in THPLOT Figures 42 through 47.

Table 21. Summary of Simulation Runs. Threshold of ground friction coefficient for rollover.

Run #	Sideslip Ratio	Friction Coefficient	Vehicle	Maximum Roll Angle, Degrees	Comments
Non-Tracking Departure: 45 mi/h (72 km/h) @ 25 DEG (Sideslip = 30 DEG)					
TST#10A	3:1	.50	Rabbit	29.2°	HVOSM-84 *Car spins out and backs down slope*
TST#10B		.50	Rabbit	31.5°	HVOSM-86 *Car returns to roadway*
TST#10C		.50	Omni	30.8°	HVOSM-86 *Car returns to roadway*
TST#11A		.55	Rabbit	Rollover	HVOSM-84
TST#11B		.55	Rabbit	34.0°	HVOSM-86 *Car returns to roadway*
TST#11C		.55	Omni	32.8°	HVOSM-86 *Car returns to roadway*
TST#12B		.60	Rabbit	Rollover	HVOSM-86
TST#12C		.60	Omni	Rollover	HVOSM-86
TST#12E		.75	LTD	25.6°	HVOSM-86 *Spinout down slope*
TST#12G		.825	LTD	31.3°	HVOSM-86 *Spinout down slope*
TST#12F		.90	LTD	Rollover	HVOSM-86
Tracking Departure: 60 mi/h (96 km/h) @ 15 DEG					
TST#13D		.55	Omni	26.0°	HVOSM-86 *Spinout parallel to roadway*
TST#13B		.65	Omni	26.6°	HVOSM-86 *Spinout parallel to roadway*
TST#13C		.70	Omni	23.5°	HVOSM-86 *Spinout parallel to roadway*
TST#13E		.75	Omni	26.2°	HVOSM-86 *Spinout parallel to roadway*

The results indicate that the changes installed in HVOSM for this project have a minimal effect on the general vehicle dynamics for the types of maneuvers investigated as a part of the Calspan research. The lack of any appreciable difference between the versions (i.e., the VW rollover on 3:1 slope at nominal $\mu = .55$ for HVOSM-84 vs. nominal $\mu = .60$ for HVOSM-86) can be explained by the magnitude of the forces associated with the tire sinkages in the soft soil as compared with the saturated tire forces. The minor differences in results between the two versions of HVOSM resulted from the minor differences in the magnitude of tire side forces associated with the differences in the tire models (the HVOSM-86 has a variation of the maximum side force friction force as a function of the load whereas the HVOSM-84 saturates at the nominal value of the friction coefficient (see related discussion in the Vehicle Input/Validation section).

The results of the simulations performed with the OMNI verify that the Calspan conclusions are representative of the mini car population.

The results of the simulation performed with the LTD with the HVOSM-86 appear to indicate that a rollover can be achieved by the large car on a 3:1 slope with a nominal friction coefficient of 0.90. This is contrary to DeLeys' findings with the HVOSM-84 that the LTD could not be rolled on the 3:1 sideslope with a friction coefficient as high as 1.6. The reason for the differences may be attributable to the minor differences in the maximum side forces obtainable with the two versions of HVOSM. The minor differences may have made a difference in the rate at which the vehicle spins out with the two programs and thereby put the vehicle at a critical yaw angle on the slope which produced a rollover.

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(6) McHenry, Raymond R., DeLeys, Norman J., "Vehicle Dynamics in Single Vehicle Accidents--Validation and Extensions of a Computer Simulation," Calspan Report No. VJ-2251-V-3, Contract No. CPR-11-3988, December 1968.

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(13) Equations from: "Typical Vehicle Parameters for Dynamic Studies--Revised for the 1980's," SAE 840561, Riede, Leffert & Cobb.

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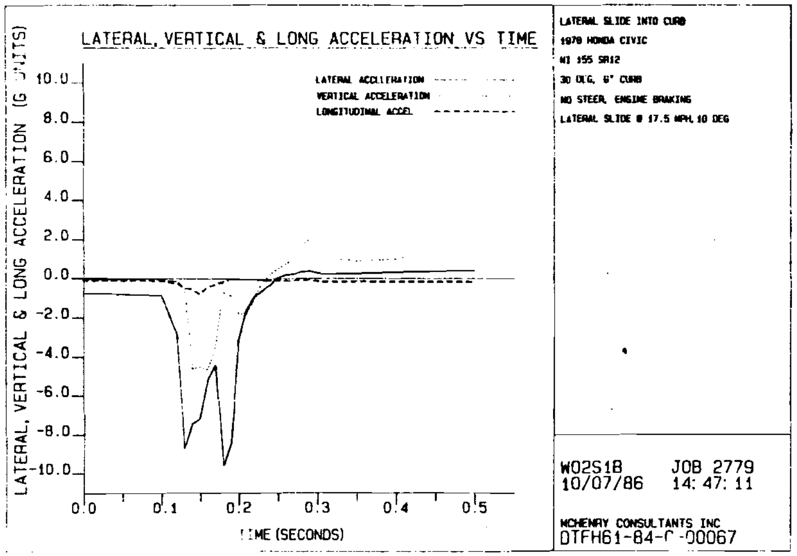
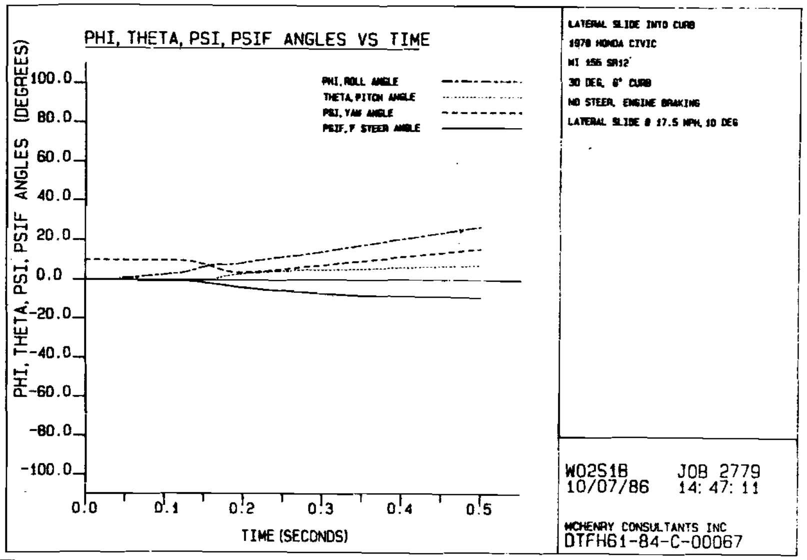




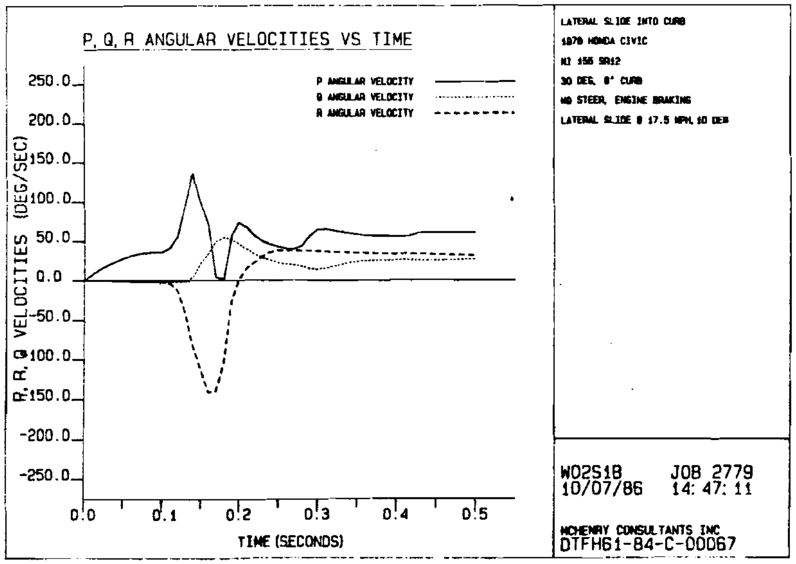


Figure 19. 1978 Honda Civic; 30°, 6-in curb; 17.5 mi/h; rollover.

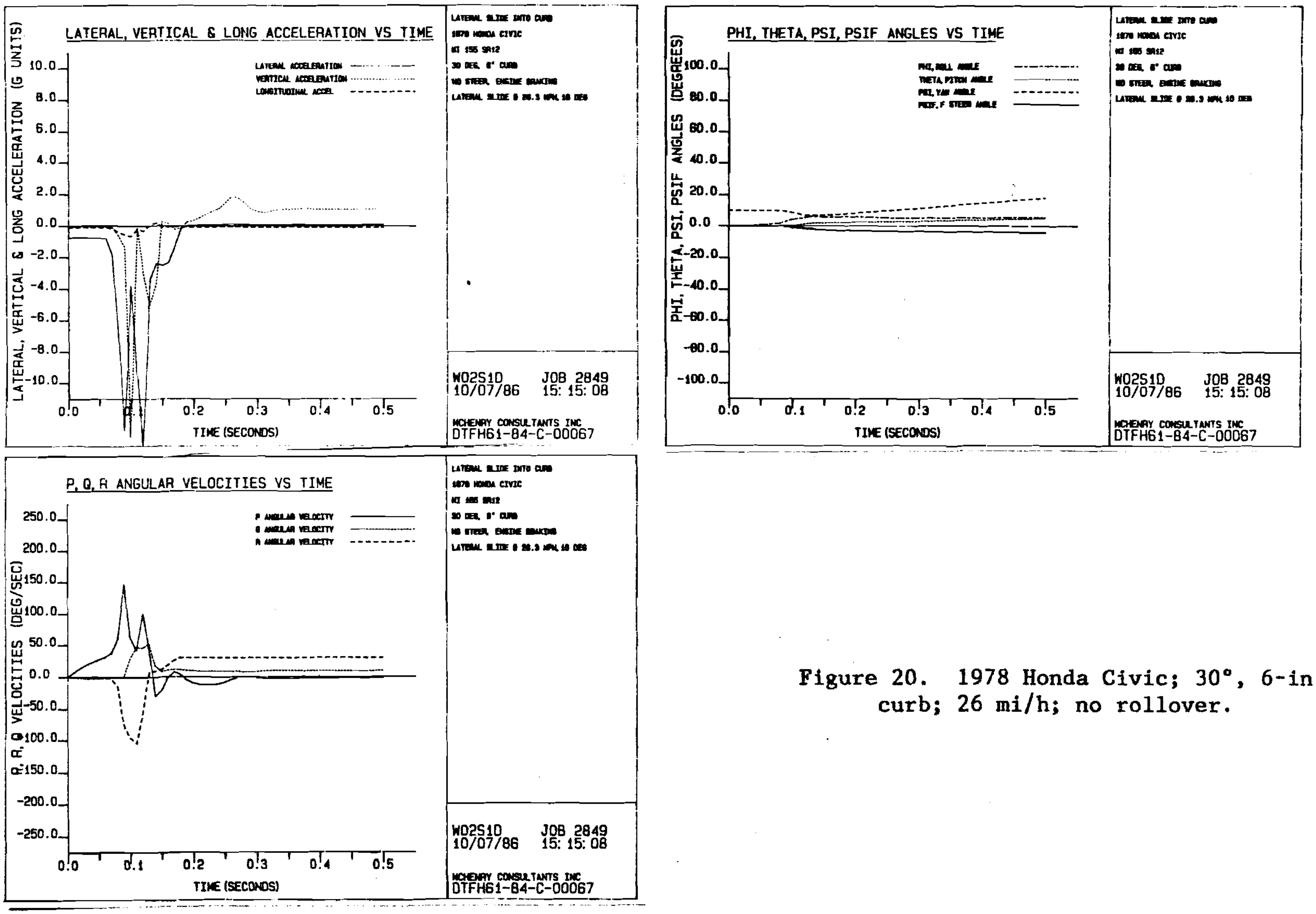
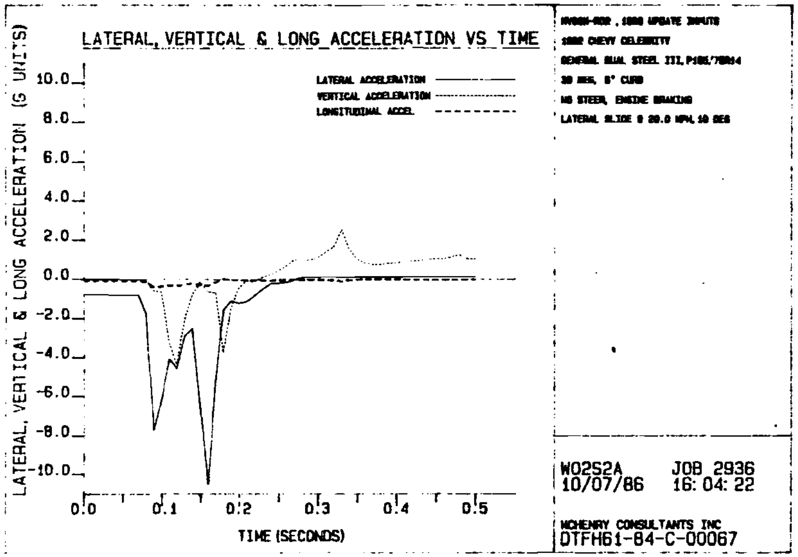
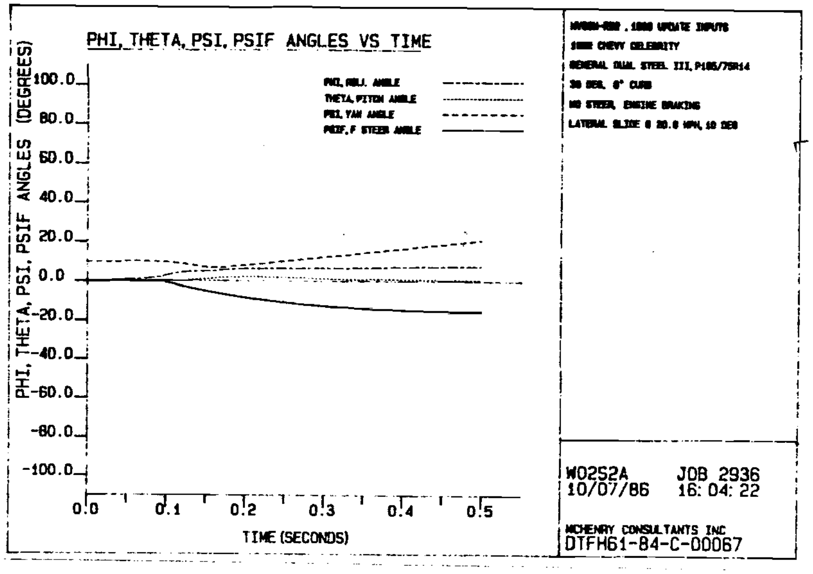


Figure 20. 1978 Honda Civic; 30°, 6-in curb; 26 mi/h; no rollover.





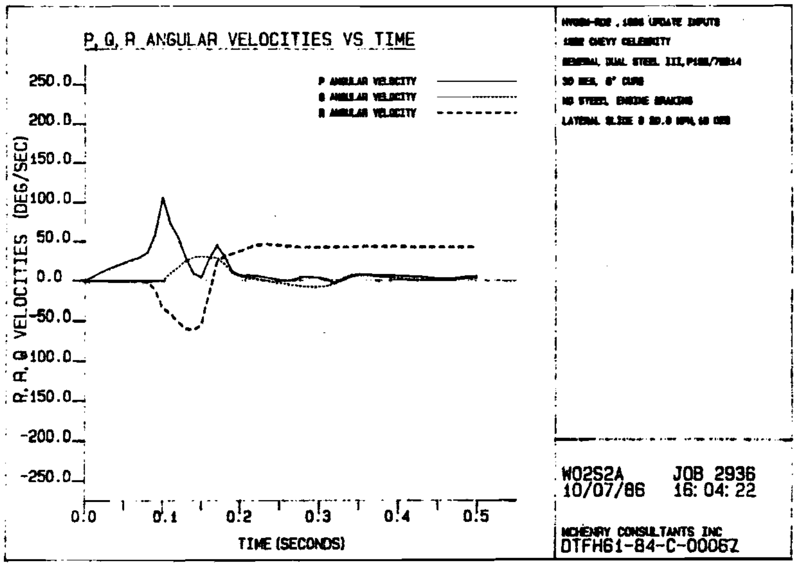


Figure 21. 1982 Chevrolet Celebrity; 30°, 6-in curb; no rollover.

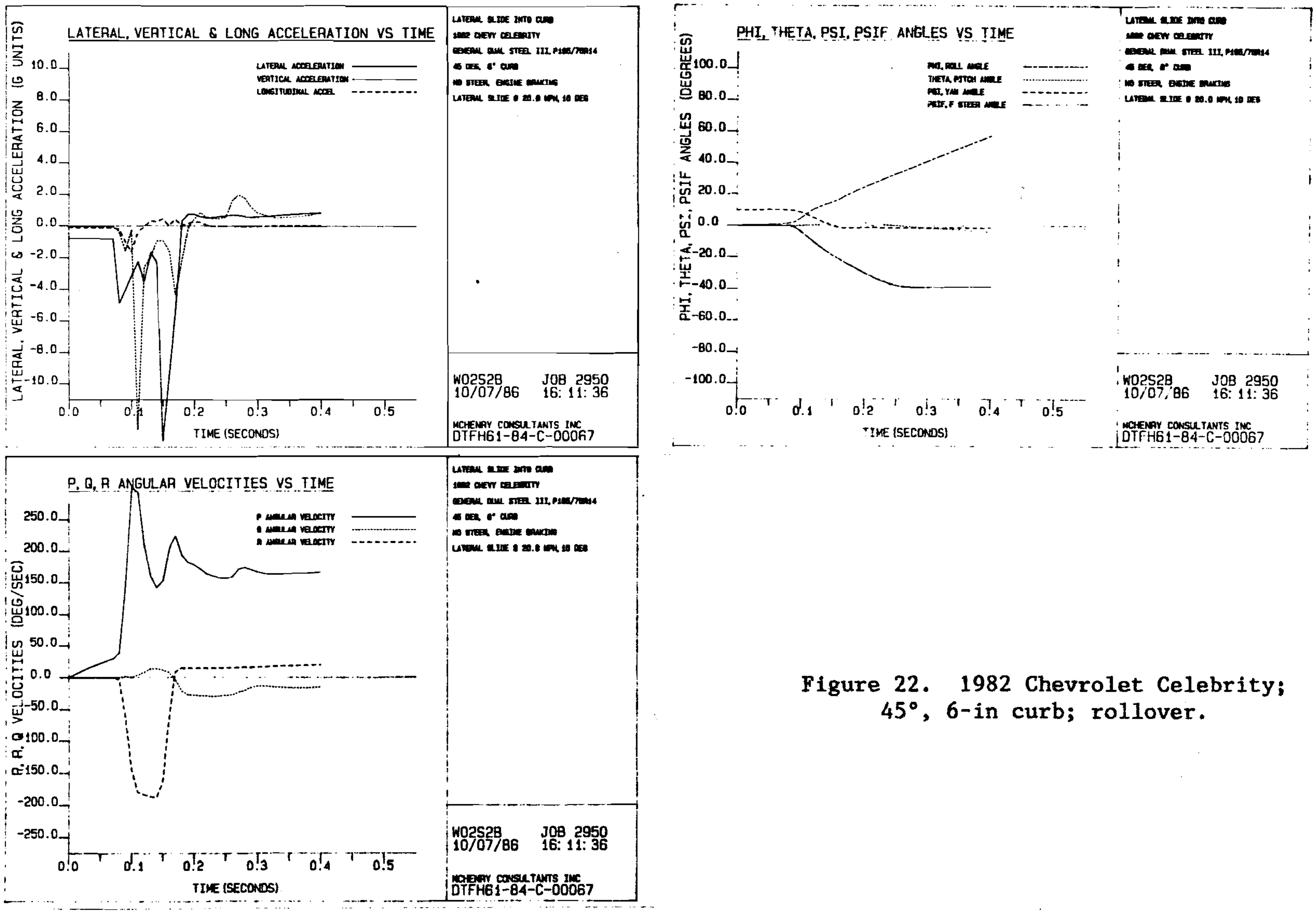


Figure 22. 1982 Chevrolet Celebrity; 45°, 6-in curb; rollover.

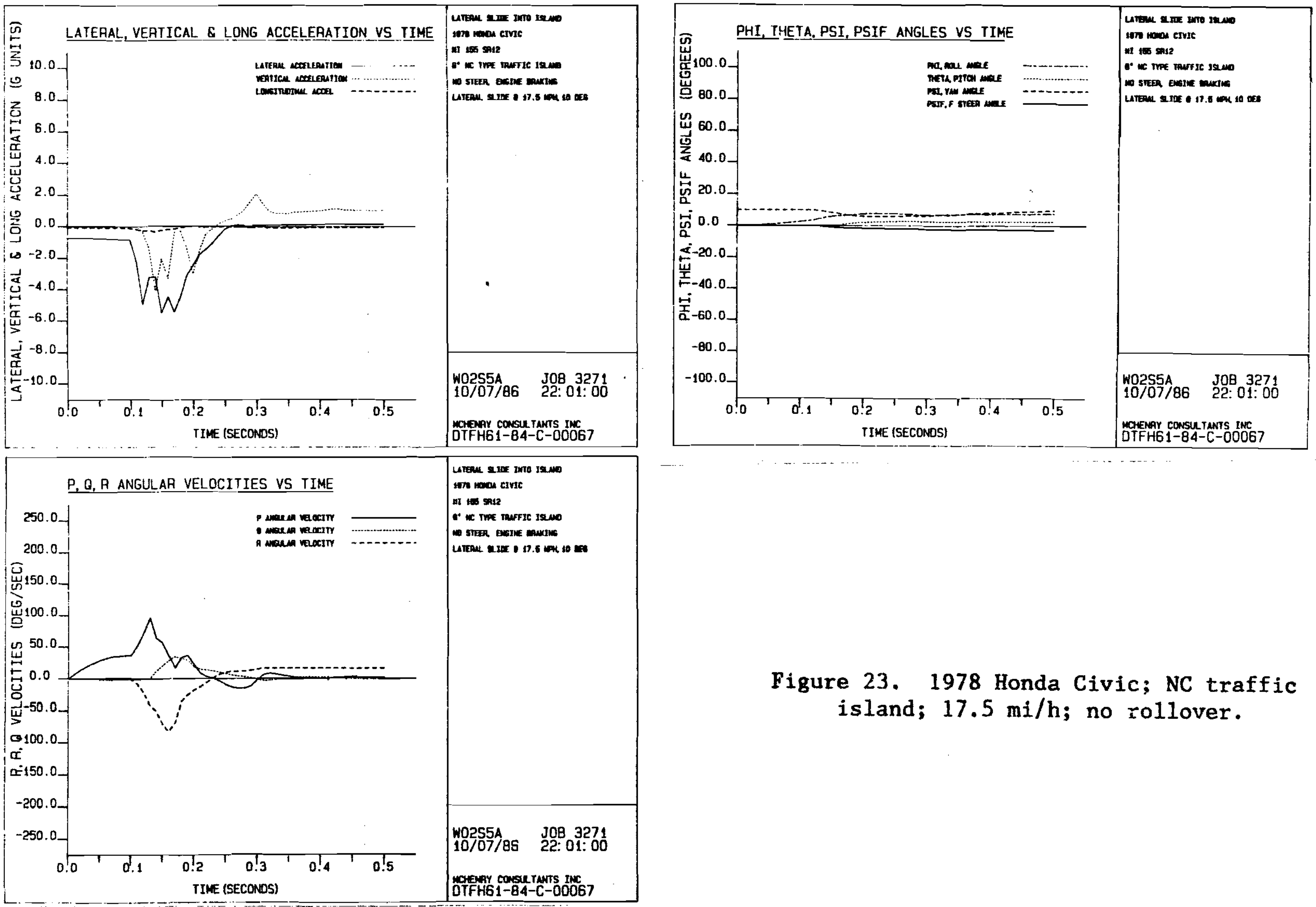


Figure 23. 1978 Honda Civic; NC traffic island; 17.5 mi/h; no rollover.

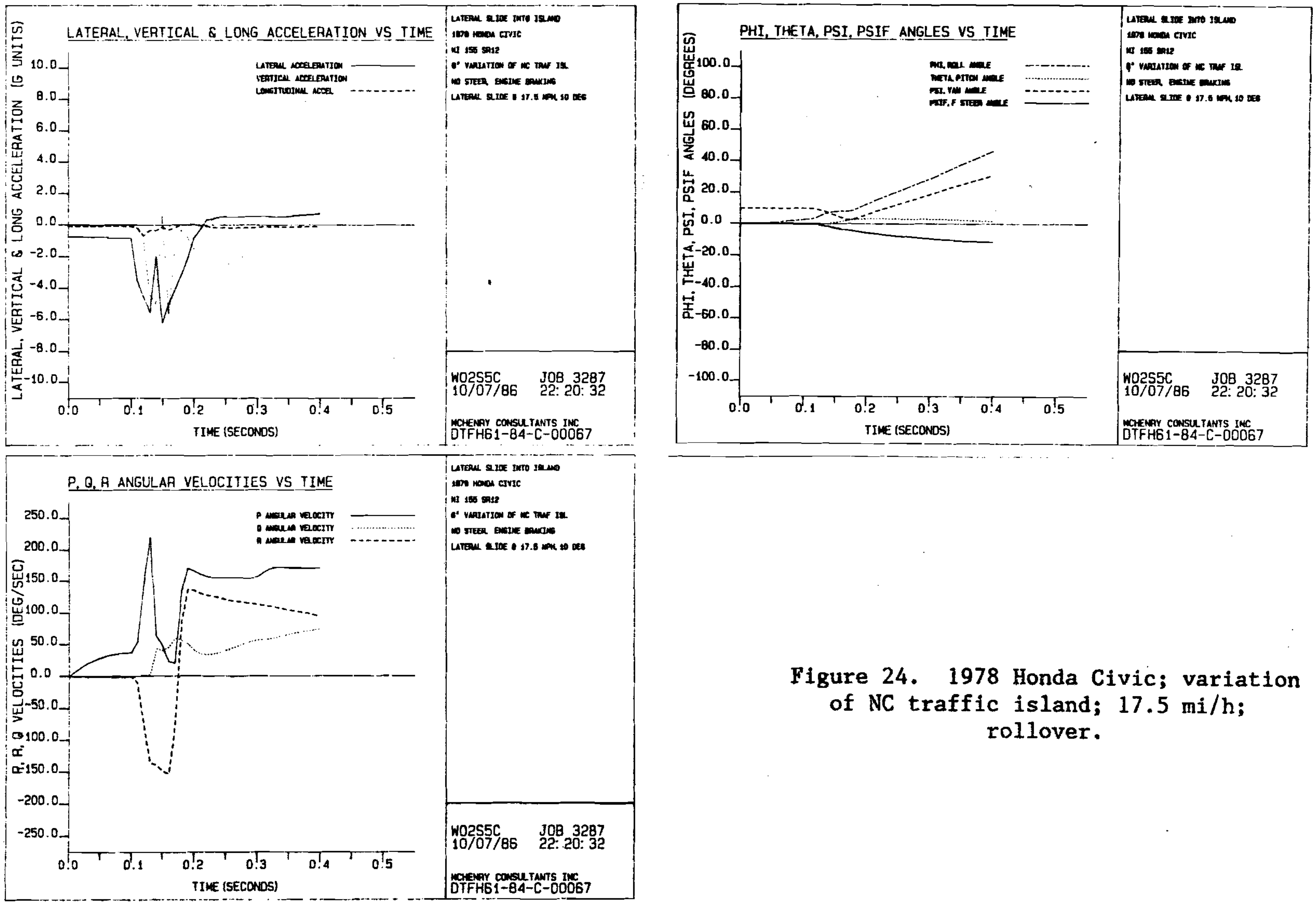


Figure 24. 1978 Honda Civic; variation of NC traffic island; 17.5 mi/h; rollover.

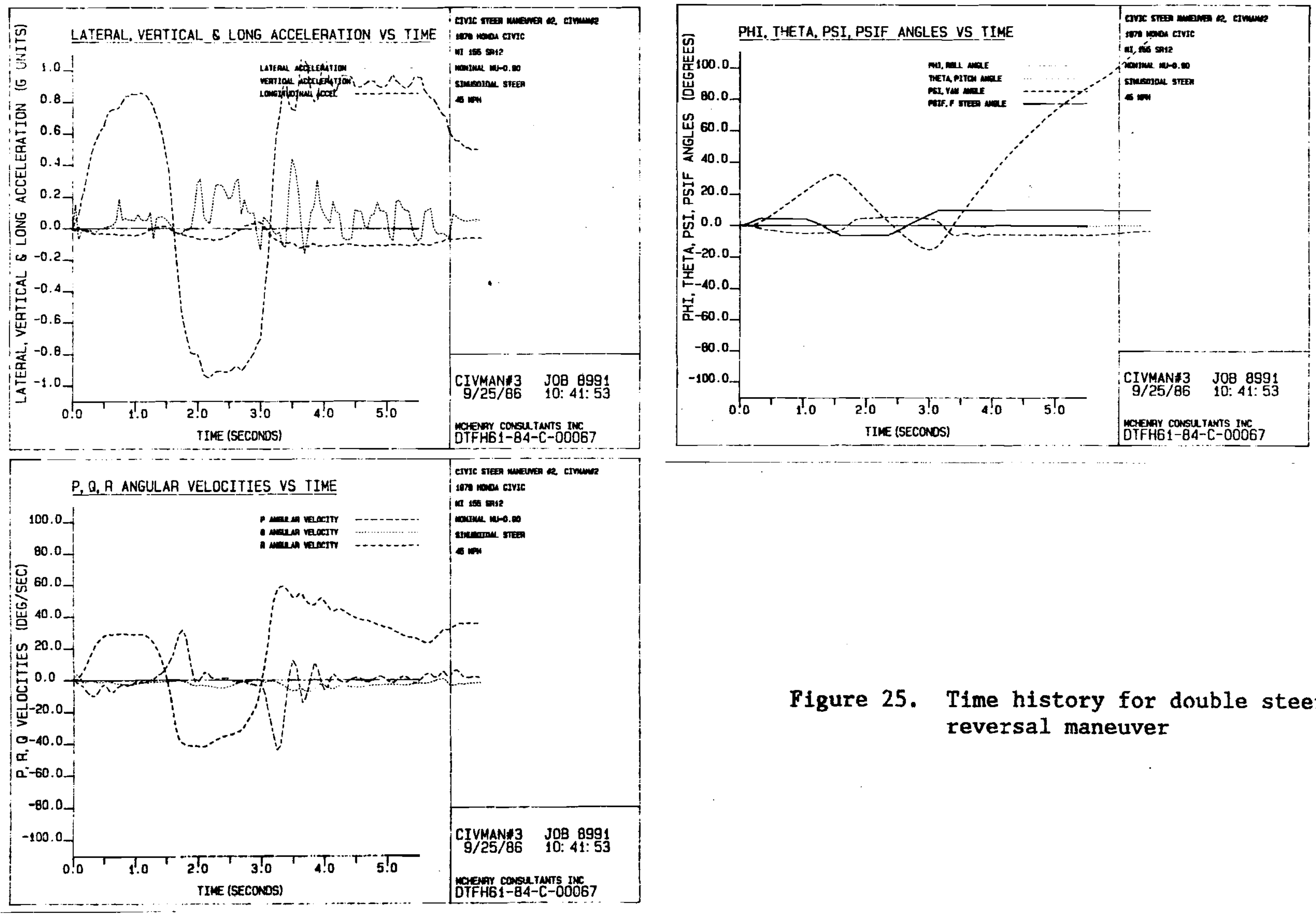


Figure 25. Time history for double steer reversal maneuver

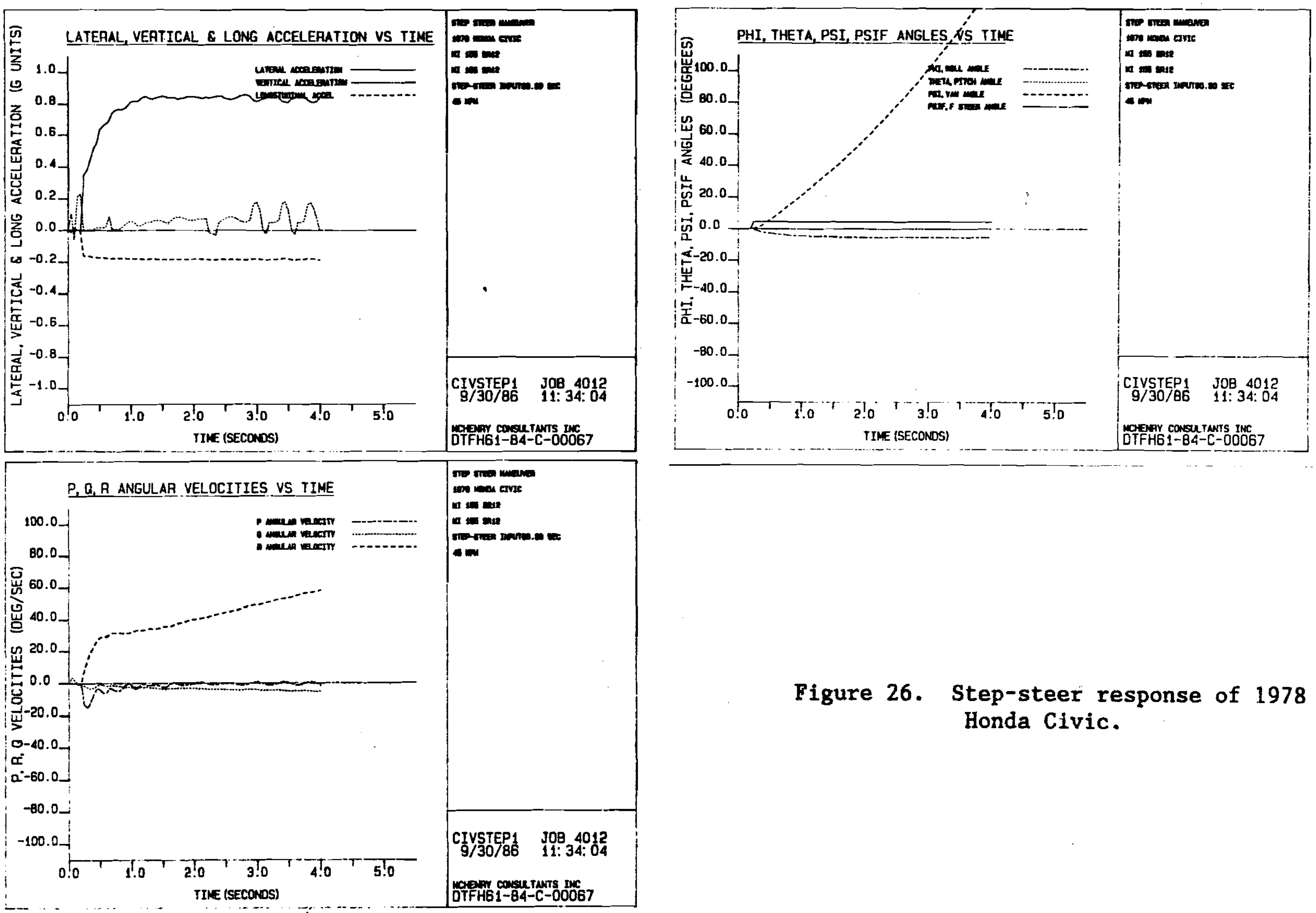


Figure 26. Step-steer response of 1978 Honda Civic.

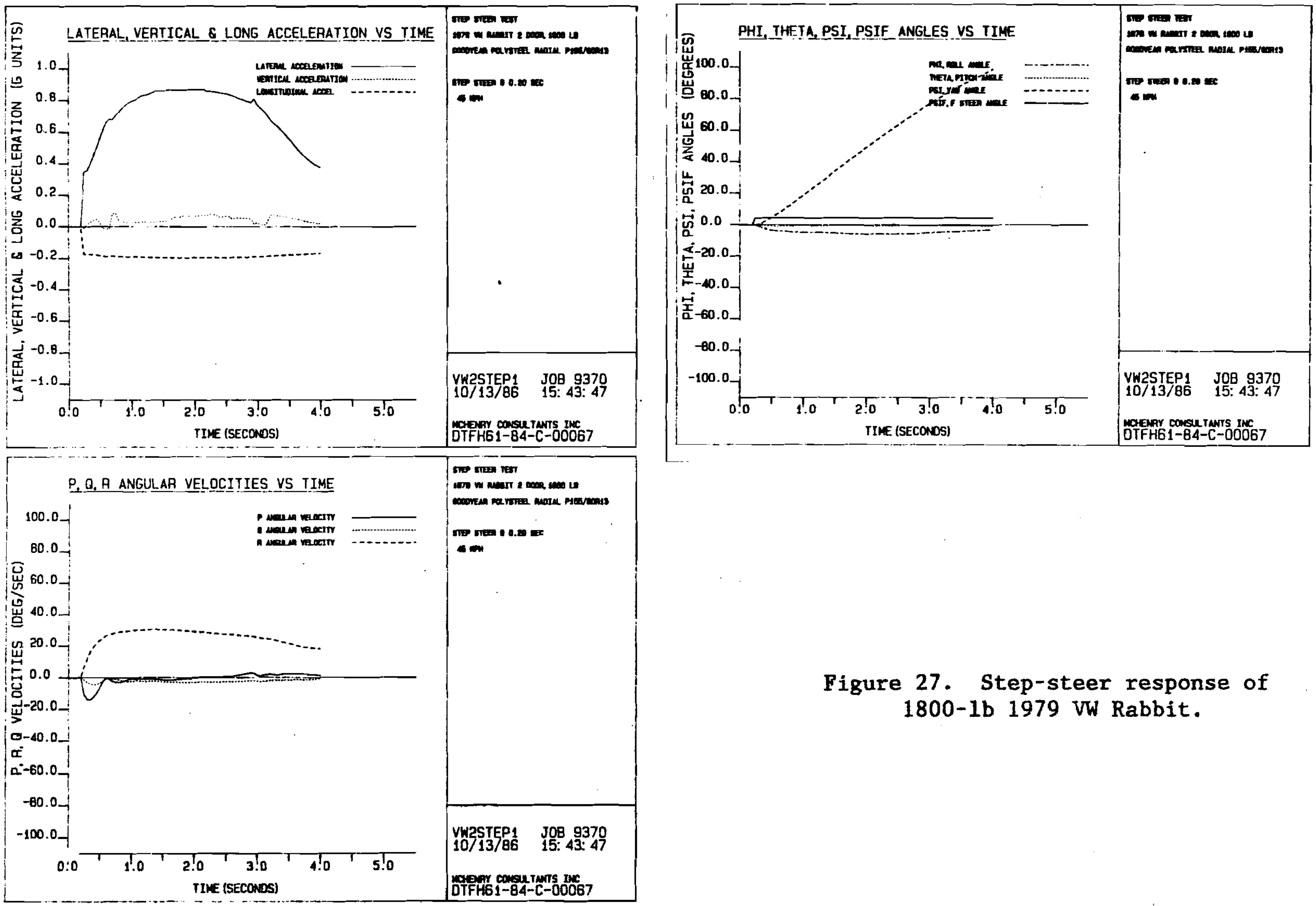


Figure 27. Step-steer response of 1800-lb 1979 VW Rabbit.

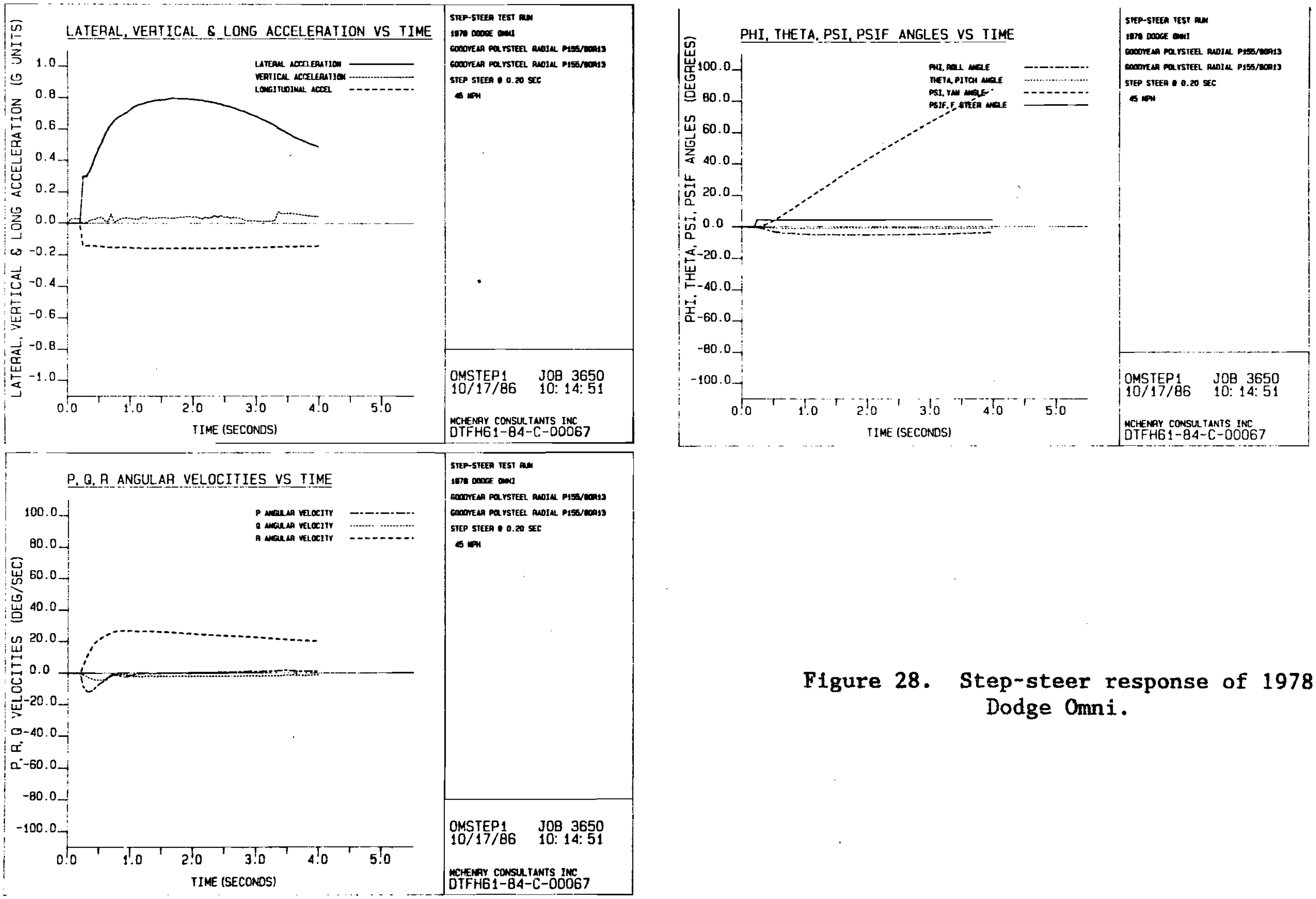
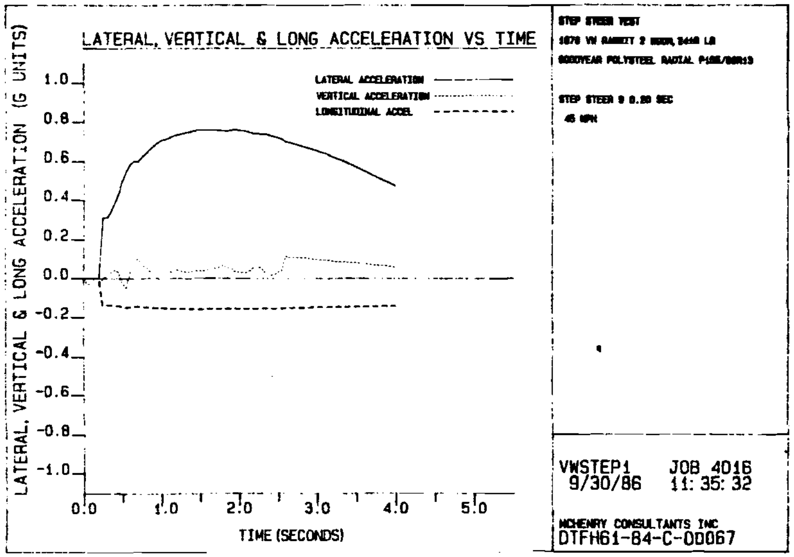
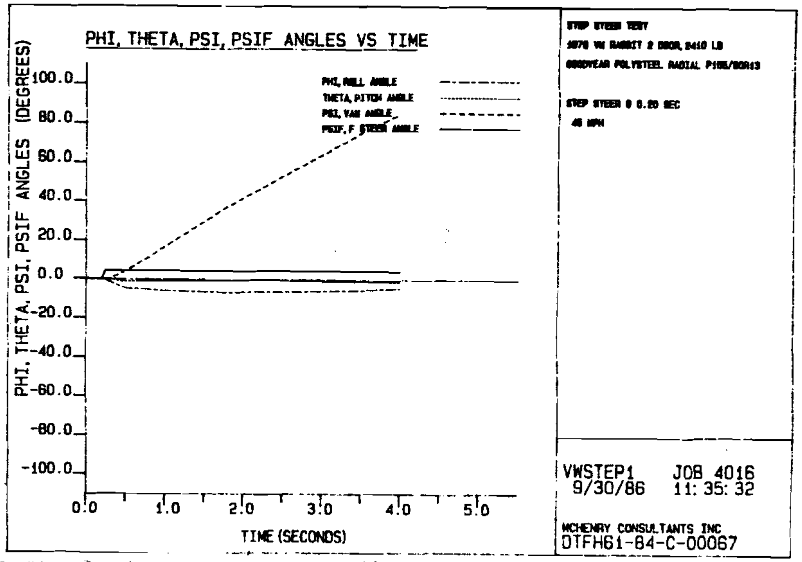


Figure 28. Step-steer response of 1978 Dodge Omni.





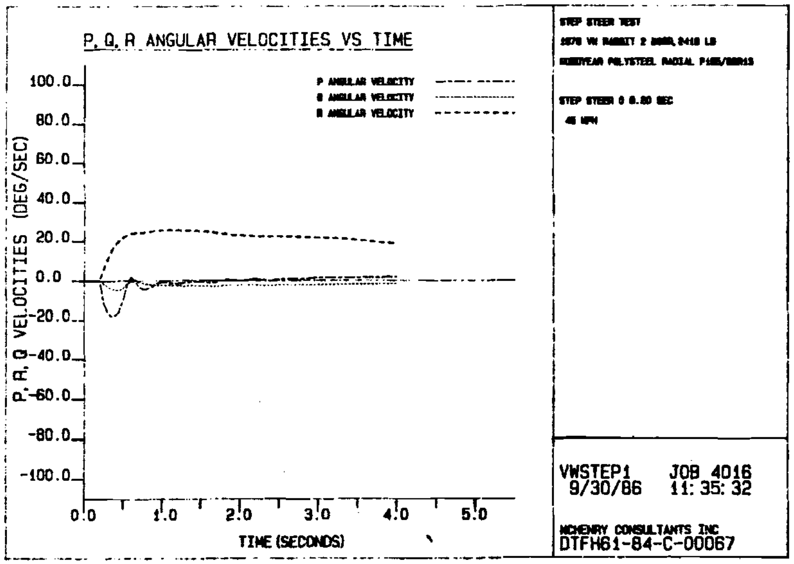


Figure 29. Step-steer response of 2400-lb 1979 VW Rabbit.

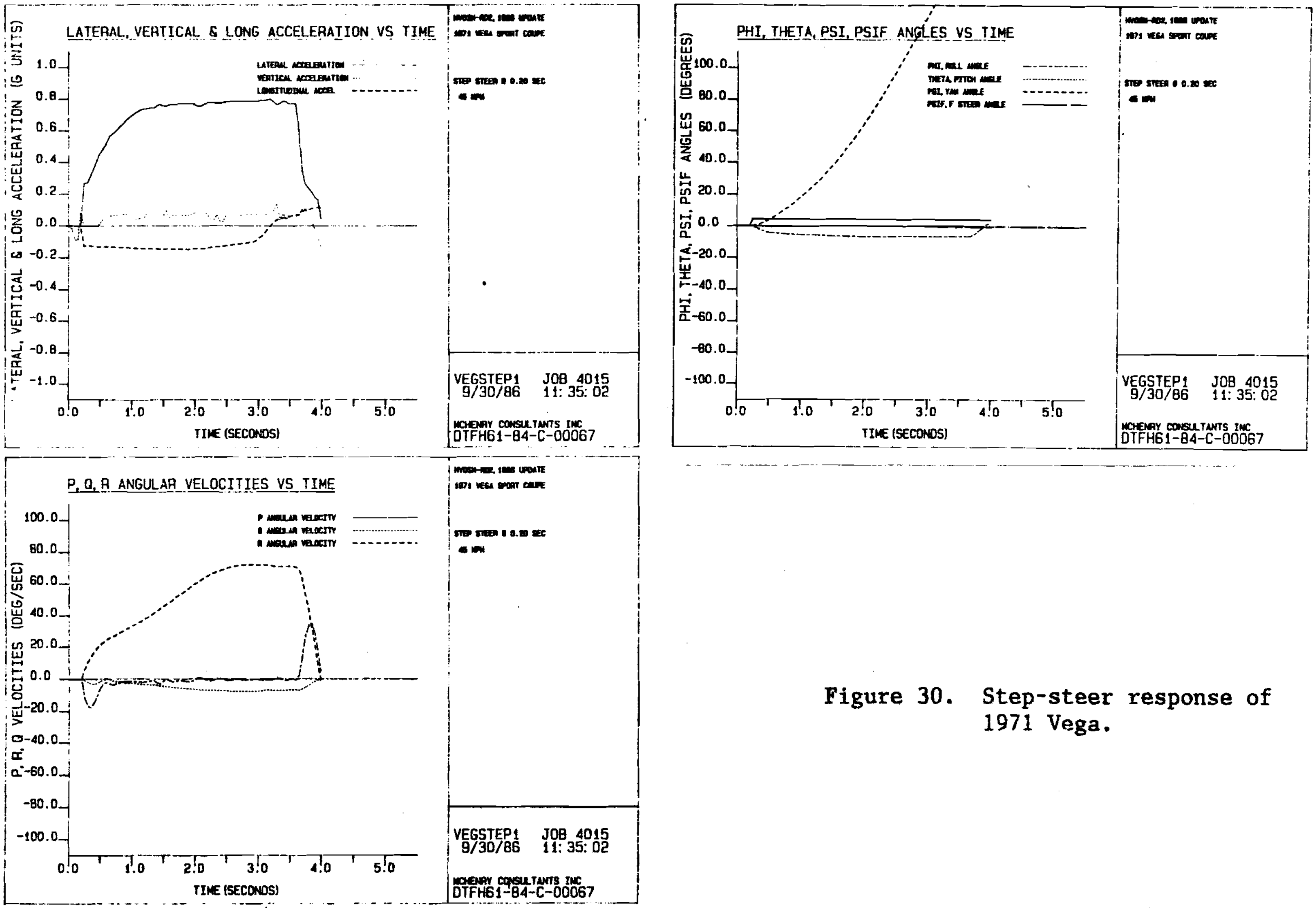


Figure 30. Step-steer response of 1971 Vega.

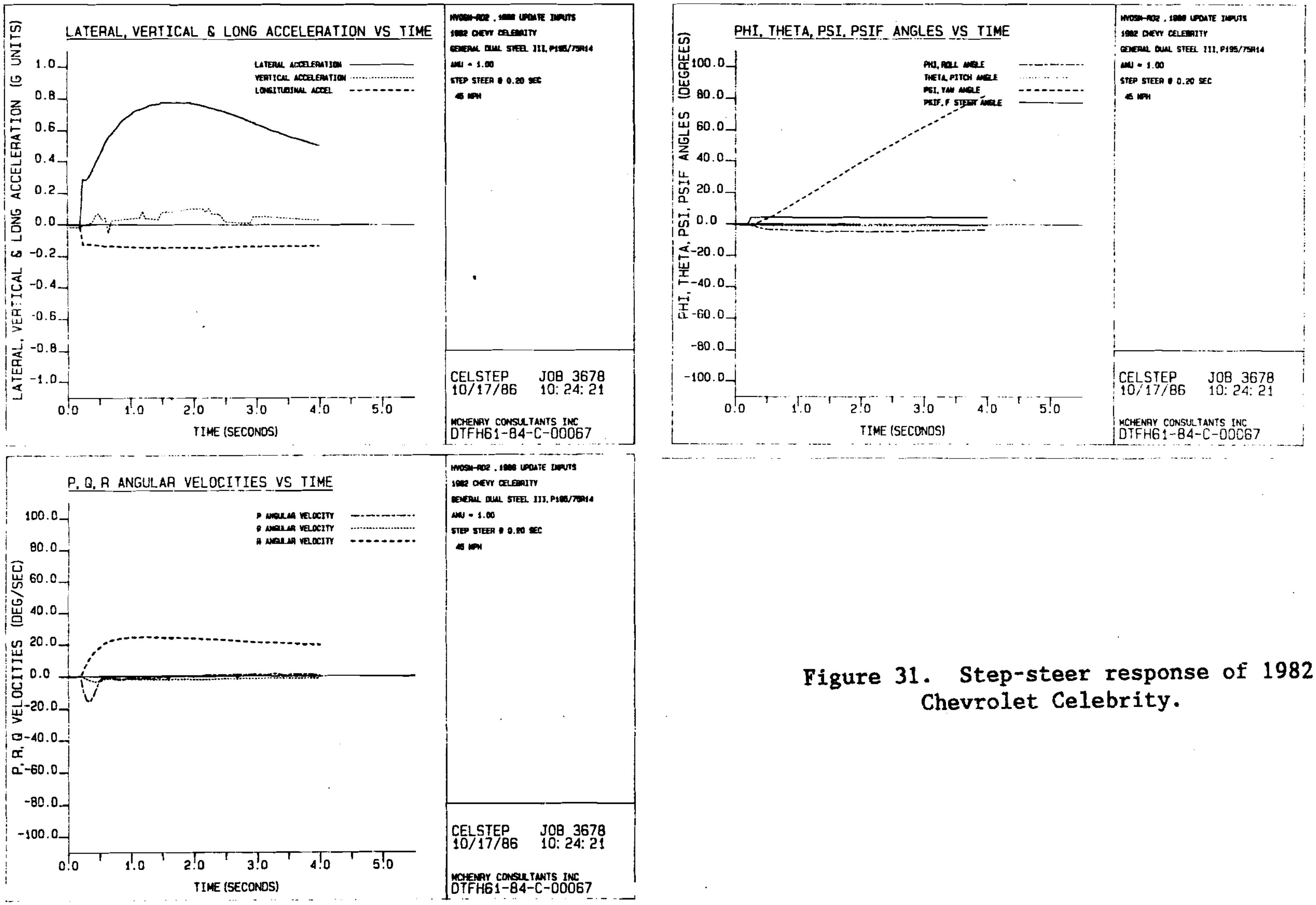


Figure 31. Step-steer response of 1982 Chevrolet Celebrity.

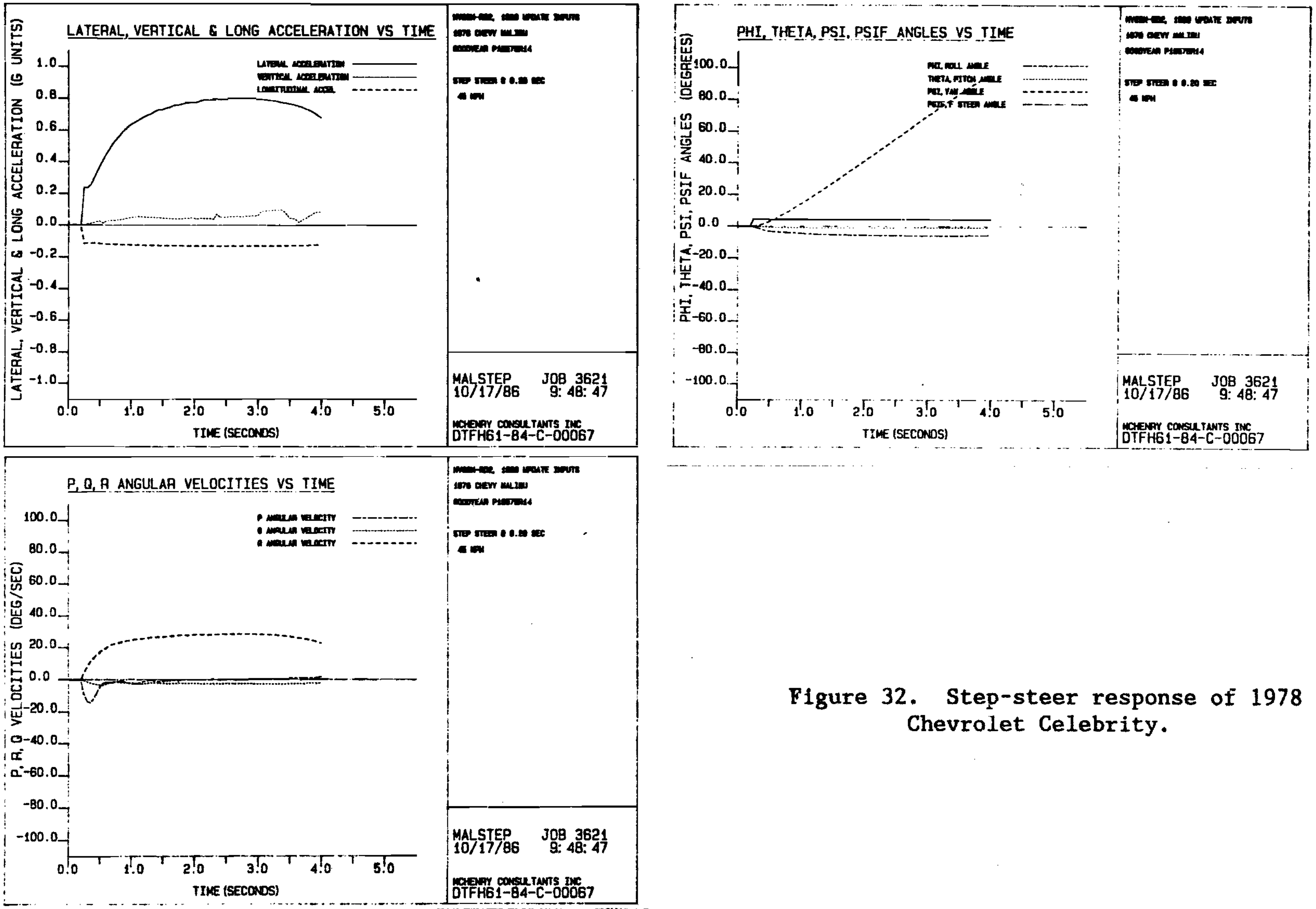


Figure 32. Step-steer response of 1978 Chevrolet Celebrity.

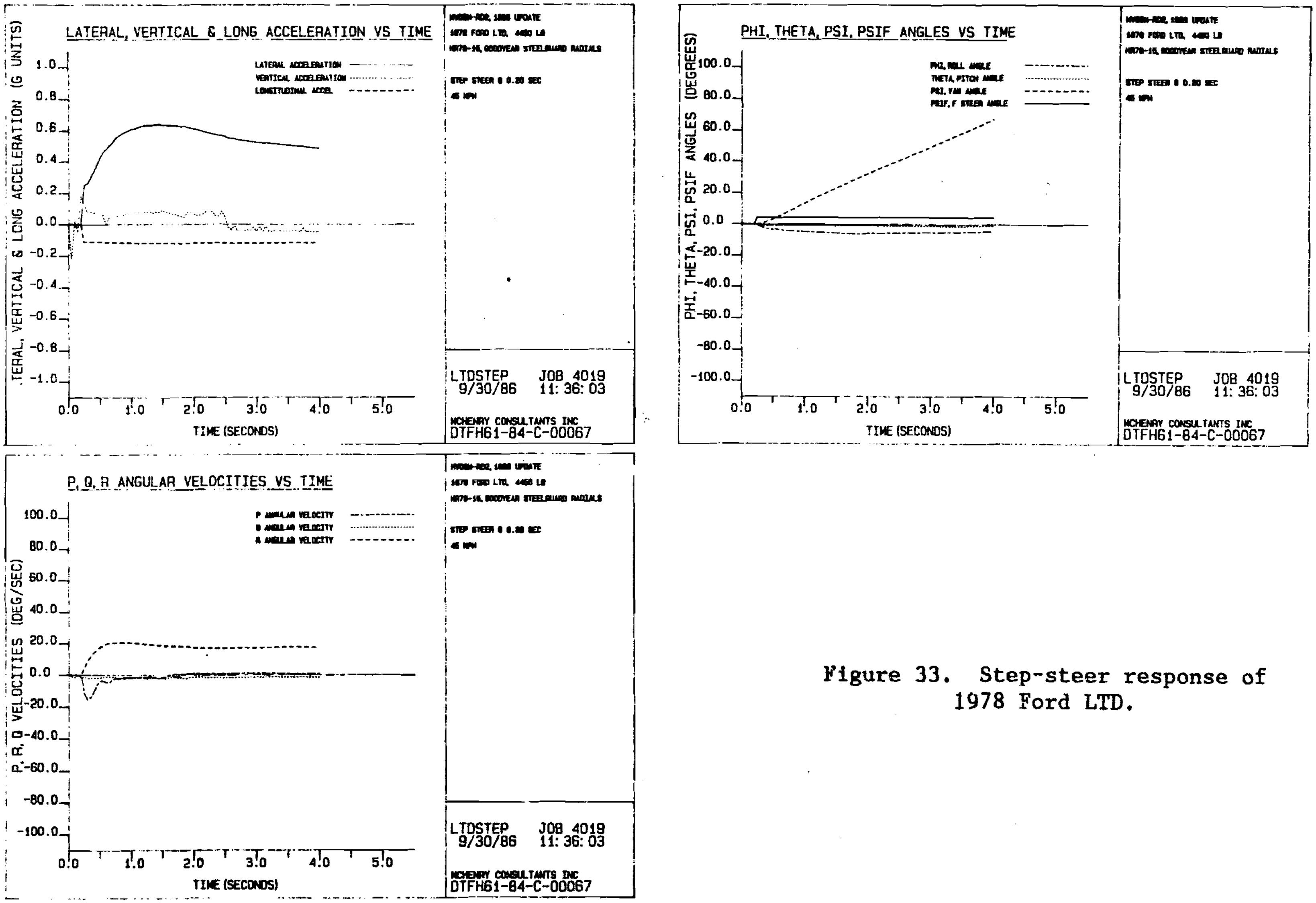


Figure 33. Step-steer response of 1978 Ford LTD.

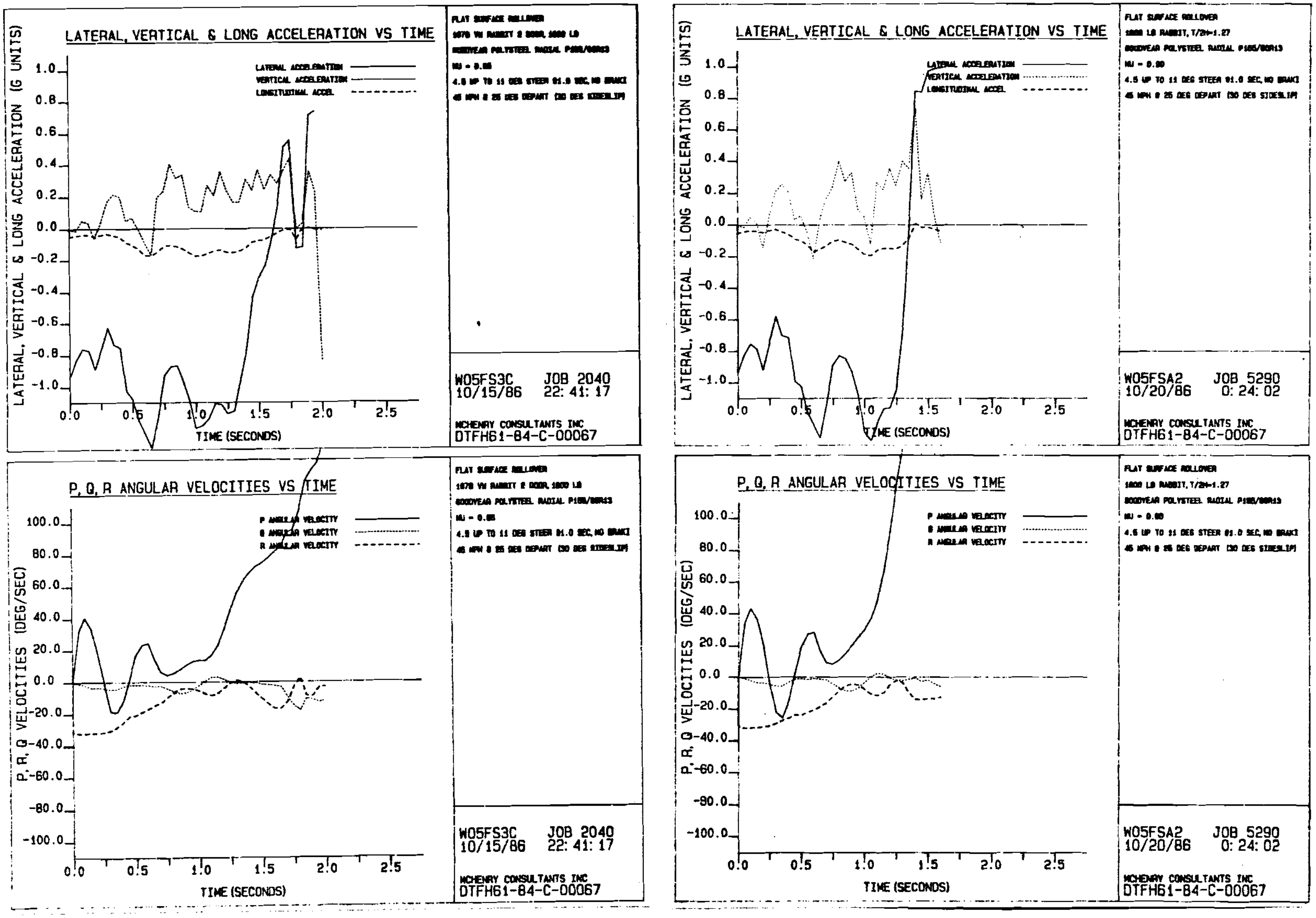


Figure 34. Comparison of 1800-lb vehicles with different CG heights
(Left column: μ = .95, T/2H = 1.37; Right column: μ = .90, T/2H = 1.27).

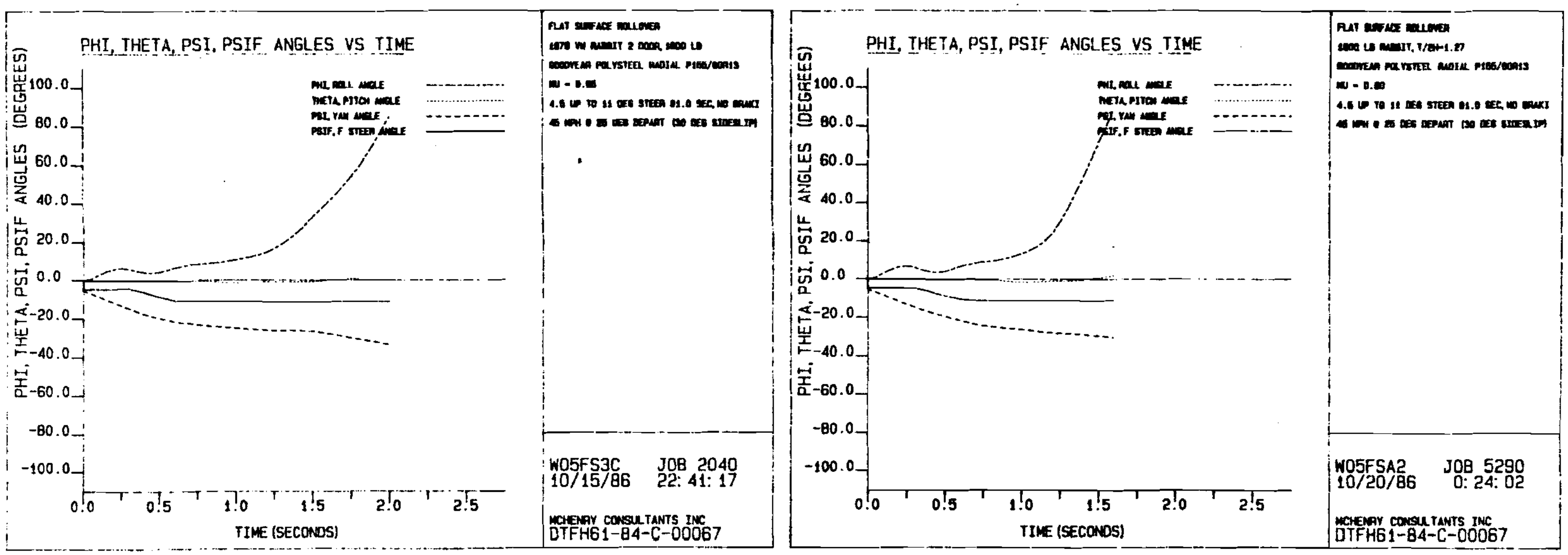


Figure 34 (cont). Comparison of 1800-lb vehicles with different CG heights (Left column: μ = .95, T/2H = 1.37; Right column: μ = .90, T/2H = 1.27).

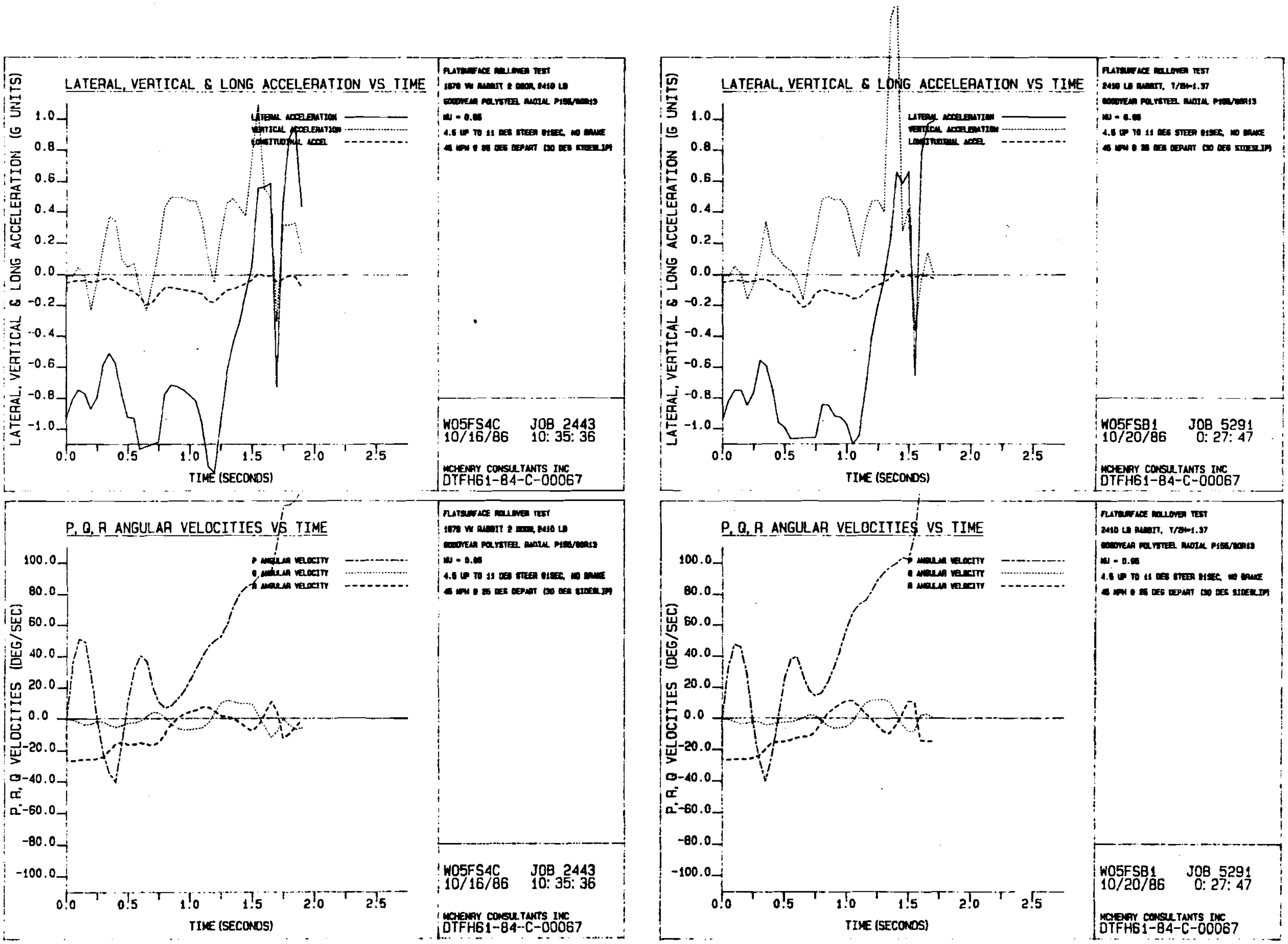


Figure 35. Comparison of 2400-lb vehicles with different CG heights (Left column: μ = .85, T/2H = 1.27; Right column: μ = .95, T/2H = 1.37).

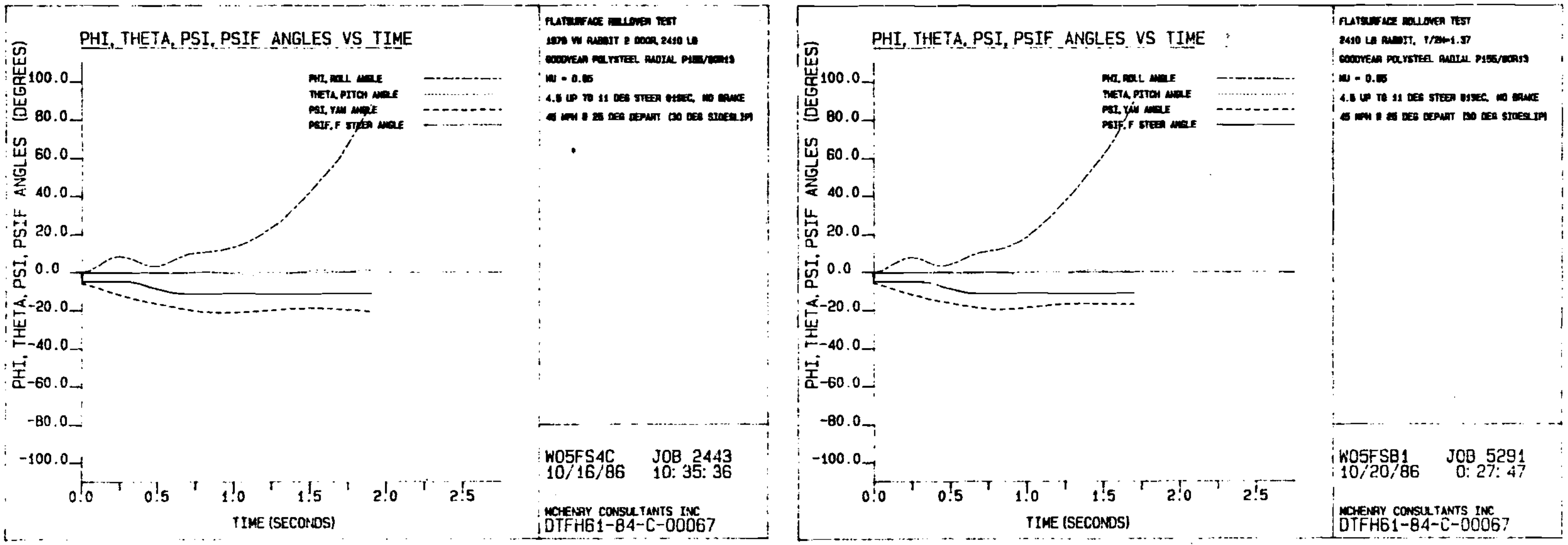


Figure 35 (cont). Comparison of 2400-lb vehicles with different CG heights (Left column: μ = .85, T/2H = 1.27; Right column: μ = .95, T/2H = 1.37).

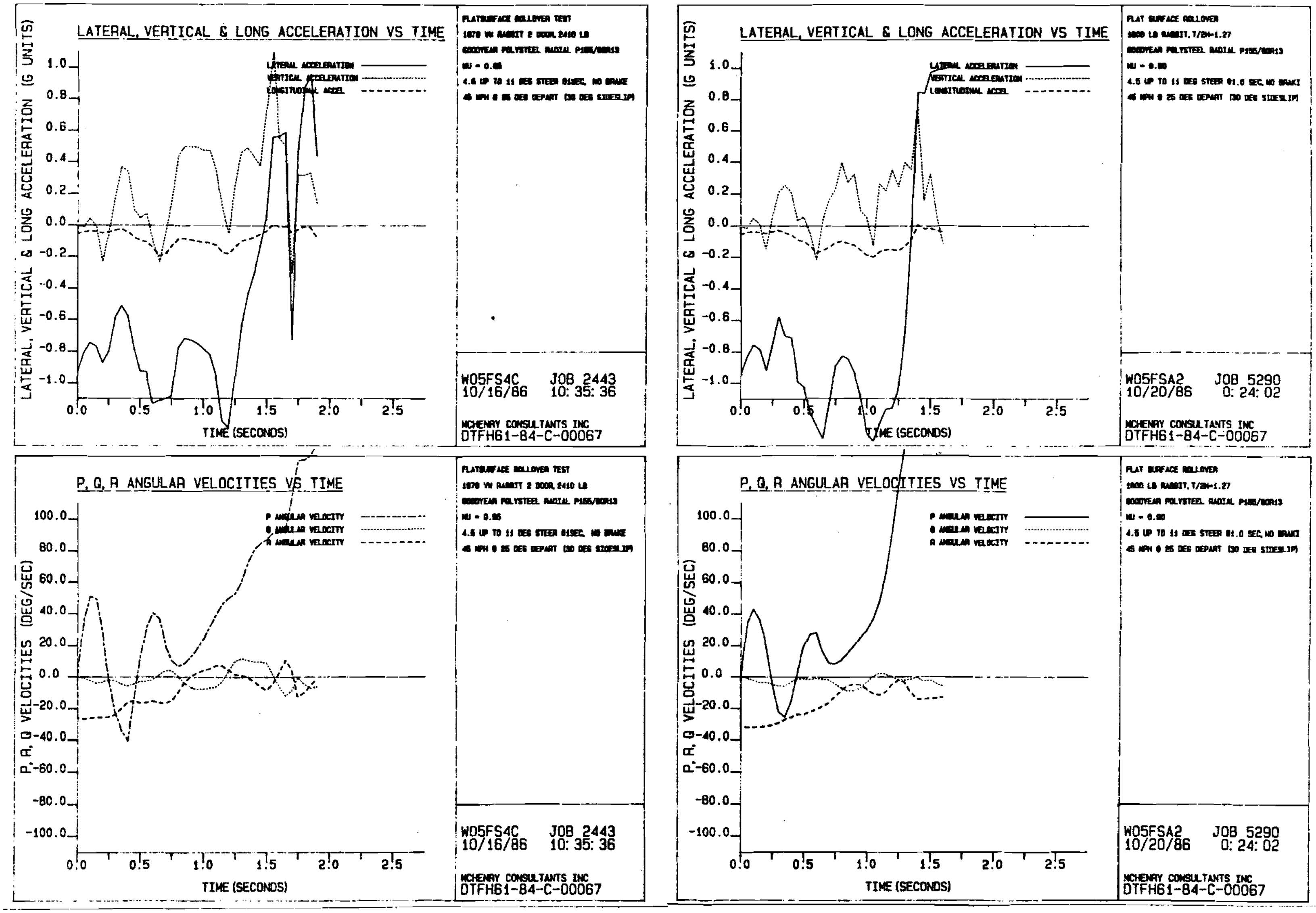
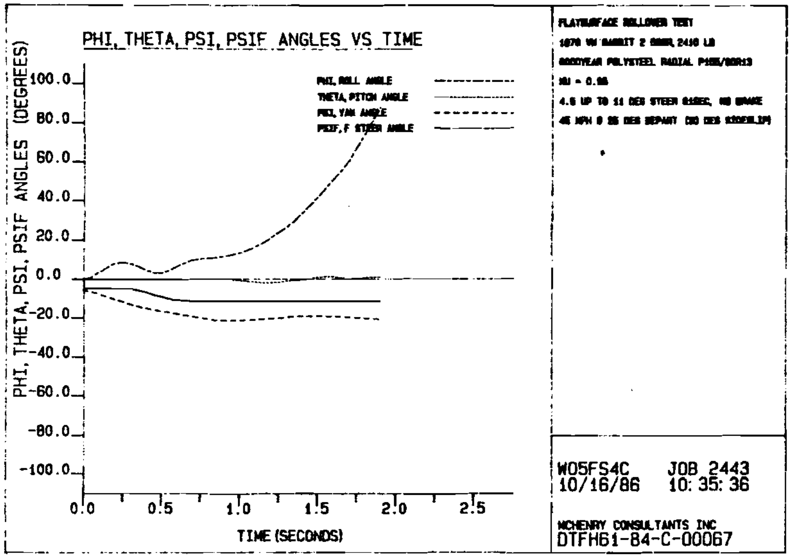


Figure 36. Comparison of 2400- and 1800-lb vehicles with same CG height (Left column: μ = .85, 2400-lb; Right column: μ = .95, 1800-lb).



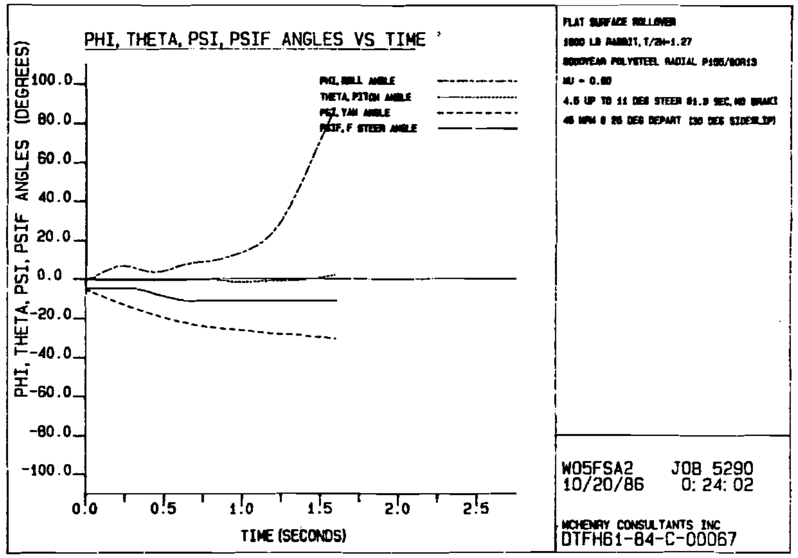


Figure 36 (cont). Comparison of 2400- and 1800-lb vehicles with same CG height (Left column: μ = .85, 2400-lb; Right column: μ = .95, 1800-lb).

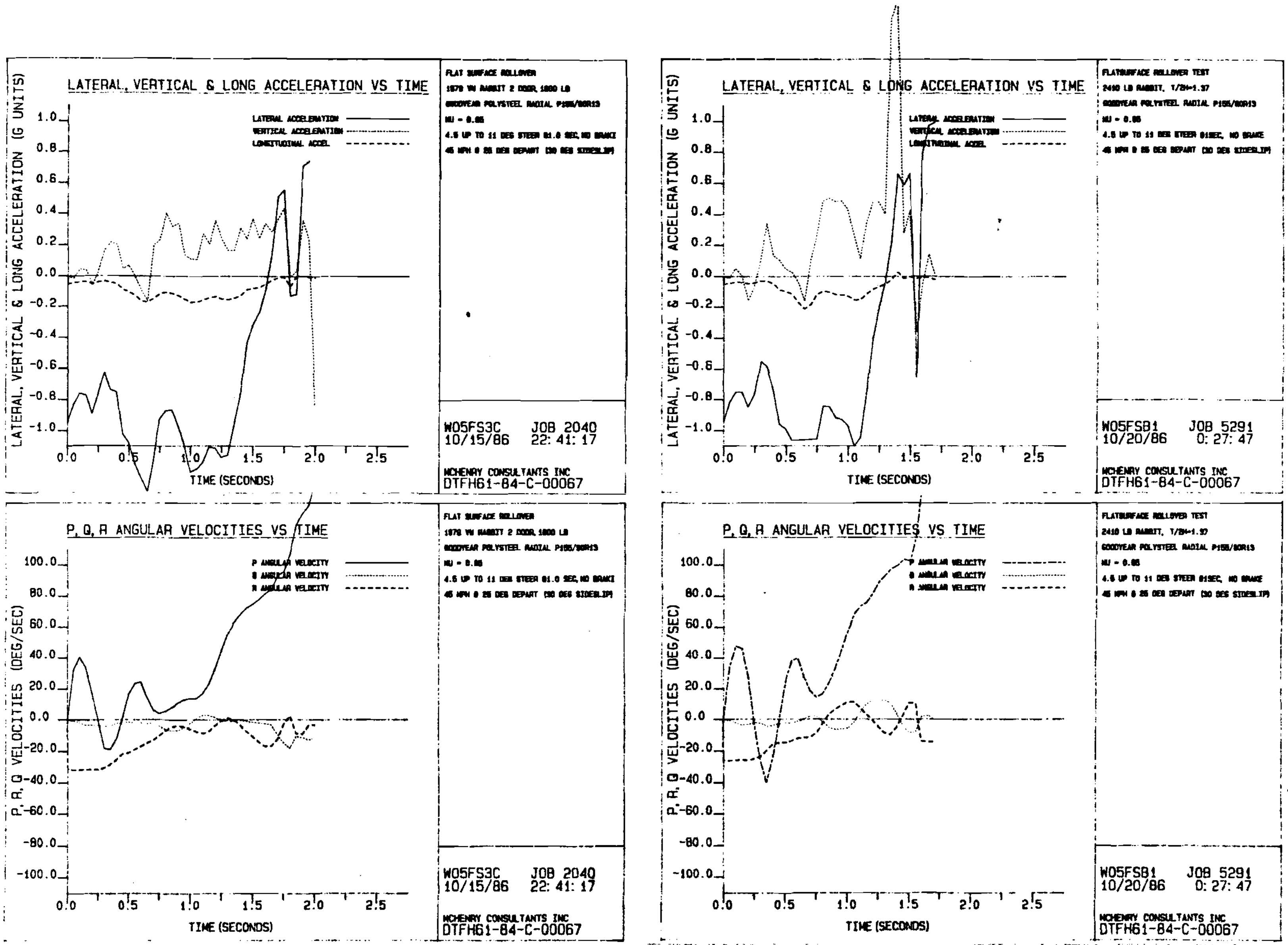
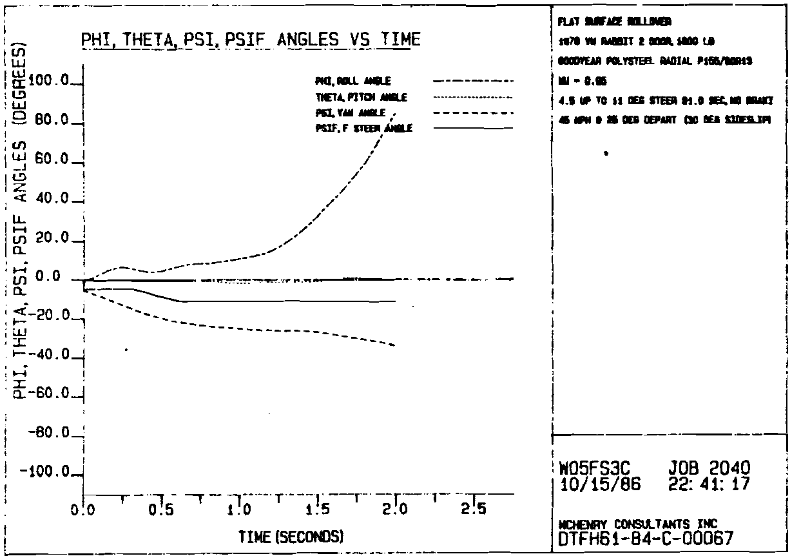


Figure 37. Comparison of 2400- and 1800-lb vehicles with same CG height (Left column: μ = .95, 1800-lb; Right column: μ = .95, 2400-lb).



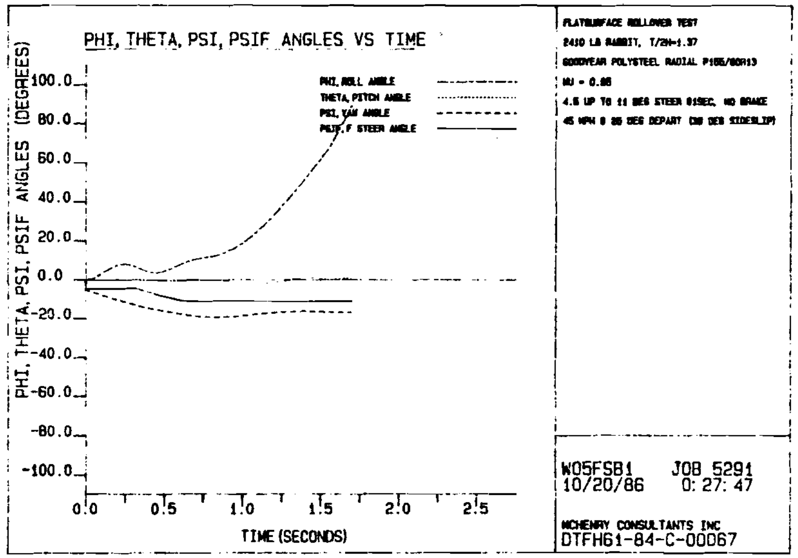


Figure 37 (cont). Comparison of 2400- and 1800-lb vehicles with same CG height (Left column: μ = .95, 1800-lb; Right column: μ = .95, 2400-lb).

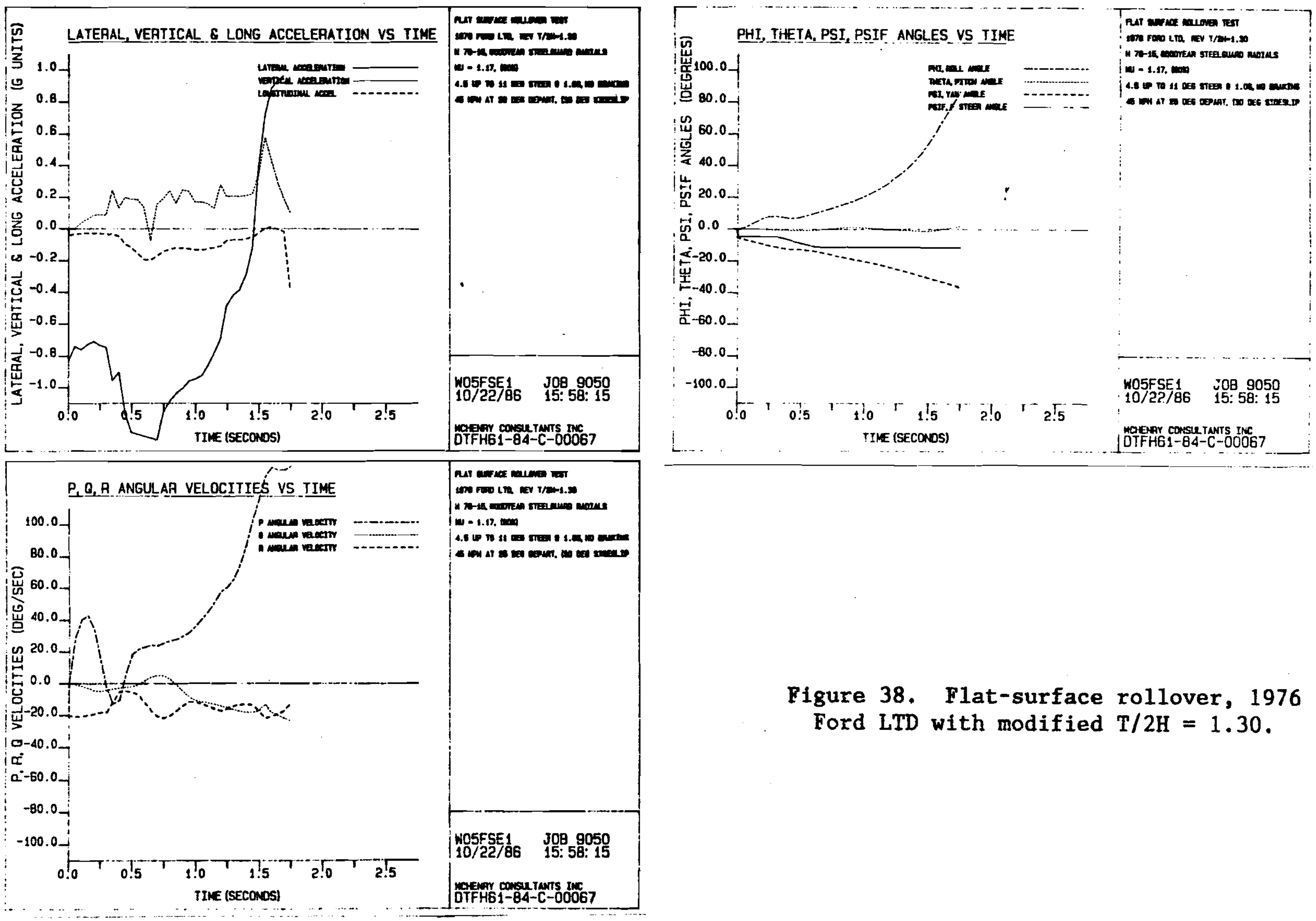


Figure 38. Flat-surface rollover, 1976 Ford LTD with modified T/2H = 1.30.

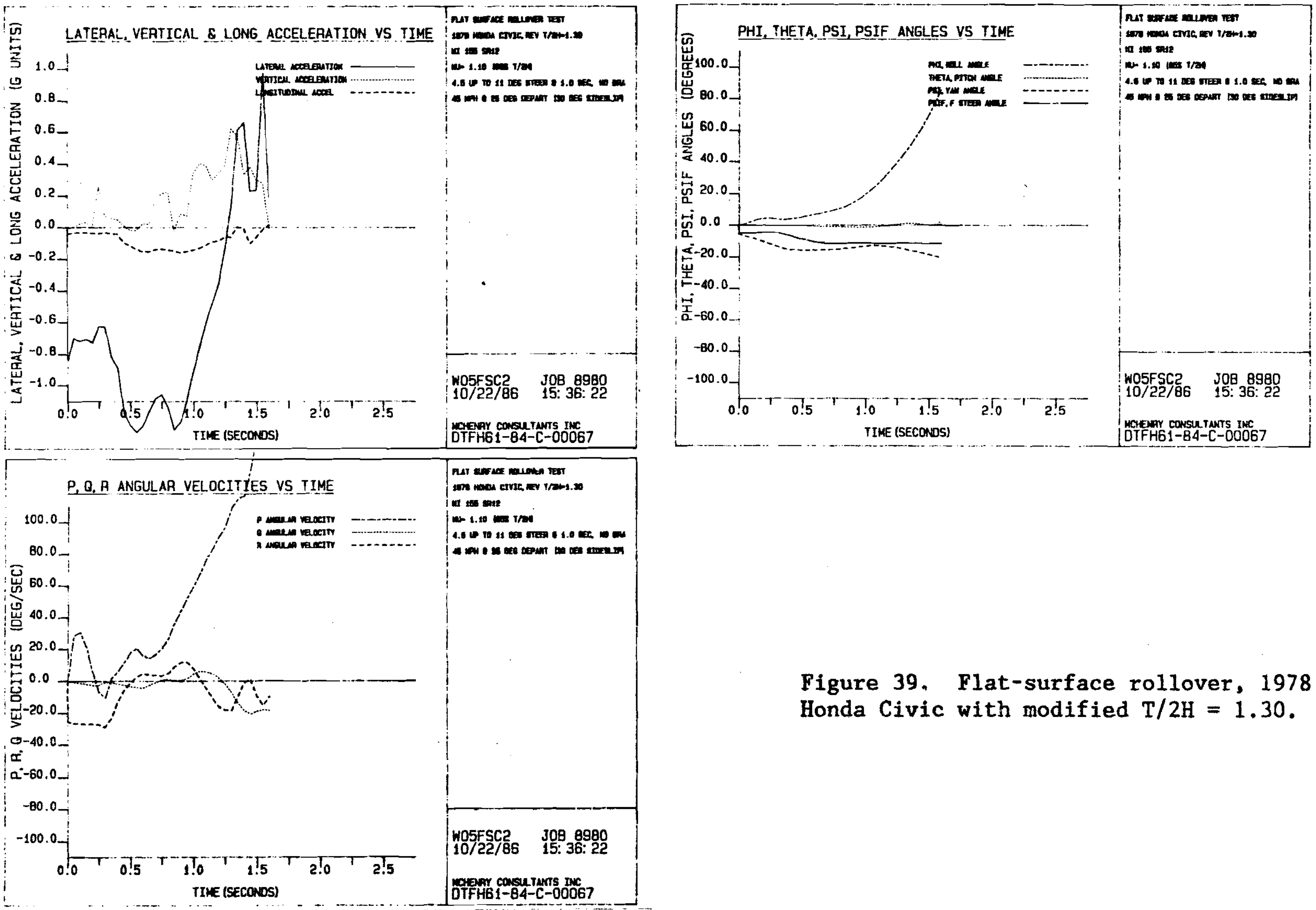


Figure 39. Flat-surface rollover, 1978 Honda Civic with modified T/2H = 1.30.

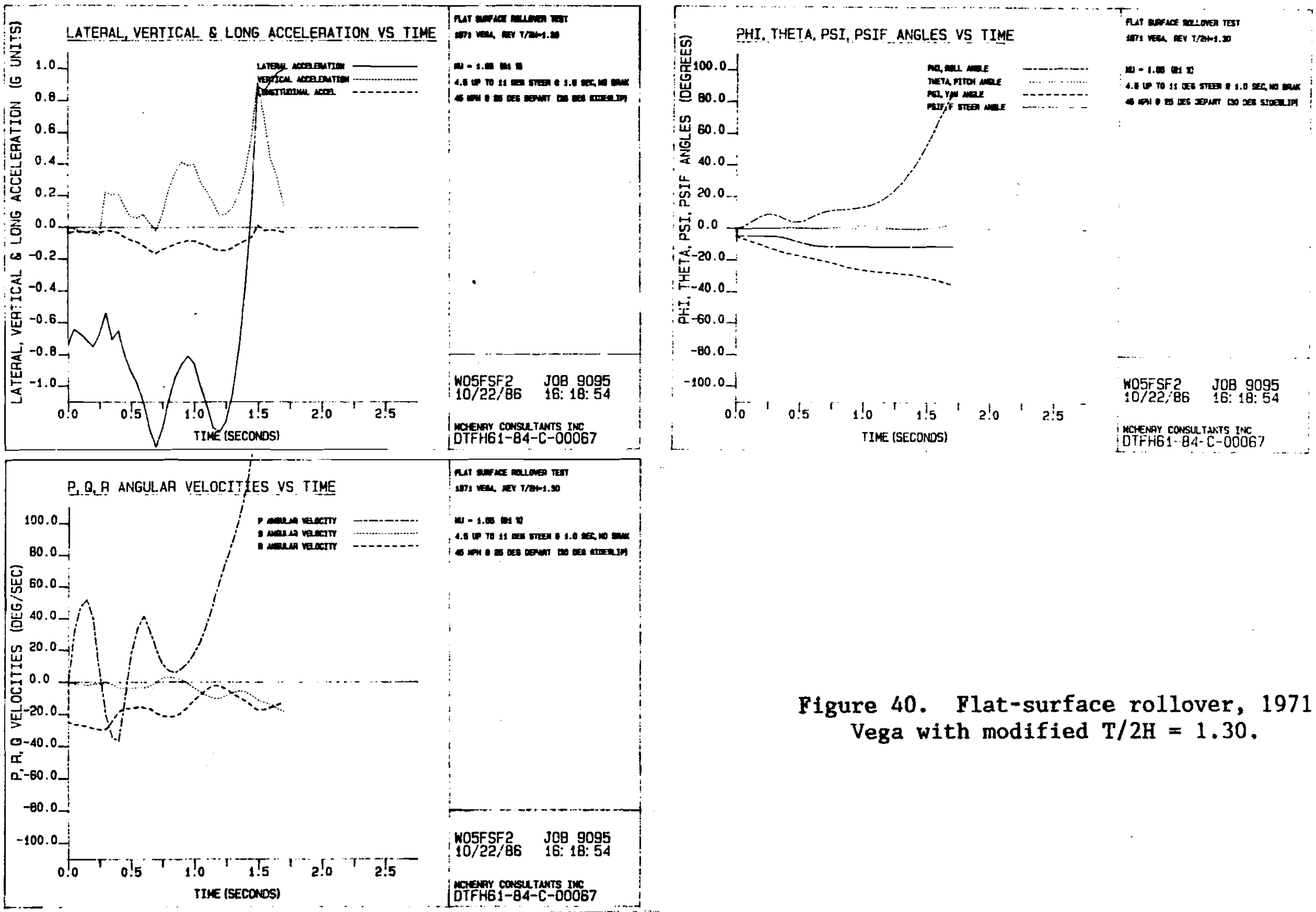
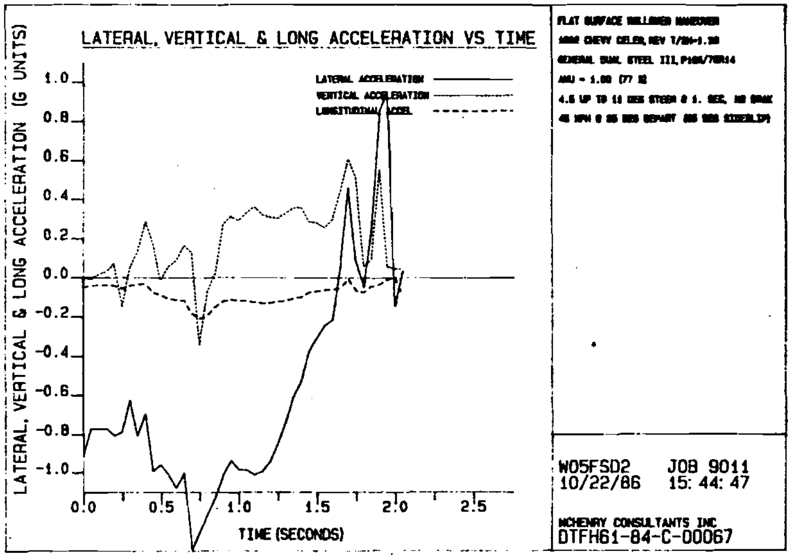
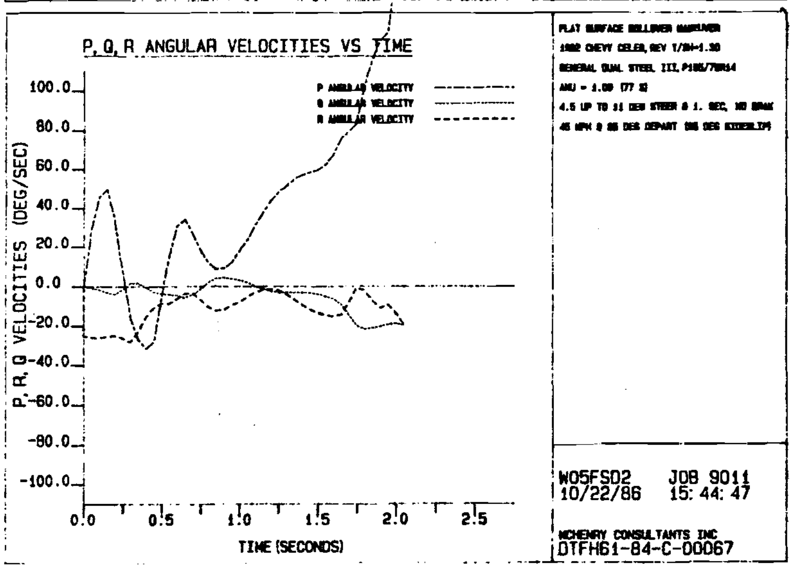


Figure 40. Flat-surface rollover, 1971 Vega with modified T/2H = 1.30.





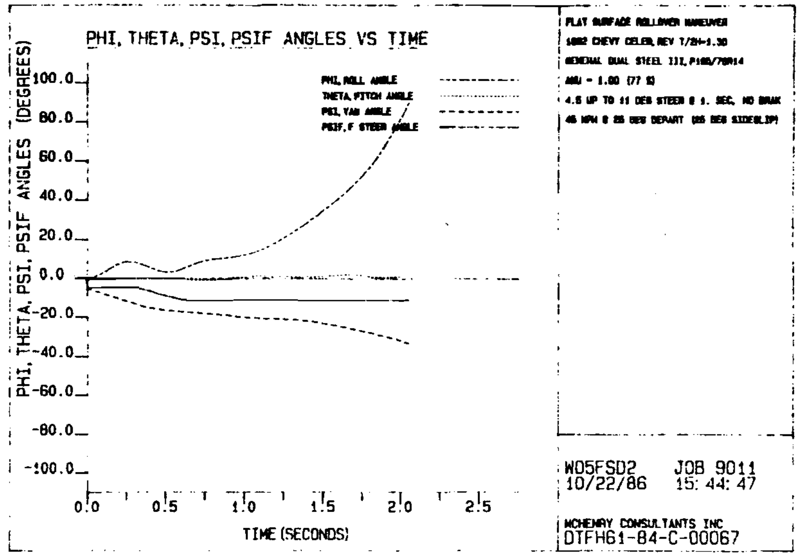


Figure 41. Flat-surface rollover, 1982 Chevrolet Celebrity with modified T/2H = 1.30.

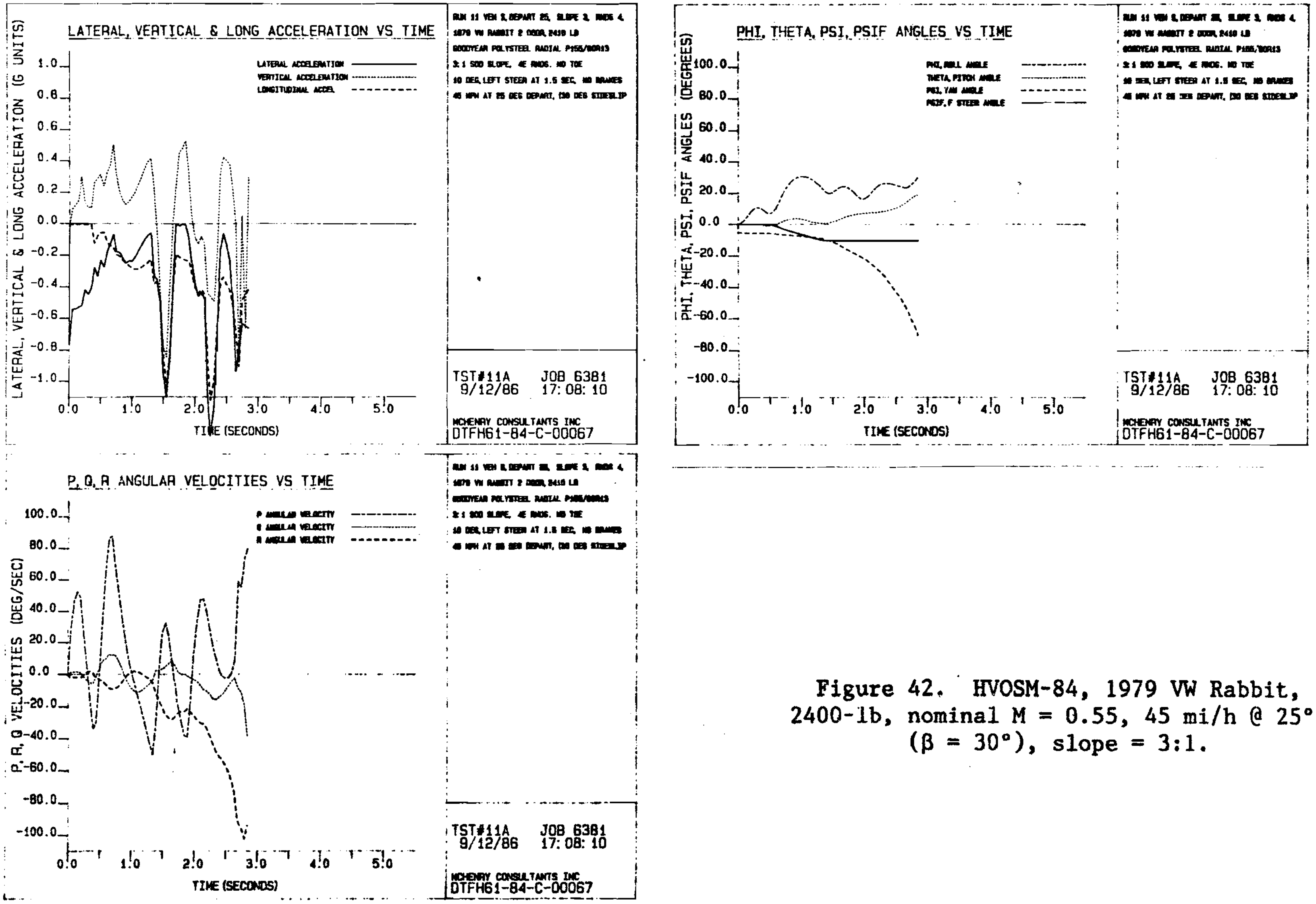


Figure 42. HVOSM-84, 1979 VW Rabbit, 2400-lb, nominal M = 0.55, 45 mi/h @ 25°, (β = 30°), slope = 3:1.

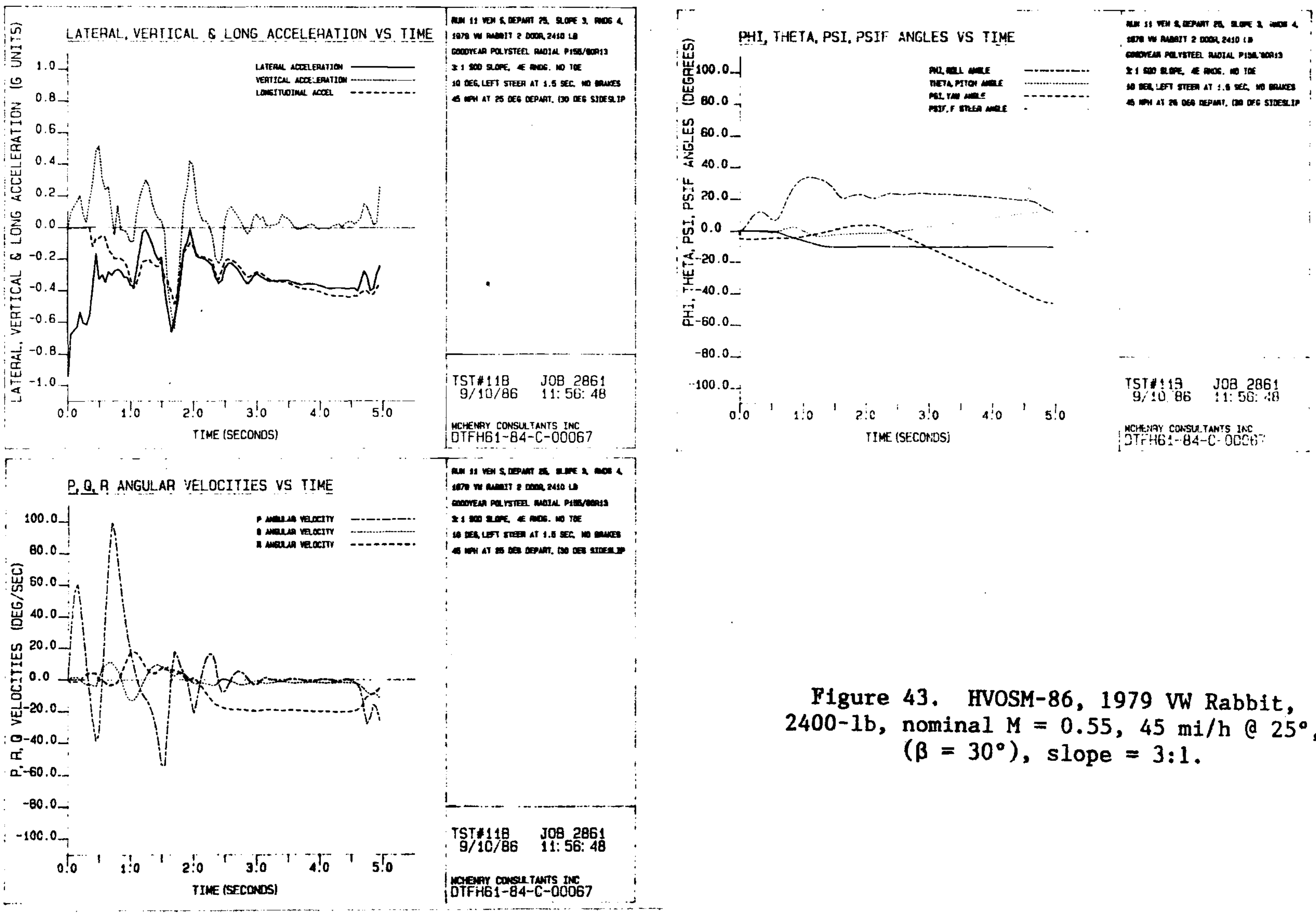
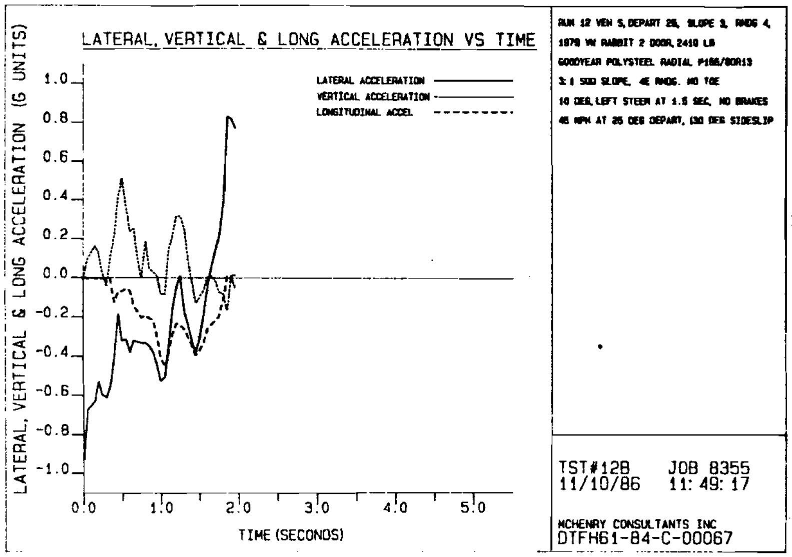
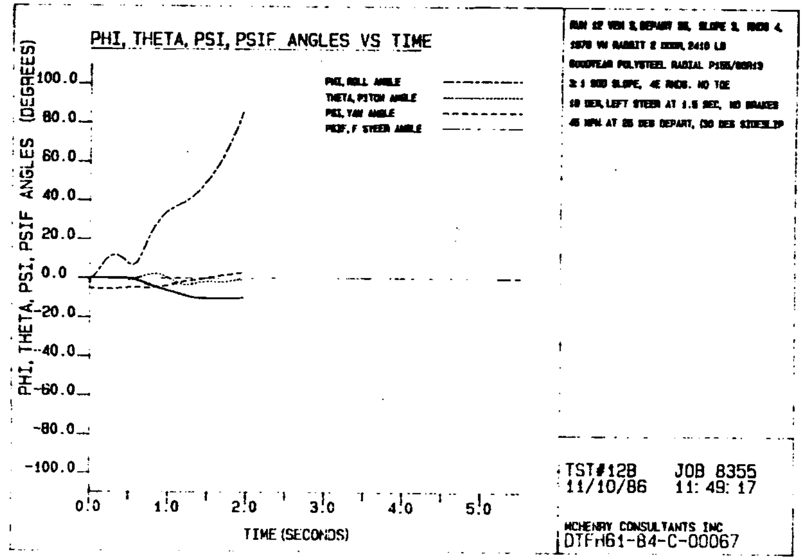


Figure 43. HVOSM-86, 1979 VW Rabbit, 2400-lb, nominal M = 0.55, 45 mi/h @ 25°, (β = 30°), slope = 3:1.





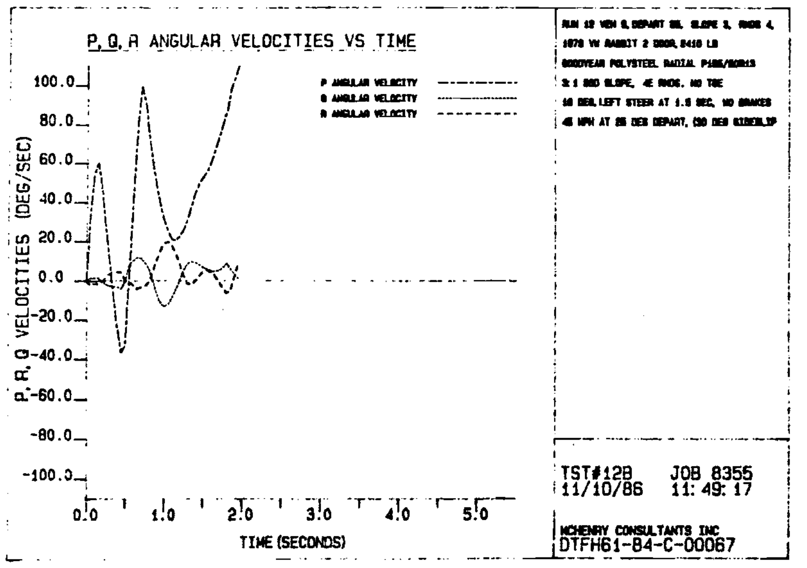


Figure 44. HVOSM-86, 1979 VW Rabbit, 2400-lb, nominal M = 0.60, 45 mi/h @ 25°, (β = 30°), slope = 3:1.

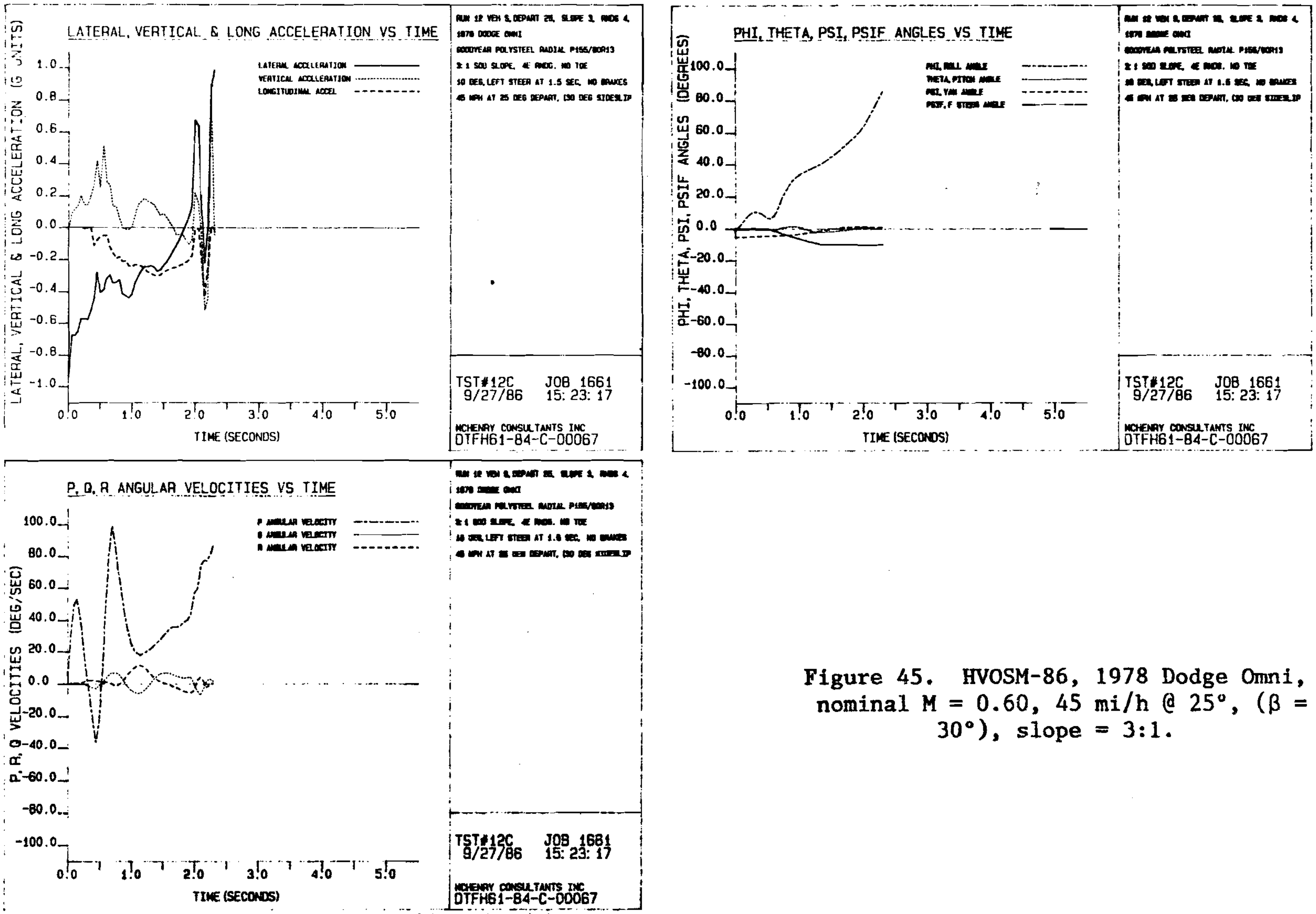


Figure 45. HVOSM-86, 1978 Dodge Omni, nominal M = 0.60, 45 mi/h @ 25°, (β = 30°), slope = 3:1.

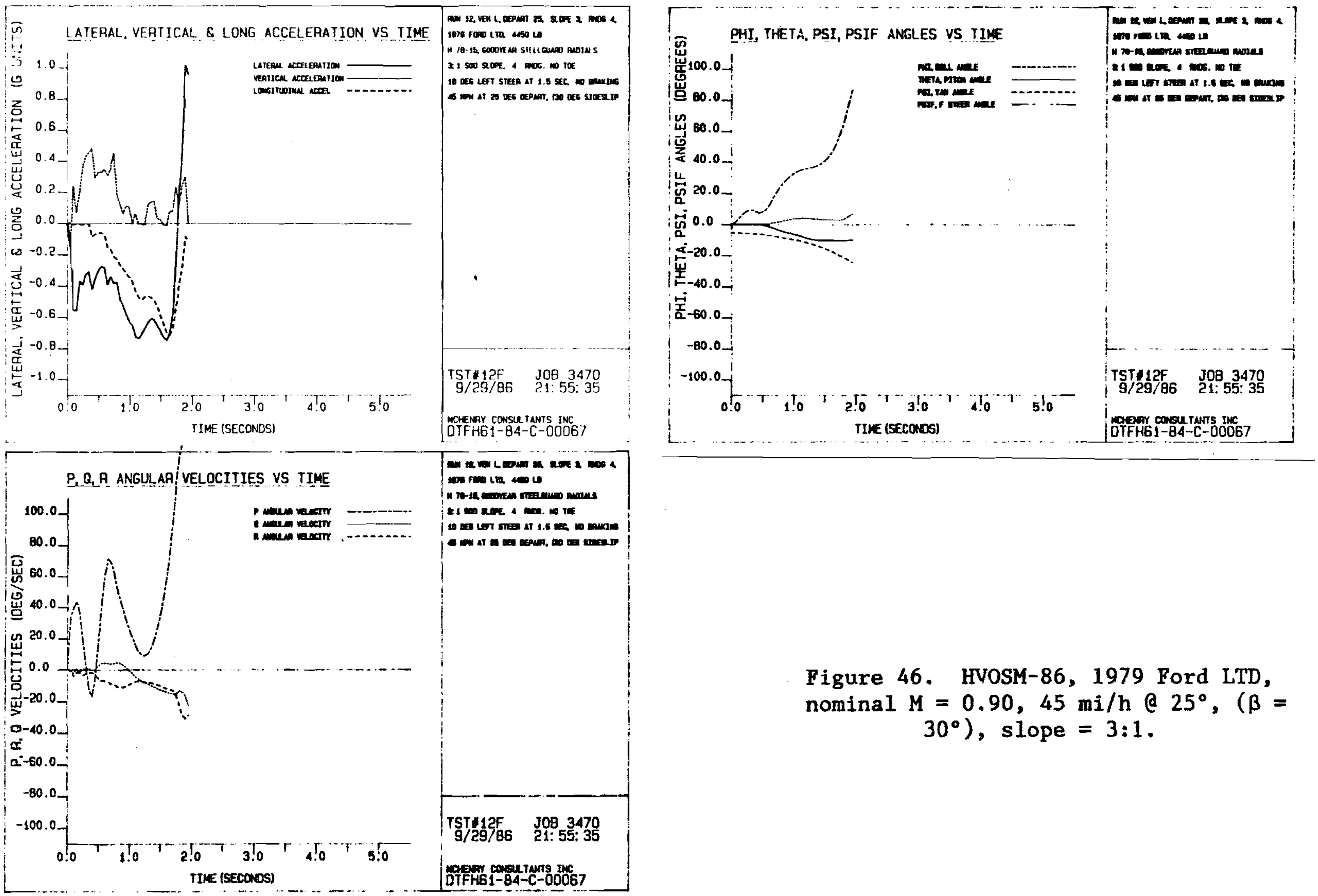


Figure 46. HVOSM-86, 1979 Ford LTD, nominal M = 0.90, 45 mi/h @ 25°, (β = 30°), slope = 3:1.

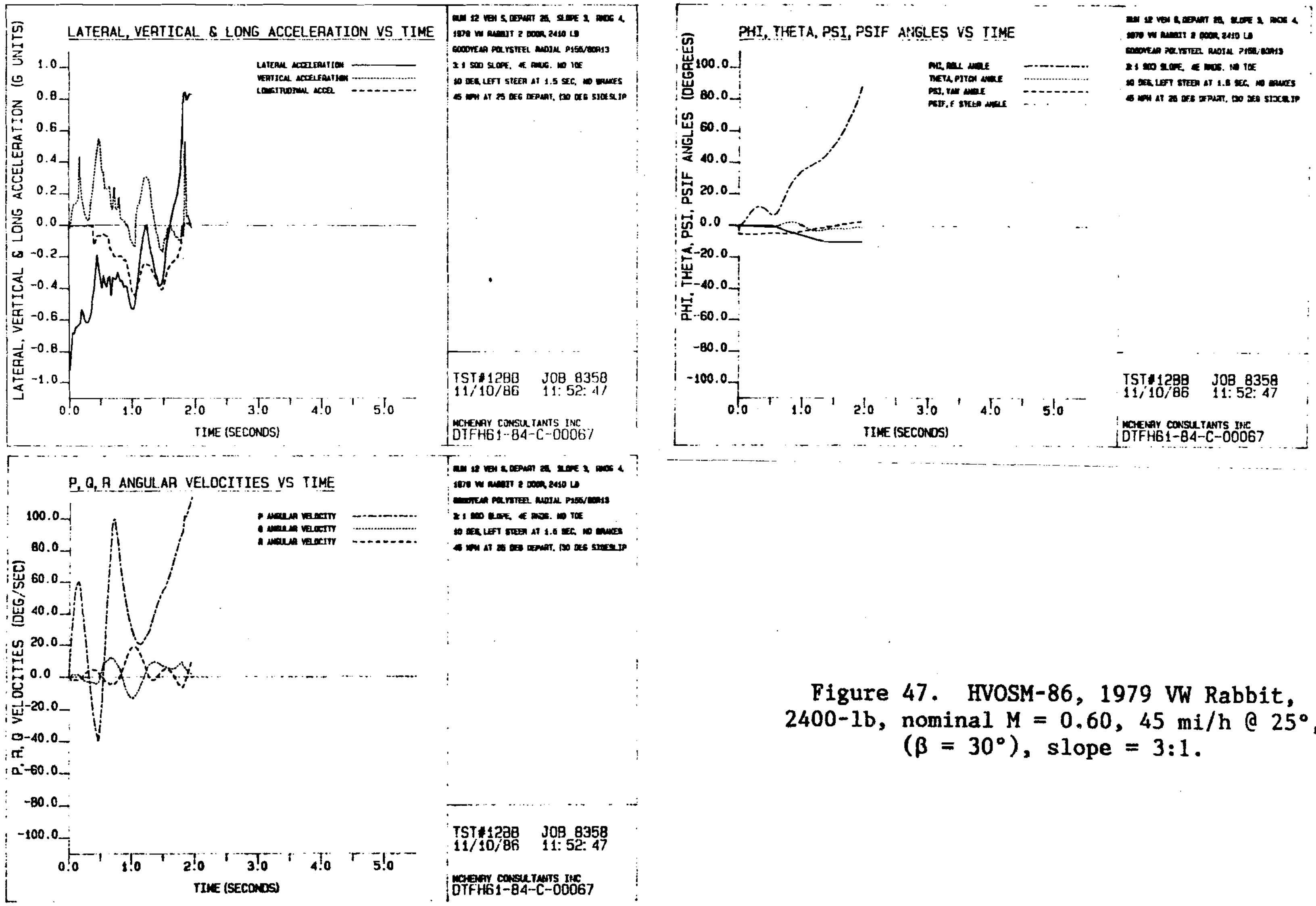


Figure 47. HVOSM-86, 1979 VW Rabbit, 2400-lb, nominal M = 0.60, 45 mi/h @ 25°, (β = 30°), slope = 3:1.

APPENDIX F

Proposed Research Plans

MINICAR INVOLVEMENTS ON SIDESLOPES

Basic Research Issue

Recent crash tests and HVOSM analyses have indicated that sideslopes 3:1 and steeper can produce rollover for minicars. Recent accident research has indicated that 3:1 sideslopes are as hazardous as 2:1 sideslopes for the total sample of accident-involved vehicles. (The data did not allow differentiating the effect by size of vehicle.) Unfortunately, there are numerous locations on rural non-Interstate roadways where these steeper sideslopes exist (e.g., current geometric design policy allows rounded slopes of up to 1.5:1 without barrier protection for smaller fill heights.) One obvious treatment is the installation of a barrier. However, barriers will not be installed at many locations due to cost considerations. In addition, even if the current geometric design policies are modified to require a barrier on any sideslope of 2:1 or steeper, slopes of 3:1 will still remain where minicar rollovers have occurred in crash tests and HVOSM runs. Thus, there is a continuing need to develop a low-cost treatment which might reduce the probability of rollover on these steeper slopes.

Background

Based on accident analysis involving all sized vehicles, Perchonok noted that fill sections (with embankments) experienced more rollovers than cut sections, and the rate increases with increases in slope steepness. Both rollover and object-struck rates increase dramatically for sideslopes steeper than 3:1.(1)

In recent accident analyses based on approximately 1,776 mi (2842 km) of 2-lane roadway sections from three States, Zegeer, et al. concluded that steeper sideslopes were associated with greater accident severity and higher single vehicle accident rates and rollover rates.(2) Using various multivariate models which controlled for the effects of ADT, lane width, shoulder width, and roadside recovery distance, the 3:1 sideslopes were characterized by approximately the same degree of hazard as the 2:1 sideslopes, and a significant increase in safety was not noted until slopes of 4:1 or flatter were examined. Unfortunately, the data could not be categorized by car size, and thus the specific effects on minicars can not be determined.

In recent nonaccident work, Buth and Campise conducted slope traversal tests on 3:1 slopes with three vehicles, one of which was a minicar. While the two larger vehicles returned safely to the roadway, the minicar front wheel plowed during the recovery steering input and the vehicle rolled.(3)

Deleys has recently conducted a series of HVOSM runs involving large, mid-sized, and small cars on different sideslopes with different friction factors. Field test involving pulling vehicles across various soils were also conducted to verify the HVOSM model allowing wheel plowing. Deleys found that the Honda Civic (a minicar) and a VW Rabbit rolled fairly consistently on 2:1 slopes, particularly in non-tracking (yawed) conditions. These vehicles sometimes rolled on the 3:1 slopes.(4)

Of interest in this work is fact that vehicles would be predicted to "spin out" rather than roll on soils with coefficients of friction less than 0.7 to 0.8, even on these steeper slopes. While spin-out sometimes resulted in a rollover, rollover occurred less than when the vehicle continued to track. It appears that vehicles might spin out more often if both the soil is firm (to reduce plowing) and the coefficient of friction is less than some critical value. Based on the soils tests, these critical values appear to be within the range of possibility.

In recent accident data analyses involving North Carolina data, the minicar experienced higher proportions of single vehicle involvements with embankments and ditch banks than do the larger vehicles. In addition, the smaller vehicles experience higher rollover rates when running off the road (23.4 percent vs 17.5 percent vs 8.6 percent, for mini-, mid, and large cars, respectively). Unfortunately, an analysis of overturns on embankments was not possible with the NC data.(5)

Research Needs

The research effort necessary will involve both an additional basic study of the sideslope issue and also a specific study of treatments as alternatives to additional barriers. The overall research needs include:

- Further verification of the effect of steeper slopes on minicar accidents and rollovers, while controlling for other contributing factors such as object clutter, shoulder width, vehicle size, etc. The research effort should be aimed at examining the effects of slopes in the 2:1 to 3:1 range on various sized cars, including the specific effects on minicars.

- Definition and study of the feasibility of treatments which could decrease rollover for minicars on steep sideslopes (slopes of 3:1 and steeper). There is a need to define alternative treatments for locations where barriers may be either inappropriate or not economically feasible. Such treatments should include but not be limited to treatments aimed at making sideslopes firmer with a lower coefficient of friction. The research effort must examine whether or not the proposed treatments could indeed reduce rollover propensity for minicars and larger vehicles, and must attempt to specify the cost-effectiveness of the alternative treatments.

Research Methodology

Reconciliation of accident-based findings. This effort will involve further analysis of existing State and Federal data related to sideslopes. While a wide range of possible data bases should be considered, it is expected that a primary data base for use will be the data base collected in a recent study of roadway cross-sections by Zegeer, et al.(2) The effort will involve combining sideslope, other roadside, and accident data from this data base with detailed accident data containing vehicle specific and maneuver specific information from certain State data bases. If supplemental data is necessary, it should be acquired from existing data sources if possible to reduce the cost of additional field collection. As described above, the reanalysis of this enhance data base will be aimed toward study of accident and rollover rates for different sized vehicles on various sideslopes while controlling for possible confounding variables. While the methodology to be used should be defined in detail during preparation of an analysis plan, it would be expected that much of the analysis would involve modelling techniques.

Determination/preliminary verification of new low cost alternatives. (Because this study is aimed at developing innovative treatments and determining their potential effectiveness, the total research scope is by necessity long term in nature, including defining treatments, preliminary assessment of potential benefit, accident-based evaluation, and determination of cost-effectiveness and implementation guides. This initial effort will concentrate on the first two short term steps in this process -- the identification and preliminary assessment of treatments. This is felt justified since the overall effort is aimed at developing new treatments with no guarantee of success. If successful in these initial efforts, additional long term accident-based evaluation will follow.)

Determination of potential treatments will be based on information from research literature and information concerning current State practices. The research plan should consider use of an expert panel in a planned idea generation effort in the initial stages.

While the research should not limit the potential treatments in any way at this initial stage, it should consider, among others, the following:

- Changes in slope firmness and friction.
- Changes in shoulder to slope transition design.
- Low-cost roadside barrier for lower traffic demands.
- Shoulder/pavement-delineation treatments to prevent roadside encroachments.

Following initial specification of potential treatments, simulation efforts involving HVOSM runs could be used to further examine the potential for reducing/eliminating rollovers on 3:1 and steeper slopes for minicars by changes in slope firmness and coefficient of friction as well as rounding design (shoulder to slope transition).

Based on the outputs of the simulation efforts, the literature review and the expert panel, final designs of proposed treatments will be prepared. These designs may require inputs from soils and vegetation experts, as well as structural and highway engineers.

Finally, the designs appearing most advantageous and feasible should undergo preliminary field/crash testing. The design of such testing will of course depend on the nature of the treatment developed. Driver behavior studies, off-road vehicle slope traversal tests, and crash tests should be considered. Design of these tests will follow basic sound research guidelines such as those presented in the Accident Research Manual and NCHRP 230, Recommended Procedures for the Safety Performance Evaluation Of Highway Appurtenances.(6,7)

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ROADSIDE DITCH DESIGN IN RURAL AREAS

Basic Research Issue

A large proportion of single vehicle crashes for all size vehicles involve the vehicle striking a ditchbank. This is particularly true in rural areas on roadways where design standards are often much lower than those found on Interstates. In addition, when these crashes involve minicars, they often result in rollover and in more severe injury to the minicar occupant.

Background

Review of past research literature indicates that while significant attention has been paid to the question of design of sideslopes and drainage ditches for Interstate type highways, very little attention has been paid to the issue of design of "small ditches," the ditches found on nonfreeway roadways in rural areas. For example, NCHRP 158, Selection of Safe Roadside Cross-Sections, reported research in which simulation and field tests were run to determine the sideslope, hinge point, and ditch designs which could be safely traversed by large (3500 to 4000 lb (1.59 to 1.81 Mg)) vehicle without rollover and with acceptable G-forces to the vehicle.(1) While the study clearly defined acceptable design standards (with front and back slopes being greater than 3:1 and 4:1), roadside combinations tested were clearly of Interstate type, with ditches being 68 feet (20.7 m) or more from the edge of pavement. Thus, it is difficult to extrapolate these findings to the case of a 10-ft (3.0 m) shoulder and a small (3-ft (0.9 m)) ditch with 1:1 front and back slopes.

Based on this work, AASHTO has published a series of preferred ditch designs. The safe design envelope for shallow ditches (3 ft (0.9 m)) requires front and back slopes of at least 3:1 with 4:1 with greater slopes being preferred.

Perchonok, et al., analyzing accident data on various roads noted that fill sections experience more rollovers than cut sections and that rollover rate increases with an increase in slope steepness. He further noted that for both ditch cuts and fills, there appears to be a critical increase in both rollover rate and rate of object struck at the 4 to 5 ft (1.2 to 1.5 m) depth level.(2)

In recent simulation work conducted at CALSPAN, Deleys conducted a limited series of five tests involving small car rollover experience on the AASHTO preferred designs and on non-safe ditch designs.(3) Ditch locations ranged from 17.5 to 76 ft (5.3 to 23.2 m) from the edge of pavement. His simulation results indicated no rollover for the minicar with designs in the safe envelope, but a rollover at 60 mi/h (97 km/h) and 15 degrees on the 3:1/4:1 VEE ditch when the vehicle was in a tracking (non-yawed) mode, and a near roll at 45 mi/h (72 km/h) and 25 degrees in a non-tracking mode.

Recent analysis of North Carolina accident data indicates that the proportion of minicar single vehicle accidents involving ditch banks is higher than the corresponding proportion for mid-size or large cars for most highway types and for both urban and rural locations. This proportion is highest on rural secondary roadways, followed by U.S., NC and secondary roadways in rural/suburban areas. No differences were found by car size in terms of proportions involving the ditch banks on Interstates or rural U.S. highways.(4) As noted by other authors, this overrepresentation could result from the fact that minicars are "missing" various fixed objects when they run off the road and are striking the final fixed object remaining -- the ditchbank. It may also be the case, however, that this overrepresentation is due to the fact that when on an embankment or in a ditchbank area, an errant minicar is less likely to be able to recover and thus more likely to be involved in a reportable accident. Some support for this hypothesis is generated by the fact that the same analysis of North Carolina accident data indicated that minicars have a higher rollover rate when striking ditchbanks than do larger cars. Here, 37 percent of minicar impacts with rural ditchbanks resulted in a rollover. This is the highest rollover proportion for any fixed object and is 28 percent higher than the rollover proportion for the mid-sized cars in similar crashes.

It is interesting to note that NCHRP 118, Location, Selection, and Maintenance of Highway Traffic Barriers and NCHRP 158, Selection of Safe Roadside Cross Sections, both provide preferred ditchbank sections.(5,1) These reports were written in 1971 and 1975 respectively, and thus knowledge concerning preferable sections has been available for quite some time. However, even though such knowledge exists, current practice is controlled not only by safety and drainage needs, but also by maintenance considerations. This is clearly demonstrated by the current use of recently designed ditch-cleaning equipment which is designed to greatly increase the number of miles of ditches that can be maintained by highway departments. (See Public Works, November 1984.) This new equipment, now in use by at least eight States, produces trapezoidal ditches with front and back slopes ranging from 2.5:1 to 1:1. It is interesting to note that most of the ditches pictured in the article and related advertising appear to have 1:1 slopes. Even the most benign of these designs (2.5:1) does not meet the criteria for the preferred section cited in the AASHTO guides, and all slopes are much steeper than those causing rollover in the Deleys work. (It is noted that the Deleys work was generally with larger ditches.)

Thus, there is a continuing need for a better definition of rural and urban ditchbank design from a safety, drainage, and maintenance viewpoint.

Scope of the Research

The scope of this research will include the following:

- Better inventory of current designs and of problems with those designs.

- o The determination of alternative designs.
- o The evaluation and testing of these alternatives and other existing treatments for the ditchbank problem.

Proposed Methodology

To meet the above research needs, the methodology to be followed will have to be multiphased. This will include the following components:

1. Review of current designs. Designs currently used on rural non-freeway roadways within the States should be surveyed in order to define a set of "standard" designs which can then undergo further testing and analysis. While part of the survey could be done through questionnaire work with various State departments to determine designs standardly used, some field surveys will have to be conducted since ditch designs implemented in the fields may not always follow State standards.

2. A better definition of "accident tradeoff" issue. While ditchbanks are involved in a fairly high proportion of accidents, there remains the issue of whether the ditchbank is less or more lethal than the alternatives behind it. If ditchbanks are eliminated, clearly some vehicles would recover. However, other vehicles would continue to depart from the roadway and would strike objects behind the ditchbank. Thus, there is a need to determine from existing data the safety tradeoff of either removal of ditchbanks or of making them safely nontraversable. Information concerning roadsides could be extracted from the recently published roadside study in which roadside inventories were conducted for approximately 5000 miles (8000 km) of rural, 2-lane roadway in seven States.(6) This study also provides the accident severities for striking various fixed objects and thus the data could be reanalyzed to provide some indication of possible tradeoffs. In addition, one methodology for developing adjustment factors for removal of objects can be found in a report by Zegeer and Parker involving utility poles.(7)

3. Simulation efforts involving current designs. Simulation efforts involving the HVOSM model could test the actual effects of current designs on minicars when the minicar is striking the ditch in both a tracking and a non-tracking mode. This simulation work will expand that work already conducted by Deleys, and could begin to develop a ditchbank design which is both non-traversable and safe -- one which might possibly capture the vehicle within the ditchbank and

slow it at an acceptable deceleration rate. This would prevent the vehicle from traversing the ditch into what could be a more hazardous situation.

4. Development of alternative designs. Based on the HVOSM work and review of State inventory and accident information, a set of alternative ditchbank designs will be developed. These designs must provide adequate drainage, ease of maintenance, and safe traversal or deceleration. The listing should also include any safe designs already in place in certain States. This will require not only inputs from safety engineers, but from maintenance and hydraulic specialists. It is suggested that part of this effort involve an expert panel of highway engineers, safety researchers, and others familiar with the issue who can help generate design ideas.

5. Simulation verification of new designs. If additional simulation work is needed following generation of the designs, this will be conducted in order to verify the potential benefit of the suggested designs and to further modify those designs.

6. Crash testing. For those designs shown to be most feasible and having the highest potential safety benefit, crash testing will be carried out. Crash testing must concentrate not only on large vehicles, but also on minicars. While test procedures specified in NCHRP Report 230, Recommended Procedures for the Safety Performance Evaluation Of Highway Appurtenances, are applicable for roadside features such as guardrails, crash cushions and breakaway supports, other features such as ditches are not addressed.(8) Thus, a special test method and crash test matrix is needed. While not specifically covered, the methodology used will parallel methodology specified in that report for other fixed object tests. While the research team will developed detailed crash test plans, two potential tests are suggested:

Test	Vehicle	Speed (mi/h)	Departure Angle* (deg)
1	minicar	50	10
2	minicar	50	20

*With centerline of road.
1 mi/h = 1.6 km/h

Desired performance criteria are for the vehicle to remain upright during and after encounter with the ditch and that the occupant risk factors (g-forces) measured in the test are less than critical values specified in (8).

7. Field testing of designs. Following crash testing, for those designs shown to provide the greatest safety, it is proposed that field testing be established. This field testing will involve the installation of these designs at various locations across the nation. It is suggested that the designs be implemented in 3R locations since 3R funds can be used for roadside clean-up and because documentation of 3R projects will allow easier monitoring of subsequent accident/encroachment experience. The field test locations and comparison locations should be monitored, with data collected on safety, maintenance costs, and subsequent drainage problems. In addition to the new designs developed in this project, field testing of alternative treatments to the ditch problem should be conducted. This could involve any ditchbank designs already in place in other States which appear to be safe and such treatments as widened shoulders and covered longitudinal piping eliminating ditches at critical ran-off-road areas.

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PAVEMENT EDGE DROP RELATED RESEARCH ISSUES

Basic Research Issues

Past research and current accident analyses have both indicated that minicars have a higher rollover propensity than larger cars in almost all crash situations. There is some evidence that rollover may be initiated by discontinuities at the pavement edge when the minicar leaves the pavement or when it is attempting to return to the pavement after a roadside encroachment. Recent field test have documented the difficulty that novice drivers have in safety returning to the roadway when encountering a vertical edge drop of greater than three inches with speeds greater than 30 mi/h (48 km/h). However, it appears that the use of a pavement wedge placed at the edge of pavement virtually eliminates this reentry problem. The issue remaining is to better define the scope and size of the pavement edge drop problem, to define other alternative treatments, and to field test those treatments appearing beneficial, particularly with respect to the minicar.

Background

Numerous studies have documented the increased propensity of minicars to be involved in rollovers in all types of accidents on almost all roadway types and under almost all crash conditions. The results of the Washington State study and the Kuroda, et al. study both noted minicar overinvolvement in overturn accidents.(1,2) Griffin, in conducting an analysis of Texas single vehicle accidents, found that smaller cars are much more likely to overturn than larger cars on all highway classes. Compared to larger cars, he found that minicars were eight times more likely to overturn on county roads, 12 times more likely on Interstates, and 37 times more likely on city streets. Deleys found a rollover rate much higher for the lighter weight vehicles, with the increasing rollover propensity trend flattening out at approximately 3500 lb (1.59 Mg).(4) Griffin also noted that minicars have higher rollover rates in involvements with fixed objects than do the larger cars in similar crashes.(3) In terms of accident severity, Deleys reported that rollovers tend to result in more injury than do non-rollover collisions for all size vehicles, primarily due to the increased chances of occupant ejection.(4) Viner noted fatal rates for rollovers ranging from 2 to 5 times as high as the fatal rates for non-rollover, depending on the data source.(5)

The difficulty in all of these past efforts stems from the lack of specific accident data related to the pavement edge itself. Very few police reports include this data and thus pertinent accident studies are usually based on very small data bases. However, some research data do indicate a tendency of a minicar to experience problems in attempting to return to the roadway. A recent analysis involving a detailed study of the sketch and narrative provided by the investigating police officer in North Carolina single vehicle crashes again indicated the high probability of the minicars to rollover when running off the roadway. When big car rollovers occur, they are predominantly on curves. Minicars are far more likely to run off the roadway and overturn on straight tangent sections than are the larger cars. When the run-off-road accidents are examined in more detail, it appear that while big cars and minicars run off the right and left side of the roadway with comparable frequencies, there are differences in the vehicle collision sequence for the two groups of vehicles. More specifically, 40 percent of the minicar rollovers on tangents and 14 percent of the rollovers on curves involve the pattern in which the minicar ran off the roadway and then overturned on or near the pavement in attempting to return to the pavement. None of the big car accidents involved this off-on-rollover sequence.(6)

Finally, in recent work specifically related to the pavement edge drop problem, Olsen, et al. conducted a series of tests in which professional and novice drivers attempted to recover from a tire scrubbing condition in which edge drops ranged from 3 inches to 4.5 inches (75 mm to 113 mm). A successful recovery was one in which the vehicle was returned to the pavement without an encroachment into the adjacent lane. In these tests, no novice driver successfully recovered from a 4.5-in (113 mm) vertical cut at any speed down to 20 mi/h (32 km/h), the lowest test speed. For a 3.5-in (89 mm) drop, novice drivers successfully recovered at 25 mi/h (40 km/h), but not at 30 mi/h (48 km/h) or above. A pavement wedge with a 45 degree face was then added to the pavement edge. In subsequent tests with a 4.5-in (113 mm) cut, the novice drivers successfully recovered in all cases tested (up to 55 mi/h (89 km/h)).(7)

Research Objectives

Based on the review of the past literature and on the recent accident analyses and field work cited above, there is a continuing need for additional research into the pavement edge question. First, even though a treatment (the wedge) appears to virtually eliminate the problem in many cases, there is the remaining question of how important edge drop is in terms of overall accident costs. The question is receiving increasing attention due to accident liability issues that are now involving State highway departments in the pavement edge drop issue. Thus, a multi-phased edge drop research program would include the following aspects:

1. Better Definition of the size, nature and cost of the edge drop problem. As noted above, it is very difficult to determine the size and scope of the edge drop problem by examining currently available computerized police accident data. On most accident report forms, there is no opportunity for the police to note the issue of an edge drop related problem. Thus, innovative research methodology is needed to better define the nature and size of the issue. There is a related need to better determine the length of roadway which are affected by this potential problem. As yet, few (if any) inventory studies have been conducted to provide insight into this area.

2. Define Alternative Treatments. Assuming that the nature and scope of the problem is large enough to warrant further research, even though the pavement wedge appears to be a usable treatment it may not be possible to implement it at all locations in a cost-effective manner. Thus, there is a need to better define other alternative treatments.

3. Specification of Cost and Benefits for Alternative Treatments. For each of the alternatives identified, there is a need to define both accident-related and implementation-related costs and associated problems. Such specification would include technology development cost (e.g., the cost of equipment to form the pavement wedge).

4. Evaluation of Advantageous Treatments. For those treatments that appear to have an acceptable benefit to cost ratios, there is need to evaluate their effectiveness in real-world situations.

Research Methodology

Definition of the size, scope, and cost of the problem. Because of the above-mentioned lack of data concerning the edge drop problem in most of the accident bases, and the strong need for a better definition of the size and scope of the problem, there is a need for an innovative analysis methodology which will require "teasing" information from existing accident data bases. While the development of the research plan should examine many alternative methodologies, one such methodology would involve expanding the hard copy analysis technique used in the earlier cited North Carolina work.(6) Here, a larger and more precisely drawn sample of hard copies of accident reports (which would include both sketches and narratives) would be targeted to rollovers on shoulders and on pavements. The data bases from which such a sample could be drawn would include the NASS system as well as appropriate State data bases. It would be hoped that with appropriate sampling, such a methodology would provide additional insight into the specifics of the how and where these accidents are occurring (road type, speed limit, shoulder type, accident width, etc.).

Given some measure of the frequency of edge drop accidents could be gained from a comprehensive study of accident data, the cost associated with such accidents could then be based on economic methodology provided by McFarland and Rollins.(8) Additional cost data on the liability cost now being associated with this type crash should be included. Collection of this information would require a detailed information collecting methodology in which a search of the legal system proceedings would be conducted.

As noted earlier, the exposed length of roadway will be virtually impossible to measure. While recent studies have collected information on roadway geometrics and roadside characteristics, no data have been collected on pavement edge drop.(9) This is partially due to the changing nature of the shoulders. However, on a sampling bases, it may be possible to augment certain existing data bases with edge drop information. This would be a very expensive inventory undertaking. Thus, it may be the case that detailed cost benefit analyses based on miles of roadway that need to be covered will not be possible. If this is the case, then findings related to each of the alternative treatments will define to the States the characteristics of edge drops which can be and need to be treated. Primary in this regard is the earlier cited work by Olsen, et al. in which 3-in (76 mm) edge drops caused problems at speeds greater than 30 mi/h (48 km/h).(7)

Definition of alternative treatments. The definition of alternative treatments should be based on a critical review of the literature and on inputs from knowledgeable experts and State engineers. This step might require the convening of an expert panel of researchers and highway engineers to provide both insight into the problem and treatments that might be usable. Possible treatments defined by an earlier panel studying this and other questions included:

- Pavement wedge.
- Paved shoulders in critical locations.
- Better shoulder stabilization based on:
  a. improved targeting of maintenance operations
  b. soil cement or other shoulder surface treatments.
- Pavement widening at critical locations.
- Innovative edge markings.

Preliminary evaluation of cost/benefits. Prior to full-scale field tests or accident evaluations, the potential list of treatments needs to be further screened based on the best estimates of proposed cost and benefits and implementation feasibility. This process will primarily involve extraction of information through several resources.

- Review of past studies. First, information on certain treatments will be available from detailed reviews of the literature. This review process should be a critical review in which the quality of information is based on the quality of the research study. The information from numerous studies pertinent to one treatment can then be combined in a weighted fashion. Some information is available on paved shoulders, pavement widening and innovative pavement markings, among others.

- Simulation. It may also be possible to gain some knowledge of potential effects and to better define certain treatment designs using simulation involving the HVOSM computer model. This effort can perhaps be used to provide information on car paths given certain driver inputs and geometrics and on vehicle responses to the discontinuity itself. It is noted that such an approach will provide only limited simulation of driver responses. Potential treatments for HVOSM study might include pavement widening, paved shoulders, and a more detailed look at the effects of the discontinuity on certain vehicle parameters.

- Limited field/test track testing. In some cases it will be necessary or desirable to conduct limited field testing of certain designs. For example, if new pavement marking schemes, curve delineation designs, or signing schemes appear to be feasible treatments, it may be necessary to conduct off-road tests of driver reactions to such designs.

Accident-based evaluations. Finally, following a preliminary evaluation, it would be desirable to implement the most promising treatment in the field and conduct a longer term evaluation of their benefits based on actual accident reductions. This effort should be designed such that sample sizes are adequate and confounding variables are controlled for. While each study may differ, the basic methodology used should be that described in the Accident Research Manual.(10) It is noted that this could be difficult research due to the nature of the variable under the study -- accidents related to pavement edge drops. Since data is not now available on such occurrences from police report files, it may be necessary to institute a special data collection effort in which the police in a given jurisdiction capture supplemental information for some period of time, or in which special accident monitoring is conducted by the research team (an expensive undertaking). If the latter approach is followed, the study needs to be developed in cooperation with the existing NASS teams.

An example of such a study would be one in which the benefit of the pavement wedge would be tested. Here, the design of the study could involve sections of roadway scheduled for upgrading under the 3R program. The sections would be (randomly) assigned to treatment and comparison groups. Based on studies of both roadside encroachments and ran-off-road accidents for specific highway classes, estimates of the number of ran-off-road accidents per mile can be developed. Using this information and a range of potential percent reductions due to the wedge, an estimate could be made of the number of miles required to show a reasonable reduction in pavement edge-related crashes. The treatment would then be implemented on the various sections, and the research team would monitor the treatment and comparison sites and evaluate the results through the three to four year period.

It may be the case that the number of edge-related accidents are found so small that required sample sizes for an accident study are impossible to acquire. If such is the case, an alternative approach would be to define and conduct a study in which some measure of roadside encroachments (both those reported as accidents and unreported encroachments) can be monitored. This might require periodic (daily, weekly) counts of shoulder encroachments (and subsequent accidents) on sections of treated and comparison roadways in 3R locations where shoulders have been recently regraded. The counts would be made manually with the shoulder being smoothed at the end of each counting period. Tire thread widths (where measurable) might give some indication of vehicle size. Additional counts would be necessary to define emergency vs. non-emergency (voluntary stopping or parking) ratios. Such a study would require the development of an innovative methodology on the part of the research team. Some inputs from past work may be gained from previous encroachment related research efforts conducted by Calcote and Cooper.(11,12)

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RURAL TRAFFIC ISLANDS

Basic Research Issue

When compared to larger vehicles, minicars overturn more frequently when striking traffic islands, particularly in rural areas. Research needs include both a reassessment of the basic need for such fixed objects at rural intersections and, if needed, the development and testing of designs which will reduce the potential for minicar rollovers.

Background

Woods notes that 30 percent of minicars have clearances less than the 6-in standard in effect for curbs, shoulders and other objects.(1) Presumably, this lower clearance could result in increased frequency and severity of accidents in collisions with such obstacles. Indeed, the Griffin analysis of accident data in Texas indicated that drivers of small vehicles experienced elevated minor and moderate (but not serious or fatal) injury rates when striking curbs. He further notes that in accidents involving curbs, the average vehicle striking the curb was much lighter than the average vehicle striking other appurtenances, indicating a higher minicar involvement rate. This could result from either heavier vehicles jumping the curb and hitting a pole or other appurtenance behind the curb and thus being reported as a "pole" accident rather than a curb accident, or could result from the heavier vehicle being able to recover better from an impact with a curb than is a lighter, less stable vehicle.(2) (It may also be the case that lighter vehicles are driven more in urban areas where more curbs exist.)

Recent analysis of Texas and North Carolina data support the findings from the past literature.(3) Analysis of Texas data indicates that in urban areas, there is a significant overrepresentation of minicars with curbs on urban Interstate, U.S., State, and local roads when compared to larger vehicles. Analysis of the North Carolina data base indicated no overinvolvement in terms of the proportion of minicars striking curbs, but higher proportions of minicars striking traffic islands than larger cars, particularly in the rural areas. This trend was true on all classes of rural roads and was statistically significant on NC routes and secondary roads. There were also significant differences between the traffic island involvements for minicars and large cars on all classes of urban streets. In addition, the analysis indicated that collisions with rural traffic islands resulted in rollover 33 percent of the time for the minicar, 32 percent for the midsize car, and only 7 percent of the time for the large car. This rollover rate represents the second highest rate experienced by minicars when striking any fixed objects, with only collisions with ditch banks producing a higher rollover rate.

To further examine this issue, simulation work involving the HVOSM model has recently been conducted by McHenry & Associates.(3) Simulations were run with both a 6-in (150-mm) curb with a 45 degree face (less hazardous than the vertical face found on many traffic islands across the nation) and with a modified face design now in use by the North Carolina Division of Highways. When the minicar (a Honda civic) struck the curb face in essentially a broadside slide and also in a yawed attitude, the simulation indicated that the minicar rolled at 17 mi/h (27 km/h) on a 45 degree face, experienced a near roll on a 30 degree face, and no rollover on a 15 degree face. Tests with the mid-size Chevrolet Celebrity showed similar results with the rollover occurring at 20 mi/h (32 km/h) on a 45 degree face. The large car (an LTD) experienced no rollover up to a 60 degree face at any speed. When the face angle and speed were varied to define a "rollover envelope," the simulation indicated that rollover can be produced for small to intermediate vehicles for curb face angles greater than 30 degrees and speeds between 15 and 25 mi/h (24 and 40 km/h).

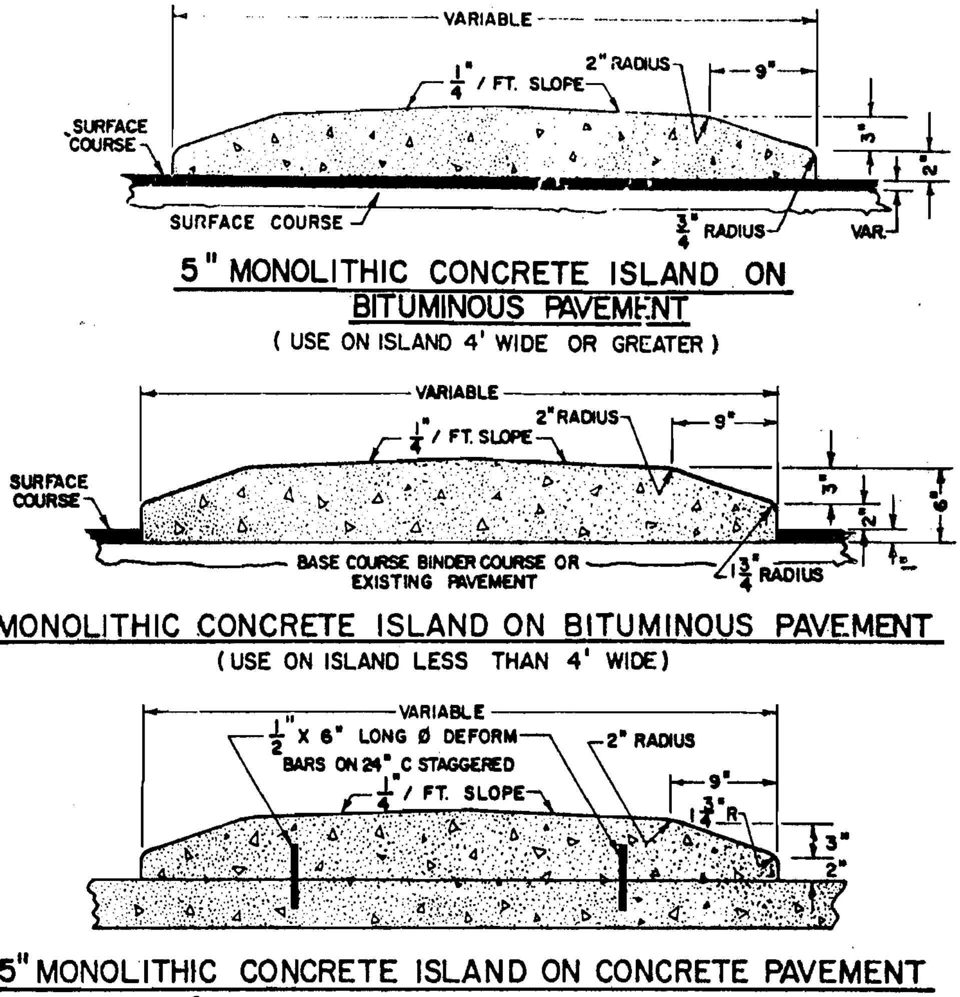
Several simulation runs were then conducted using a traffic island design currently in place in North Carolina. As shown in the accompanying figure, this design includes two inches of face at 60 degrees, followed by a vertical rise of three inches with a 20 degree face, and the remaining rise at 1 degree to the center of the traffic island. Runs similar to those described above indicated no rollover either for the minicar or the mid-size car in comparable situations.

Research Needs

There appears to be the possibility of a traffic island design which might reduce the rollover propensity in crashes involving such islands. However, even with this improved design, the impacts would still occur and might result in reportable or injury-producing accidents (although less severe than before). Unfortunately, there has been very little research into the basic need of such islands, particularly in rural areas, and perhaps even less research into appropriate cross section design. The Intersection Channelization Design Guide (NCHRP 279) provides the latest information and design procedures to be used in channelization efforts. Review of the report indicates little documentation of the accident-based need for such raised channelization in rural areas. In addition, the report provides few details of appropriate cross-section design of islands. Thus, there remains the basic question of whether traffic islands are needed in rural areas at all, and if so, could raised islands be replaced with such channelization as painted islands. In summary, the remaining research program should include:

- A reexamination of the basic need for channelization, particularly in rural areas.

- An evaluation of the comparative effect of raised islands versus painted islands on driver behaviors.



1\4 in/ft = 2 percent
1 in = 25.4 mm

Figure 48. Details of traffic islands used by the North Carolina Department of Transportation.

- A better definition of alternative designs for traffic islands which are less likely to result in reportable crashes and/or rollovers for minicars.

- Crash tests of alternative designs.

- Field tests of beneficial designs.

Research Methodology

The preceding section has described an overall research program aimed at determining the need for and appropriate design for rural traffic islands. The methodology to conduct each of the steps described above will vary. In designing the research methodology to be used, the following proposed procedures should be considered.

Examination of need. Channelization of rural intersections is presumably based on the need for reducing possible conflicts between crossing flows of traffic. However, there has been no recent reexamination of the basic needs for such channelization, particularly at low volume rural intersections. It is possible that many traffic islands are in place as a haven for necessary stop signs or due to long-standing practice within a State. This reexamination of the basic need for channelization would require identification and review of past studies on which design and channelization standards were based. This critical review must be made with current vehicle sizes and capabilities in mind, particularly as related to the minicars and larger single unit and combination trucks. As part of this examination of need, following the critical review of literature concerning channelization, the research team could convene a panel of expert traffic engineer and intersection specialists to further discuss both the past research findings, current and future expected vehicle changes and driver needs, and potential alternative designs.

Driver behavior study. One alternative to raised traffic islands are painted islands at places where it is deemed necessary to separate traffic with more than simply lane markings. Such painted islands are currently widely used in many different types of roadway and intersection situations in almost all States. As an output of the literature review, situations where rural traffic islands are felt to be needed could be specifically defined. The research team would then locate examples of such locations where traffic islands exist and where a painted island or no island exists. The study methodology would entail either filmed data or manual visual monitoring of traffic behaviors at the three types of locations. Data to be collected would include both approach speeds and speed changes in the vicinity of the islands, encroachments on the islands, encroachments into opposing traffic, and some measure of conflicts with the target and the crossing flow. Other measures of effectiveness would be specified by the research contractor. The sample size should be large enough to encompass a wide variety of driver characteristics and as full a spectrum of vehicle sizes as possible.

Simulation work. There is a need to extend the simulation work conducted in the current effort in attempting to define alternative cross section designs for raised islands. This work would be aimed at further testing and defining the cross sections of the islands and would include verification of the work done in the current study related to the North Carolina design.(3)

Crash tests. Whereas the minicar overturn tendency during interactions with rural traffic islands and curbs has been identified from accident studies and confirmed to a limited degree by computer simulations, critical approach conditions are not known. However, the evidence points to a non-tracking small car with a combination of forward, lateral and yawing velocity. Such conditions are outside the scope of NCHRP Report 230, Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances. To evaluate dynamic performance of existing curbs and traffic islands, a non-tracking test car is recommended in which (1) the minicar heading angle is parallel to the test article axis, (2) the velocity vector is 0 with the test article axis and (3) the minicar yaw velocity is zero. A minimum matrix of two tests is presented:

Test	Vehicle	Heading Angle* (deg)	Velocity Vector Angle* (deg)	Speed (mi/h)
1	mini	0	10	50
2	mini	0	20	50

*With axis of test vehicle
1 mi/h = 1.6 km/h

Assessment criteria is based on the vehicle remaining upright during and following the interaction. As a baseline, the two test series can be performed with larger sedans. Since these tests are new, the method for controlling and accelerating the test vehicle to impact conditions is left to the research agency, but the method should be fully justified and documented in the test report.

At least one traffic island design (i.e., North Carolina tapered cross-section) indicates excellent potential during computer simulations to perform well with the test matrix. Other designs are also expected to perform well.

Field tests of beneficial designs. For those designs that are shown to be effective through the simulation work and the crash tests, attempts should be made to place them in the field and monitor their use. It is understood that even if a more suitable design is produced and tested, it will not be economically feasible to replace all substandard traffic islands in all locations across the nation. However, FHWA could consider two alternatives. First, in all Federally funded projects involving intersections where traffic islands are to be installed, FHWA could clearly require the placement of the newer designed islands and monitoring of the accidents related to these islands. The second alternative would be for FHWA to establish a field test in which at certain specific high volume locations where conflicts between flows have been encountered in the past, the States be provided money with which to remove older islands and replace them with new islands. A comparison set of similar locations would not be treated. Comparisons could then be made of both driver behaviors and accidents and accident-related rollovers by car size for these locations. Necessary sample sizes would be based on the estimated propensity of traffic island crashes and rollovers in Council (3) and other studies and could be calculated using methodology provided in the Accident Research Manual.(4) Analytical techniques could also follow guidelines presented there.

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ROLLOVER PROPENSITY AS INFLUENCED BY VARIOUS VEHICLE PARAMETERS

Basic Research Issue

The overinvolvement of minicars in accidents involving overturning has been well documented. Since rollover accidents, in general and minicar rollover accidents, in particular, tend to produce more injuries than non-rollover accidents, the factors contributing to this phenomenon need to be investigated. The research should determine whether minicars are overinvolved in rollover accidents simply because of their size and/or weight or whether there are other specific vehicle parameters that contribute to this overrepresentation.

Background

Numerous studies have documented the increased propensity of minicars to be involved in rollovers under almost all roadway and crash conditions. The results of the Washington State study and the Kuroda, et al. study both noted minicar overinvolvement in overturn accidents.(1,2) Griffin conducted an analysis of Texas single vehicle accidents and found that smaller cars are much more likely to rollover than larger cars on all highway classes. Compared to larger cars, he found that minicars were eight times more likely to overturn on county roads, 12 times more likely on Interstates, and 37 times more likely on city streets. Griffin also noted that minicars experienced a higher rollover rate in involvements with fixed objects than did the larger vehicles. Deleys (1986) found a rollover rate much higher for the lighter weight vehicles, with the increasing rollover propensity trend flattening out at approximately 3500 lb (1.59 Mg).(3)

In terms of accident severity, Deleys reported that rollovers tend to result in greater injury than non-rollover collisions for all size vehicles, primarily due to the increased chances of occupant ejection.(4) Viner noted that fatal accident rates for rollovers are approximately 1.9 times higher than for nonrollovers. Fatal accident rates range from 2 to 5 times as high for rollovers as for nonrollover, depending on the data source.(5)

In terms of the possible causes of such rollovers, various hypotheses and analyses results have been suggested in the literature. As expected, most of these centered around the fact that smaller vehicles may "trip" more easily than larger vehicles, or may roll over more easily after striking fixed objects. McGuigan and Bondy noted prior impacts with roadside objects in over one-half of the rollovers in the NASS and FARS data files, and found that given an impact with a fixed object, a rollover occurred in 59 percent of the cases.(6) Wright and Zador indicated that objects causing rollovers did not necessarily have to be large objects. They mentioned curbs, edge drop-offs, ditches, and soft soil as probable causes for these rollover crashes.(7) Griffin noted that the reasons for the high urban rollover rate found in his data may very well be due to the presence of small appurtenances such as curbs, drains, traffic islands, etc., which may not cause the larger vehicles to overturn but will trip the smaller vehicles.(3) Woods notes that 30 percent of the mini-compact cars have clearance which is less than the 6-in (152-mm) roadway design standard, leading to possible vehicle snagging and overturning.(8)

In terms of vehicle positioning and maneuvers prior to overturns, Deleys notes that 85.7 percent of rollover accidents of all vehicles involved locked wheels, and that 30.7 percent of all single vehicle accidents involved "non-tracking vehicles" (vehicles which are either skidding sideways with locked wheels or in some manner not under the steering control of the driver). The authors noted that skidding sideways and "spinning out of control" are overrepresented in terms of rollover causative maneuvers.(4)

Finally, in terms of vehicle handling and design, in his book on vehicle characteristics, Jones indicated that factors associated with rollover potential in rural areas include: (1) the vehicle design and handling parameters of "minimum velocity for overturning" (tripping in hard-steer maneuvers), (2) the ratio of vehicle height to track width, and (3) the ratio of height of the center of gravity to track width. The strongest association is with the first of these parameters. None of these three were associated with increased likelihood to rollover in urban areas.(9)

Recent analyses of data bases from North Carolina, Texas, and Washington supported the above findings in the literature.(10) The North Carolina data base indicated that mini cars overturn more frequently than large cars in almost all situations. This held true for rural and urban locations on all highway types. In the rural areas, the minicar rollover percentages were lowest on the Interstates (28 percent) and increased progressively on the US (35 percent), NC (39 percent) and secondary routes (46 percent). The Texas data indicated much the same thing. Here minicars had an elevated rollover propensity when compared to larger cars in single vehicle accidents for all four highway types -- both urban and rural. The percent of single vehicle accidents resulting in a rollover is shown in the table below for Interstate, U.S. and State, farm-to-market, and local roads. It is interesting to note that in the Texas data, the highest minicar rollover percentage in rural areas is on the Interstates, perhaps denoting differences in Interstate roadsides between North Carolina and Texas (i.e., that Texas Interstate roadsides may be forgiving enough at certain locations to "require" a rollover before a reportable crash is recorded).

In the same study, limited additional computer runs were made to further examine the yaw instability of minicars, the possible contribution of front wheel drive as a factor in rollover propensity in minicars, and the question of whether the origin of the minicar (Japanese, European, or U.S.) affects its rollover potential or crashworthiness.

With respect to the first question, the authors attempted to analyze the point of contact for vehicles of various sizes on the assumption that non-tracking vehicles would be less likely to strike a fixed object off the

Table 22. Rollover percentages by location and highway type (Texas data).

	Urban	Rural
Interstate	15.9%	50.5%
US/State	16.6%	39.1%
Farm to Market	19.7%	40.4%
Local (urban = city streets rural = county roads)	10.3%	32.4%

roadside with the front of the vehicle and more likely to strike it with some other area of the car. The analysis indicated that in general, minicars experienced slightly lower frontal proportions of impact and slightly higher left and right side impacts in rural areas than did the larger sized cars.

With respect to the front wheel drive question, preliminary analysis indicated that the front wheel drive (FWD) minicars experienced a higher rollover rate than did the rear wheel drive (RWD) minicars or front or rear wheel drive cars of larger sizes. This increased rollover rate for FWD minicars primarily occurs in rural areas on all categories of roadway except Interstates. Here, while the mid-sized front wheel drive vehicles experience either the same or lower rollover rates than did their rear wheel drive companions, the FWD minicars experienced higher rollover rates in low speed crashes on secondary roads and higher rollover rates in medium and higher speed crashes on both major highways and secondary roads. Additional analyses were then conducted to determine if this increased rollover rate could be an artifact of adverse weather or pavement conditions. This did not appear to be the case. In the final analysis related to country of origin, the proportion of 1971 and later model vehicles overturning was compared by car size and origin within each of eight roadway types. Data were later screened to include only 1978 and later model cars in order to reduce any potential bias that might have resulted from comparing newer U.S. minicars to older foreign designs. Both analyses indicated that minicars and mid-sized cars of U.S. origin consistently experience lower rollover rates than their foreign counterparts across all highway types. As expected, the major significant differences were in rural crashes. What cannot be answered from these runs is the question concerning the cause of these differences. They may well result from weight differences, wheel base differences, or even driver-related differences not yet controlled for.

In a related analysis, an attempt was made to examine whether or not the vehicle origin resulted in a difference in serious or fatal driver injury rate given a rollover had occurred. After controlling for belt use and speed prior to impact, there was little indication of any difference between the U.S., Japanese and the European-manufactured cars. For accidents involving a rollover, serious injury rate was consistent across all countries of origin. The only exception to this was in higher speed crashes where unbelted drivers in Japanese minicars experienced a slightly lower proportion of serious and fatal injuries than did the drivers of U.S. or European cars (15 percent, 18 percent, and 23 percent, respectively). Again, this apparent effect may be confounded by driver-related differences where the unbelted drivers of Japanese minicars may be younger, and thus less prone to serious and fatal injuries, than the drivers of U.S. or European cars.

Research Needs

There is a need to precisely quantify the role of specific vehicle parameters in the minicar accident problem. The potentially interactive effects of vehicle usage patterns (exposure) and driver-related factors need to be identified. The relationship of certain static vehicle characteristics and certain dynamic vehicle handling characteristics to accident involvement and injury causation needs to be determined. Specifically, there is a need to:

- Better define the possible contribution of front-wheel drive (FWD) as a factor in contributing to the higher rollover propensity of minicars.
- While controlling for other factors, better determine if the origin of the minicar (Japanese, European, or U.S.) affects the propensity for rollover involvement or crashworthiness, and if so, why.
- Identify the relationship between specific vehicle parameters (center of gravity height, suspension characteristics, roll-related moments of inertia, etc.) and the involvement of minicars in rollover accidents.

Research Methodology

A sequential three-step approach is suggested as being appropriate to meet the research objectives. First, additional analysis of computerized accident files is needed to better isolate the potential confounding factors associated with minicar rollover accidents. Second, in-depth analysis of hard-copy accident reports is needed to identify the specific accident scenarios that result in minicar rollover accidents. Third, additional HVOSM efforts are needed to identify the effects that specific vehicle parameters have on precipitating these minicar accident scenarios. These three steps are described in detail below.

Additional analyses of computerized accident files are needed to precisely identify the role of FWD and country of origin in minicar rollover accidents. These additional analyses should be designed to control for the possible effects of such factors as:

- o Driver age
- o Driver sex
- o Roadway type
- o Operating speed
- o Time of day
- o Weather
- o Road surface condition.

In order to have a sufficient number of accidents to draw statistically meaningful conclusions, it may be necessary to expand and/or combine existing accident files. For example, to examine accidents involving 16- to 30-year-old male drivers on high speed secondary roads in wet weather operating both FWD and RWD vehicles will require a large total sample of accidents.

Computerized accident files do not provide sufficient detailed information to precisely determine the nature of the rollover accident. Vehicles may run off the roadway to the outside of a curve and roll over. Vehicles may run off the roadway to the inside of a curve and roll over. Vehicles may run off the roadway (to either the inside or the outside), come back on the roadway and roll over. The characteristics of minicars (FWD vs. RWD and US vs. Non-US) may influence which of these scenarios are most likely to occur. By examining the hard-copy accident reports, specifically the collision diagram and the accident narrative, a number of accident types or accident scenarios can be identified. The role of specific vehicle characteristics (size, FWD - RWD, US - Non-US, etc.) in precipitating these various accident types could then be determined. These accident types will also be useful in subsequent HVOSM analyses.

Additional HVOSM efforts are needed to determine what it is about specific vehicles that affects their propensity to rollover. As noted above, the ratio of track width to center of gravity height has been previously used as an indication of vehicle stability. However, HVOSM testing on a limited sample of vehicles has noted that while T/2h is a predictor of rollover, rollover propensity varies for vehicles with similar ratios. More descriptive vehicle information is needed on a larger sample of vehicles in order to further explore the relationship of T/2h and additional parameters with rollover propensity. The sample of vehicles should include those make/model combinations that are most frequently found in the accident files so that details of the typical accident scenarios are available as HVOSM input. Additional vehicle properties that should also be investigated include, but are not limited to, the following:

- CGH (center of gravity height)
- Roll-yaw product moment of inertia
- Suspension spring rates
- Effective tire rates
- Roll stiffness - front and rear
- Rebound and jounce roles
- Sprung weight/unsprung weight

Once the critical properties in determining rollover propensity have been identified by HVOSM, test track validation of the parameters would be appropriate.

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HORIZONTAL CURVATURE AS RELATED TO MINICAR ACCIDENTS

Basic Research Issue

Minicars are overrepresented in single vehicle accidents on curves, particularly where poor geometry exist. Their accident pattern seems to involve loss of control and an inability to correct without either experiencing a single vehicle accident or returning to the pavement and striking another vehicle. Very few analyses have examined this issue in depth by car size, and thus little is known about the effects of certain geometric factors such as transition spirals or superelevation on minicar crashes (or crashes involving larger cars). Thus, there is a need to explore this problem in more detail and to evaluate the effects of such treatments as adding transition sections to curves, clearing roadsides, widening shoulders, adding adequate superelevation, and others.

Background

Review of past research literature indicates very little research related to horizontal curvatures which is specific to car size. In a Washington State study, the data indicated a higher minicar involvement on horizontal and vertical curves compared to the proportion of minicars in the registered vehicle population.(1)

In a study not specific to vehicle size, but with a great amount of detail related to horizontal curvature, Glennon, et al. found that the sharper and longer the curve and the narrower the shoulder and pavement width, the higher the probability of an accident. The major discriminant between high and low accident curves was roadside design, while roadway curvature, shoulder width or design were also among variables of importance. Simulation efforts indicated that, with the driver monitoring and correcting his path as he enters the curve, spirals could reduce the friction demands on critical curve transitions. Field studies, on the other hand, indicated that drivers position themselves prior to the curve in order to drive a spiral even when the spiral was not present. (No field data were collected on curves with spirals and thus no comparisons can be made.) Finally, drivers tended to "overshoot" the curve regardless of the curve radius and then to have to make a sharper correction than the curve itself would have demanded if the "curve overshoot" phenomenon had not existed.(2) (Again, this finding was not tested on curves with transition spirals.)

With respect to superelevation, Zador et al. studied superelevation on grades and on curves where fatal crashes had occurred. They found that superelevation deficiencies existed both on curves which were located on downgrades and on curves with prior fatal accidents.(3)

In recent accident analyses conducted by Council, et al., analysis of Texas data indicated minicar overinvolvement on horizontal curves when compared to the minicar proportion in single vehicle accidents. This finding held true on all urban classes and farm-to-market and local classes in rural areas. For farm-to-market roads (i.e., the roads with the least favorable geometry), there was an increasing overinvolvement with increasing degree of curve.

Using Washington data, and attempting to control for the exposure of the different car sizes by using the accident experience on adjacent tangent sections, the minicar class seems to be overrepresented on curves on most roadway types with and without spirals. The greatest overrepresentation was noted on curves with very low or very high degree of curvature. The analysis do not indicate clear findings concerning the effects of the presence of spirals.

In a related effort, a sample of hard copies of North Carolina accidents were pulled and the narrative and sketches were examined to extract more detail concerning the occurrence of accidents. Here, minicars were involved in higher proportions of single vehicle accidents than large cars. However, given that a ran-off-road accident had occurred, there was no difference between the mini- and the large car in the proportion occurring on curves. When a rollover occurs, the minicar rollovers were equally distributed between curves and tangents, while large car rollovers were predominantly found on curves. In the same analysis of multivehicle accidents, it was interesting to note that in a sample of crashes involving both a minicar and a large car (where each size vehicle had the opportunity to be the striking vehicle 50 percent of the time), minicars were found to be the striking vehicle (i.e., the vehicle crossing the center line and "causing" the head-on collision) more often than were big cars in head-on collisions. Here, minicars were the striking vehicle in 62 percent of the cases. When the minicar was the striking vehicle, the collisions occur on a curve only 17 percent of the time. In 38 percent of these head-on collisions, the minicar ran off the road to the right and then returned to the pavement, crossed the center line, and struck a large car. No big cars were involved in such off-road, on-road, crash scenarios, but instead were simply stated as having crossed the center line when they were the striking vehicle.(4)

Research Needs

Based on the review of the literature and recent accident analysis, three basic research needs are defined:

- Identification of geometric features. First there is a need to better define those geometric factors which result in minicar overrepresentation on curves, and to better specify which of these factors are the most important.

- To further study the issue of the minicar "head-on striking vehicle" trend. As indicated above, it appears from a limited analysis that the minicar is more often the striking vehicle in head-on collisions, and that this problem quite often occurs on curves after a ran-off-road maneuver. There is need to further analyze this issue to better define the dynamics that are involved.

- Evaluation of treatments to reduce minicar accidents. Finally, there is a need to define and evaluate various treatments which could reduce both the minicar curve-related accident rate and the corresponding accident rates of larger vehicles. Specifically, this evaluation should examine the role of:

  Curvature, spirals or other transition sections.
  Superelevation
  Roadside clearzone on curves
  Innovative signing, marking, and/or delineation at hazardous curves

Research Methodology

It is anticipated that some accident analysis of overall vehicle type involvement on curves (although not by specific vehicle size) will be conducted in a current FHWA project entitled, "Cost Effective Geometric Improvements for Safety Upgrading of Horizontal Curves" (DTFH61-86-C-00041). The preliminary analysis described above has indicated a certain number of accident-related issues which need to be further studied. It is anticipated that the methodology be used will include further modeling efforts, particularly with emphasis on spirals, superelevation, and clear road sides. A remaining issue is whether this subsequent accident analysis should be vehicle-size specific or not. While the minicar clearly has problems, it appears that all cars have problems on curves and that treatments affecting all size cars might have even more enhanced effects on minicars.

A second methodology which can be used in this effort involves the HVOSM computer simulation model. Perhaps the most appropriate use of the model would involve the enhancement of runs done in the earlier Glennon, et al. work by use of a more sophisticated driver response model in the spiral-related analysis that was conducted. This enhanced simulation would involve driver monitoring at varying distances in front of the vehicle and changes in the vehicle path correction model that was used in the earlier work. Simulation could also provide valuable information related to certain characteristics of the roadside for various sized vehicles. For example, as noted in a related research effort concerning roadside ditch design, there is a need to conduct simulation work related to currently used roadside ditch designs on non-Interstate roadways and to attempt to determine a ditch design that would prevent minicar rollover and would entrap the vehicle to prevent it from hitting more dangerous obstacles behind the ditch.

Finally, this research effort should also involve field studies, such as a field evaluation of innovative delineation attempts. Innovative delineation (e.g., pavement markings or roadside delineators), would be placed at various locations and driver behaviors would be monitored at those locations either visually or through photographic techniques.

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MINICAR COLLISIONS WITH SPECIFIC FIXED OBJECTS

Basic Research Issue

When compared to larger vehicles, minicars experience a higher rollover rate when colliding with any fixed object. Certain obstacles are particularly troublesome by virtue of the fact that they result in a higher proportion of vehicle rollovers when struck by the minicar than do other objects. Others are troublesome because minicars experience a very large rollover overrepresentation when compared to large cars in similar crashes. Certain types of fixed objects are being covered in other research plans. Three remaining objects will be covered here -- rural bridge piers, rural culverts and catch basins, and median barrier faces. The basic research issues concern why this increased rollover propensity exists and what can be done to alleviate it. (It is noted that these three classes of fixed objects could be treated in separate research efforts. They are grouped here for discussion purposes and because the proposed accident-related methodologies are similar.)

Background

Numerous studies have documented the increased propensity of minicars to be involved in rollovers in most types of accidents on almost all roadway types. The results of the Washington State study and the Kuroda, et al. study both noted minicar overinvolvement in overturn accidents.(1,2) Griffin, in conducting an analysis of Texas single vehicle accidents, found that smaller cars are much more likely to rollover than larger cars on all highway classes. Compared to larger cars, he found that minicars were eight times more likely to overturn on county roads, 12 times more likely on Interstates, and 37 times more likely on city streets. He also noted a higher rollover rate when the minicar strikes fixed objects as compared to the larger vehicles. Deleys (1986) found a rollover rate much higher for the lighter weight vehicles, with the increasing rollover propensity trend flattening out at approximately 3500 lb (1.59 Mg).(3)

In terms of accident severity, Deleys, et al. reported that rollovers tend to result in more injury than do non-rollover collisions for all size vehicles, primarily due to the increased chances of occupant ejection.(4) Viner noted fatal rates for rollovers ranging from 2 to 5 times as high as the fatal rates for non-rollover, depending on the data source.(5)

Recent analysis of both Texas and North Carolina accident data support these past findings.(6) In an analysis of Texas single vehicle accidents, the minicar experienced higher rollover proportions on all rural road classes than did companion larger cars. Using North Carolina data, the issue of minicar rollover in crashes involving fixed objects was examined in more detail. As shown in the table on the following page, minicars have elevated rollover rates in involvements with any fixed object when compared to larger cars. In collisions with bridge piers and median barrier faces, the minicar experiences a much higher percentage of rollovers than with most other fixed objects. When the rollover rate for minicars is compared to large cars in collisions with these two objects, the minicar is also shown to have a higher rollover rate. Rural culverts and catch basins, while characterized by a high percentage of minicar rollovers, are not characterized by as large a difference between car sizes. This may be some indication that the catch basin/culvert objects are a serious problem for all sized vehicles.

Because the median barrier-face rollover problem has been suggested in the past by certain accident researchers and because there is a great deal of attention paid to the design of median roadside guardrails and barriers, the Texas Transportation Institute is currently conducting a research effort aimed at providing information on the question of minicar crashes into median barrier faces. In this effort, four crash tests were run involving vehicles weighing between 1250 to 1800 lb (0.56 to 0.81 Mg) with impact speeds of 60 mi/h (97 km/h) and entry angles of 15 and 20 degrees into a New Jersey Safety Shape barrier. There were no rollovers for any of the small cars tested. Within the constraints of the test conditions used, these crash test results would clearly indicate less of a rollover problem than do the accident results cited above.

Research Needs

Bridge piers. With respect to bridge piers, the current study (6) did not determine whether or not bridge pier-involved rollovers resulted in overall injury potential that was higher than the non-rollover bridge pier hits. Thus, given that an impact into a bridge pier could be so severe that subsequent rollover does not lead to increased injury, there is a need to determine if rollovers are indeed a problem. If the rollover-related crashes do involve more injury, then there is a need to determine the dynamics of the crashes resulting in rollovers for minicars and to design and test appropriate treatments.

Catch basins or culverts. In the computerized accident data used in the study by Council, it was not possible to fully quantify the types of catch basins or culverts which were struck.(6) This category could involve primarily ditch (driveway), culverts, or could involve collisions with drop inlets or other catch basins beside the roadway. There is a need to first determine which of these situations is the case. Then more detailed information is needed on both the nature of the object and the nature of the crash to determine, for example, if culvert crashes are occurring primarily on curves or some other specific location. Based on such findings, appropriate treatments can then be developed.

Median barrier faces. There is a clear difference between what the accident data seem to be showing and what the current crash tests results are indicating. Thus, there is first a need to examine the issue in more detail to determine why the difference exists. Obviously, the differences could be the results of problems in accident data definitions where police are coding some form of barrier as concrete or where the rollover is occurring prior to impact with the barrier. The differences could also be the result of the nature of the crash tests where well-graded approach and exit areas near the barrier itself may differ from those conditions found in real world crashes. After reconciliation of these differences, research is then needed to determine whether changes to the barrier designs are necessary.

Research Methodology

Bridge pier research. Bridge pier research would primarily involve accident analysis using both appropriate State accident data bases and data bases in the NASS and FARS systems to determine if severity differences exist between rollover and non-rollover collisions with bridge piers while other factors are being controlled for. Such an analysis will require use of hard copies of accident reports to obtain better indications of the crash dynamics that were occurring and the type of pier being struck.

Catch basin/culvert research. Basically, the research methodology necessary to answer the above-stated issues with respect to culverts and catch basins are the same as those for bridge piers -- an analysis of hard copies of accident reports from State and Federal data files. If the initial analysis indicates that the problem is more related to catch basins than to culverts, then there may be a need to do a detailed inventory of the types of catch basins that are being struck and to compare them with current design standards. If the problem is more related to culverts, then the research should be included in the ditch design research area and treatments such as drive-through ditches, covered ditches at critical locations, and culvert-end modifications based on previous work by TTI should be considered and tested.

Median barrier-face research. To attempt to reconcile differences between accident results and crash tests, detailed examination is needed of hard copies of accident reports from the NASS and the FARS systems and appropriate State data bases. This examination would be aimed at determining the type of barrier being struck and the dynamics of the crash involved. Particular emphasis should be placed on the nature of the roadside in the area of the barrier and to any indication of pavement edge or other fixed object involvement before or after the barrier is struck.

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SEVERITY REDUCTION TECHNIQUES FOR MINICAR CRASHES INVOLVING UTILITY POLES

Basic Research Issue

Although minicars do not appear to strike utility poles any more often than do larger cars, the severity of such crashes is much greater than for most other fixed objects. While pole treatments, including breakaway designs, have been developed for use, two problems continue to exist. First, the breakaway designs have not been tested in the field. Second, certain breakaway designs do not appear to work as well for minicars as for larger cars, particularly at lower (but dangerous) speeds.

Background

Numerous past research studies have looked at the issue of utility poles without regard to car size and also more specifically at the issue in crashes involving small cars. For example, a study by Zegeer and Parker for FHWA found that of 9,583 utility pole accidents in four States, 46.3 percent involved injury and 1.0 percent involved fatalities.(1) Similarly, Mak and Mason found that of 1000 utility pole accidents, 51.8 percent resulted in one or more injuries and 1.6 percent involved a fatality.(2) Viner using FARS data and Griffin using Texas data both indicate that poles are the most frequently struck man-made object and that the injury severity for occupants of minicars is significantly higher than for larger vehicles.(3,4) Griffin concluded that the minicar occupant is approximately 2.4 times more likely to experience a serious or fatal injury in a utility pole crash than the driver of a 3500-lb (1.59-Mg) car.

Recent accident-related findings of analyses based on North Carolina data have supported the findings of past research.(5) Here the data indicate that utility poles are the most often hit man-made obstacle (with the exception of the ditch bank). Of all minicar crashes involving fixed objects, crashes with utility poles account for approximately 10.2 percent.

It is clear that such collisions between minicars and utility poles result in high injury rates. The North Carolina analyses indicate that, for all vehicle types, a significantly higher proportion of drivers experience serious or fatal injury when striking poles than when striking other fixed objects. For the population of minicar crashes, those striking poles have a rate of serious and fatal accidents which is 1.7 times as high as for other fixed objects in rural areas, and a rate 1.9 times as high in urban crashes. Compared to occupants of larger cars, minicar occupants are approximately 1.5 times as likely to experience a serious or fatal injury in a rural pole crash and 1.9 times as likely in an urban utility pole crash.(5)

In comparison to the highly successful breakaway design features for luminaire and sign supports, development of a similar breakaway design that can be retrofitted to the timber utility pole has been slow, due to a number of unique and difficult technical problems. For example, a breakaway coupling mounted near grade must be able to sustain huge bending moments induced by wind gusts on ice-coated service lines. Even with successful activation of the breakaway coupling during a vehicle collision, the heavy mass of the pole segment with its inherent inertial effects can produce additional life-threatening vehicle decelerations, especially for high-speed impacts involving the small car. Hazard of severed power lines and the possibility of disrupted critical services detract from the highway safety benefits of a breakaway system. Nevertheless, considerable progress has been made in recent years by Labra and Ivey in developing promising hardware and techniques that address the more important concerns.(6,7) In particular, three techniques are currently in various stages of development and field demonstration, and although not specifically pinpointed to the small car, the three techniques may have application:

- Hawkins Breakaway System (HBS) consists of a slip base modified from a design evaluated by Labra (6) and an upper hinge mechanism. An extensive series of vehicle crash tests has indicated that the HBS performs acceptably for a range of vehicle sizes and speeds (i.e., 1800-lb (0.82 Mg) cars at 20 mi/h and 40 mi/h (32 and 64 km/h) up to 4500-lb (2.04 Mg) cars at 60 mi/h (84 km/h)). Under an HPR study, HBS is planned for field evaluation at about 36 sites in Massachusetts beginning in mid-1987.

- CAM REDIRECTOR (CAM) is a hybrid collision barrier/crash cushion system comprised of a crushable ring, thrie-beam guardrail and a support post with directional slipbase.(6) Rather than severing the timber utility pole, the errant vehicle is either redirected or stopped under controlled conditions. A single vehicle crash test (i.e., 3800-lb (1.72 Mg) car at 41 mi/h (66 km/h)) produced promising results.

- Pole Crash Cushion (PCC) is a small crash cushion that girds and is attached to the timber pole. It is in the early design stage at TTI by Ivey, et al. and would be applicable to the numerous low to moderate speed urban impacts.

Research Needs

As a continuation to research efforts conducted in the past, basic research needs involving utility poles include the following:

- Field test of breakaway designs. There is a need for further verification that the designs which appear technically feasible and successful in crash tests will indeed work when implemented in the real world. In addition, based on this field testing, there is a need to identify what necessary changes in both the designs and the implementation policies (i.e., whether the breakaway poles should be placed at all locations on the outside of rural high speed curves, or at specific locations identified as experiencing high accident rates or frequencies).

- Continued development of minicar treatments. As indicated above, while the breakaway designs developed thus far appear to work satisfactorily with larger cars, there is a continuing research need to develop either enhanced breakaway designs or other protective devices which would protect minicar occupants in utility pole crashes.

Research Methodology

Field tests in which current designs will be evaluated require the placement of these designs in the field at critical locations and the monitoring of subsequent crashes. This demonstration effort is now being initiated in the State of Massachusetts and may be initiated in Kentucky and Alabama. Because of the fact that the demonstration effort is beginning, details of the methodology will not be discussed here. In terms of the development of work, however, there is the continuing need for development of utility pole treatments that will work for the smaller vehicles.

The developmental effort and crash testing study would involve an expansion of the work cited above. Each of the designs noted there -- HBS, CAM and PCC -- offers a range of performance with the small car. It is important that these designs are tailored to the small car at all stages of their development. Specific needs are the following:

- HBS. In the planned field evaluation, special consideration should be given to accidents involving small cars and that the accidents be investigated and reported in detail to permit reconstruction.

- CAM. Based on promising results from the single exploratory crash test, the CAM design should be further developed particularly for the small car and then subjected to an extensive array of vehicle crash tests. Following this research phase, the CAM should be in-service evaluated at selected sites.

- PCC. A development effort is needed to define optimum size, crash properties and performance range. Prototype hardware should then be evaluated by laboratory and crash tests to define a performance envelope. A collision envelope consisting of mini and full-size sedans at impact speeds up to 30 mi/h (48 km/h) would address nearly 70 percent of urban pole collisions.(6) Because of the mature nature of crash cushion technology, this effort is expected to be low risk and direct.

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