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16. Abstract <p>Although work zones certainly present hazards to all drivers, truck drivers in particular are presented with many demanding situations in work zones. These situations include narrow lane widths, poor superelevation, and reduced passing opportunities.</p> <p>Pavement/shoulder drop-offs occur frequently in work zones that require excavation or removal of pavement and shoulder material adjacent to lanes open to traffic. Such drop-offs present obvious hazards to vehicles that run off the work zone roadway.</p> <p>This report presents the results of research on these two issues. Operational and accident data were analyzed from nine truck study sites in three states. Pavement/shoulder drop-offs were studied via simulation modeling of the drop-off maneuver and via analysis of operational and accident data from four pavement/shoulder drop-off sites located in two states.</p> <p>Results of the study of truck problems in work zones revealed insufficient design speed of a temporary crossover roadway as the most critical truck problem observed. Other problems noted included insufficient merging or acceleration areas for trucks in work zones, reverse superelevation of a paved shoulder used as a work zone traffic lane, and rear-end accidents on work zones located on long steep downgrades.</p> <p>The modeling of pavement/shoulder drop-off traversals resulted in development of a "window of safety" to define maximum tolerable drop-off heights as related to vehicle speeds and adjacent lane widths. Operational data revealed that vehicles do not slow down in response to a pavement/shoulder drop-off. Lateral placement of vehicles relative to the drop-off edge did vary based on the type and placement of traffic control devices used to delineate the drop-off.</p>			
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PREFACE

This final report was prepared by Midwest Research Institute for the Federal Highway Administration under Contract No. DTFH-80-C-00146. Mr. Justin True of the Office of Safety and Traffic Operations Research and Development, Federal Highway Administration was the contract manager.

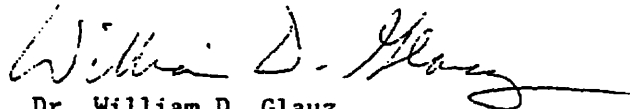
We wish to acknowledge the contributions of the following persons in State highway agencies who served as principal contacts for field and accident data collections: Mr. Fred Rooney, California Department of Transportation; Mr. Eldon Orth, Nebraska Department of Roads; Mr. John H. Shafer, New York State Department of Transportation; Mr. Troy Peoples, North Carolina Department of Transportation; and Mr. J. R. Doughty, Pennsylvania Department of Transportation. Many other individuals in the departments mentioned provided invaluable assistance which is gratefully acknowledged.

The work reported herein was carried out in the Center for Safety and Engineering Analysis under the administrative direction of Dr. William D. Glauz. Mr. Jerry L. Graham, Senior Traffic Engineer served as the principal investigator.

Mr. Graham and Dr. John C. Glennon, Transportation Consultant were co-authors of this report. Portions of the discussion on modeling of drop-off maneuvers were prepared by Mr. Brian B. McHenry and Mr. Raymond R. McHenry of McHenry Consultants, Inc. Ms. Karin Bauer contributed to writing of sections dealing with statistical analysis. Other consultants to the MRI project staff were Mr. Fred R. Hanscom, Transportation Research Corporation; Dr. John W. Hutchinson, University of Kentucky; and Dr. Patrick T. McCoy, University of Nebraska. Other members of the MRI staff who contributed to the work reported include Mr. Douglas W. Harwood, Mr. Patrick J. Heenan, Ms. Rosemary Moran, Ms. Debra Hodge, and Mr. Andy St. John.

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III. PAVEMENT/SHOULDER DROP-OFFS IN HIGHWAY WORK ZONES

Pavement/shoulder drop-offs frequently occur in work zones that require excavation or removal of pavement and shoulder material adjacent to lanes on which traffic is maintained. Examples of the type of work in these projects include roadway widening, shoulder reconstruction or median barrier installations.

These drop-offs present a hazard to traffic if a vehicle should wander into the drop-off area. Many times accidents occur at pavement/shoulder drop-offs when vehicles lose control while attempting to return to the travel lane. This chapter presents background information on past drop-off studies, results of drop-off maneuver simulation, operational and accident studies at four drop-off sites, and conclusions gained about pavement/shoulder drop-offs and the effectiveness of traffic control devices used to delineate drop-offs.

A. Background

The study "Identification of Traffic Management Problems In Work Zones"¹³ ranked the problem of "Abrupt Changes in Elevation at the Edge of Through Traffic Lanes" fourth among twenty identified work zone problems in its probable impact on work zone safety. One aspect that attributed to this high priority rating was the judged high exposure of the motoring public to pavement/shoulder drop-offs.

The California Department of Transportation performed a limited investigation of the pavement/shoulder drop-off disturbance to investigate effects on the stability and control of vehicles at high speeds (i.e., 60 MPH), to establish maximum tolerable heights for drop-offs, and to verify current maintenance standards for allowable drop-off heights.¹⁴

Fifty full-scale test runs were performed on three drop-off heights (1-1/2 in., 3-1/2 in., 4-1/2 in.) with small, medium, and large passenger cars and a pickup truck.

The conclusion drawn from the test results was that there were no particular handling problems with drop-offs within the investigated range. The results, however have been criticized based on the following:

1. The use of a former race car driver to perform the tests, coupled with a lack of vehicle instrumentation gives no insight into the tolerances and capabilities of the test driver and the relationship of those driver characteristics to the average driver.
2. A 5-foot wide asphalt-concrete (AC) shoulder area was used between the 12-foot traveled way and the low shoulder providing a 17-foot recovery area from the drop-off edge.

3. The "surprise" element of the pavement/shoulder drop-off maneuver was not addressed.

The California DOT tests demonstrated that with experience one can perform a pavement/shoulder drop-off maneuver at high speeds with no apparent handling problems. In all of these tests, the driver eased the test vehicle at about 60 mph out of the far right traveled lane across the 5 ft asphalt concrete shoulder and over the drop-off. The angle of departure across the drop-off was 1 to 7 degrees and generally in the 3 to 5 degree range. The driver then straightened the vehicle and remounted the drop-off at an angle of 1 to 8 degrees (generally 3 to 5 degrees) and eased across the shoulder back into the right traveled lane. The path of the vehicle was such that the first tire to remount the drop-off reached a distance of at least 1 ft and usually about the 3 ft laterally from the drop-off.

Later tests¹⁵ were done to investigate traversing a crumbling edge on an AC shoulder next to a muddy shoulder. Three tests were run using a professional driver in a pickup truck traveling 60 mph. Again in these tests the drop-off did not throw the vehicle out of control and no unusual control methods were required for the driver to traverse the drop-off.

The Calspan Corporation, as part of an investigation into the characteristics and capabilities of automobile drivers,¹⁶ included two items of interest in relation to the subject research: the off-road recovery and the surprise intrusion.

The off-road recovery test area used in the cited research is depicted in Figure 11. The right side of the vehicle was guided off the road by the use of pylons and the driver was given a 100-foot section to return to the travel way. The test section consisted of a 10-ft traveled lane, a 4-in. drop-off (produced by use of steel plates butted together, depicted in Figure 11), and a 3-ft shoulder recovery area. The success of the maneuver was determined by the number of failure cones contacted by the vehicle (i.e., lane boundary exceedence). The maneuver did not produce as demanding a task as had been anticipated.

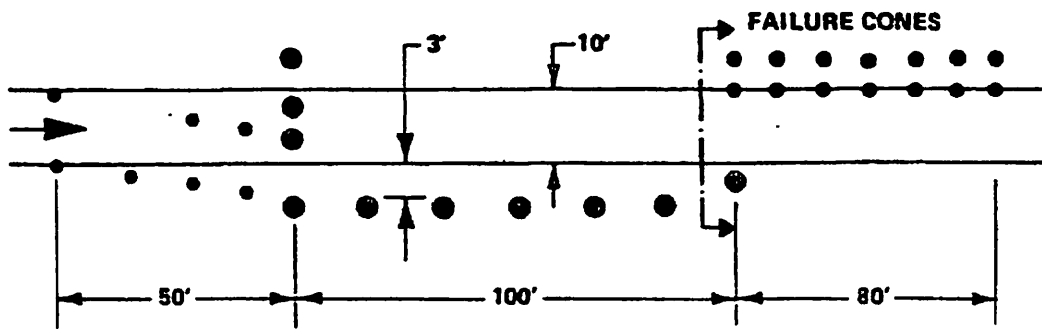
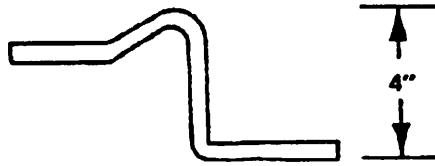
The second item of interest investigated in the Calspan study was a surprise intrusion which consisted of a barrel being thrown in the path of a vehicle. The test results give insight into the response characteristics of a driver in the extremely hazardous situation of impending collision. A summary of pertinent results is presented which depicts possible extreme response characteristics of a driver to a pavement/shoulder drop-off:

1. Mean reaction time (time between barrel ejection and first evidence of driver avoidance action--steering or braking) was .65 seconds.

2. In 75% of the cases the first reaction was pure braking or combined steering and braking.

3. Drivers averaged a maximum lateral acceleration of about 0.45 g's.

**OFF-ROAD RECOVERY
CURB**



OFF-ROAD RECOVERY

Figure 11 - Calspan Off-Road Recovery Curb and Test Site Layout

4. Subjects were able to employ steering wheel rates of over 500 deg/sec with success.

Systems Technology, Inc., as part of their investigation into the Influence of Roadway Disturbances on Vehicle Handling,¹⁷ performed an in depth investigation into the mechanics of the pavement/shoulder drop-off maneuver.

In the STI study of the drop-off maneuver, 73 closed-loop test runs were performed on 4-1/2 in. drop-off heights (see Figure 12) with three different vehicles utilizing "unsuspecting" drivers. The researchers found that characteristics of runs in which the lane boundary was exceeded usually included a combination of tire sidewall-pavement edge scrubbing and high speed.

The STI researchers also performed a number of open-loop test runs utilizing professional drivers and four different instrumented vehicles in the following maneuvers:

1. Test runs were performed with various known reentry angles for a range of vehicles and speeds. Figure 13 shows the relationship found between normal velocity required to mount the drop-off and drop-off height.

2. The vehicle was forced into a tire sidewall-pavement edge scrubbing condition and the steer angle was gradually increased until the edge was mounted, to determine the steer angle required to mount for various speeds and vehicles. The most hazardous condition in a pavement/shoulder drop-off maneuver results when the vehicle is scrubbing one set of tires on the shoulder edge or encountering the edge at a shallow heading angle. The hazardous condition is produced because of the large front wheel steer angle required to climb the edge and its effect on the driver/vehicle system subsequent to the climb. Figure 14 shows the steer angle required to climb the drop-off as a function of drop-off height. This relationship was independent of speed.

The STI results have very important implications in understanding the ability of drivers to remount a drop-off after their right wheels have run off the road. Figure 13 shows for higher drop-offs at higher speeds, it becomes more likely that a car will be redirected rather than mounting the drop-off. This redirection may well put the driver in a position parallel to the drop-off with his tires scrubbing against the face of the drop-off. Figure 14 illustrates that, as drop-off height increases, drivers require increasingly larger steer angles in order to remount a drop-off. This large steer angle produces a large component of speed across the road that develops suddenly upon remount and may force the driver to encroach on the opposing lane or to run off the other side of the roadway before he can straighten his wheels (the "slingshot" effect).

The Texas Transportation Institute (TTI) investigated vehicle responses to impacts with several types of curbs in 1974.¹⁸ The research included 18 full-scale impact tests using a 1963 Ford Galaxie and two different curb configurations (i.e., AASHTO Type C and Type E).

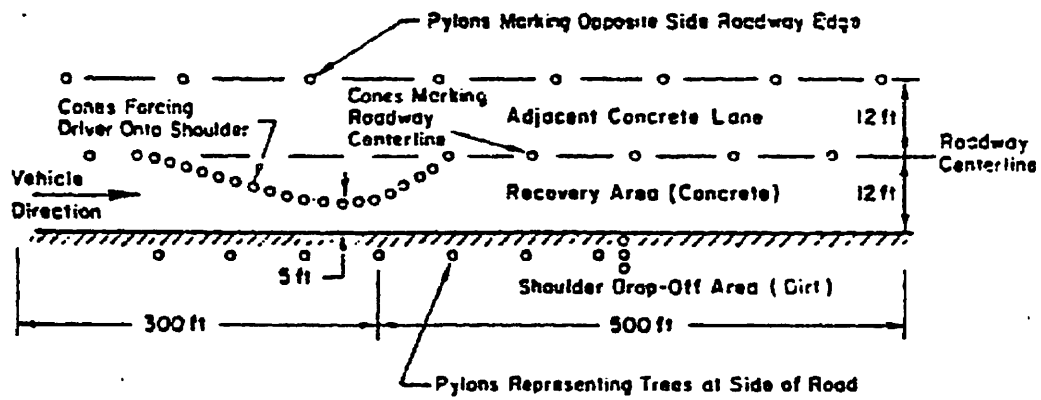


Figure 12 - Systems Technology, Inc., Closed-Loop Test Site Layout

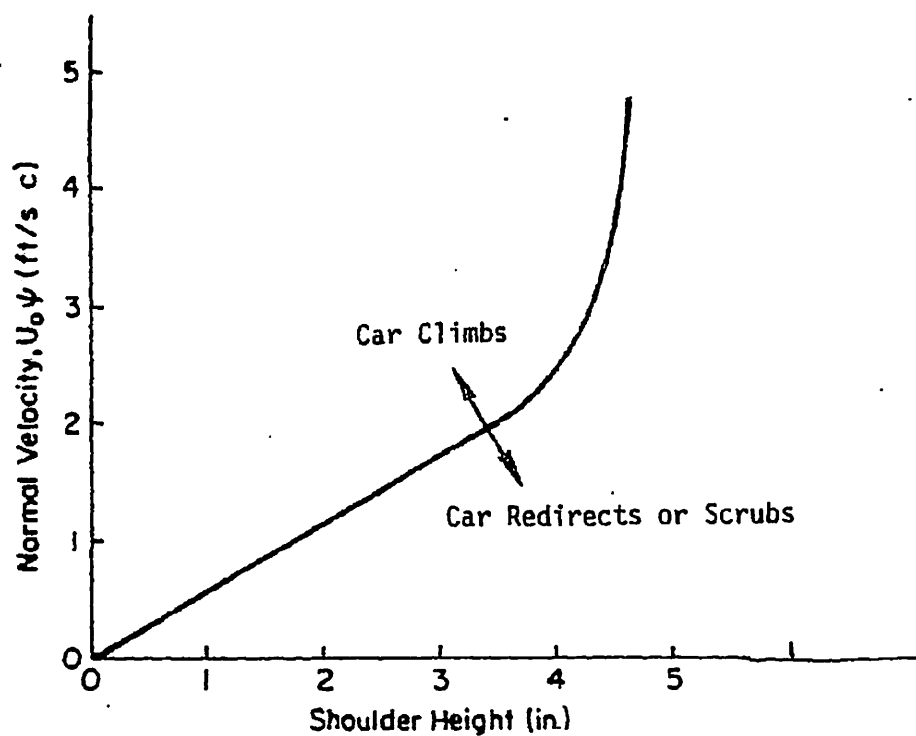


Figure 13 - Systems Technology Documentation of Shallow Angle Encounter Tests

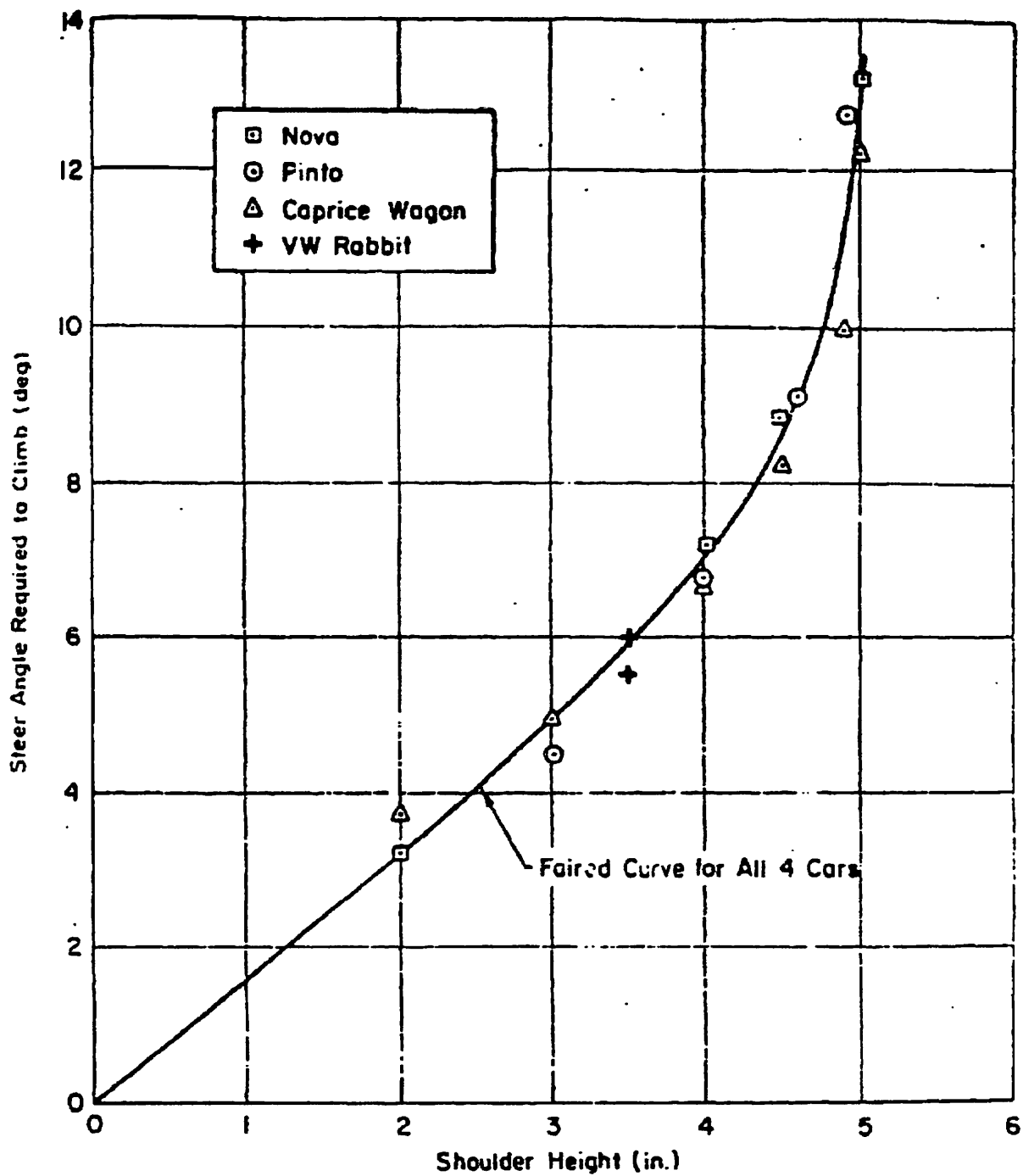


Figure 14 - Systems Technology Documentation of Steer Angle Required to Climb Various Drop-Off Heights from Scrubbing Condition

4. Lateral accelerations measured in the intermediate size vehicle ranged from a low of 0.07 g at 1-1/2 in. drop-off height to 0.88 at the 4.5 in. drop-off height.

5. The factors found to most influence safety in the drop-off remounting were, in the order of importance, drop-off height, method used to return to the pavement, and speed.

6. Small differences were observed between the four vehicles used in the study.

The results of the full-scale test runs revealed that appreciable undercarriage contact and/or suspension bottoming can occur when encountering an equivalent 5 to 6 in. terrain elevation change at a 5 degrees or greater encounter angle.

A recent study¹⁹ at the Texas Transportation Institute involved traversal of an asphalt pavement to soil shoulder drop-off by professional, semiprofessional and untrained drivers. The tests were conducted at the TTI Proving Grounds next to a concrete runway. The runway was overlaid with asphalt and a soil shoulder was added next to the runway to provide a drop-off condition. The drop-off heights tested were 1-1/2 in., 3 in. and 4-1/2 in. Three edge shapes were tested: an edge that was vertical with minimal corner rounding, an edge fully rounded and an edge with a 45 degree slope. Four test vehicles were used: full-size, intermediate, mini-compact, and a pickup. The full-size and intermediate vehicles were tested with both bias ply and radial tires. Three vehicle paths were driven: (a) two wheels off drop-off with a very flat remount angle to produce scrubbing, (b) two wheels off drop-off with a sharp remount angle, (c) and all four wheels off the drop-off with a sharp remount angle. Tests were run at 35, 45 and 55 mph.

Photographs were made of each test run employing a camera in a lead vehicle and also a camera positioned on the drivers door aimed at the driver. The driver used a remote switch to start and stop this camera. Electronic instrumentation was installed in the intermediate size vehicle to measure velocities, lateral acceleration, yaw rate, and wheel angle.

In addition to the photographic and electronic data, the drivers expressed the severity of each test run using the following numerical ranking scheme:

- | | |
|--------------------|--|
| 1. Undetectable | 6. Extra effort |
| 2. Very mild | 7. Tire slip (slight lateral skidding) |
| 3. Mild | 8. Crossed centerline and returned |
| 4. Definite jerk | 9. Crossed centerline and no return |
| 5. Effort required | 10. Loss of control |

Over 300 test runs were made, however only the professional driver was used in the runs with 4.5 in. drop-off height.

Some of the conclusions of the study include:

1. Using runs at the 3 in. drop-off height, the severity rankings for each of the drivers were fundamentally equal.

2. Comparing bias and radial ply in the scrubbing condition, the bias ply tire produced slightly higher severity levels at all heights.

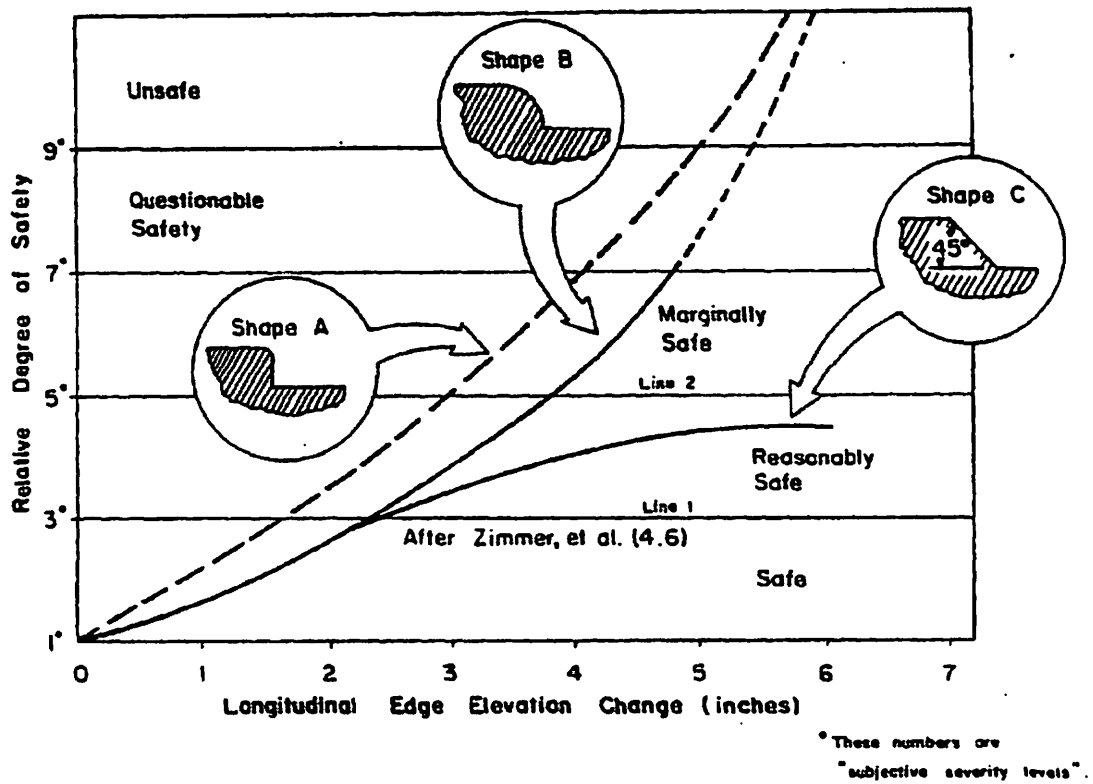


Figure 15 - Relative Degrees of Safety for Various Edge Conditions

Maintenance Standards of the State of California suggest a 3/4-in. allowable drop-off between a through lane and paved shoulders, while other agencies use 1.5-, 2-, or even 3-in. values."

B. Simulation Results

1. General description of pavement/shoulder drop-off traversal:

An integral part of the performance of the research included the development of an understanding of the pavement/shoulder drop-off maneuver including an investigation of the effects of the driver/vehicle and environmental factors on the outcome of the drop-off traversal.

The vehicle encounters a pavement/shoulder drop-off when the vehicle either inadvertently or intentionally leaves the lane of travel, either partially or fully, and goes onto the lower shoulder. Seven potential outcomes of the drop-off traversal are shown in Figure 16 linked with the exit conditions and driver/vehicle responses that produce each subsequent outcome.

The exit phase of the pavement/shoulder drop-off maneuver includes the initial vehicle response as the wheel(s) drop onto the low shoulder. The vehicle response to the wheel drop onto the low shoulder is an increase in the vehicle roll and pitch angle toward the low shoulder. The extent of the vehicle response is a function of the vehicle speed, heading angle with respect to the edge, and the difference in elevation between the right vs. left and front vs. rear tires.

When the departure angle of the vehicle with respect to the edge is small (i.e., 3.0 deg), the vehicle may also respond to the effects of the tire sidewalls being compressed against the edge during the drop. The sidewall induced forces can cause a change in the front wheel steer angle as well as a change in the heading (yaw) angle. Outcomes 1 through 6 as illustrated in Figure 16 are possible when the exit angle is low to moderate. If the exit angle is moderate to high and the driver does not steer or brake quickly the vehicle will continue to exit the roadway and overturn or collide with a fixed object on the roadside (outcome 7).

The primary driver perception/reaction to the pavement/shoulder drop-off is the first perception/reaction the driver has of the situation. Does the driver perceive imminent danger? Does the driver perceive a loss of control of the vehicle? Has the driver experienced a similar situation before? Does the driver brake or steer or use a combination of both?

The use of a primary driver perception/reaction is to encompass the effects of "surprise" on the driver's perception of the situation and the subsequent reaction to the perception. The driver has been alerted to the fact that the vehicle is encountering a change in orientation and the primary perception and reaction of the driver to that change in orientation prescribes the ensuing vehicle response characteristics.

The secondary driver perception/reaction to the vehicle responses includes all the driver/vehicle interaction subsequent to the primary driver perception/reaction. The driver realizes that the vehicle is in an adverse situation (i.e., partially or fully on shoulder) and the driver must decide how best to remedy the situation.

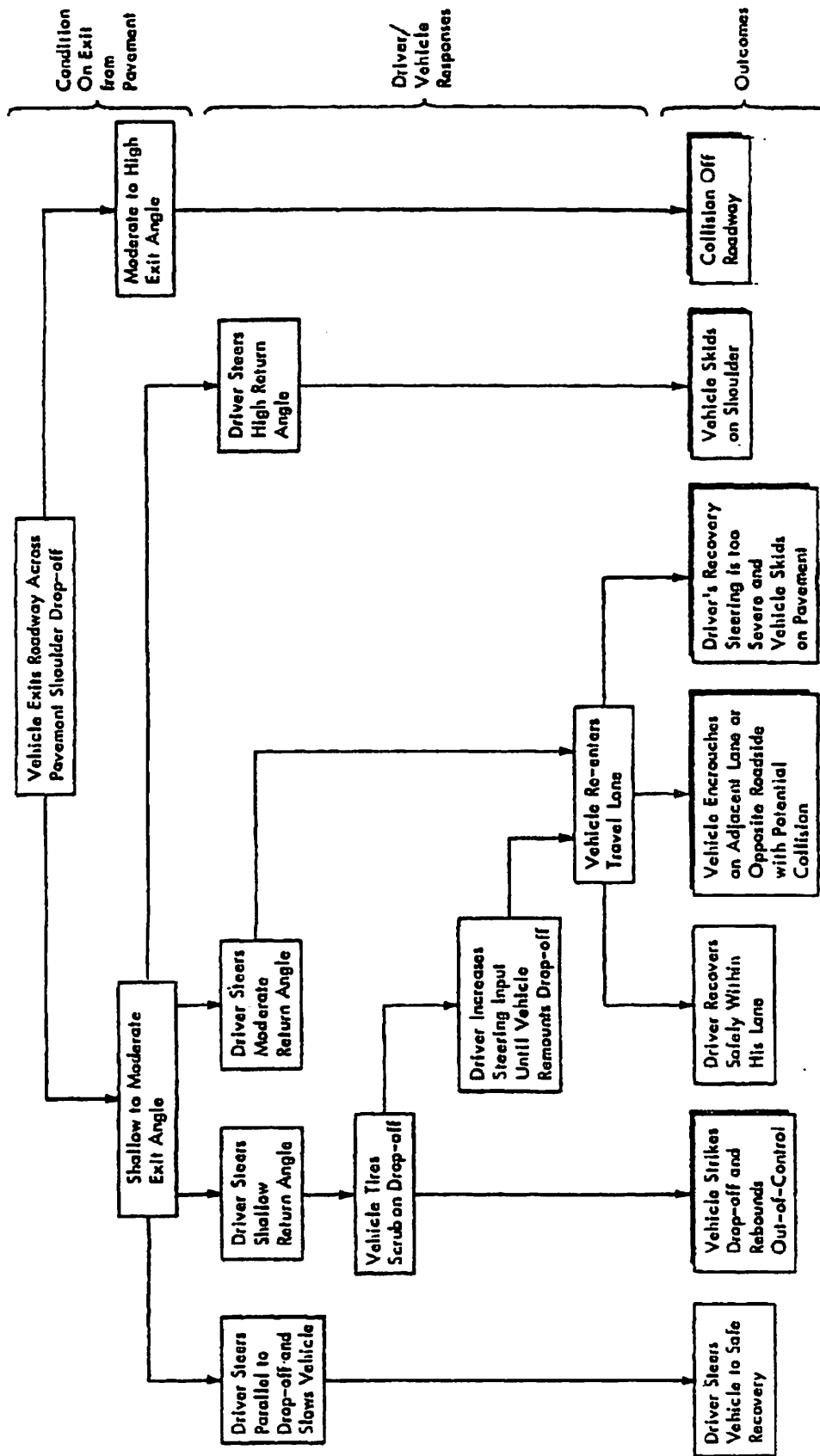


Figure 16 - Drop-Off Maneuver Outcomes

The driver involved in a pavement/shoulder drop-off ultimately must maneuver the vehicle back to the lane of travel. The difficulty of the maneuver is compounded by the adverse roll angle resulting from the different elevations of the road and shoulder. The driver is performing a cornering maneuver on a terrain analogous to an adversely superelevated curve (i.e., the adverse roll angle increases the centrifugal forces acting on the driver). Also the difficulty is compounded if the skid resistance of the pavement and shoulder differ. When this condition is met the vehicle will yaw toward the low skid resistance surface.

If the driver steers a high return angle the vehicle will skid on the shoulder resulting in loss of control (outcome 6). Of course the driver may also elect to steer parallel to the drop-off and slow the vehicle to a stop while on the shoulder (outcome 1).

If the driver steers at a shallow or moderate return angle, the vehicle will either remount the pavement edge or fail to remount and the vehicle tires will scrub along the face of the pavement/shoulder drop-off and possibly rebound out-of control (outcome 2).

A scrubbing reentry occurs when the wheel which contacts the pavement/shoulder edge does not have a sufficient velocity component perpendicular to the edge to overcome the retarding force produced by the tire/edge contact and the wheel is redirected via a steering system response into a "scrubbing" condition. The term "scrubbing" is used to describe a near-parallel orientation of the tire and pavement edge in which a relatively large contact area occurs between the tire sidewall and the pavement/shoulder edge. The wheel which has been thus redirected develops a large resistance to mounting the pavement/shoulder edge, and the driver subsequently increases the steer angle of the front wheels in a further attempt to mount the edge. The interplay of the sidewall and the pavement/shoulder edge continues until the front wheel steer angle is sufficient to overcome the retarding force of the edge and to create a sufficient side force at the unobstructed (left) front wheel to lift the obstructed (right) tire over the edge. Once the obstructed front tire has mounted the edge, the large front wheel steer angle that was necessary to achieve the mounting produces a large lateral acceleration and a large yaw velocity which act to create a rapid lateral movement into the lane of travel. The lateral movement continues until the driver reverses the steer angle and the vehicle has time to respond to the steer reversal. The vehicle responses produced by a scrubbing reentry condition constitute the primary hazard associated with a pavement/shoulder drop-off edge. The most common outcomes of vehicles remounting from a scrubbing condition are outcomes 4 and 5.

A nonscrubbing reentry occurs when the tire velocity component perpendicular to the pavement/shoulder edge is sufficient to overcome the retarding force produced by sidewall contact with the edge and, therefore, the edge is mounted. Subsequent to the mount from a nonscrubbing reentry, the driver must realign the vehicle heading parallel to the travel lane centerline. Any of outcomes 3, 4, or 5 are possible when a vehicle remounts from a nonscrubbing condition.