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16. Abstract

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.

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.

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.

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.

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.

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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 tests[15] 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.

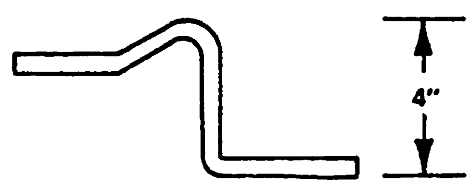
The off-road recovery test area used in the cited research is depicted in Figure 11. The right side of the vehicle was guided off the road by the use of pylons and the driver was given a 100-foot section to return to the travel way. The test section consisted of a 10-ft traveled lane, a 4-in. drop-off (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 excedence). The maneuver did not produce as demanding a task as had been anticipated.

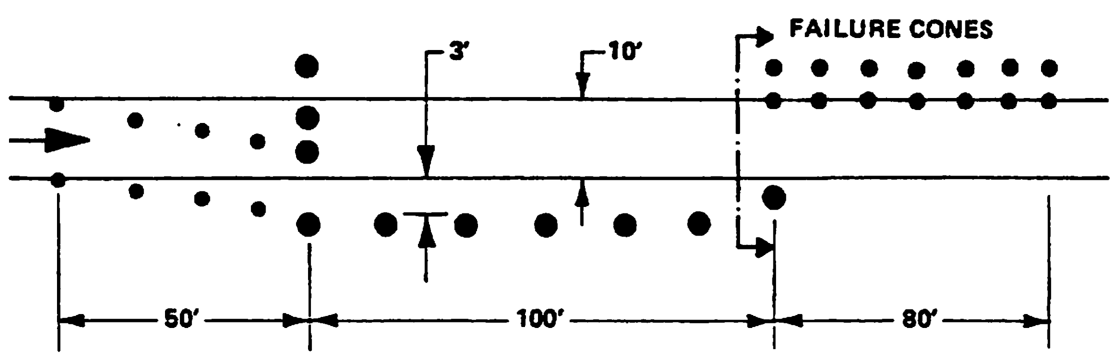
The second item of interest investigated in the Calspan study was a surprise intrusion which consisted of a barrel being thrown in the path of a vehicle. The test results give insight into the response characteristics of a driver in the extremely hazardous situation of impending collision. A summary 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

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).

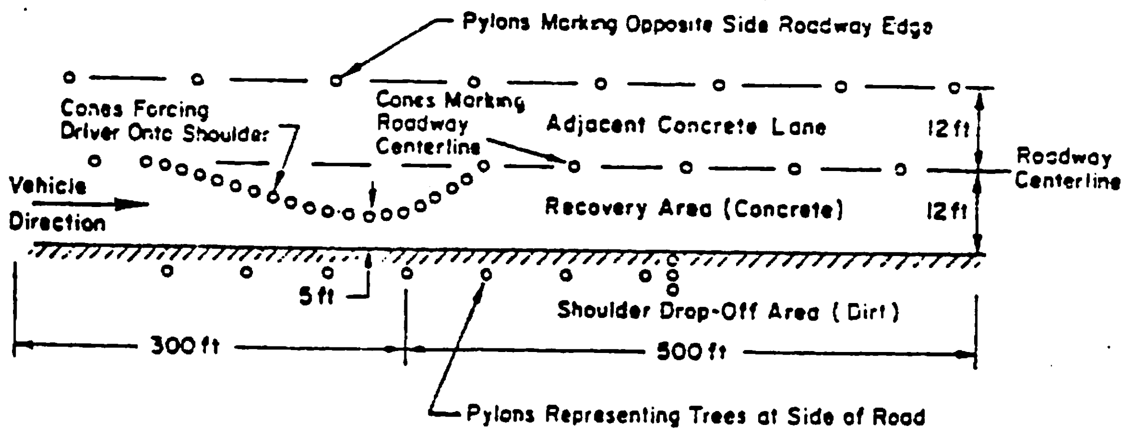


Figure 12 - Systems Technology, Inc., Closed-Loop Test Site Layout

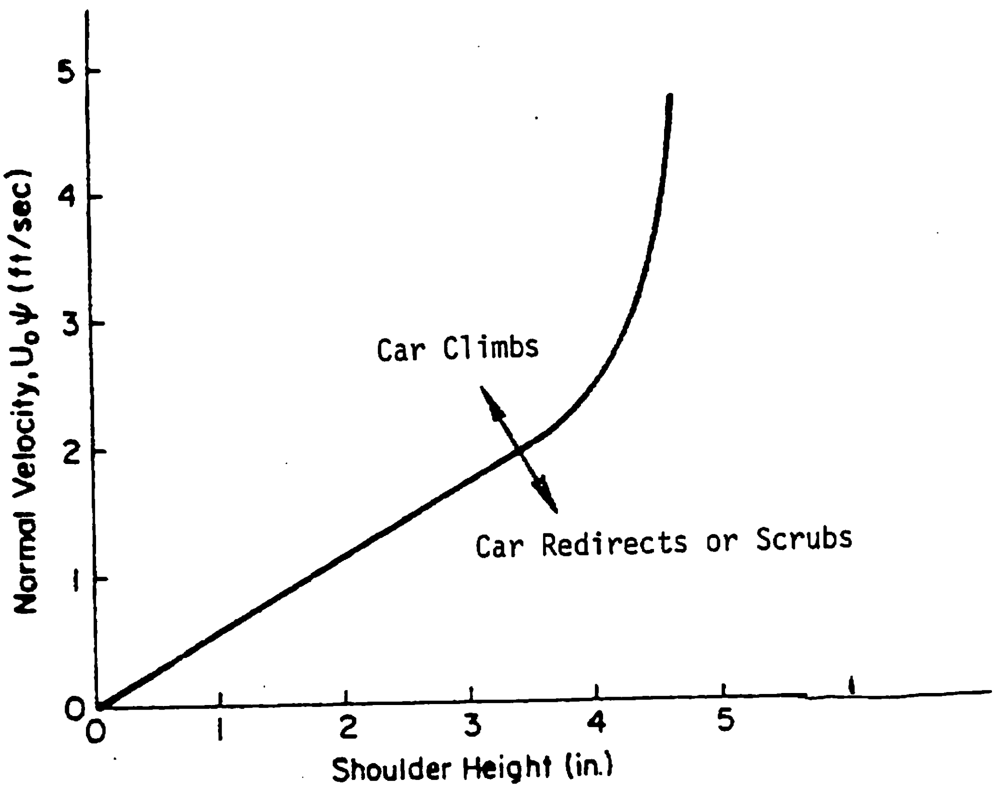


Figure 13 - Systems Technology Documentation of Shallow Angle Encounter Tests

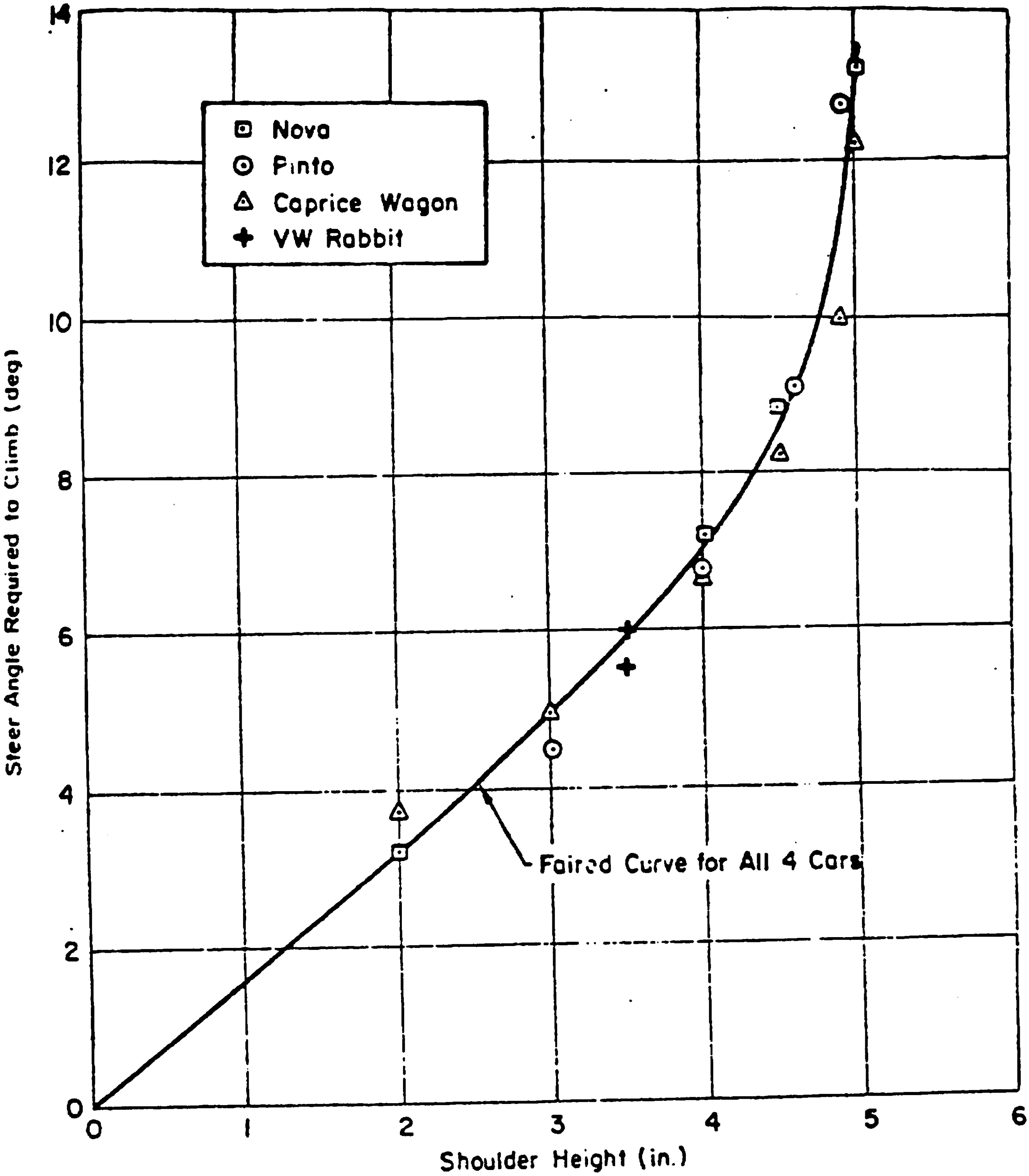


Figure 14 - Systems Technology Documentation of Steer Angle Required to Climb Various Drop-Off Heights from Scrubbing Condition

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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 study[19] 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 overlayed 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 minmal 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
2. Very mild
3. Mild
4. Definite jerk
5. Effort required
6. Extra effort
7. Tire slip (slight lateral skidding)
8. Crossed centerline and returned
9. Crossed centerline and no return
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.

3. The effect of speed was determined using only professional driver runs. Averaging across all vehicle types, a nearly linear increase in severity occured as speed increased. The 4.5 in. edge height was rated as potentially unsafe (i.e., severity ranking above level 5) even at the 35 mph speed.

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.

Figure 15 summarizes the study findings under the scrubbing condition. The severity rankings of one to three were judged as safe, three to five reasonably safe, five to seven marginally safe, seven to nine questionable safety, nine to ten unsafe. The study concluded that shape A drop-off would be safe up to and including 3 in. The shape B drop-off would be safe up to 3-3/4 in. The study authors felt that shape C would only be a problem when the vehicle suspension or other underbody elements contacted the pavement edge. The authors felt vehicle contact would not occur for drop-off heights up to 5 in. for even the smallest current automobile.

Several state highway agencies have adopted policies concerning the maximum height of pavement/shoulder drop-offs. However, these policies do not specifically address pavement/shoulder drop-offs in work zones. The Florida Department of Transportation is the only agency of which we are aware that has adopted a policy concerning traffic control devices to be used to warn drivers of pavement/shoulder drop-offs in work zones. The Florida policy calls for the use of no control, cones, vertical panels, drums, and/or Type II barricades in various situations defined by five criteria: (a) depth of drop-off below pavement elevation; (b) distance from edge of pavement to edge of drop-off, (c) length of continuous drop-off existing at one time; (d) length of time the drop-off will exist; and (e) speed and volume of traffic. For example, on high-speed, heavily-travelled highways, no control is required for drop-offs less than 2 in. in height within 10 ft of the traveled way or for drop-offs less than 6 in. height between 10 and 30 ft from the traveled way.

Also the Federal Highway Administration has promised to provide information on drop-offs in the traffic control devices handbook portion of "Work Zone Traffic Control Standards and Guidelines."

Information found in the literature is perhaps best summarized by a conclusion reached in the study, "Identification of Traffic Management Problems in Highway Work Zones."[13]

"While many incidents apparently do occur where vehicles encounter the pavement edge differential without a serious consequence, the number of accidents documented in this study, reported by field personnel, and reflected by litigation indicates a high rate of incidents with serious consequences. Many agencies have, as a result, adopted standards relating to height differentials and/or the length of time they may be tolerated. Little research is available, however, as to just what criteria should be adopted. The 1974

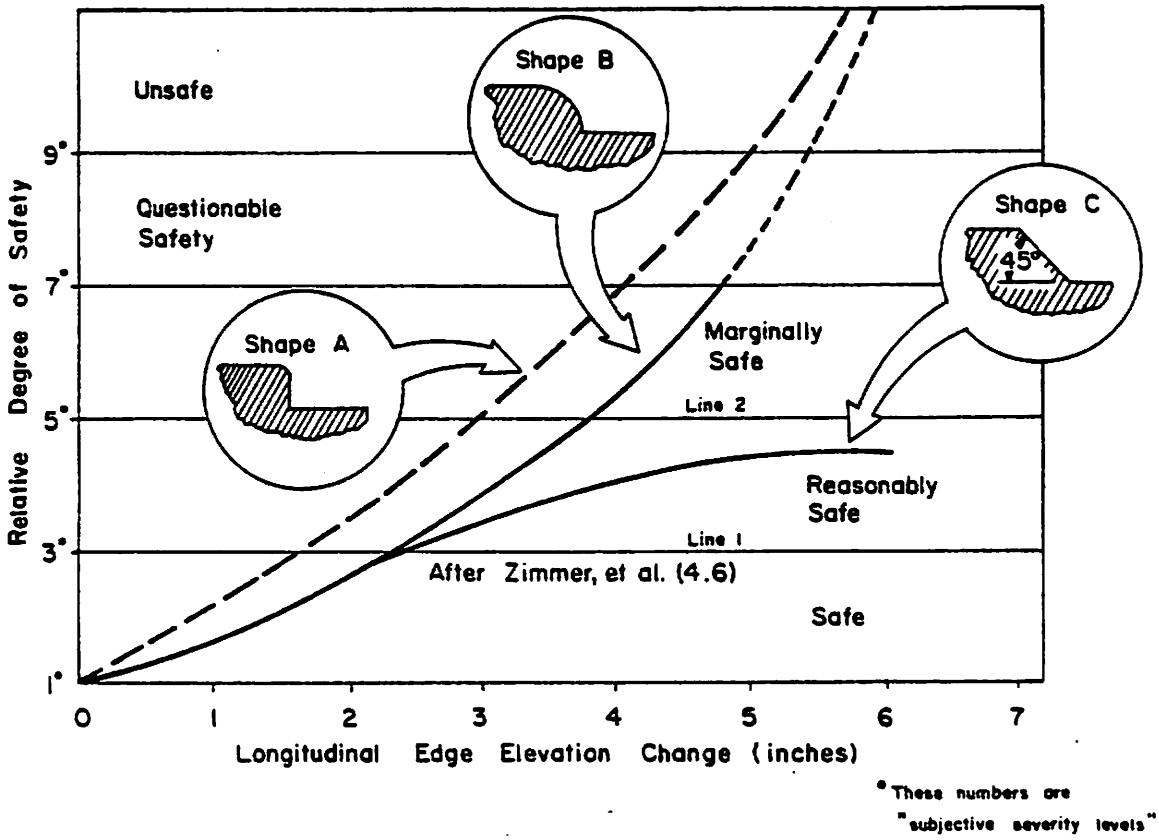


Figure 15 - Relative Degrees of Safety for Various Edge Conditions

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.

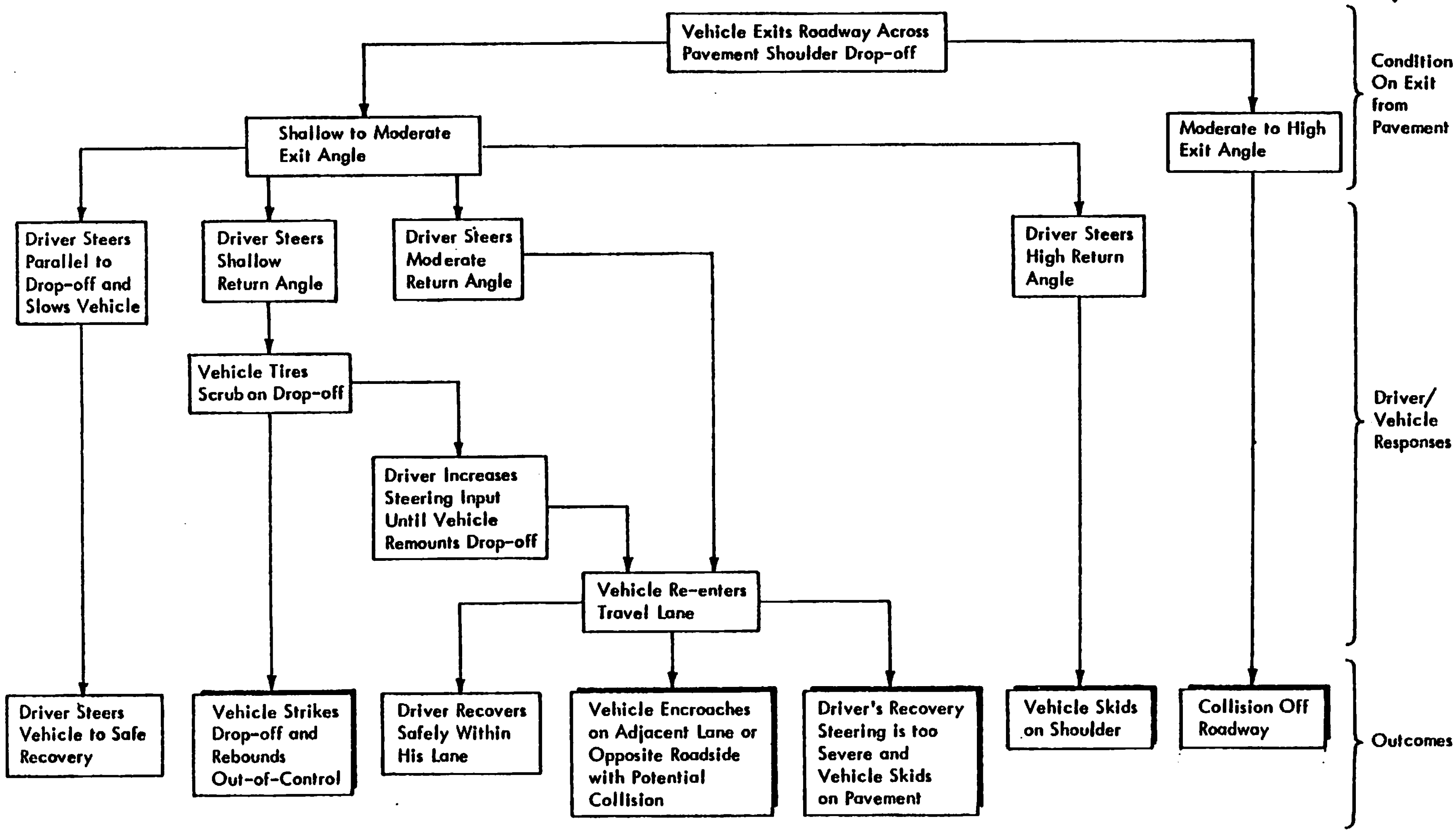


Figure 16 - Drop-Off Maneuver Outcomes

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 perpenicular 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.

As seen in Figure 16, of the seven possible outcomes from traversing a drop-off only two are desirable: outcome 1 - driver steers to safe recovery on shoulder; and outcome 3 - driver remounts the drop-off and recovers safely within his lane.

The investigation undertaken in the simulation portion of the research was aimed at determining the maximum tolerable pavement/shoulder drop-off height.

The simulation portion of this study was orginally planned to consist of a determination of vehicle responses to various drop-off heights and other characteristics by using the Roadside Design version of the Highway-Vehicle-Object-Simulation-Model (HVOSM) currently available from FHWA. However, the successful application of the HVOSM was limited to characterizing vehicle dynamics as a result of travel lane recovery from a scrubbing condition.

It was found that the best method for characterizing the results of drop-off remounting at moderate and severe recovery angles was by applying Newtonian physics with simplifying assumptions about drivers' perception-reaction times and tolerable lateral acceleration.

The next three sections discuss modeling of a scrubbing reentry maneuver, modeling of a nonscrubbing reentry maneuver, and modeling of skidding maneuvers on the shoulder. A summary of the simulation results concludes this section.

2. Modeling of the scrubbing reentry maneuver: This section reports on the modeling of the reentry maneuver from a scrubbing position. The simulation model used in this part of the study was the roadside design version of the Highway-Vehicle-Object-Simulation-Model (HVOSM). A description of this model and the modifications made to the model in this investigation are discussed in Appendix B. Two basic aspects of this maneuver are discussed:

1. HVOSM verification of the relationship between the drop-off height and the normal velocity (a function of vehicle speed and encounter angle) needed to climb the drop-off.

2. HVOSM determination of the maximum extent of lateral movement after remounting the drop-off from a scrubbing position as a function of speed and drop-off height.

a. Comparison of HVOSM responses with test results in the literature: Although the initial runs using the Variable Torque Path Follower (VTPF) driver model (described in Appendix B) were unsuccessful in terms of modeling the total pavement/shoulder drop-off maneuver, the results were usable for comparing HVOSM results with the results of the STI research[17] relating drop-off height to the normal velocity required to mount the drop-off. This phenomena, of course, is simply a function of the vehicle speed and heading angle for a given drop-off height.

Figure 17 shows a comparison of the various HVOSM runs with the resultant plot of the STI full-scale tests. Although these HVOSM runs were not performed for the express purpose of verification and/or calibration, the general agreement of the revised HVOSM with the STI results indicates an adequate sensitivity of the revised HVOSM for shallow angle encounters with various drop-off heights, particularly at heights of 4 inches or below.

b. <u>HVOSM simulation of scrubbing reentry maneuver</u>: The STI report[17] gave some indication that, because of the large steer angle required to mount a drop-off when a vehicle is in the scrubbing mode, there is a high probability of loss of control (commonly called the "slingshot" effect), particularly for higher speeds and drop-off heights. For this reason, a limited number of HVOSM scrubbing reentry runs were performed to determine the severity of the maneuver as a function of speed, drop-off height, and vehicle type.

In modeling this maneuver, there are two possible performance criteria as follows:

1. An attempt can be made to force the vehicle to recover within its own travel lane, in which case the level of lateral acceleration of the vehicle is the figure of merit; or

2. A practical limit can be placed on the maximum level of tolerance of the driver to lateral acceleration, in which case the maximum extent of lateral movement becomes the figure of merit.

For either case, the results should correctly identify a seriously hazardous maneuver, because if under the second case there is a large lateral excursion, the alternative choice of controlling the vehicle within the lane should yield a high lateral acceleration, and vice versa.

For ease in modeling, the maximum lateral excursion (distance from the drop-off edge) was chosen as the figure of merit. For this purpose the Emergency Maneuver Driver Control Model (DRIV2) (described in Appendix B) was developed and installed in the HVOSM. The HVOSM inputs used in the scrubbing reentry series were as follows:

1. <u>Vehicle</u>: The primary vehicle data set was for a 1971 Dodge Coronet 4-door sedan. For checking sensitivity to vehicle size, a 1971 Chevrolet Vega was used.

2. <u>Vehicle speed</u>: Because of budget constraints on the number of runs, only speeds of 30 and 45 mph were used. From the STI report, this range of speeds was expected to yield the critical threshold of vehicle operations under the scrubbing reentry mode.

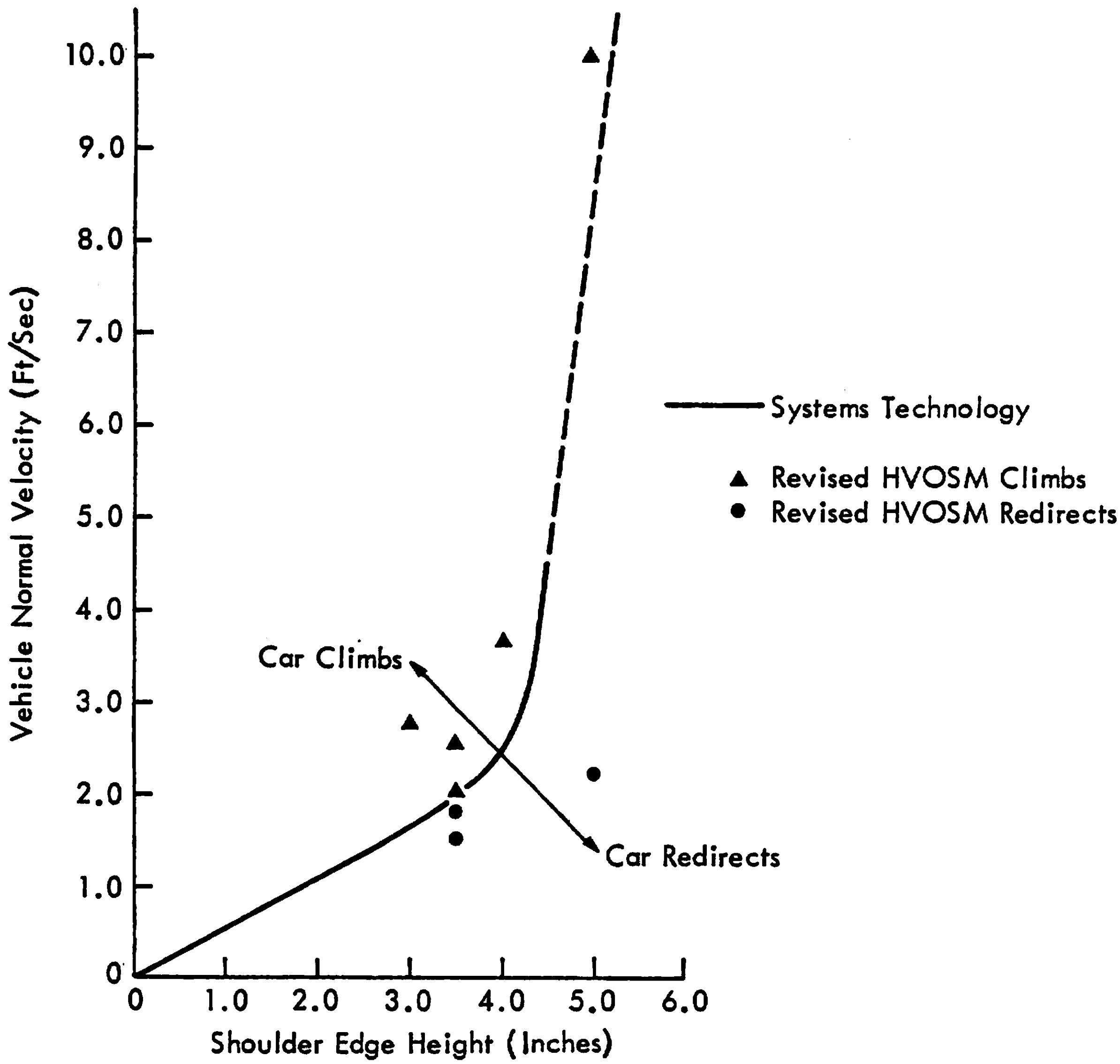


Figure 17 - The Normal Velocity Required to Mount Drop-Off-Comparison of HVOSM Results with Systems Technology Results

3. Drop-off height: Because of budget constraints on the number of runs, only heights of 2 and 3 inches were used. From the STI report this range of heights was expected to yield the critical threshold of vehicle operations under the scrubbing reentry mode.

4. Initial steer angle: The maximum initial steer angle for scrubbing is a function of the drop-off height as shown in Figure 14. These values were 3 degrees for a 2-inch drop-off and 5 degrees for a 3-inch drop-off.

5. Driver perception/reaction time: A number of experimental studies have included investigation of the perception/ reaction time for driver braking and steering responses. The results indicate a range of times from 0.3 to 2.0 sec. The average value for steering responses in the various studies is approximately 0.60 sec.

   Johansson and Rumar in their study of brake reaction times[20] found a median perception/reaction time for anticipated brake application of 0.66 sec. They further found an average increase of 35% in the mean perception/reaction time for drivers for unanticipated vs. anticipated braking.

   The Calspan Corporation, as part of their investigation into the characteristics and capabilities of automobile drivers,[16] found a mean reaction time of 0.65 sec for braking and/or steering response in their "surprise intrusion" tests (i.e., tests in which an obstacle was projected into the travel lane).

   Examination of the two STI pavement/shoulder drop-off runs included in their documentation indicate approximately 0.55 sec perception/reaction time between the right front wheel mount and the initiation of a steer response.

   In consideration of the cited results for steering response times and the objective of obtaining conservative results, a value of 0.70 sec for perception/ reaction time was used in the scrubbing reentry series.

6. Maximum lateral acceleration: The Calspan study[16] found that drivers utilized an average maximum lateral acceleration of about 0.45 g-units during evasive maneuvers. The STI study[17] reveals that the lateral acceleration increases to the range of 0.6-0.8 g-units during the recovery subsequent to the RF wheel mount in a pavement/ shoulder drop-off maneuver.

The input to the HVOSM of a maximum "comfort factor" was used as a flag to the open-loop driver control to begin deceleration of the steer velocity back to zero. In recognition of the transient nature of the vehicle responses and of the large extent of overshoot of the lateral acceleration that occurs subsequent to the steer velocity reduction, a "comfort factor" value of 0.30 g-units was used for the scrubbing reentry series.

This meant that the model driver began to reduce his steer velocity after a value of 0.3 g lateral acceleration was reached. This did not mean that the maximum value of lateral acceleration was 0.3 g.

7. Maximum front wheel steer velocity: The Calspan researchers in their study[16] found that the test subjects were able to employ steering wheel rates of greater than 500 degrees/sec. The two time-history plots included in the STI report[17] indicate average maximum steering wheel velocities of approximately 680 degrees/sec. For the scrubbing reentries series the peak steering wheel velocity was limited to 70% of the average of the two studies (i.e., approximately 400 degrees/sec).

   The corresponding input to the HVOSM is for the front wheel steer velocity rather than the steering wheel velocity. The ratio of the front wheel steer velocity to the steering wheel velocity is approximately 20:1. Therefore, a value of 20 degrees/sec was used as input to the HVOSM for the front wheel steer velocity.

8. Maximum front wheel steer acceleration: The STI results[17] indicate an average steering wheel acceleration rate of approximately 5,400 degrees/sec**2. For the scrubbing reentry series a value of approximately 70% of the maximum, rate (i.e., 3,500 degrees/sec**2) was used.

   The corresponding input for the HVOSM is for the front wheel steer acceleration rate, and therefore a value of 175 degrees/sec**2 was used (i.e., 20 of the steering wheel rate).

The HVOSM scrubbing reentry results are shown in Table 14. These results indicate that as speed and drop-off height increase both the extent of lateral excursion and the maximum lateral acceleration increase. The extent of lateral excursion varied from 12.5 ft for a 2-in. drop-off at 30 mph to more than 30 ft for a 3-in. drop-off at 45 mph. The maximum lateral acceleration was 0.3 for the 2-in. drop-off at 30 mph and 0.8 g for the 3-in. drop-off at 45 mph.

TABLE 14

RESULTS OF HVOSM SCRUBBING REENTRY TEST

	Inputs			Outputs		
Run No.	Auto Type	Vehicle Speed (mph)	Drop-off Height (in.)	Max. Excursion (ft)	Max. Heading Angle (degrees)	Max. Lateral Accel. (g's)
1	Mid-Size	45	3	> 30	25	0.80
2	Mid-Size	45	2	20	15	0.60
3	Mid-Size	30	2	12.5	11	0.30
4	Compact	45	2	23	17	0.60

Runs 2 and 4 employed the mid-size and compact cars under identical conditions of a 2-in. drop-off and speed of 45 mph. The maximum lateral excursion of the compact was 23 ft compared to 20 ft for the mid-size car. The maximum lateral acceleration was 0.6 g in both runs.

The results indicate that as drop-off height and speed increase both the extent of lateral excursion and the maximum lateral acceleration increase. Even at relatively low speeds and drop-off heights, the average driver is likely to have either a maximum excursion beyond the normal 12 ft lane or conversely a lateral acceleration that exceeds the frictional capability of almost any pavement surface.

Responses to the drop-off were nearly identical for a mid-size and compact automobile. The compact did have a slightly larger maximum excursion, probably due to its shorter wheelbase which results in a higher heading angle during the reentry maneuver.

3. Modeling of nonscrubbing reentry maneuvers: The nonscrubbing reentry in a pavement/shoulder maneuver occurs when the vehicle has a normal velocity perpendicular to the drop-off edge sufficient to overcome the retarding force of sidewall contact with the edge. The normal velocity component required to mount the drop-off can be determined from Figure 13 and used to determine the minimum reentry angle ($\sin^{-1} \frac{V_N}{V_F}$) for various forward vehicle speeds as shown in Table 15.

TABLE 15

MINIMUM REENTRY ANGLES REQUIRED FOR MOUNTING DROP-OFF

Drop-off Height (in)	Minimum Normal Speed ft/sec	Minimum Normal Speed mph	Minimum Reentry Angle (Degrees) for Various Forward Speeds (mph) 25	35	45	55
2	1.1	0.75	1.7	1.2	1.0	0.8
3	1.7	1.16	2.7	1.9	1.5	1.2
4	2.4	1.63	3.8	2.7	2.1	1.7
4.5	3.8	2.59	6.0	4.3	3.3	2.7
5	9.0	6.12	14.2	10.1	7.8	6.4

As with the scrubbing reentry maneuver, the severity of the nonscrubbing reentry maneuver was of interest. However, because of the limitation of project funds, a simpler analytical approach similar to the HVOSM modeling was performed for the nonscrubbing reentry, and the HVOSM was used to confirm these results and test the sensitivities of automobile size and soft-soil shoulder conditions. This approach assumes that after reentry the vehicle will travel a straight path determined by the reentry angle during the driver's perception reaction time and then be steered in a circular path tangent to the initial path until it reaches a path parallel to the highway, the circular path being determined by the maximum lateral driver discomfort (centrifugal acceleration in g's). With the left front corner of the vehicle 4.5 ft into the travel lane when the right-front tire contacts the drop-off, the motion is described by the following equation (see NCHRP Report 214[21] for derivation):

$$W = \frac{V^2\ (1-\cos\theta)}{15\ f} + 1.47\ Vt \sin\theta + 4.5 \qquad [1]$$

where:
W = maximum lateral excursion from the drop-off edge, feet
V = forward speed of vehicle, mph
f = maximum driver discomfort factor, g's
θ = reentry angle, degrees
t = driver perception/reaction time, sec.

To exercise this equation of motion requires two further assumptions which were previously employed in the scrubbing reentry modeling. These are:

1. A maximum level of driver discomfort of 0.30 g's; and

2. A driver perception-reaction time of 0.7 sec. Employing these two assumptions yields the following form for the equation of motion:

$$W = \frac{V^2\ (1-\cos\theta)}{4.5} + 1.029\ V \sin\theta + 4.5 \qquad [2]$$

Using this equation and the relationships between drop-off height, speed, and minimum nonscrubbing reentry angle, the maximum lateral excursions associated with minimum nonscrubbing reentry angles can be computed as shown in Table 16. A small sample of these results were confirmed by HVOSM application.

Notice that the lateral excursion is completely insensitive to speed at a given drop-off height. This occurs because of a trade-off in the equasion between reentry angle and speed. A speed increase has the tendency to increase the lateral excursion, but when speed increases the minimum angle required to remount decreases, which tends to decrease the lateral excursion.

From Table 16 it is seen that apparently safe recovery maneuvers can be accomplished for a 12-ft lane within a reasonable speed range if: (1) the vehicle reentry angle is at or slightly above that required for nonscrubbing reentry; and (2) the drop-off height is about 4.8 in. or less. Since excursions into the adjacent lane would be expected for greater drop-off heights, these heights would appear to have no safe reentry mode available.

TABLE 16

MAXIMUM LATERAL EXCURSIONS RELATED TO MINIMUM NON-SCRUBBING REENTRY ANGLES

Drop-off Height (in.)	Maximum Lateral Excursion (feet) from Edge of Drop-off Related to Minimum Reentry Angles at Various Speeds (mph) 25	35	45	55
2	5.4	5.4	5.4	5.4
3	5.8	5.8	5.8	5.8
4	6.5	6.5	6.5	6.5
4.5	7.9	7.9	7.9	7.9
5	15.1	15.1	15.1	15.1

Perhaps a more meaningful exercise is to find the minimum non-scrubbing reentry angle that produces encroachment into the adjacent lane. The difference between this angle and the minimum angle for nonscrubbing reentry would be the safe range of reentry angles. That is the range of approach angles that assumes that the vehicle will remount the drop-off and not go into the scrubbing condition, and when the vehicle does remount its heading will allow it to recover safety within the lane width. Table 17 lists these reentry angles that produce encroachment, and a comparison with Table 16 shows that the safe angle range increases with lane width and decreases with drop-off height and vehicle speed.

TABLE 17

MINIMUM NONSCRUBBING REENTRY ANGLE REQUIRED TO HAVE A LANE EXCURSION EXCEEDING THE LANE WIDTH

Lane Width (ft)	Reentry Angle for Adjacent Lane Encroachment for Various Speeds (mph) 25	35	45	55
9'	7.5	5.7	4.1	3.4
10'	8.7	6.6	4.9	3.9
11'	10	7.4	5.4	4.5
12'	11.3	8.2	6.1	5.0

Paired HVOSM sensitivity runs performed with standard and compact vehicles indicate that for a nonscrubbing reentry, compact vehicles require less shoulder area to maneuver the vehicle back towards the lane of travel and less travel lane width to return the vehicle to an orientation parallel with the roadway centerline.

HVOSM simulation runs were also performed to determine the effects of soft soil on the shoulder area. A new routine was created and implemented into the HVOSM to permit the simulation of vehicles traversing soft soil shoulders (see Appendix B for a description of the simplified model). The results of this sensitivity analysis indicate that for soil sinkages of less than 2-in., the presence of soft soil on the shoulder has no adverse effects on the reentry maneuver. However, soft soil adjacent to the pavement/shoulder drop-off may act to increase the effective drop-off height and thereby require a greater angle to permit a successful remount. Also, the presence of soft soil or mud may reduce the frictional forces which are developed between the tire sidewall and the pavement/shoulder edge and thereby prevent the reentry to the traveled way.

4. Modeling of skidding maneuvers on the shoulder: If a driver recovering from a shoulder trajectory attempts to recover too quickly, skidding on the shoulder could result. For a circular recovery path starting from an initial parallel position, the reentry angle is a function of the radius of path and the distance from the front wheels to the drop-off edge. For a 4 ft initial lateral offset the equation for the reentry angle is:

$$\theta = \cos^{-1} \frac{R-4}{R}$$

The critical θ for skidding can be determined by computing the critical R for any speed using the centripedal acceleration equation $R = V^2/15\ (e+f)$ where R = radius of curvature, e = superelevation and f = side friction factor. The superelevation term, e, is the effective negative cross slope as a function of drop-off height created with the left wheels on the pavement and the right wheels on the shoulder. For purposes of illustration the f term was assumed to be a nominal 0.55.

Table 18 shows the critical reentry angles above which skidding will occur on the shoulder under the assumed conditions. In comparing Table 18 with Table 15, it is seen that for combinations of higher drop-off heights and vehicle speeds, the critical skidding reentry angles are only slightly higher than the minimum nonscrubbing reentry angles.

TABLE 18

CRITICAL SKIDDING REENTRY ANGLES

Drop-off Height (in.)	Reentry Angle (degrees) at Which Skidding Will Occur for Various Vehicle Speeds (mph)			
	25	35	45	55
1	18.3	13.1	10.2	8.2
2	18.0	12.8	9.9	8.1
3	17.5	12.5	9.7	8.0
4	17.2	12.3	9.5	7.8
4.5	17.1	12.1	9.4	7.7
5	16.9	12.0	9.3	7.6

5. <u>Summary of modeling of pavement/shoulder drop-off maneuver</u>: Considering the modeling efforts described in the last three sections, a reasonably coherent description of the hazard associated with pavement/shoulder drop-offs can be compiled. Figures 18 through 20 show a selected group of relationships between speed and reentry angle for the various event thresholds as a function of drop-off height and lane width. Figures are shown for drop-off heights of 1, 3, and 4-1/2 in.

Each of the graphs have three curves defining the boundaries between four areas of the graph. One area in each of the graphs is labeled "window of safety." This window defines the range of speeds and reentry approach angles that will allow a vehicle to safely remount a drop-off without encroachment on adjacent lanes. The "window" becomes narrower with higher speeds, higher drop-off heights and narrower lanes. The "window" is very narrow at the 4 and 4-1/2 in. drop-off heights. The area labeled "encroachment or high potential of skidding on the pavement" shows the speeds and reentry approach angles where a vehicle would encroach on adjacent lanes or skid on the pavement attempting to stay in its lane. The severity of this encroachment would vary depending on unidirectional or two-way traffic and traffic volumes.

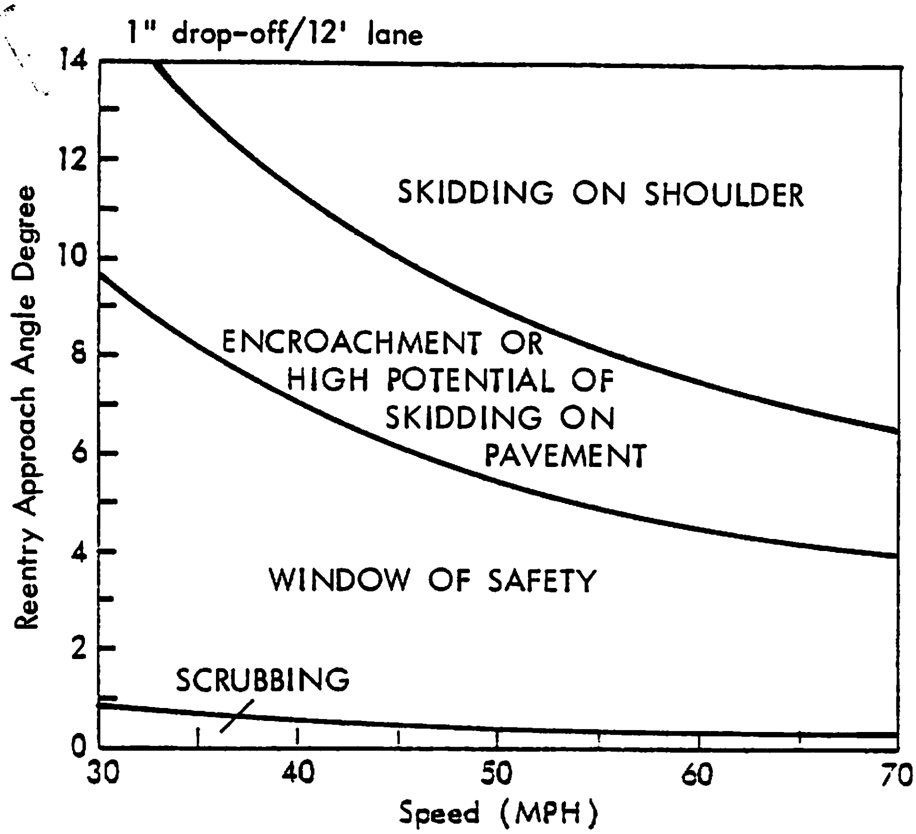
The top area of each graph is labeled "skidding on shoulder" and shows the speeds and reentry approach angles where a vehicle would skid on the shoulder before remounting the drop-off.

As seen in these figures, the range of reentry approach angles at which a safe recovery can be performed is very limited, and decreases as drop-off height and vehicle speed increase and as pavement width decreases. Figure 21 summarizes the "window of safety" for various speeds and drop-off heights for 12 ft lanes. To select a drop-off height at which the use of traffic controls is warranted to warn drivers or channelize vehicles away from the drop-off, a minimum "window of safety" or range of approach angles must be selected.

Table 19 shows the minimum drop-off height that would require traffic controls for various levels for the window of safety. Since little information is available on the reentry approach angles that are chosen by drivers during actual drop-off maneuvers, a level should be chosen to provide an acceptable level of safety based on the driver's perception and ability to control his vehicle.

In the study conducted by the California DOT[14] the approach reentry angles employed to remount were 1 to 8° and generally in the 3 to 5 degree range. If a professional driver alerted to the drop-off generally requires a 2 degree range for remounting, it would seem reasonable to allow at least a 5 degree window for unaware, untrained drivers under actual conditions.

As seen in Table 19, if a 5 degree window of safety is specified a 2 in. drop-off would be the maximum tolerable drop-off with a speed limit of 45 mph and a 12 ft travel lane adjacent to the drop-off. At speeds of 50 mph or above practically all drop-offs would require traffic control.



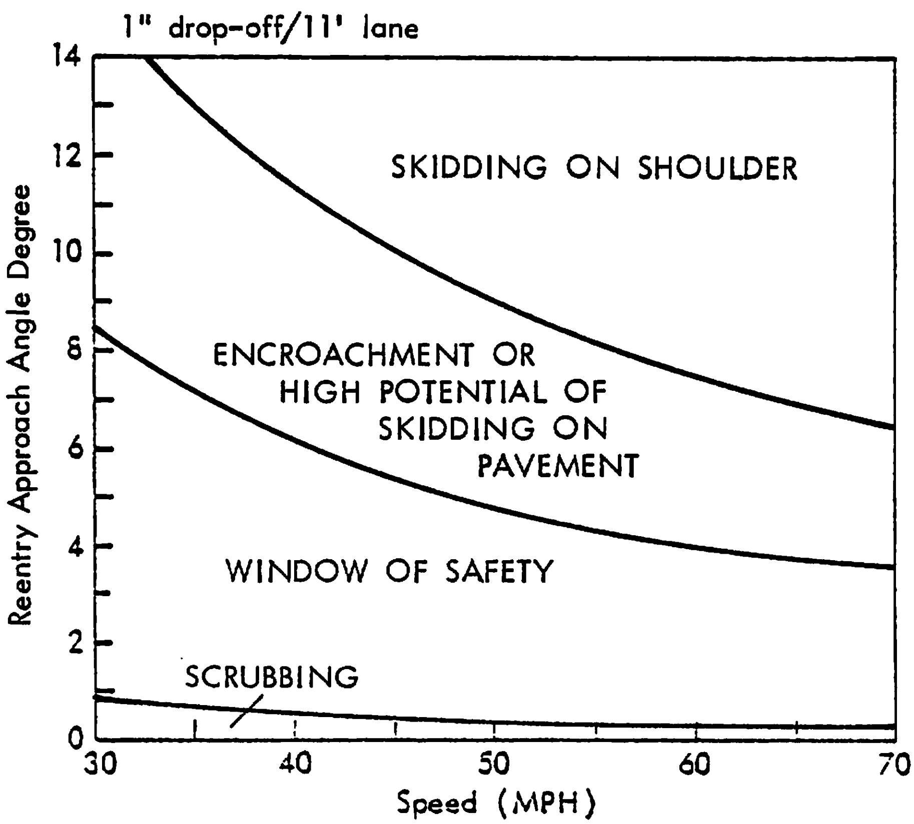
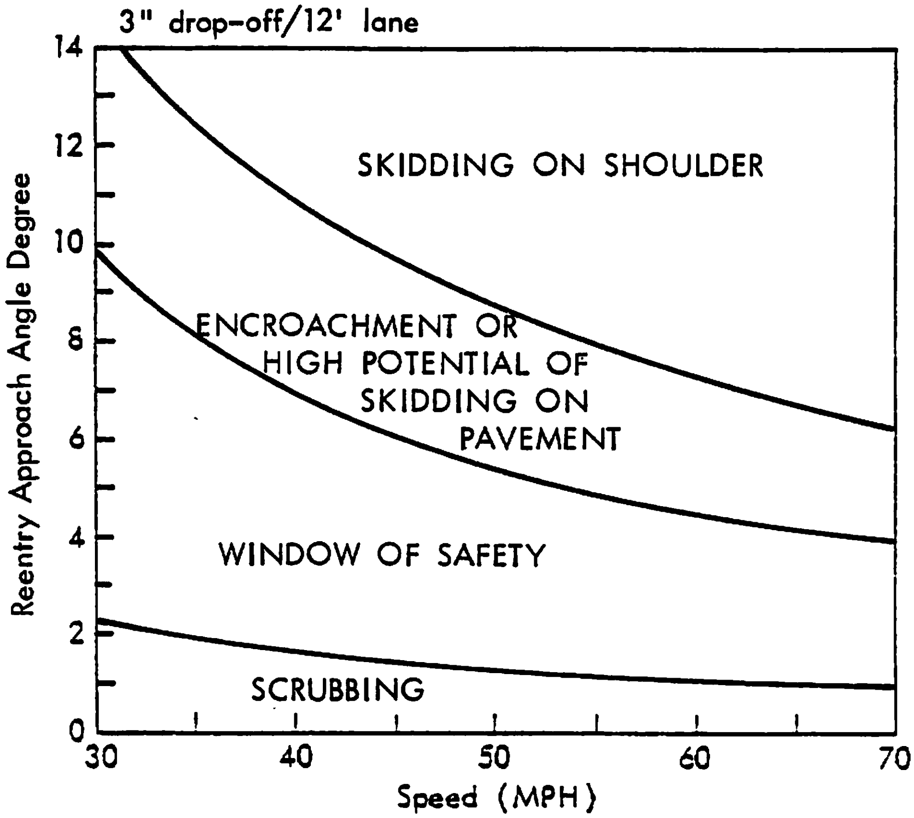


Figure 18 - One-Inch Drop-Off



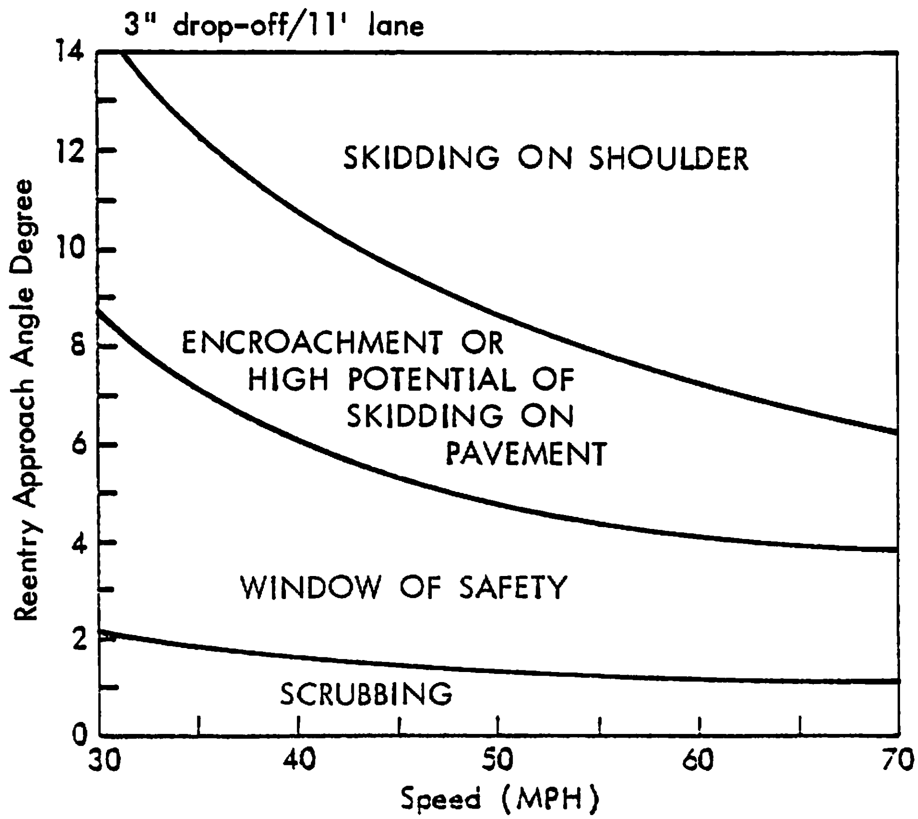


Figure 19 - Three Inch Drop-Off

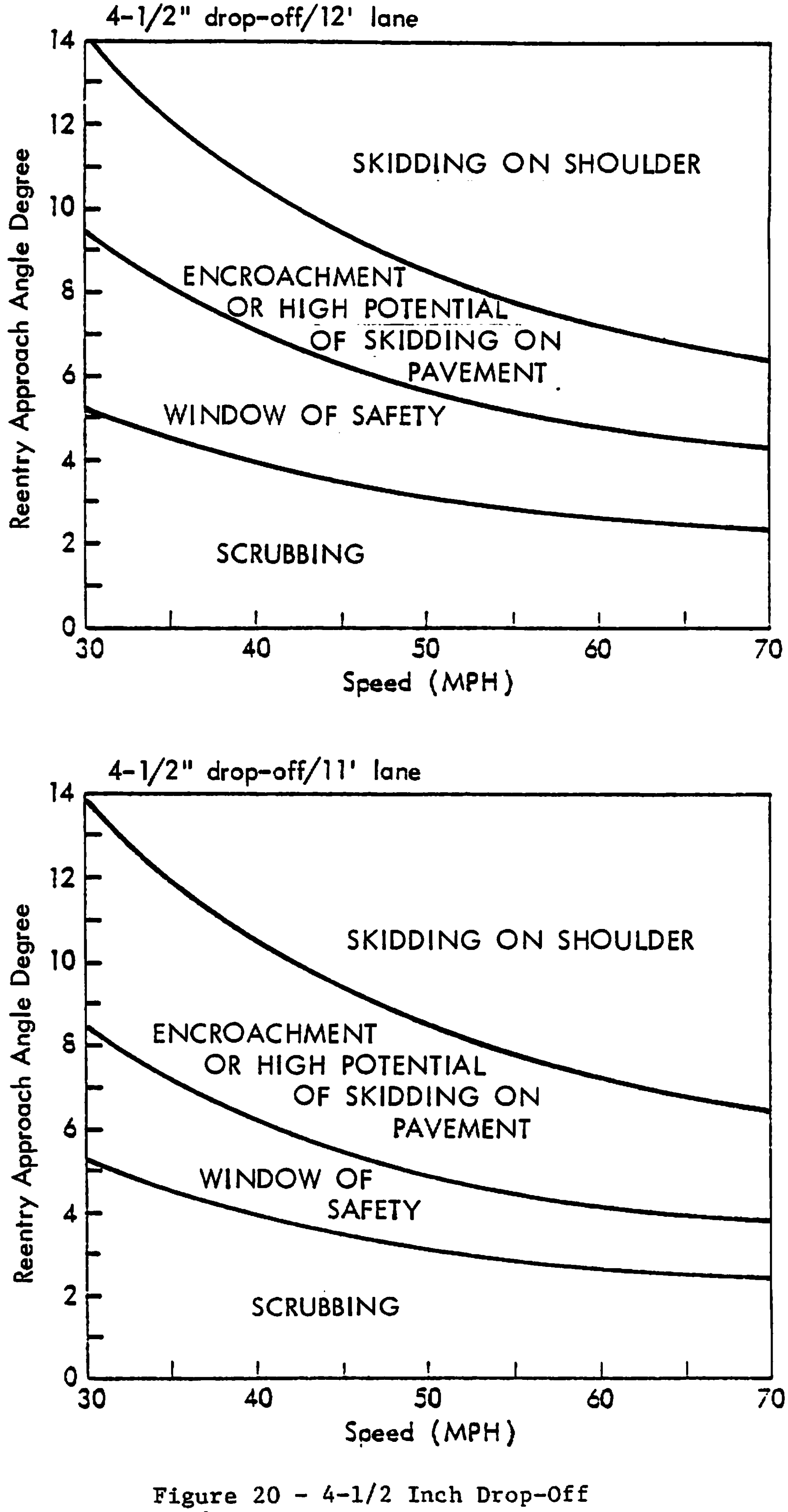


Figure 20 - 4-1/2 Inch Drop-Off

DRAFT

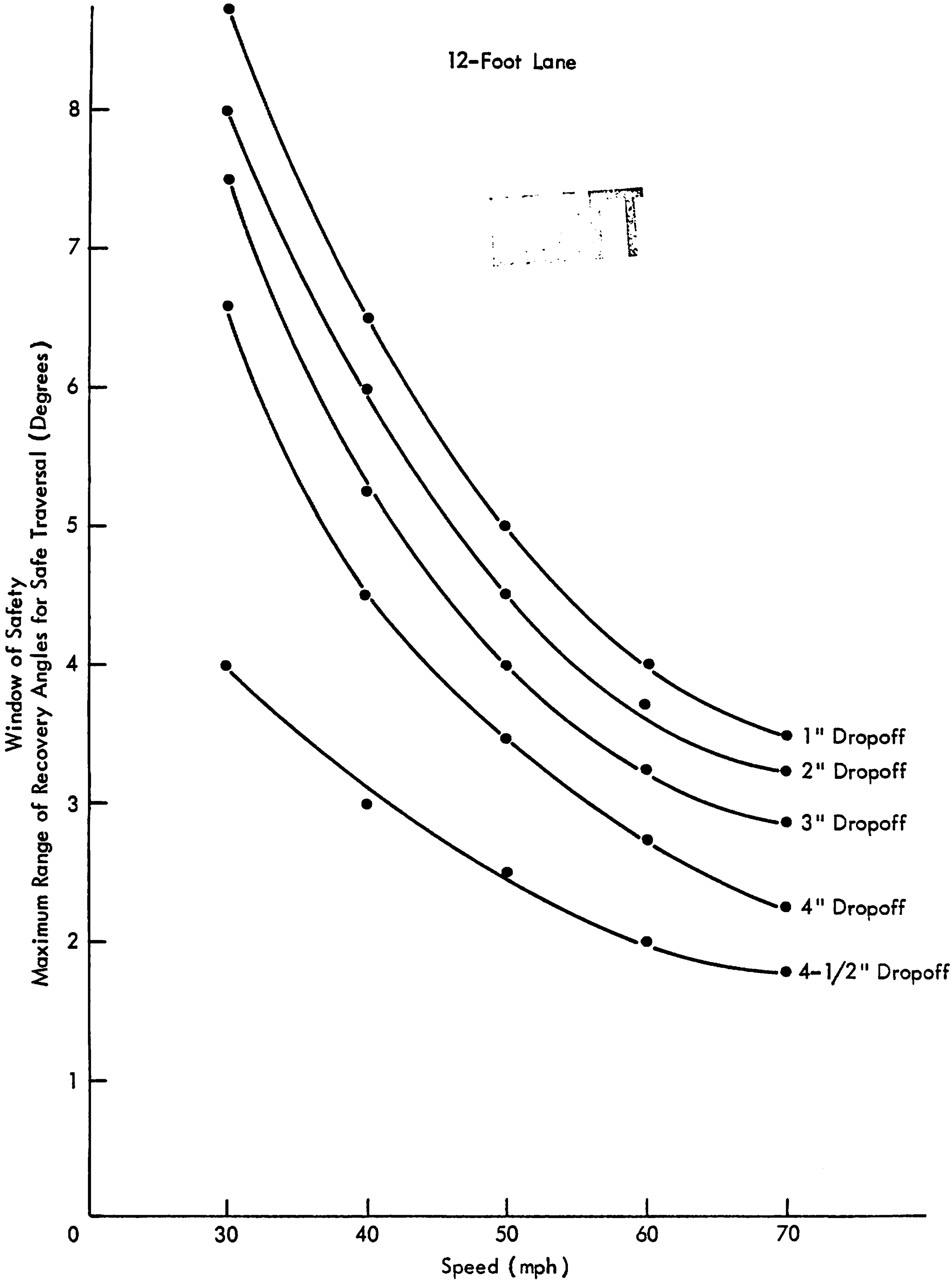


Figure 21 - Speed Vs Window of Safety - 12-Ft Lane

TABLE 19

DROP-OFF HEIGHTS WARRANTING TRAFFIC CONTROL UNDER VARIOUS WINDOW OF SAFETY CRITERIA

Speed mph	Warranting Drop-Off Height (in.) for Various Lane Widths (ft)			
	12	11	10	9
6 Degree Window of Safety				
30	4	3	2	1
35	3	2	1	1
40	2	1	1	1
≥ 45	1	1	1	1
5 Degree Window of Safety				
30	4	4	3	2
35	4	3	2	1
40	3	2	1	1
45	2	1	1	1
≥ 50	1	1	1	1
4 Degree Window of Safety				
30	4-1/2	4	4	3-1/2
35	4	4	3-1/2	2-1/2
40	4	3-1/2	3	1-1/2
45	4	3	2	1
50	3	2	1	1
55	2	1	1	1
60	1-1/2	1	1	1
65	1-1/2	1	1	1
70	1	1	1	1

Several problems with the modeling effort that should be considered in reviewing the simulation results are presented below.

An integral part of any simulation analysis is the availability of full-scale test run data to allow for the calibration of the simulation model. The initial plan for this research assumed that this kind of data existed particularly as back-up to References 14 and 17. However, on initiation of the research it was found that some of this data was not available and some required costs for retrival were beyond the budget constraints of the research contract. This lack of data required the development of certain hypotheses concerning the total trajectory of a roadside encroachment and assumptions about driver steering responses.

Of course the most important data, not contained in any reference, is the real response of drivers when they traverse a pavement/shoulder drop-off. It is quite clear from the literature that it is possible for even nonprofessional drivers to remount drop-offs as high as 4 in. in test track runs. It is not known how drivers react to drop-offs in actual work zone situations.

The modeling that was done also required modifications to the HVOSM program such as the tire-sidewall contact modification (described in Appendix B). Also, two different driver models were used in the modeling, the second being used to determine the excursions from a scrubbing condition. In all of these modifications, values were assumed for parameters such as steering wheel maximum velocity and lateral stiffness of tires. These values were assumed based, where possible, on values reported in the literature and the desire to use conservative values. For example, the peak steering wheel velocity was limited to 70% of the average of two former studies.

The scrubbing modeling effort revealed that excursion beyond a 12 ft lane would occur even with a 2 in. drop-off and a vehicle speed of 30 mph. Thus, the "window of safety" criteria were developed to minimize the possibility of a vehicle ever being in a scrubbing condition.

C. Delineation Field Tests

The objectives of the investigation of pavement/shoulder drop-offs were to determine the maximum tolerable pavement/shoulder drop-off and to develop guidelines for delineating drop-offs of an acceptable height and protecting motorists from drop-offs which are not acceptable.

In order to determine the effectiveness of various delineation devices, field tests were conducted at four sites with pavement/shoulder drop-offs. The devices tested included Type II barricades, barrels, cones, and object markers. Three of the sites were located on rural two-lane highways and one was located on an urban freeway. Other drop-off study site characteristics are shown in Table 20.

The primary measures of effectiveness of the various delineation devices were vehicle speed and lateral placement relative to the drop-off.

TABLE 20

DROP-OFF STUDY SITE CHARACTERISTICS

Site No.	Highway Type	Drop-Off Height	Length (Mi)	Duration (Days)	ADT	Delineation Devices Tested
1	U.S. Highway	5	5.4	88	2,000	Type II Barricades, Cones
2	U.S. Highway	4	17.6	89	803 (80) 836 (82)	Type II Barricades, Cones, Object Markers
3	U.S. Highway	3-4	7.05	205	727	Barrels
4	Interstate	6-9	3.2	180	58,588 (82)	Barrels

A typical data collection set-up for study of drop-offs on two-lane highways is shown in Figure 22. The speeds and lateral placements of vehicles on the approach to the work zone were measured at location 1. These measurements were obtained by using a Z-trap consisting of three piezoelectric sensor taped to the roadway. Times of axle passage over the sensors were recorded with the traffic data recorder system (TDR) described in Appendix A. The data collection and reduction procedures were identical to those described in Section II.C for truck studies. Data were collected between August 1 and September 30, 1982.

The data analysis is described in two parts. First the three sites on two-lane rural highways are discussed and secondly analysis of the site on an urban freeway is presented.

1. <u>Drop-offs on rural two-lane highways</u>: Table 21 shows mean and 85th percentile speeds for the three drop-off sites on rural two-lane highways. Table 22 contains the mean and 85th percentile lateral placements for the same sites. Each table also shows the differences in speeds or lateral placement from the approach of a work zone to the drop-off. In some cases only one approach location is compared to two or more drop-off locations. In these cases the approach values are shown more than once even though there was only one set of approach observations.

Table 21 shows that for two of the three sites there was not a consistent speed reduction from the approach to the work area. Differences in means were tested via a t-test and differences in 85th percentiles were tested via a Z-test as described in Section II.C.

For sites 1 and 2, of six significant mean speed differences, four were speed reductions and two differences showed speed increases. Most of the mean speed differences ranged from -3.5 mph (an increase in mean speed from the approach to the drop-off) to 3.3 mph.

Site 3, in contrast to sites 1 and 2, showed consistent speed reductions of about 5 mph for passenger cars and about 12 mph for trucks. A review of the signs for this site showed that "rough road" warning signs were installed at this site which may account for some or all of the speed reduction. Eighty-fifth percentile speeds followed the same trends as mean speeds for all three sites. In some cases, small sample sizes or unreliable data did not permit a meaningful determination of mean or 85th percentile speeds.

Table 22 shows that differences in mean lateral placement at sites 1 and 2 were often not significantly different from the approach to the drop-off. At site 3 the mean lateral placement did change from the approach to the drop-off varying from 0.8 to 1.8 ft. Trucks often had lower values of lateral placment than passenger cars which means that they were closer to the drop-off edge. However, their response to the drop-off did not vary from that of passenger cars.

Within each of two drop-off sites, No. 1 and 2, the mean lateral placements measured at the work areas were compared to test whether drivers react differently to different treatments.

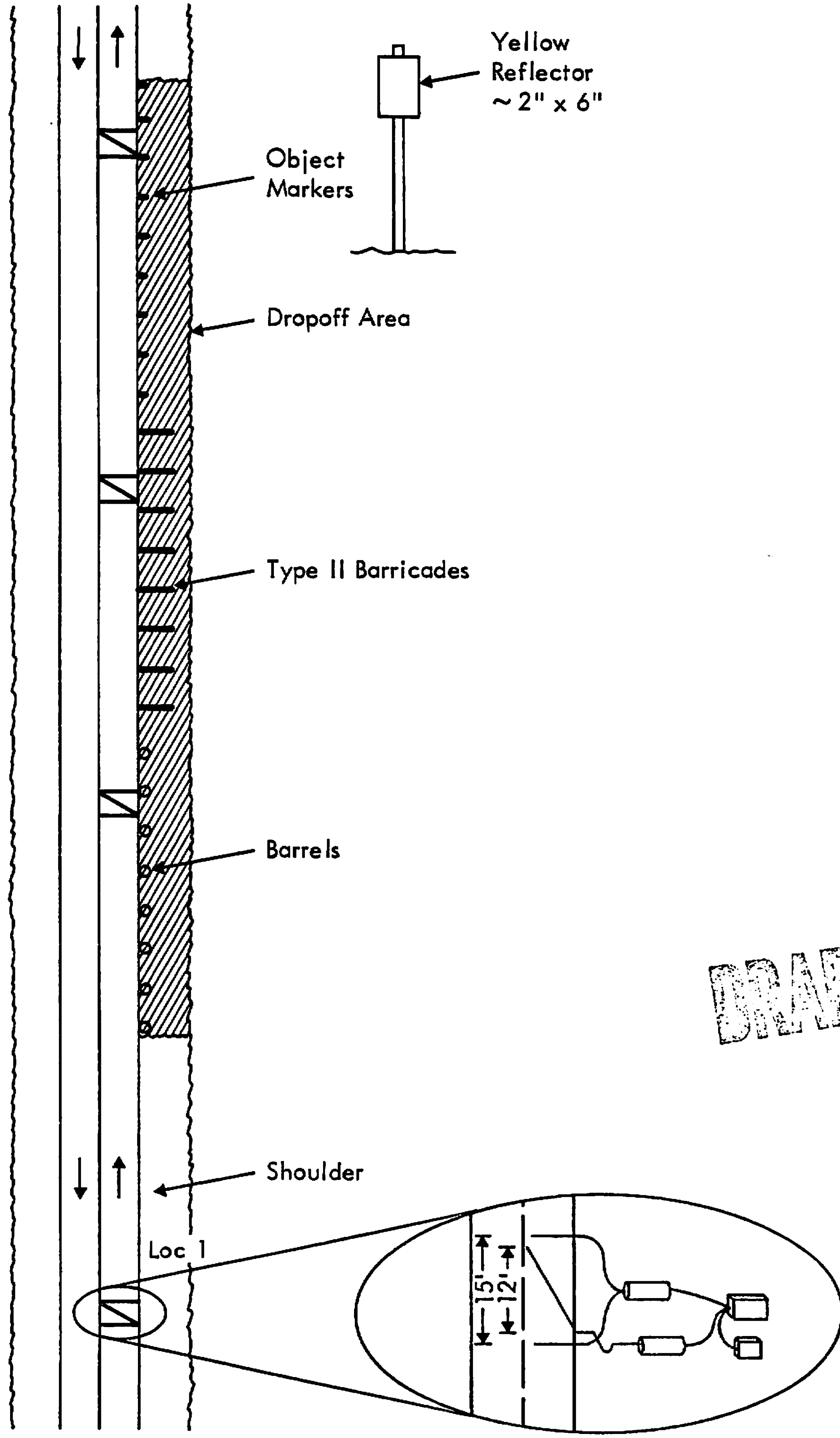


Figure 22 - Typical Drop-Off Data Collection Setup on Two-Lane Rural Highways

TABLE 21

DROP-OFF SITES ON TWO-WAY RURAL HIGHWAYS

			Mean Speeds (MPH)						85th Percentile (MPH)					
			Approach		Drop-off		Differences		Approach		Drop-Off		Differences	
Site No.	Treatment	Light Condition	Cars	Trucks	Cars	Trucks	Cars	Trucks	Cars	Trucks	Cars	Trucks	Cars	Trucks
1	None	Day	55.2	49.7	53.3	50.8	1.9[a]	-1.1	59.8	59.3	61.1	57.6	-1.3	1.7
	Barricades	Day	55.2	49.7	52.7	48.0	2.5[a]	1.7	59.8	59.3	59.0	57.8	0.8	1.5
		Night	51.8	51.0	55.3	58.5	-3.5[a]	-7.5[a]	57.9	57.3	62.6	67.8	-4.7[a]	-10.5[a]
	Cones	Day	55.4	51.7	52.2	50.3	3.2[a]	1.4	61.8	58.9	58.6	58.8	3.2[a]	0.1
2	Object Markers	Day	56.8	56.9	53.8	52.4	3.0	4.5[a]	64.6	66.8	62.3	57.9	2.3	8.9[a]
		Night	55.7	56.5	55.2	58.1	0.5	-1.5	64.6	66.7	63.9	b	0.7	NA
	Barricades	Day	56.8	56.9	54.2	53.5	2.6	3.3	64.6	66.8	63.3	63.5	1.3	3.3
		Night	55.7	56.5	55.9	59.0	-0.2	-2.5	64.6	66.7	62.3	b	2.3	NA
	Cones	Day	56.8	56.9	54.5	56.4	2.3	0.5	64.6	66.7	b	b	NA	NA
3	Barrels	Day	50.6	49.5	45.2	37.3	5.4[a]	12.2[a]	59.3	54.7	53.4	43.6	5.9[a]	11.1[a]
		Night	50.2	45.6	45.2	33.7	5.0[a]	11.9[a]	57.6	66.8	52.4	b	5.2[a]	NA

[a] Significant $\alpha = 0.05$.

[b] Sample size too small for reliable computation.

NA = not applicable.

TABLE 22

DROP-OFF SITES ON TWO-LANE, TWO-WAY RURAL HIGHWAYS

Site No.	Treatment	Light Condition	Mean Lateral Placement (ft) Drop-off Cars	Drop-off Trucks	Aproach Cars	Aproach Trucks	Differences Cars	Differences Trucks	85th Percentile Lateral Placement (ft) Drop-off Cars	Drop-off Trucks	Approach Cars	Approach Trucks	Differences Cars	Differences Trucks
1	None	Day	3.2	2.7	3.2	2.5	0.0	0.2	4.1	3.2	4.0	3.2	0.1	0.0
	Barricades	Day	3.1	3.0	3.2	2.5	-0.1	0.5[a]	3.6	4.0	4.0	3.2	-0.4	0.8[a]
		Night	3.3	3.2	3.6	2.7	-0.3[a]	0.5[a]	4.2	4.6	4.5	3.8	-0.3	0.8[a]
	Cones	Day	3.6	2.8	3.2	2.5	0.4[a]	0.3	4.4	3.8	3.8	3.3	0.6[a]	0.5[a]
2	Object Markers	Day	3.8	3.7	4.4	4.8	-0.6[a]	-1.1[a]	4.5	4.8	5.3	6.5	-0.8	-1.7
		Night	4.0	4.9	5.3	5.9	-1.3[a]	-1.0	4.9	b	6.2	6.9	-1.3	NA
	Barricades	Day	4.5	4.3	4.4	4.8	0.1	-0.5[a]	5.2	5.1	5.3	6.5	-0.1	-1.4
		Night	5.2	5.2	5.3	5.9	-0.1	-0.7	5.9	b	6.2	6.9	-0.3	NA
	Cones	Day	c	c	4.4	4.8	NA	NA	b	b	5.3	6.5	NA	NA
3	Barrels	Day	4.0	3.6	2.2	2.2	1.8[a]	1.4[a]	5.2	4.7	3.1	3.2	2.1[a]	1.5[a]
		Night	3.8	3.9	3.0	2.3	0.8[a]	1.6[a]	4.7	b	4.0	4.3	0.7[a]	NA

[a] Significant at $\alpha = 0.05$.

[b] Sample size too small for reliable computation.

[c] Data judged unreliable.

NA = Not applicable.

At drop-off site No. 1, only day data were available for comparing the three treatments: barricades, cones, and no treatment, for both cars and trucks. A linear model was fitted to the data, the mean lateral placement for each vehicle type and treatment, and the error mean squares were computed to perform an F-test on the differences. The statistics are summarized in Table 23. Out of the six comparisions, only two were significant at the 95% level; passenger car drivers drive further away from cones than from barricades or from the drop-off edge when no devices are present. In the remaining four cases, no difference in drivers behavior as measured by the lateral placement was detected at the 95% confidence level. In otherwards, cars were not placed differently for no device treatment or barricades and trucks did not react differently to any treatment.

TABLE 23

TREATMENT COMPARISONS AT DROP-OFF SITE NO. 1
(No Treatment, Barricades, Cones for
Lateral Placement, Day Time Only
in Work Area)

Treatment	Cars	Trucks
None	(112) 3.178 ft	(54) 2.681
Barricades	(158) 3.075 ft	(37) 2.977
Cones	(156) 3.645 ft	(54) 2.753
None - Barricades	0.103 (F = 0.78)	-0.296 (F = 2.15)
None - Cones	-0.467[a] (F = 15.87)	-0.071 (F = 0.15)
Barricades - Cones	-0.570[a] (F = 28.46)	0.224 (F = 1.23)

---

[a] Significant at the 95% confidence level; the critical F is $F_{1,565} = 3.86$ at the 95% level. The error mean square is $S^2 = 0.896$.

At drop-off site No. 2, two treatments--object markers and barricades--were tested on both vehicle types, during night and day time. The test procedure is identical to the one above. The test procedure is identical to the one above. The results of the analysis are presented in Table 24. All but one difference in lateral placement were significant at the 95% level, with cars, during the night, showing the largest difference. In each case where there was a significant difference, vehicles drove farther away from the barricades than from object markers.

2. Drop-off at an urban freeway site: Table 25 shows the mean and 85th percentile speeds at drop-off study site 4 on a urban freeway. Table 26 shows the mean and 85th percentile lateral placements at the same site. Site 4 was instrumented in a different manner than the other drop-off sites. The data collection sensor layout for site 4 is shown in Figure 23.

TABLE 24

TREATMENT COMPARISONS AT DROP-OFF SITE NO. 2
(Object Markers vs. Barricades for Lateral Placement)

Treatment	Day/Cars	Night/Cars	Day/Trucks	Night/Trucks
Object Markers	(32) 3.813	(27) 3.984	(20) 3.748	(8) 4.941
Barricades	(29) 4.517	(17) 5.208	(29) 4.337	(6) 5.162
Difference (Barr-Object)	0.704	1.224	0.589	0.221
F-Statistic	7.555[a]	15.660[a]	4.115[a]	0.168

[a] Significant at the 95% confidence level; the critical F value is $F_{1,160} = 3.91$ at the 95% confidence level; the error mean square is $S^2 = 0.998$.

TABLE 25

URBAN FREEWAY DROP-OFF SITE

Site No.	Treatment	Light Condition	Mean Speeds: Approach Cars	Mean Speeds: Approach Trucks	Mean Speeds: Work Area Cars	Mean Speeds: Work Area Trucks	Mean Speeds: Differences Cars	Mean Speeds: Differences Trucks	85th Percentile Speeds: Approach Cars	85th Percentile Speeds: Approach Trucks	85th Percentile Speeds: Work Area Cars	85th Percentile Speeds: Work Area Trucks	85th Percentile Speeds: Differences Cars	85th Percentile Speeds: Differences Trucks
4	Barrels Up	Day	51.0	48.7	49.9	47.6	1.1[a]	1.1[a]	56.0	54.1	55.0	52.9	1.0[a]	1.3[a]
	Barrels Down	Day	49.0	47.0	48.4	47.5	0.6[a]	-0.5	54.0	51.6	53.5	51.0	0.5	0.6
	Barrels Up	Night	52.3	51.6	50.7	50.4	1.6[a]	1.2	57.5	57.0	56.6	55.9	0.9	1.1
	Barrels Down	Night	51.5	50.7	50.4	49.1	1.1[a]	1.6[a]	57.0	55.3	56.3	56.0	0.7	-0.8

[a] Significant at $\alpha = 0.05$.

TABLE 26

URBAN FREEWAY DROP-OFF SITE

			Mean Lateral Placement (ft)						85th Percentile Lateral Placement (ft)					
Site		Light	Work Area		Approach		Differences		Work Area		Approach		Differences	
No.	Treatment	Condition	Cars	Trucks	Cars	Trucks	Cars	Trucks	Cars	Trucks	Cars	Trucks	Cars	Trucks
4	Barrels Up	Day	9.8	8.9	5.7	4.8	4.1[a]	4.1[a]	10.9	10.1	6.5	6.0	4.4[a]	4.1[a]
	Barrels Down	Day	8.9	8.0	5.3	4.6	3.6[a]	3.4[a]	10.1	9.3	6.2	5.7	3.9[a]	3.6[a]
	Barrels Up	Night	10.1	9.9	6.1	5.3	4.0[a]	4.6[a]	11.3	11.1	6.9	6.8	4.4[a]	4.3[a]
	Barrels Down	Night	9.7	9.0	5.9	4.9	3.8[a]	4.1[a]	11.0	10.4	6.9	6.4	4.2[a]	4.0[a]

[a] Significant at $\alpha = 0.05$.

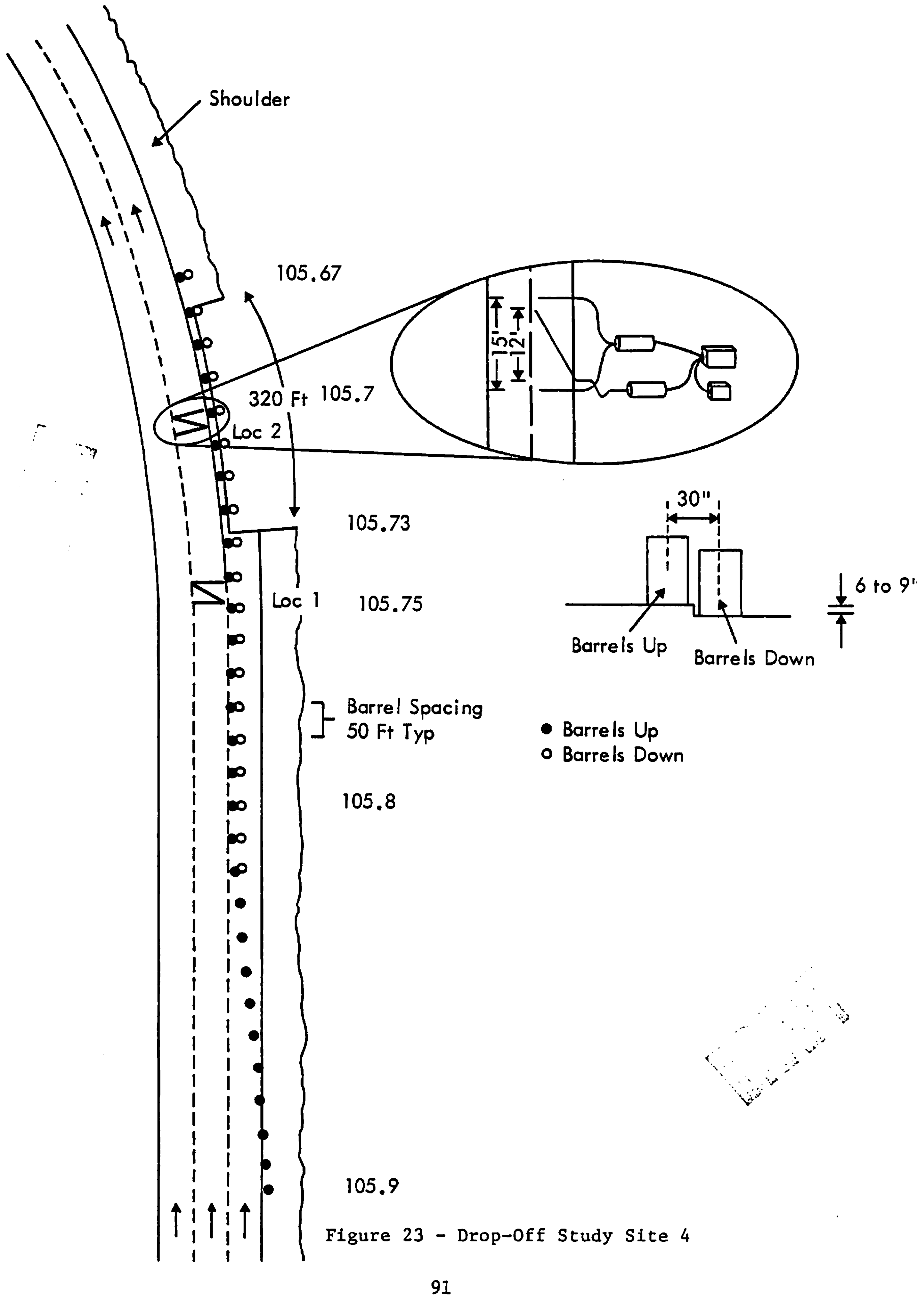


Figure 23 - Drop-Off Study Site 4

As shown in Figure 23 the approach measurement location was very near to the start of the drop-off rather then on the approach to the zone as was typical in other studies. As shown in Figure 23 barrels were the only delineation treatment used at site 4. The placement of the barrels was varied from up on the pavement to down in the drop-off immediately adjacent to the pavement edge. The location of the barrels approaching the drop-off area was also altered to make a straight line of devices in both the placement conditions of barrels up on the shoulder and barrels down in the drop-off.

The mean speed differences from the approach location to the drop-off were very small, usually between 1 and 2 mph. Even though many of these differences were statistically significantly different because of the large sample sizes, they were not of practical importance. It was also evident that the traffic volumes were affecting speeds more than the delineation treatments because speeds under both treatments increased slightly at night when traffic volumes were lower.

Eightly-fifth percentile speed differences were even smaller than changes in mean speeds.

Lateral placement changes were much more significant as shown in Table 26. Mean lateral placements were about 4 ft on the average from location 1 to location 2 with vehicles being further from the shoulder at location 2. Much of this difference, however, is due to a difference in placement of the two Z sensor layouts. The typical Z sensor layout was deployed so that lateral placements were measured relative to the pavement edge line. At site 4 the drop-off sensor configuration was deployed to measure lateral placements relative to the pavement/shoulder drop-off. This was done to allow measurement of lateral placements of vehicles traveling to the right of the pavement edge line. If these differences are accounted for, the difference in lateral placements can be largely explained by the difference in reference points. This does not hamper the comparison of the different treatments (barrels up on pavement, barrels down in drop-off) since the layouts remained unchanged during all study periods.

To better examine the effects of the treatments an analysis of variance was completed for this site utilizing the following factors:

1. Location (approach and drop-off),

2. Vehicle type (passenger car and trucks),

3. Time-of-day (day and night), and

4. Delineation treatment (barrels up on pavement or down in drop-off).

Since the location effect was discounted due to the reference point differences, the effects of interest are interactions with location. That is, how the changes in lateral placement relate to the other factors. The two way interactions of each of the other factors with location are shown in Table 27.

TABLE 27

DROP-OFF STUDY SITE 4
LOCATION INTERACTION EFFECTS

Interaction	Interaction Effect	Standard Error	Significant[a]
Treatment x Location	-0.496	±0.0949	Yes
Vehicle Type x Location	+0.167	±0.0949	No
Time-of-Day x Location	+0.295	±0.0949	Yes

[a] At $\alpha = 0.05$.

The interaction effects are the differences in the difference of group means from the approach to the drop-off. The interpretation of these interaction effects is that barrels up resulted in lateral placements about 1/2 ft farther from the drop-off than the barrels down treatment. Night resulted in about 0.3 ft larger change than day, and trucks showed about 0.16 ft larger change than cars, though this difference was not significant at the $\alpha = 0.05$ level.

There was also a significant vehicle x time-of-day by location interaction, where cars and trucks showed about the same change in lateral placement during the day, but trucks showed a slightly larger change at night.

The variances at both locations for both speed and lateral placement data were compared as part of the t-test procedure. For the eight time-of-day-vehicle groups of speed data, the variances at the two locations were significantly different for five groups, three of the groups that had significant differences had larger variances at the drop-off location. The lateral placement variances were more consistent, six of the eight vehicle-time-of-day groups had significantly different variances from the approach to the drop-off. All six of the groups that were significantly different had larger variances at the drop-off location than at the approach location.

The incidence of time-to-collisions of less than 10 seconds was relatively high at this site. The highest percent of vehicles traveling at a low time to collision was 2.5% for the night data at location 2 taken with the barrels down. Other data sets had percentages of 0.7 to 1.8%. The incidence of time-to-collisions did not appear to relate to the location of the measurement or the delineation treatment in place. The relatively high percentages are probably most related to the high traffic volumes observed at this site.

The assumption of normality was made in testing the means and 85th percentile values of both speed and lateral placement data. Tests of the speed distribution are discussed in Section II.C. The hypothesis of normality for the lateral placement data was tested using the SAS Univariate procedure utilizing lateral placement data from drop-off study site 4.

A typical SAS output sheet for one group of lateral placement data from site 4 is shown in Figure 24. The top of the page presents all statistics of the lateral placement data (sample size, mean, standard deviation, etc.). Next a histogram, box plot, and normal probability plot are displayed. If the data are from a normal distribution, they should tend to fall along the reference line (marked by the + signs) on the probability plot. Eight plots were generated for lateral placement data at study site 4.

The probability plots for lateral placement show a normal distribution with a small group of high values. The high values can probably be explained by vehicles that were changing lanes or straddling the lane at the drop-off location. The D-statistic with its associated probability is printed above the bar chart. This statistic is computed to test the hypothesis that the data values are a random sample from a normal distribution. If the probability is less then 0.05, then one would reject this hypothesis at the 95% confidence level. However, large sample sizes and the presence of outliers such as the high values mentioned above, tend to result in such a rejection, although the plots show normality.

In summary, examination of the eight plots reveals that the lateral placement data can be assumed to be normal, and this does not violate the basic assumptions for comparing mean and 85th percentile speeds.

D. Accident Case Studies

The safety performance of the four drop-off study sites was studied by reviewing police accident reports from each of the two states where the four sites were located.

The procedure for obtaining accident data at the drop-off sites was identical to the procedure described for the truck study accident data. During operational studies at the site, the field crew documented the limits of each site and the height of the drop-off and spacing any type of devices around. Pictures were also taken of each of the sites. After the field studies were completed the cooperating states were recontacted to determine the duration of the project and any problems observed.

After the duration and limits of the project were determined, two types of accident data were requested: (a) "hard copy" police accident reports for the during construction period; and (b) line computer accident summaries for a before period the same length and dates as the during construction period, but 1 year earlier.

The four drop-off study sites were located in two states. One of the states furnished "hard copy" accident data for the during period and a line summary of before accidents. The other state was not able to furnish

UNIVARIATE

VARIABLE=XLATPL

MOMENTS

N	377	SUM WGTS	377
MEAN	10.0611	SUM	3793.04
STD DEV	1.60729	VARIANCE	2.58337
SKEWNESS	1.36935	KURTOSIS	3.31706
USS	39133.6	CSS	971.348
CV	15.9752	STD MEAN	0.0827795
T:MEAN=0	121.541	PROB>!T!	0.0001
SGN RANK	35626.5	PROB>!S!	0.0001
NUM ^= 0	377		
D:NORMAL	0.086924	PROB>D	<0.01

QUANTILES

100% MAX	16.96	99%	16.1328
75% Q3	10.77	95%	12.678
50% MED	9.9	90%	11.842
25% Q1	8.965	10%	8.288
0% MIN	6.51	5%	7.958
		1%	7.239
RANGE	10.45		
Q3-Q1	1.805		
MODE	9.78		

EXTREMES

LOWEST	HIGHEST
6.51	16.03
7.14	16.08
7.2	16.32
7.25	16.36
7.29	16.96

MISSING VALUE	.
COUNT	1
% COUNT/NOBS	0.26

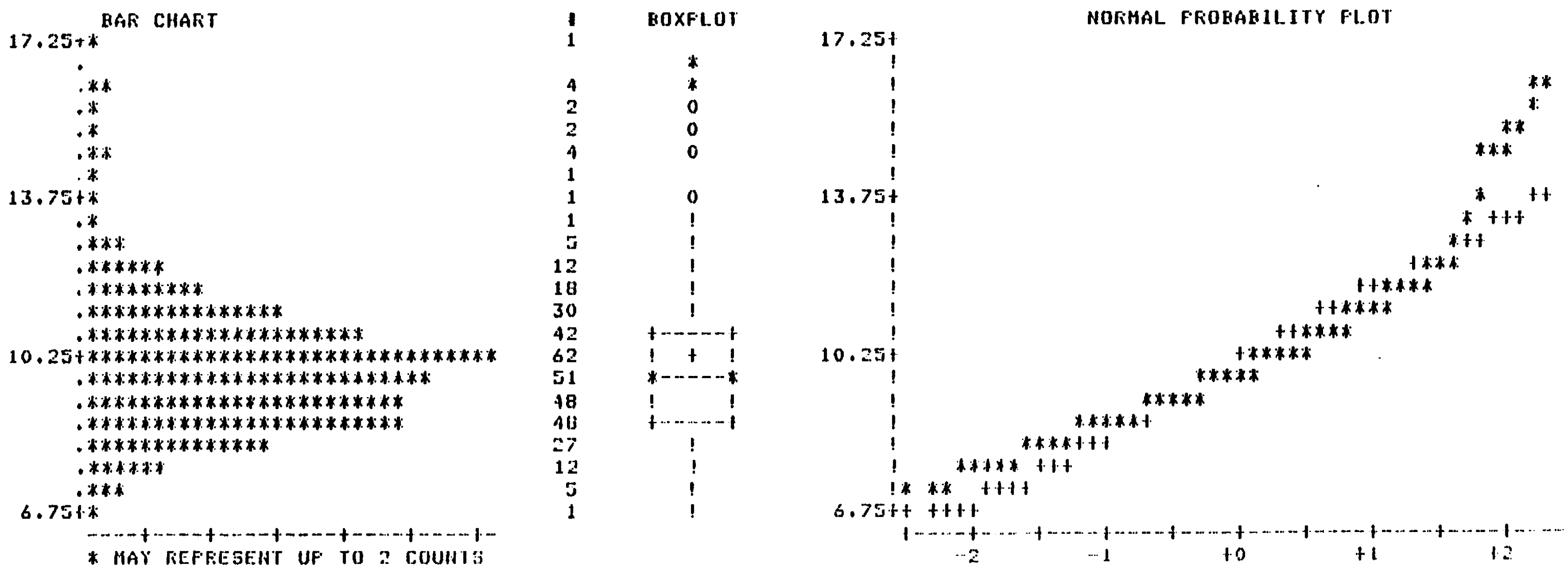


Figure 24 - SAS Output. Lateral Placement Statistics and Test of Normality for Cars, Nighttime, Work Area at Drop-Off Study Site No. 4

"hard copy" reports, but did furnish detailed line summaries of accidents occurring in both the before and during periods.

A summary of the accidents occurring at the drop-off sites before and during construction is shown in Table 28. Accident rates were computed by the standard formula:

$$AR = \frac{(N)\ 10^6}{(ADT)(D)(L)}$$

where
AR = accident rate in accidents per million vehicle miles,
N = number of accidents occurring in the work zone,
ADT = average daily traffic,
D = duration of construction period in days, and
L = length of section in miles.

TABLE 28

DROP-OFF ACCIDENT STUDIES

Drop-Off Study Site	Before Accidents Total	During Accidents Construction Related	During Accidents Total	Before Accident Rate (Veh/MVM)	During Accident Rate	Before to During Percent Change
1	0	1	1	0.0	1.052	NA
2	1	1	3	0.779	2.291	194.1
3	3[a]	2	2[a]	2.855	1.903	-33.3
4	26[a]	7	30[a]	0.770	0.889	15.5
Total	30	11	36	0.810	0.971	19.9

[a] Information regarding the quantity of non-reportable accidents were available but were not included due to lack of details.

A total of 36 accidents occurred at the four drop-off sites during construction. Of these 36 accidents 11 or 30.6% were related to construction. However, none of these accidents could be directly attributed to the pavement/shoulder drop-offs present at the site. The four sites experienced 30 accidents in the before period. Comparison of accident rates before and during the construction period revealed a 19.9% increase in the accident rate during construction.

Six accidents occurred on sites 1, 2, and 3 which were on two-lane rural highways. One of the construction-related accidents was a fatal single-vehicle accident that occurred when a driver struck a portable concrete barrier at a bridge that was narrowed to one lnae. Another accident involved a construction vehicle that pulled in front of an oncoming car in foggy weather. At site 3 one of the two accidents involved a worker on foot being struck by a vehicle, and the other accident involved a left-turning vehicle being struck from behind. Lack of pavement markings may have contributed to the latter accident.

Site 4 was a major interchange reconstruction project on an urban freeway. Thirty reportable accidents occurred during construction at site 4. Of these 30 accidents, seven were judged to be related to construction. Eighteen of the 30 during construction accidents were injury accidents. In the before period at site 4, 26 accidents occurred and 18 of these were injury accidents.

The seven accidents that were judged to be construction related were single-vehicle accidents with the exception of one rear end accident. Three of the six single-vehicle accidents were overturning accidents and the other three involved collisions with fixed objects or unknown objects. One of the fixed object accidents specified that a "pavement defect" contributed to the accident. In another of the fixed object accident the vehicle action was described as "avoiding object in road."

Overall the accident history of site 4 contains several single-vehicle accidents that could have been related to drop-off. However, no accidents were located at the drop-off studied in the field studies, and accident reports do not contain enough information to positively state that any of the accidents involved drop-offs.

Additional efforts were undertaken to examine drop-off accidents evident in other accident data bases. An accident data base assembled by MRI in 1975 was reviewed to determine if drop-off accidents could be determined.

This data base was also reviewed by the University of Tennessee in preparation of the FHWA Report, "Identification of Traffic Management Problems in Work Zones."[13] In preparation of 30 accident case studies from the 79 construction projects in this data base, they identified 12 projects where there were accidents within the work zone in which pavement height differentials or low shoulders were contributing factors. A total of 27 accidents were reported or 5% of all construction-related accidents at the 30 sites. One of the accidents resulted in a fatality.

Twenty-one drop-off accidents from the same data base were reviewed in this study. Seventeen of the 21 accidents were single-vehicle accidents. Several drivers complained of being forced into drop-off or low shoulder by another vehicle. Five of the accidents involved wet weather and a mud or soft shoulder was mentioned in these accidents. Four of the accidents actually involved drivers running into raised pavement sections and losing control of their vehicles. Differences in elevation were specified in five of the accidents and varied from 3 to 15 in.

E. Pavement/Shoulder Drop-off Summary

1. Simulation modeling conducted during this research and past studies showed that drop-offs above 4 in. are definite hazards and traffic exposure to these drop-offs should be minimized by use of barriers or short exposure to moving traffic.

2. The most difficult portion of the pavement/shoulder drop-off maneuver modeling effort is specifying driver reaction to the drop-off. Most past studies have employed professional drivers or drivers who were aware of the drop-off.

3. A "window of safety" was defined as the range of speeds and reentry approach angles that will allow a vehicle to safety remount a drop-off without encroachment on adjacent lanes. The drop-off heights warranting traffic control for a 5 degree window of safety are shown below:

	Warranting Drop-Off Height (in.) for Various Lane Widths (ft)			
Speed mph	12	11	10	9
30	4	4	3	2
35	4	3	2	1
40	3	2	1	1
45	2	1	1	1
$\geq$ 50	1	1	1	1

4. Modeling efforts revealed that a compact car can be expected to have a slightly larger lateral excursion than a mid-size vehicle at a given speed and drop-off height from a scrubbing condition. From a scrubbing condition at a 2 in. drop-off with a speed of 45 mph the compact car had a maximum lateral excursion of 23 ft and the mid-size car had a maximum lateral excursion of 20 ft. The maximum lateral acceleration for both vehicles was 0.6 g.

5. Modeling efforts revealed that for soil sinkages of less than 2 in., the presence of soft soil has no adverse effects on the reentry maneuver. Soft soil adjacent to the drop-off may increase the effective drop-off height or reduce frictional forces between the tire sidewall and the drop-off edge and thereby retard reentry to the traveled way.

6. Operational data on vehicle speeds and lateral placement relative to the pavement/shoulder drop-off edge were collected at four sites. Three of these sites were on rural two-lane highways, and one was on an urban freeway. At three of the four sites vehicle mean and 85th percentile speeds did not decrease from the approach of the work zone to the drop-off. The only site where speed decreases were observed had signs on the approach warning drivers of "Rough Road Ahead."

7. Tests of delineation devices revealed that vehicles do drive farther from the drop-off with delineation devices present. Devices tested on rural two-lane highways included object markers (small 4 x 6 in. delineators), cones, Type II barricades, and barrels. Lateral placements were

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also measured with no treatment at one site. Results showed that vehicles were farther away from the drop-off edge with the barrel or cone treatment, followed by barricades, and were closet with the object marker treatment.

8. At the urban freeway site, barrels were tested in two positions relative to the drop-off. These were up on the pavement edge, along the drop-off, and down in the drop-off itself. Vehicle lateral placements from the drop-off were about 1/2 ft greater with the barrels on the pavement edge.

9. Trucks usually have smaller lateral placements from drop-off, probably due to their greater width.

10. Lateral placement values were usually larger at night.

11. Drop-off accidents that were reviewed showed that the four drop-off study sites had an accident rate increase of 19% from the before to during period. However, it was not possible to relate any of the accidents occurring at these sites to the presence of drop-offs.

12. Review of drop-off accidents in a previously assembled work zone accident data base revealed several accidents occurring in wet weather and a number of accidents related to high pavement edges.

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IV. CONCLUSIONS

This chapter contains conclusions gained primarily from analysis of operational and accident data at nine truck study sites and four pavement/shoulder drop-off sites. Results of past studies and modeling of pavement/shoulder drop-off maneuvers were also considered. The conclusions are presented in two sections following the structure of the study. The first section presents conclusions concerning truck problems in work zones and possible solutions to these problems. The second section presents recommendations on the maximum tolerable pavement/shoulder drop-off height and effectiveness of various delineation treatments.

A. Truck Problems in Work Zones

Trucks are more vulnerable than passenger cars to a number of geometric characteristics commonly found in highway work zones. Also work zones located at sites where there are problems in truck operations before roadway work commences can have severe problems when the work zone's reduced geometrics are superimposed on a difficult situation.

This research examined a number of work zones that were expected to create truck operational and accident problems. These work zones included sites on steep grades (both upgrades and downgrades), sites with poor horizontal curvature, and sites where trucks were restricted to one lane in the work area. In total, nine sites in three states were studied by collecting operational data during the construction period and analyzing accidents occurring during and in a similar period before the construction.

Several problems specific to truck operations in work zones were observed in these studies. The most severe truck accident problem was noted in another portion of this research that studied two-lane, two-way work zone (TLTWO) operations on a normally divided roadway. This study noted that use of a 35 mph design speed for design of a temporary median crossover on a 55 mph roadway can result in a concentration of severe overturning and fixed object accidents. Loaded trucks were particularity vulnerable to this deficient design.

Work zones on downgrades also had truck accident problems that were noted in accident case studies in this research. Operational data revealed that speeds for all vehicles are higher in the work area of a downgrade work zone. Trucks respond to the work area in reducing their speeds, but their speed reduction was slightly less than passenger cars at downgrade sites. The most common truck accident type on the downgrade sites was rear end accidents, followed by fixed object and overturning accidents.

Truck problems were also noted where trucks were moved onto a paved shoulder serving as a travel lane during construction. The paved shoulder was not designed for moving traffic and problems were noted relative to provision for acceleration areas at on-ramps, provision for disabled vehicles, and correct superelevation at curves in the work zone roadway.

Overall the accident rate at the nine truck sites studied increased only 7.65% from before construction to during construction. Truck mean and 85th percentile speeds were usually lower than passenger car mean speeds and their speed reduction patterns were similar to other vehicles at all sites except downgrades where they slow slightly less as noted above.

One of the truck study sites on a poorly designed horizontal curve had a 41% decrease in accident rate during construction, probably due to the fact that speeds of all vehicles were reduced during the construction period. No accident problems were noted in connection with two narrow 10 ft lanes with portable concrete barrier along the right edge of the traveled way.

The most evident solution for truck problems is to provide work zone roadways with geometrics at full design standards. Obviously this is not possible during many work activities. The most critical decision considerations relating to truck problems noted in this research are provision of sufficient design speeds at locations that involved horizontal curves or lateral shifts in the traffic path. Studies of TLTWO work zones concluded that portable concrete barrier was not a cure for poor geometric design and may increase the hazard if the barrier reduces the buffer or recovery area available to vehicles.

Lane closures on downgrades that reduce the traveled way to one lane should be minimized where possible. Trucks will need warning of speed restrictions prior to the downgrade if they are expected to slow down a great deal or stop. Provision must also be made for improved design of paved shoulders if they are to be used for moving truck traffic. This provision should include adequate superelevation, and on-ramp acceleration lengths plus provision for disabled vehicles. Trucks should also be provided with early warning of short merging distances. Merging areas may need to be lengthened on upgrade sections.

B. Pavement/Shoulder Drop-offs in Work Zones

Pavement/shoulder drop-offs were studied via modeling of the drop-off traversal maneuver and analysis of operational and accident data at four work zone sites with pavement/shoulder drop-offs.

The goal of the modeling effort was to define the maximum tolerable pavement/shoulder drop-off. The most difficult aspect of the modeling effort is specifying the reaction of unaware drivers to actual pavement/shoulder drop-offs. The results of the modeling efforts were described by specifying a "window of safety" defined as the range of vehicle speeds and re-entry approach angles that will allow a vehicle to remount a pavement/shoulder drop-off without encroachment on adjacent lanes. Drop-off heights warranting traffic control for various windows of safety are shown in Table 19. A 5 degree window of safety is recommended.

The measurement of vehicle speeds on the approach to and at pavement/shoulder drop-offs revealed that vehicles do not reduce their speeds significantly in response to the drop-off. The only site that experienced speed reductions near the drop-off also had signs warning of "rough road ahead."

Measurements of lateral placement of vehicles in relation to the drop-off edge were made at three drop-off sites on rural two-lane highways. The delineation devices tested included object markers (small delineators), cones, type II barricades, and barrels. A drop-off with no delineation treatment was studied at one site. Results of the analysis of lateral placement data revealed that passenger cars placed themselves farther from the drop-off with the treatments of barrels or cones, followed by type II barricades, and finally object markers. Trucks in most cases did not vary their placement in relation to cones, type II barricades, or object markers.

Measurements of lateral placements at a urban freeway site were made with two placements of barrels in regard to the drop-off. Barrels were placed on the pavement edge or down in the drop-off. Vehicles placed themselves about 1/2 ft farther from the drop-off edge with the barrels up on the pavement. Vehicles also drove about 0.3 ft farther from the drop-off at night.

Review of accidents at the drop-off study sites revealed an accident rate increase of 19% during construction. However, the association of the drop-off to the accidents was not apparent from review of police accident reports. Review of a previously assembled work zone accident data base revealed several drop-off accidents during periods of wet or icy pavement conditions, and a number of accidents caused by vehicles running into high pavement edges.

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APPENDIX A

FIELD DATA COLLECTION EQUIPMENT

The field data collection was completed through use of piezoelectric road cables and transducers connected to a Traffic Data Recorder (TDR), which consists of a Motorola MEK6800 microprocessor, a cassette tape recorder, and appropriate software to record, playback, and analyze the data. The basic TDR system was recently developed as a research tool at the University of Toronto. Figures 25 and 26 show a TDR unit and a typical data collection setup.

The heart of this system is the microprocessor which is actually a microcomputer when linked with data storage elements (RAM's and ROM's) and Input/Output devices. As presently programmed, this microcomputer can perform the following functions:

1. Automatically record the time of triggering of up to four vehicle sensors;

2. Record times of events entered manually via single key depressions, with up to six character identification of event;

3. Record hexadecimal data characters; and

4. Automatically provide an output signal that can, for example, trigger a camera to take one photograph per vehicle using the vehicle sensor input data.

The following options are available on the above functions:

1. Visual indication of proper operation of vehicle sensors and camera;

2. External time synchronization of several TDR systems;

3. Automatic start and stop of sampling at specified times;

4. Real-time determination of end of vehicle from sensor inputs;

5. Triggering of camera on end of vehicle; and

6. Automatic playback of recorded data via standard EIA Rs-232C interface.

When an event such as a sensor actuation occurs, the time of the event is stored internally in an element of memory. When 63 of these elements have been stored, the tape recorder is turned on and the data is written out to tape. The writing of one block of data onto tape takes about 11 seconds. The internal memory organization of the 6800 microcomputer is such that there are four of the 63-element buffer blocks available for internal data storage, and while one block is being written onto tape the other three blocks are used to buffer and store incoming data.

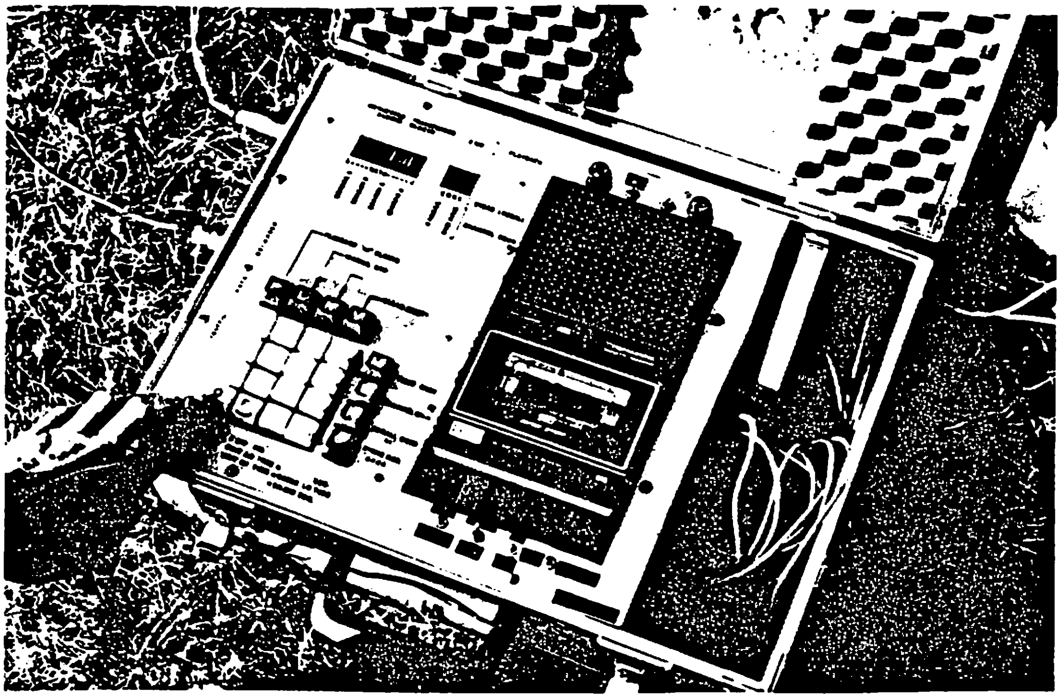

Figure 25 - Traffic Data Recorder

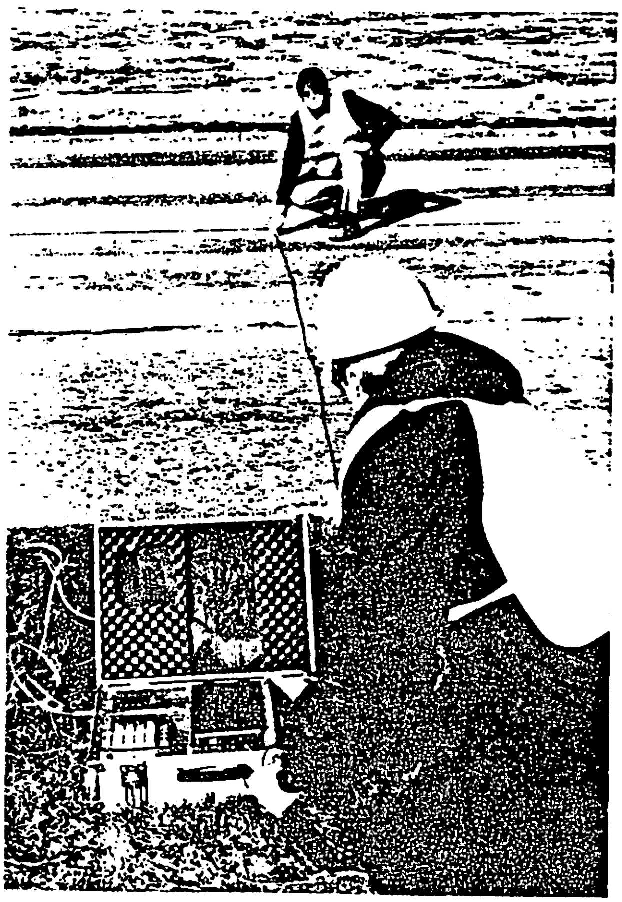

Figure 26 - Traffic Data Recorder Field Deployment Utilizing Piezoelectric Cable

Three methods of playback are available. In each of these methods the data is read drom the tape into the microcomputer memory. It can then be transferred to a time-sharing computer, to a terminal, or to the self-contained display.

Playback to the TDR display is useful to check that data are useable while the field crew is still in the field. However, for the actual data reduction effort the cassette tapes recorded in the field are brought back to MRI and played back through the TDR into MRI's DEC PDP 11/23 PLUS computer. The TDR data are checked for consistency both during playback and after being placed in a computer file by means of a Data Check program. This program identifies errors and inconsistencies in the data before the data are analyzed. For example, each block of TDR data contains a checksum that is used to assure that the entire data block has been transferred correctly from the TDR to the computer. Errors and inconsistencies found in the data are corrected either by editing the file or by rereading a portion of the cassette tape.

Three FORTRAN IV analysis programs have been developed for use with the data. The first program checks the data for improper block format, missing blocks, parity errors, and check sum errors, and gives a summary of the number of channel events and the number of times various codes were entered. The second program provides a listing of the hexadecimal data in a more readable format.

The third program produces vehicle parameters such as headway, speed, acceleration, wheelbase, and number of axles from the use of two vehicle sensors spaced a fixed distance apart. The program can be used in conjunction with data from a third diagonal sensor to determine lateral placement. The program incorporates vehicle separation techniques, vehicle type classification of wheelbase and number of axles, and detection of unclassifiable vehicles. A sample of the vehicle-by-vehicle output from the program is shown in Figure 27. Summaries of variables such as speed for the study period are also produced by this program. An example of a speed summary is shown in Figure 28.

The TDR records the time of each axle passage over a sensor to the nearest 1/1,200 sec (0.000833 sec). For a vehicle traveling 45 mph the computation of speed using the TDR data is accurate to within ± 0.16 mph with a 15-ft trap and the computation of lateral placement is accurate to within ± 0.66 in. with a 45 degree diagonal sensor. For a vehicle traveling 55 mph, comparable values for the accuracy of speed and lateral placement computations are ± 0.25 mph and ± 0.80 in.

TDR OUTPUT FILE

IVEHNO	NO. OF AXLES	TRANSIT TIMES(HMS) UPSTREAM	TRANSIT TIMES(HMS) DOWNSTREAM	HEADWAY (SEC)	SPEED (FT/SEC)	ACCELERATION (FT/SEC**2)	WHEELBASE (FT)	LATERAL PLACEMENT (FT)	VEH TYPE	TIME TO COLLISION (SEC)	FOLLOWING DISTANCE (FT)
1	2	11.45.16.121	11.45.16.344	-99.000	67.164	0.0	11.08	-99.00	5	-99.00	-99.00
2	4	11.47.11.289	11.47.11.500	115.168	70.922	-0.531	36.77	-99.00	10	60.00	5000.00
3	2	11.48. 8.617	11.48. 8.867	57.331	60.133	0.542	11.23	-99.00	5	-99.00	4023.27
4	2	11.48.50.129	11.48.50.320	41.508	77.798	1.291	10.25	-99.00	3	60.00	2478.79
5	-99	11.49. 3.738	11.49. 4.141	13.611	-99.000	-99.000	-99.00	-99.00	13	-99.00	1042.64
6	3	11.49.54.590	11.49.54.777	50.853	80.812	-1.018	28.33	-99.00	13	-99.00	-99.00
7	2	11.50.14.496	11.50.14.695	19.905	75.630	0.0	10.34	-99.00	5	-99.00	1574.24
8	2	11.50.16.641	11.50.16.852	2.144	71.146	0.0	7.83	-99.00	1	-99.00	145.83
9	2	11.52.40.965	11.52.41.152	144.325	80.717	0.0	10.83	-99.00	5	60.00	5000.00
10	5	11.53.24.105	11.53.24.297	43.140	78.947	0.0	50.39	-99.00	10	-99.00	3465.32
11	2	11.54.32.445	11.54.32.645	68.338	74.206	-1.306	8.59	-99.00	1	-99.00	5000.00
12	2	11.55. 8.277	11.55. 8.520	35.832	61.644	0.0	9.09	-99.00	2	-99.00	2644.40
13	2	11.55.10.906	11.55.11.168	2.631	57.809	0.532	10.17	-99.00	3	-99.00	147.08
14	2	11.55.16.008	11.55.16.215	7.099	72.289	0.0	9.76	-99.00	3	27.22	394.23
15	2	11.55.38.961	11.55.39.160	20.956	75.314	0.0	9.48	-99.00	2	60.00	1499.12
16	2	11.55.40.656	11.55.40.855	1.693	74.689	0.0	11.14	-99.00	5	-99.00	112.05
17	2	11.55.45.230	11.55.45.441	4.577	71.146	0.0	11.26	-99.00	13	-99.00	324.68
18	2	11.55.56.902	11.55.57.082	11.668	82.723	-1.695	9.16	-99.00	2	60.00	812.89
19	2	11.56.23.973	11.56.24.172	27.072	75.000	0.0	9.17	-99.00	2	-99.00	2224.35

Figure 27 - Example of a TDR Output File

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SPEED SUMMARY 101A5 1-2-0

SPEED RANGE (FT./SEC)	NUMBER OF VEHICLES	NUMBER OF PASSENGER CARS	NUMBER OF TRUCKS-BUSES-RVS
X <= 5.000	0	0	0
5.000 < X <= 10.000	0	0	0
10.000 < X <= 15.000	0	0	0
15.000 < X <= 20.000	0	0	0
20.000 < X <= 25.000	0	0	0
25.000 < X <= 30.000	0	0	0
30.000 < X <= 35.000	9	6	3
35.000 < X <= 40.000	12	8	4
40.000 < X <= 45.000	13	12	1
45.000 < X <= 50.000	13	7	6
50.000 < X <= 55.000	53	41	12
55.000 < X <= 60.000	132	113	19
60.000 < X <= 65.000	231	194	37
65.000 < X <= 70.000	192	161	31
70.000 < X <= 75.000	175	153	22
75.000 < X <= 80.000	45	43	2
80.000 < X <= 85.000	9	9	0
85.000 < X <= 90.000	1	1	0
90.000 < X <= 95.000	0	0	0
95.000 < X <= 100.000	0	0	0
100.000 < X <= 105.000	0	0	0
105.000 < X <= 110.000	0	0	0
110.000 < X	0	0	0
TOTAL =	885	748	137
MEAN VALUE =	64.070	64.487	61.792
STD DEVIATION =	8.514	8.301	9.300
MINIMUM VALUE =	31.892	31.892	33.504
MAXIMUM VALUE =	88.235	88.235	76.946
MISSING VALUES=	5	0	0

Figure 28 - Example of Speed Distribution Printout from TDR Analysis Program

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APPENDIX B

DESCRIPTION OF THE HIGHWAY-VEHICLE-OBJECT-SIMULATION-MODEL (HVOSM)

This Appendix discusses the capabilities of the HVOSM simulation model, modifications made to the model to investigate vehicular response to pavement/shoulder drop-offs, and limitations of the model and problems encountered in modeling the pavement/shoulder drop-off maneuver.

A. General Discussion

The HVOSM is a computer simulation model of an automobile for prediction of dynamic responses in relation to handling maneuvers and accident reconstruction. The model predicts the general three-dimensional motion resulting from vehicle dynamics, control inputs, traversal of irregular terrain, and collisions with roadside barriers. The output of each simulation run provides the vehicle path and orientation and accelerations to which the vehicle is subjected as functions of time; these data can be used to judge the criticality of any particular combination of input variables, such as vehicle speed and drop-off height. Two versions of the HVOSM program are available: the roadside design version and the more sophisticated vehicle dynamics version. The roadside design version was considered appropriate for all of the applications performed within the subject research effort.

The HVOSM computer program has been extensively validated for a variety of vehicle response predictions.[22] One option available in HVOSM was developed to study the impacts of errant vehicles with barrier curbs. It has been determined that the curb impact option of HVOSM is generally appropriate to the investigation of pavement/shoulder drop-offs. The geometrics of pavement/shoulder drop-offs are very similar to geometrics used in the curb impact studies. However, the vehicle approaches from the top of the drop-off rather than from the base of the curb, and driver reaction to encountering a drop-off may be different from driver reaction to encountering a curb. A study by Systems Technology, Inc.[17] found that the critical safety problem at a pavement/shoulder dropoff occurs not in the initial descent of the dropoff but rather in subsequent attempts to return to the roadway. Systems Technology found that the driver's reaction in encountering a drop-off was important because shallow-angle contact or "scrubbing" of the tire against the pavement edge with two or four tires off the pavement created a critical situation that could lead to loss of control. Less critical results may be obtained if the driver first steers away from the pavement edge before trying to mount it.

B. Modifications to HVOSM

Several extensions and refinements of the HVOSM were incorporated to provide improved detail in the tire force routine and to accommodate anticipated needs in the driver model in the performance of pavement/shoulder drop-off maneuvers. In particular, the modifications included extensions to the HVOSM tire routine to include tire sidewall contact forces, the additions of a capability for variable-torque path following model (VTPF), and later an emergency maneuver driver control model (DRIV2).

1. Tire sidewall contacts: In a recent HVOSM simulation study of curb impacts,[23] the correlation with test results was found to be reasonably good at high speeds and large approach angles, but it was considered to be unacceptable at low speeds and shallow angles. A primary source of response discrepancies in the shallow-angle case is believed to be the lack of representation in the tire simulation of contact forces that act directly on the tire sidewalls. The modifications to the HVOSM to account for sidewall forces is described below.

The simulation in HVOSM of tire forces during curb contacts has remained unchanged since 1967[24] with the minor exception that the maximum number of curb slopes was extended from three to six in 1972.[18] The vehicle tires are represented by a single, thin disc that generates forces primarily in the plane of the wheel. The thin-disc representation of a tire generates forces perpendicular to the wheel plane (i.e., side forces) only through the mechanisms of (1) combined slip and camber angles, and (2) components of the tire load normal to the local terrain. The points of application of side forces determine the corresponding moments about the kingpin axes that act on the simulated steering system of the vehicle.

On the basis of the Systems Technology study,[17] an important aspect of a shallow-angle traversal of a pavement/shoulder drop-off is the relatively large side force requirement to overcome the contact force produced by scrubbing of the tire sidewall on the pavement edge (see Figure 29). When the pavement edge is mounted, the sudden release of the scrubbing contact force creates an unbalanced side force toward the roadway and also tends to increase the already excessive steer angle by removing resistance to driver input torque at the steering wheel. The existing form of HVOSM was extended to include an approximation of the indicated scrubbing contact force and of steering wheel torque inputs, as opposed to position inputs, by the driver.

The existing thin-disc representation of the tire is illustrated by the left-hand portion of Figure 30. Tire forces are represented by a series of radial springs distributed at 4 degree intervals around the tire. The elastic forces generated in these springs are scanned and summed at fixed intervals by the computer program. Revisions were incorporated such that tire sidewall contact forces are approximated in an analogous manner through the use of discrete points (or "springs"), with elastic lateral load-deflection properties, on the tire sidewalls adjacent to the existing radial springs. The positions of these lateral springs are illustrated in the right-hand portion of Figure 30 and Figure 31.

The analytical approach was selected with a view toward minimizing the extent of related programming changes. The explanation of this approach is necessarily presented in the terminology used in HVOSM. These terms will be briefly defined and described here; for a more detailed discussion, the reader is referred to the documentation of the program development.[25]

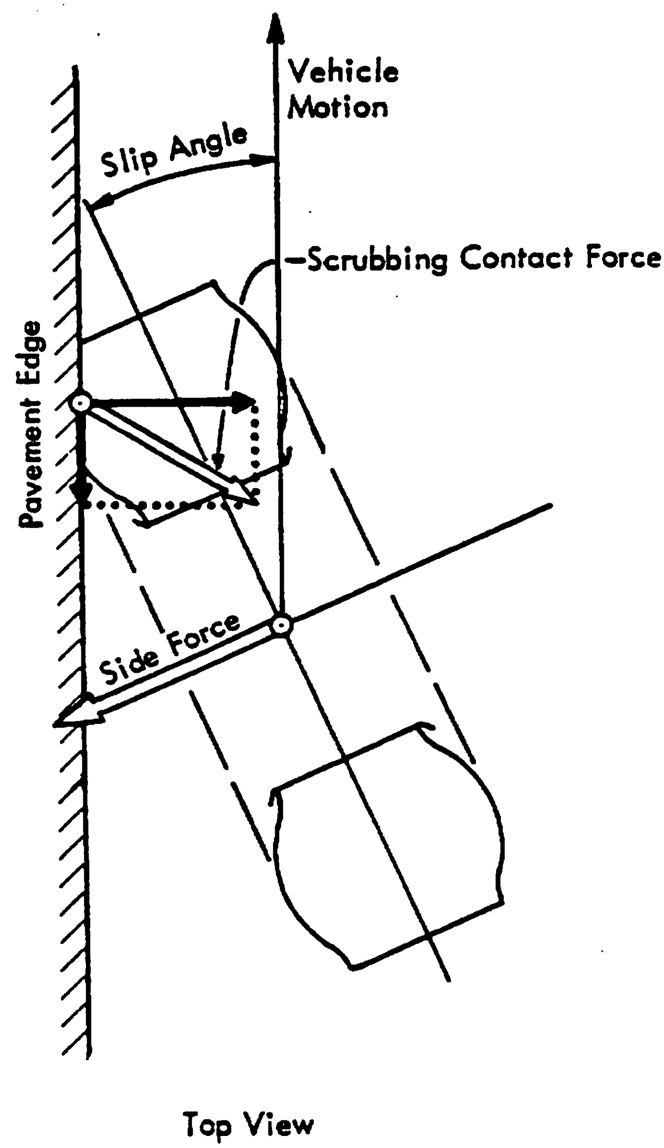
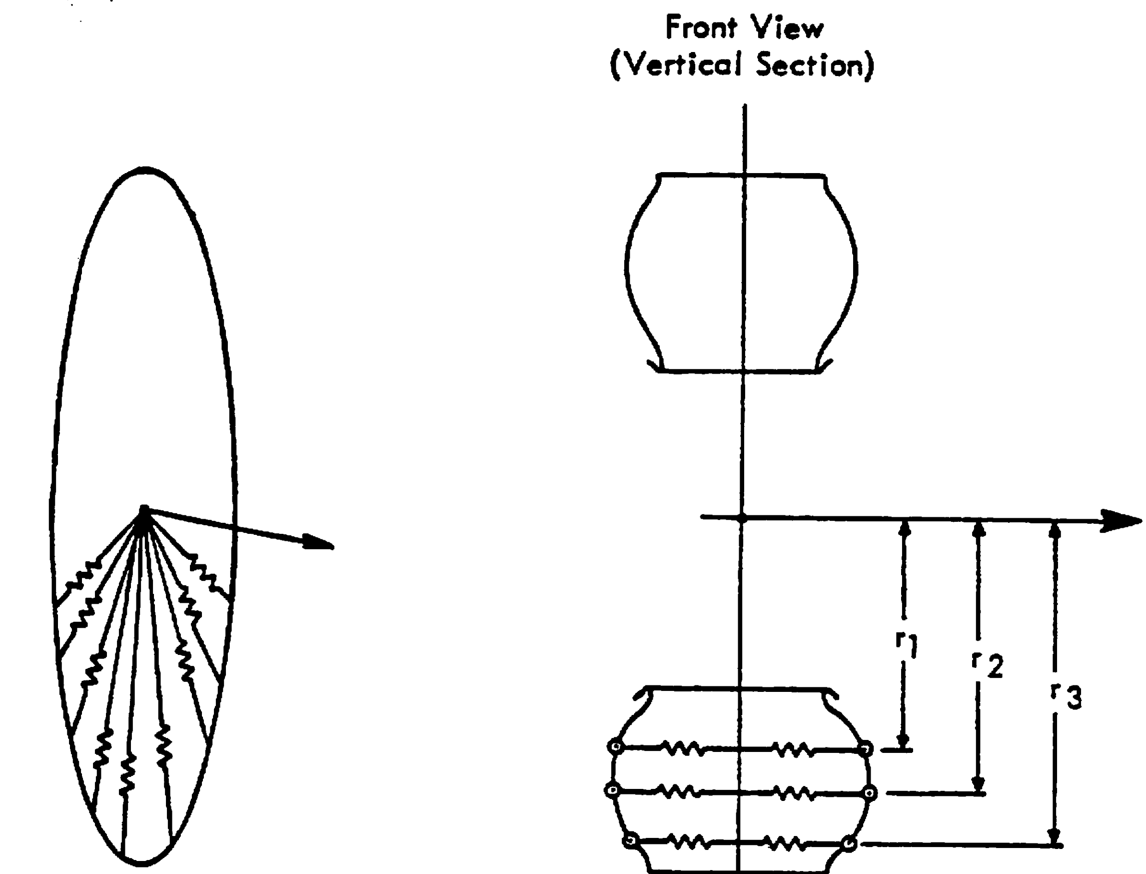


Figure 29 - Scrubbing Contact in Shallow-Angle Approach to a Pavement Edge



Distributed-Contact Radial Spring Model of Tire Used in Curb Contacts (4° Intervals)

Proposed Discrete Points to Represent Sidewalls (At Radial Spring Locations)

Figure 30 - Tire Model Extension

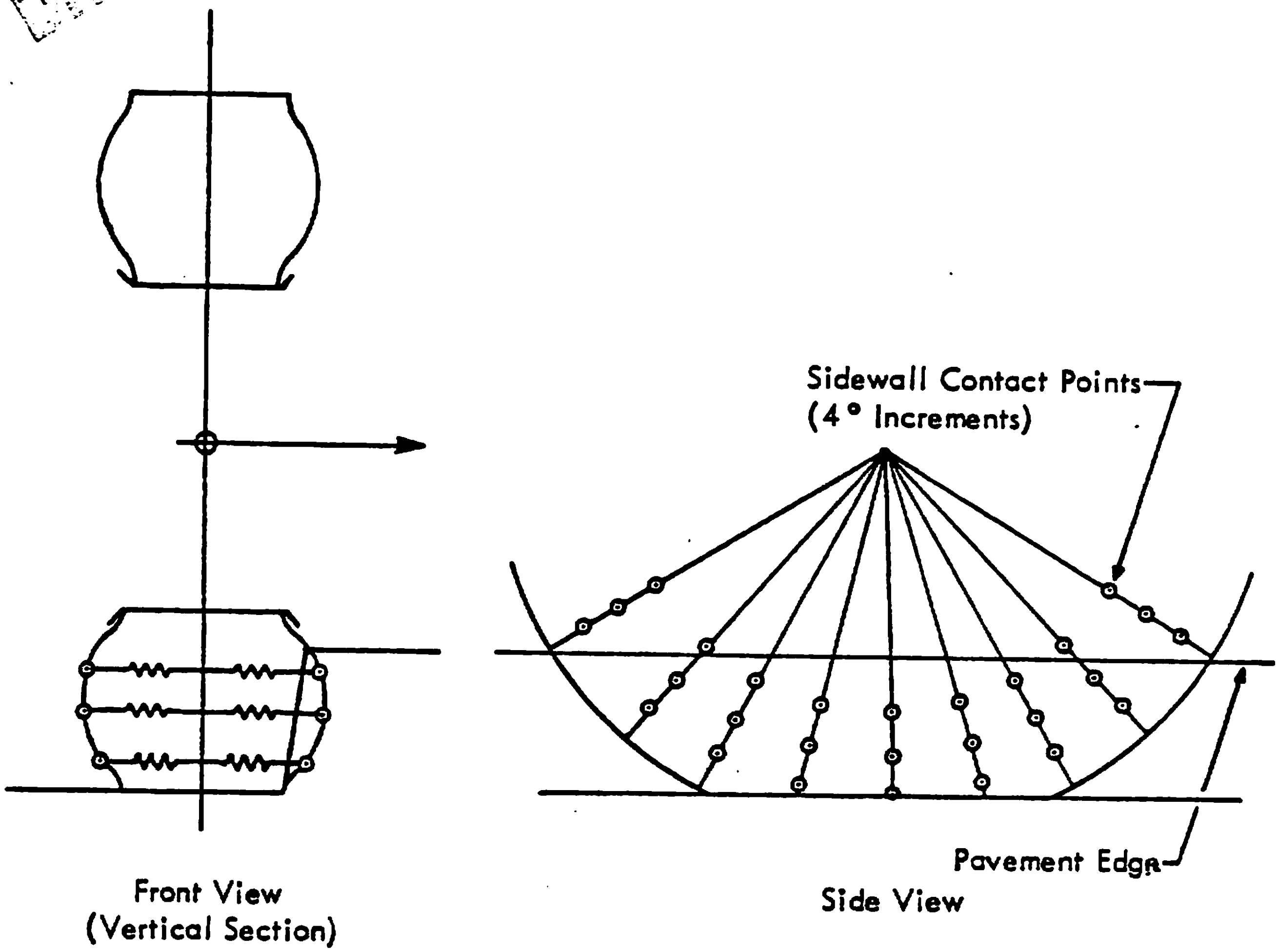


Figure 31 - Sidewall Contact with Pavement Edge

The analysis of tire contact forces in curb impacts uses three coordinate systems: a space-fixed coordinate system; a vehicle-fixed coordinate system; and a wheel-fixed coordinate system. For example, in the space-fixed coordinate system the x-axis represents distance along the roadway (positive forwards), the y-axis represents distance across the roadway (positive to the right) and the z-axis represents elevation (positive downwards). In the HVOSM program, the matrix $\|Aj\|$ is used to transform the coordinates of a point j on the circumference of wheel i into the vehicle-fixed coordinate system. This matrix corresponds to the sequence ϕi, ψi, θj, where:

ϕi = camber angle of wheel i,

ψi = steer angle of wheel i, and

θj = angular position of point j.

Similarly, a matrix $\|A\|$ is used to transform the vehicle-fixed coordinates of $\|Aj\|$ into space-fixed coordinates. matrix $\|B\|$ is defined as $\|A\| \cdot \|Aj\|$ and it is used to transform points on the circumference of wheel i directly into the space-fixed coordinate system. Thus, the space coordinates of point j on the periphery of the wheel disc are obtained as:

$$\left\|\begin{matrix} X'_j \\ Y'_j \\ Z'_j \end{matrix}\right\| = \left\|\begin{matrix} X'_i \\ Y'_i \\ Z'_i \end{matrix}\right\| + \|B\| \cdot \left\|\begin{matrix} 0 \\ 0 \\ h'_j \end{matrix}\right\| \qquad (1)$$

where X'_i, Y'_i, Z'_i are the coordinates in space of the center of wheel i, and h'_j is the radial distance, in the wheel plane, to the point of interest. Equation (1) is used in the existing model to determine what portion of the tire is in contact with the pavement.

A determination of the portion of the sidewall in contact with the pavement/shoulder drop-off can be obtained from additional solutions of Equation (1) with the following substitutions in the column matrix for the wheel:

$$\left\|\begin{matrix} X'_j \\ Y'_j \\ Z'_j \end{matrix}\right\| = \left\|\begin{matrix} X'_i \\ Y'_i \\ Z'_i \end{matrix}\right\| + \|B\| \cdot \left\|\begin{matrix} 0 \\ y_n \\ r_n \end{matrix}\right\| \qquad (2)$$

where n = the number of points defining the sidewall, and y_n = one-half of the tire width at radius r_n. If the tire sidewall is in contact with the drop-off, a series of additional calculations within the existing wheel scans can provide the basis for detections and approximation of sidewall contact forces (see Figure 31). The forces and moments on wheel i that are produced by the individual contact points will be added directly to the existing summations in the equations of motion for the steering system and for the vehicle equations of motion.

The implementation of the modifications required estimation of the lateral stiffness of tires. For the present study, the lateral stiffness of the tires was approximated as being equal to the radial stiffness already used in the program.

2. Variable torque path following (VTPF) driver model: Prior to the present research effort, the simulation of impacts with curb-like obstacles (i.e., pavement/shoulder drop-offs) could be performed only in a "hands-off" steering mode. The use of either the input steer tables or path follower driver model was abandoned and a steering system degree-of-freedom was activated once a simulated tire came into contact with a curb. The steering system degree-of-freedom included the simulation of external forces, such as aligning torques and the effects of terrain irregularities (i.e., curbs) in the determination of the front wheel steer activity.

The variable-torque path following (VTPF) driver model was incorporated into the HVOSM Roadside Design Version as part of the present research to give the HVOSM user an alternative to the "hands-off" steering mode. However, on the basis of initial application results, the VTPF was found inadequate for the simulation of the total pavement/shoulder drop-off maneuver. Although maneuvers were reasonably simulated for exit angles less than 3 degrees, the VTPF was unstable for exit angles greater than 3 degrees.

The VTPF driver model includes:

1. A "wagon-tongue" type of guidance algorithm which calculates a driver-applied front wheel steering torque proportional to the path error at a point on a forward extension of the x-axis of the vehicle, relative to the desired path.

2. An interface within HVOSM to convert the variable inputs of standard roadway geometric path descriptors to a second-order polynomial definition of the desired path.

3. Inclusion of a variable input "neuro-muscular" filter within the HVOSM driver model which permits the simulation of first-order effects of the neurological and muscular systems of a human driver.

4. A variable input damping term and closed-loop amplitude limits on the steering system activity.

The calculated torque from the VTPF driver model is included in the steering system degree-of-freedom to create a path following mode. The incorporation of the VTPF into the steer degree-of-freedom permits the simulation of maneuvers, such as the pavement/shoulder drop-off, where the driver inputs corrective torque to the steering system during the obstacle contact and the return to the lane of travel.

Applications of the VTPF within the presently reported research effort included the specification of (1) the centerline of the travel lane, and (2) a curvilinear path as the desired path for the driver model.

The specification of the centerline of the travel lane as the desired path was found to be insufficient to permit the simulation of a wide range of speeds and exit angles on the pavement/shoulder drop-off. Although a number of successful maneuvers were simulated for exit angles less than 3 degrees, the VTPF was found to be unstable for exit angles greater than 3 degrees. The instability of the VTPF was caused by the rapid rate of increase of the error from the desired path (i.e., lane centerline) for angles greater than 3 degrees. The resulting driver torques caused oscillations in the steering system for the larger exit angles.

The second mode of exploratory application of the VTPF involved the specification of a curvilinear desired path to guide the vehicle back to the lane. The curvilinear path provided improved control over the desired vehicle maneuver (i.e., see Figure 32); however, a universal stabilization of the VTPF for a range of speeds and curves could not be attained. Also, the specification of a desired path (i.e., see Figure 32) was an arbitrary procedure which probably would not withstand critical appraisal in the absence of real-world data on which to base the path specification. The lack of applicable data on driver behavior, coupled with an inability to universally stabilize the VTPF within the available funds, led to a decision to abandon further attempts at closed-loop control for the subject research effort.

3. <u>Emergency maneuver driver control model</u>: After the unsuccessful attempt to model the entire pavement/shoulder drop-off maneuver starting from the initial exit from the pavement, the practical decision was made to continue the research in an attempt to learn more about the recovery once the vehicle had encountered the shoulder. One part of this further research used the HVOSM to investigate the relationships between maximum extent of lateral excursion, speed, and drop-off height for a vehicle remounting the drop-off from a scrubbing condition. A new open-loop driver control algorithm (DRIV2) was developed and installed in the HVOSM to simulate driver response to an emergency maneuver.

The DRIV2 was used in the performance of the scrubbing reentry series which simulate the driver recovery maneuver subsequent to the remount, from a scrubbing condition of the pavement/shoulder drop-off edge.

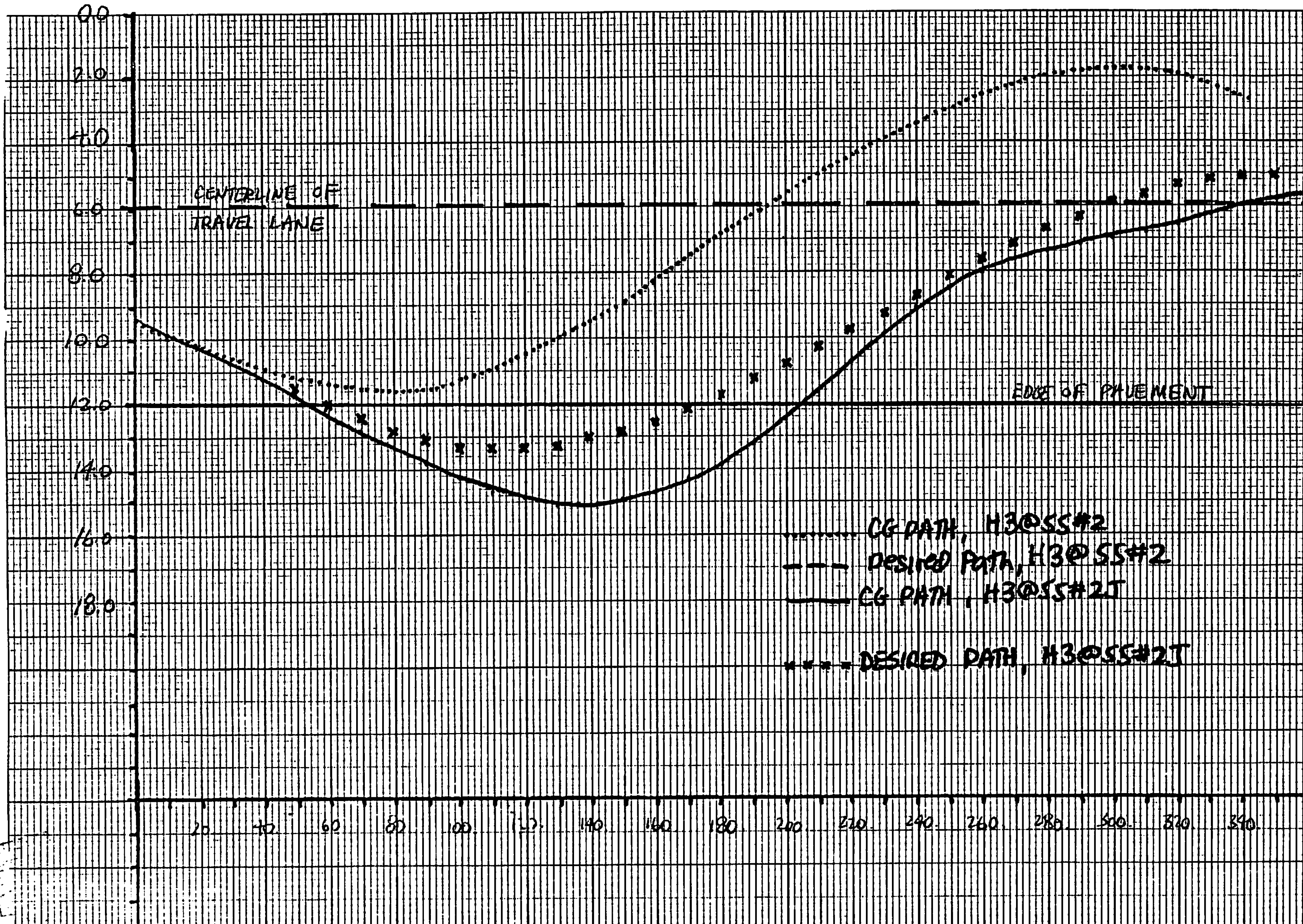


Figure 32 - Comparison of Two VTPF Techniques

The DRIV2 model was used to accelerate and decelerate change in the front wheel steer angle based on the following user inputs describing driver characteristics:

Variable	Description	Units
TPRB	Driver perception/reaction time	seconds
PSIDM	Maximum front wheel steer velocity	deg/sec
PSIDDM	Maximum front wheel steer acceleration and deceleration	deg/sec^2
PMAX	Maximum driver discomfort level at which deceleration of the steering system is to begin	G-units
PSIMAX	Maximum front wheel steer angle	deg.

After TPRB seconds have elapsed in the simulation run, DRIV2 accelerates the front wheel steer velocity to PSIDM by the following relationship:

$$PSID = 0.5 * PSIDM * (1. - \cos((T - TPRB) * \pi/(PEAKT)))$$

where: PSID = Front wheel steer velocity at time T
PSIDM = Maximum front wheel steer velocity
TPRB = Driver perception reaction time
PEAKT = π * PSIDM/(PSIDDM * 2.0)

The front wheel steer velocity remains at PSIDM until either (1) the comfort factor (CMFCG) exceeds PMAX or (2) the front wheel steer angle (PSI) exceeds PSIMAX. If either (1) or (2) is true, then the front wheel steer displacement velocity is decelerated back to 0.0 by the following relationship:

$$PSID = PSIDM - 0.5 * PSIDM * (1. - \cos((T - T1) * \pi/(PEAKT)))$$

where: PSID = Front wheel steer velocity at time T
PSIDM = Maximum front wheel steer velocity
T1 = Initial time of deceleration
PEAKT = π * PSIDM/(PSIDDM * 2.0)

Once PSIDM is decelerated to zero the front wheel steer angle remains constant.

The acceleration/deceleration characteristics for the DRIV2 algorithm were derived by numerically integrating the two time-history plots of the steering wheel activity from the STI report.[17] Figures 33 and 34 are time-history plots of the numerical integration.

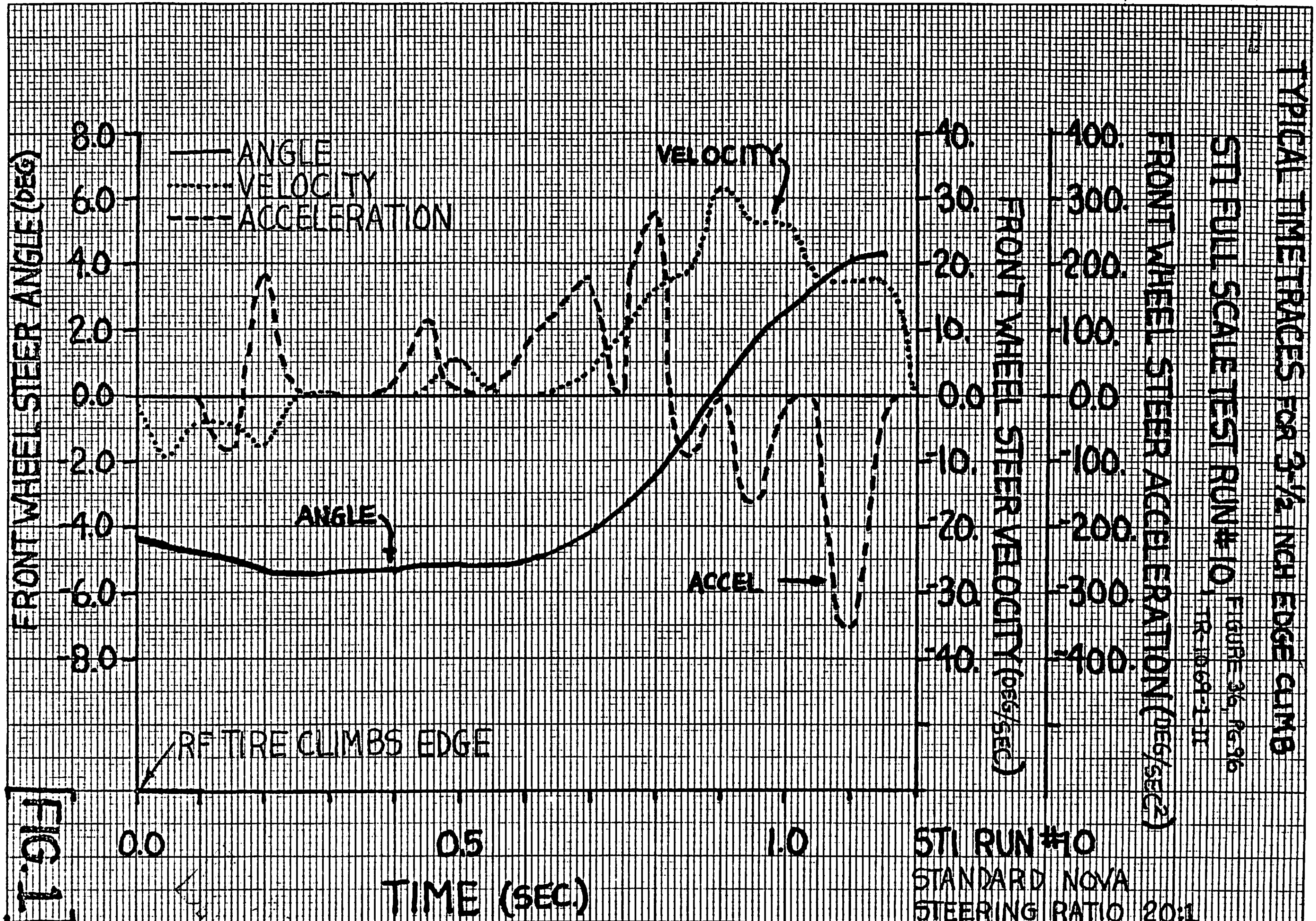


Figure 33 - Time-History HVOSM Plot

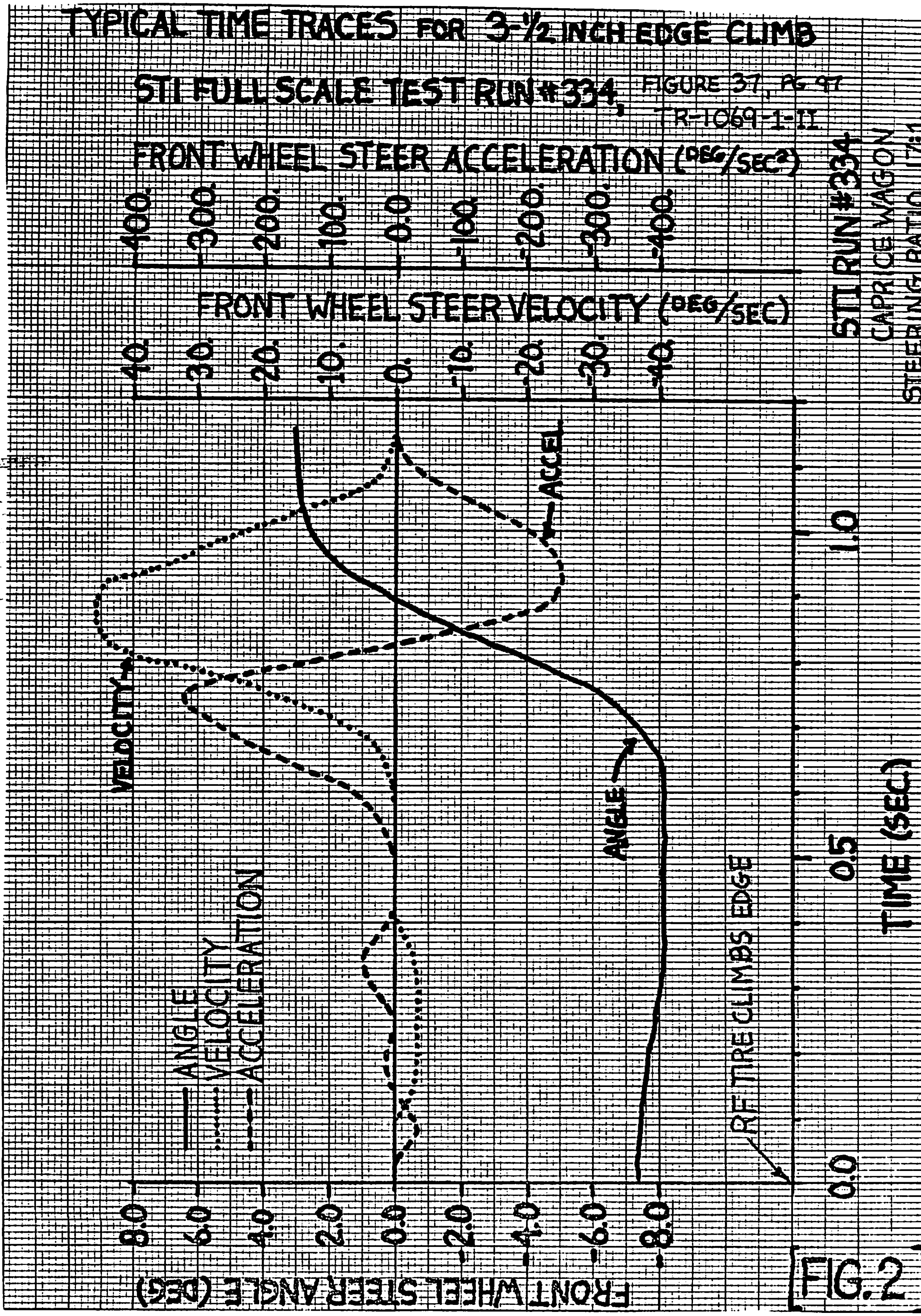


Figure 34 - Time-History HVOSM Plot

Figure 35 is a sample algorithm test run of DRIV2 utilizing inputs representative of the characteristics of Figure 34 (Note: DRIV2 algorithm only, no vehicle simulated, and steering system deceleration was started immediately after acceleration completed). Figure 36 is another algorithm test run utilizing the driver characteristics that have been used in the initial scrubbing excursion run series (Note: The steering system was not decelerated in the run depicted in Figure 36).

4. Modifications dealing with motion resistance due to soil sinkage: The basic phenomena that were simulated within the present research effort were the overall vehicle/driver system responses to the drop-off of one or two vehicle wheel(s) from the travel way onto a soft-soil shoulder. Tire sinkage into soft soil produces motion resistance forces which increase the difficulty associated with maneuvering the vehicle back onto the travel way. The characteristics of forces associated with tire sinkage include both a drag force opposing the motion of the wheel as well as an aligning torque which tends to align the wheel with the direction of travel (i.e., opposing steering inputs).

To permit the simulation of motion resistance forces associated with wheel sinkage in various soils, minor modifications of relationships developed by Bekker[26,27] for a rigid wheel in homogeneous soils were incorporated into the HVOSM. The reason for the use of Bekker's relationships for a rigid as opposed to an elastic wheel are as follows:

1. The relatively cumbersome nature of Bekker's equations for the motion resistance of elastic wheels which, among other things, require the experimental determination of two empirical resiistance coefficients.

2. For inflation pressures above 25 to 30 psi, the magnitude of the motion resistance force appears to be independent of the inflation pressure[26] and the average inflation pressure of pneumatic tires used in conventional passenger cars is at or above this range.

The minor modifications of Bekker's relationships that were incorporated into the HVOSM for the present research effort included an adjustment of the magnitude of the motion resistance force for a side-slipping tire and the application of a torque to the steering system to approximate the aligning effects produced by the combination of tire sinkage and vehicle motion.

The basic procedure utilized to calculate the magnitude of the motion resistance forces is as follows:

1. Determine tire sinkage.

2. Determine tire sideslip angle.

3. Determine the projected area of tire/soil interface.

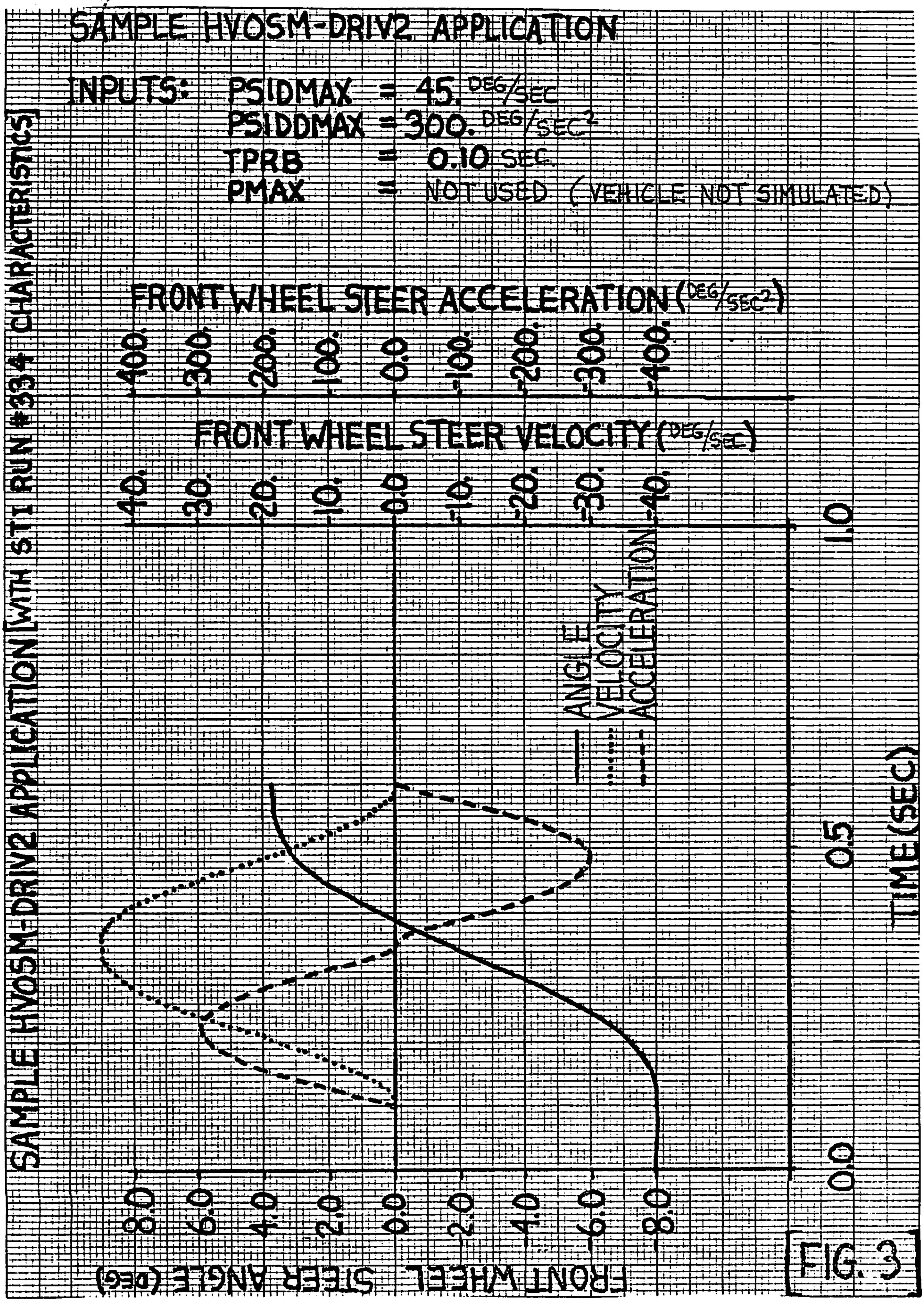


Figure 35 - DRIV2 Test Run

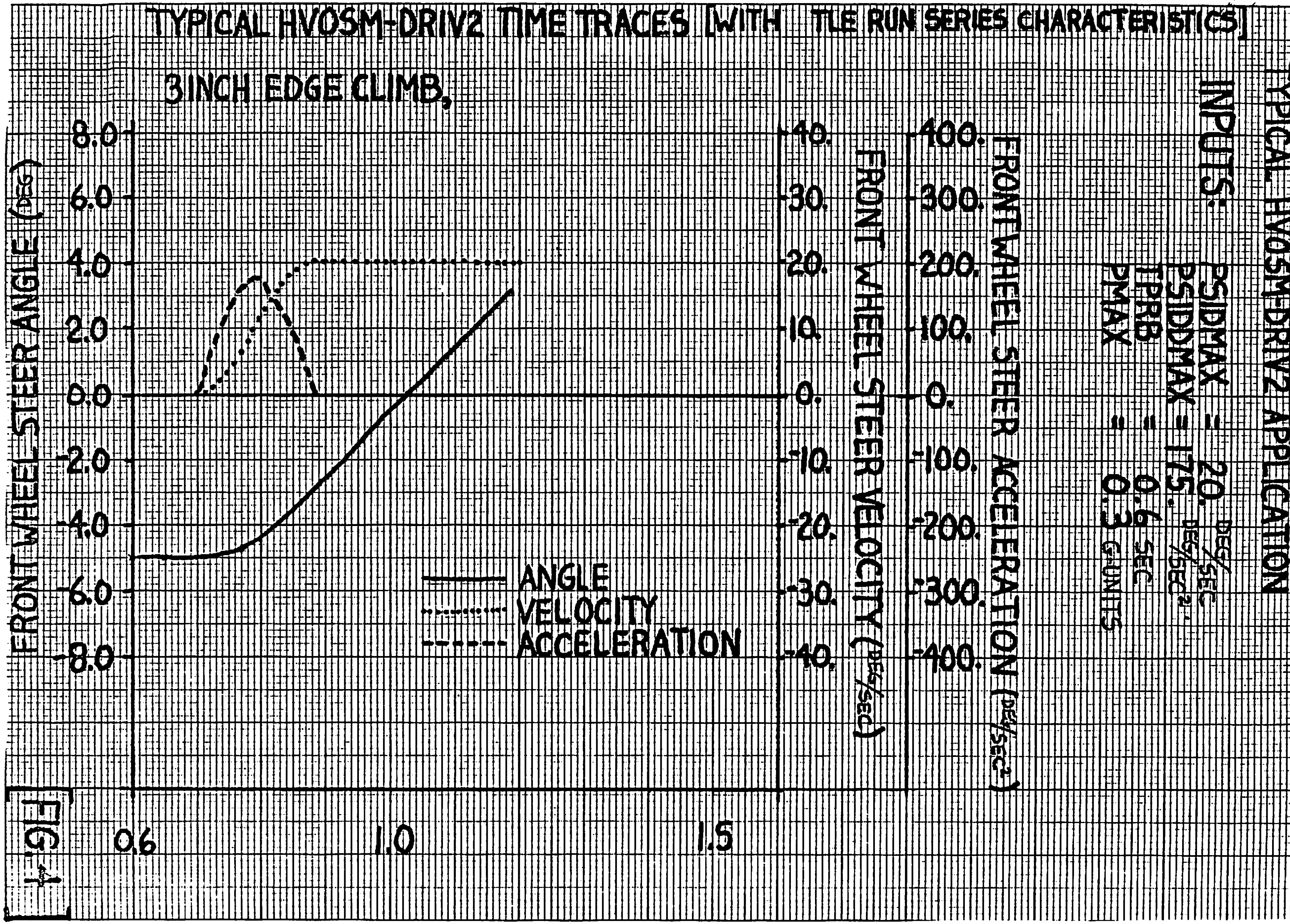


Figure 36 - Scrubbing Excursion Run

4. Calculate the motion resistance force for a tracking wheel.

5. Adjust the magnitude of the motion resistance force for a side-slipping tire.

6. Apply the motion resistance force.

A discussion of the steps follows.

a. Tire sinkage: The sinkage of the vehicle tire for a given load, W, can be approximated by Bekker's equation:[27]

$$Z = \left[\frac{3W}{(3-n)(K_c + bK_\phi)\sqrt{D}}\right]^{\frac{2}{2n+1}}$$

where:
Z = tire sinkage, inches
W = tire load, lbs
K_c = modulus of soil deformation due to cohesive ingredients of the soil, lbs/in^{n+2}
K_ϕ = modulus of soil deformation due to frictional ingredients of the soil, lbs/in^{n+2}
n = exponent of the soil deformation
b = tire tread width, inches

The constants, K_c, K_ϕ and n are determined by means of measurement techniques outlined by Bekker.[27]

b. Determination of the tire Sideslip angle: The tire sideslip angle is the angle between the longitudinal tire axis and the direction of motion of the tire. The tire sideslip angle is calculated as follows:

$$\alpha_i = \arctan\left(\frac{V_{Gi}}{U_{Gi}}\right) - \psi_i$$

where:
α_i = tire i sideslip angle
V_{Gi} = tire i contact point lateral velocity in the direction parallel to the tire-terrain contact plane
U_{Gi} = tire i wheel center forward velocity in the direction parallel to the tire-terrain contact plane
ψ_i = steer angle of tire i projected into the tire-terrain contact plane

The calculation of the tire sideslip angle permits the calculation of the tire/soil interface area (step 3) and the resolution of the resultant motion resistance force to oppose the motion of the wheel (step 6).

c. Determination of the tire/soil interface area: Utilizing the previously determined sideslip angle and tire sinkage, the projected tire/soil interface area can be approximated by:

$$A_p = \cos\left|\alpha_i\right| * A_F + \sin\left|\alpha_i\right| * A_S$$

where: A_p = projected tire/soil interface area
α_i = tire sideslip angle
A_F = approximate area of the front of the tire in contact with the soil
≅ tire width * tire sinkage
A_S = approximate area of the side of tire in contact with the soil
$\cong \frac{1}{2} R^2 (\theta - \sin\theta)$

where: R = tire radius

$$\theta = 2 \arccos \frac{(R-Z_o)}{R}$$

Z_o = tire sinkage

d. Calculation of the motion resistance force: The relationship presented by Bekker[26] for determining the magnitude of the motion resistance force for moderate sinkage (i.e., < 1/6 of the wheel diameter) of a rigid wheel will be utilized for the present research effort. The general equation is as follows:

$$R = \frac{3W^{\varepsilon}}{3-n^{\varepsilon}(n+1)(K_c+bk_{\phi})^{\frac{1}{2n+1}} D^{\varepsilon/2}}$$

where: $\varepsilon = \frac{2n+2}{2n+1}$

R = motion resistance force, lbs.
D = wheel diameter, inches
W = wheel load, lbs.
n, K_c, b, K_{ϕ} = Bekker's soil constants, see a above.

Numerous values for the soil constants required as input to the tire sinkage and motion resistance relationships are available as follows:

Ref. 26, p. 55.
Ref. 27, pp. 240, 332, 340

A check of the values for soil constants contained in the literature for an approximate nominal tire load configuration (i.e., wheel load = 1,000 lbs, tire width = 4 in.) reveals that in a number of instances Bekker's relationships produce excessive and probably unrealistic estimates for tire sinkage and motion resistance force (i.e., << 1/6 wheel diameter). Therefore, for the present research effort, the types of soils that have been used are those which exhibit less than 2 in. of sinkage for the nominal tire load configuration.

A check was also installed in the corresponding routines of HVOSM for the following:

1. If at the nominal load the tire sinkage is estimated at greater than 2 in., the program execution will terminate.

2. If at any time during the program execution the tire sinkage exceeds one-sixth the wheel diameter, the program execution will terminate.

The relatively simplistic approach within the limited scope of the present research effort for approximating the motion resistance forces associated with tire sinkage in soil required that these be installed.

e. Adjustment of the motion resistance force: The results of measurements made by Söhne[28] contained in reference 27 indicate that a sideslipping tire produces an increase in the magnitude of the motion resisting force. Intuitively, the data presented appear to indicate that the increase in the motion resistance force is due to an increase in the tire/soil interface area.

To approximate this effect, the magnitude of the motion resistance force calculated in Step 4 was adjusted proportional to the increase in the tire/soil interface area for a sideslipping tire.

f. Application of motion resistance forces and moments: The resultant motion resistance force was applied opposing the wheel motion as follows:

$$FPLOWX = R_{RES} * \cos \alpha_i$$

$$FPLOWY = R_{RES} * \sin \alpha_i$$

where: FPLOWX = resultant motion resisting force in the tire X direction

FPLOWY = resultant motion resistance force in the tire Y direction

R_{RES} = total resultant motion resisting force

α_i = tire sideslip angle

A corresponding moment was also applied to the steering system as follows:

$$M_{PLOW} = F_{PLOWY} * PT_{PLOW}$$

where: M_{PLOW} = Moment due to tire sinkage

F_{PLOWY} = Y component of motion resistance force

PT_{PLOW} = tire plow force pneumatic trail

The application of a moment approximates the effects of the tire sinkage on alignment of the steered wheels with the direction of motion.