MEDIAN DIKE IMPACT EVALUATION: SENSITIVITY ANALYSIS

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An impact sensitivity analysis was performed on earthen drainage dikes that are constructed in the median of divided highways perpendicular to the roadway (1). Six parameters are examined: approach velocity, approach angle, dike lateral impact position, dike approach slope, soil type, and median profile. Results are evaluated by comparing maximum values of acceleration, incremental velocity change, and center-of-gravity height. Dynamic variable data are presented for selected cases. The simulation program is described along with the modifications necessary for simulating travel over soft soil (a common condition in drainage control areas). Conclusions indicate the probable unsafe character of the current dike standard.

•IN current Michigan freeway design practice, dikes are placed in the median perpendicular to the right-of-way to control surface water runoff. Because of the proximity of the dikes to traffic and ramp-like cross sections, a program was initiated to evaluate dike configurations in terms of the dynamic response imparted to an impacting vehicle. The purpose of the evaluation is to define an optimum cross section for both minimizing the hazard to errant vehicles and maintaining positive drainage control.

Dynamic interaction of the vehicle and dike was simulated by means of the Cornell Aeronautical Laboratory Single Vehicle Accident (CALSVA) model. The model is programmed for use on a digital computer and was altered where necessary to simulate specific dike-vehicle interaction phenomena. The primary modification was the inclusion of a high-speed, soft soil subroutine.

PROBLEM DEFINITION

The current standard dike configuration used in Michigan (2) is shown in Figure 1. The approach slope on both sides of the crest is 1:6. The objective of the program is to examine this cross section and variations of it to arrive at a more optimum design standard.

The final section must be evaluated over the range of impact conditions that exist in the operational environment to ensure its adequacy. In addition, criteria for evaluation must be developed that relate impact phenomena to occupant safety.

Operational Impact Conditions

Operational impact conditions fall into four main areas: vehicle type, approach velocity, approach angle, and impact position along the dike. The range of interest for the first three of these can be determined from survey data that have been collected for other purposes.

Vehicle type data in the form of weight frequency and distribution (3) are shown in Figure 2. Because more than 85 percent of all vehicles weigh between 1,500 and 4,500 lb, this weight range was chosen for this study.

Approach velocity data are difficult to ascertain because of the probable differences between highway speeds and actual impact speeds after some braking has occurred. The

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Figure 1. Basic median profile with 1:6 dike face slope.

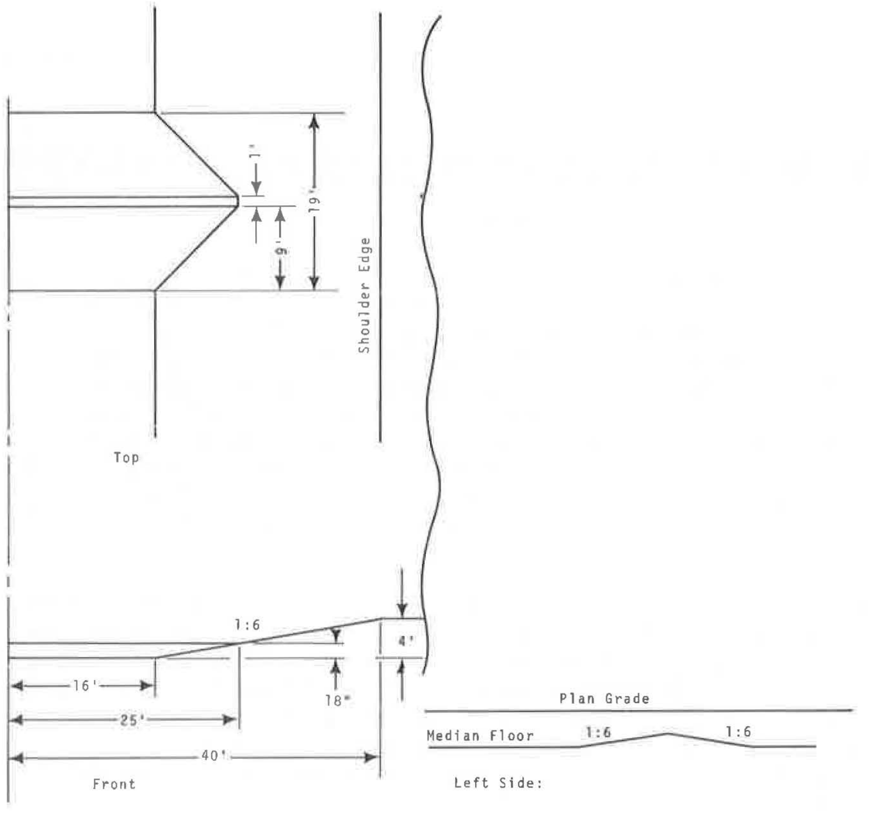
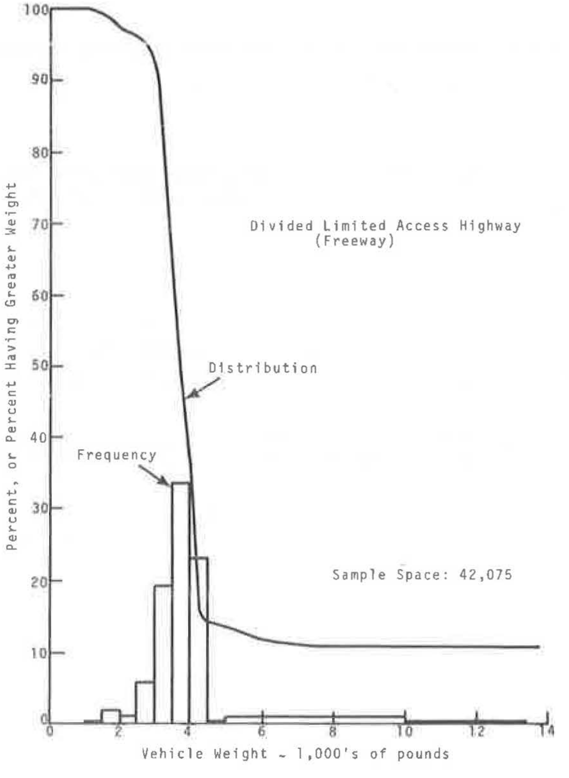


Figure 2. Vehicle weight distribution and frequency.



range for approach velocities was therefore taken from two sources: actual highway speed survey data (4) and impact speed data estimated by investigating police officers (5). The two kinds of data are shown in Figures 3 and 4 respectively. From these data the range of applicable impact speeds was chosen to lie between 40 and 80 mph. This covers 98 percent of the vehicles in the highway speed survey and 86 percent of the vehicles in the estimated impact speed range.

The range of approach angles was taken from the Hutchinson data (6) shown in Figure 5. Ninety percent of the roadway exit angles measured in this study were between 0 and 25 deg; this was therefore chosen as the range of interest.

Evaluation Criteria

Criteria for evaluating a particular dike cross section must involve considerations of safety as well as drainage efficacy. Drainage is not an overriding consideration, however, because primary drainage control requirements can be used to calculate minimum dike height. Therefore, if a minimum height constraint exists the controlling factors in dike design are related to the safety of motorists.

Occupant safety, in turn, can be correlated with the time histories of injury-related kinematic variables as the vehicle contacts the dike. According to current understanding (7), the primary kinematic variables that influence occupant injury are incremental change in velocity, acceleration, and acceleration onset. Velocity change manifests itself in the relative velocity of a passenger in a secondary collision with the vehicle interior; acceleration and acceleration onset are shown through the internal loading and deformation of body parts. Of the three, least is known about the effects of acceleration onset.

The level, direction, and duration of action of these variables are generally considered in assigning tolerance levels. The situation is complicated by several factors, however, some of which include passenger restraint, age, vital condition, and body orientation. Therefore, a sharp cutoff between injury and no injury in terms of kinematic variables does not exist, and injury assessment on this basis can only be made in a general sense. Working-range thresholds used in this evaluation are as follows (7, 8):

	Injury Threshold	
Criterion	Magnitude	Duration
ΔV_z	12 fps	—
a_z	10 g	100 to 200 msec

No threshold is listed for da_z/dt (acceleration onset) because of the general lack of applicable experimental data. Therefore, only ΔV_z and a_z were used as injury-related evaluation criteria. Each is associated with vertical motions of the passenger because this is the primary direction of the forces imparted to the vehicle as it crosses the dike.

MATHEMATICAL MODEL

The basic digital computer simulation program used in the study was developed and validated by McHenry and DeLeys at Cornell Aeronautical Laboratory. Briefly, the vehicle is represented in the program by an assemblage of four rigid masses: the main vehicle body, or "sprung mass," a solid rear axle, and two independent front wheels with their attendant suspension systems. The sprung mass has 6 degrees of freedom (roll, pitch, and yaw rotations and longitudinal, lateral, and vertical displacements); the rear axle has two (roll rotation and vertical displacement); and each front wheel has one (vertical displacement). An additional degree of freedom can be associated with the steering system as a user option. Other vehicle simulation features include representations of front-wheel camber, rear-axle roll steer, anti-pitch suspension characteristics, nonlinear suspension springs in both extension and compression (including bump stops), Coulomb and viscous friction in the suspension, elastic roll stiffness, and nonlinear tire aligning torque. A more extensive description of the program is given elsewhere (9, 10, 11).

Figure 3. Vehicle speed distribution and frequency for passenger automobiles.

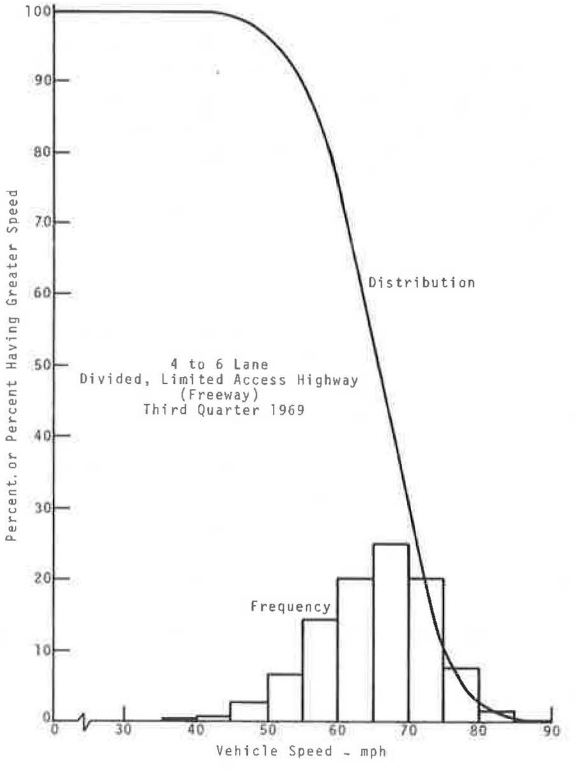


Figure 4. Estimated impact speed distribution and frequency for passenger automobiles.

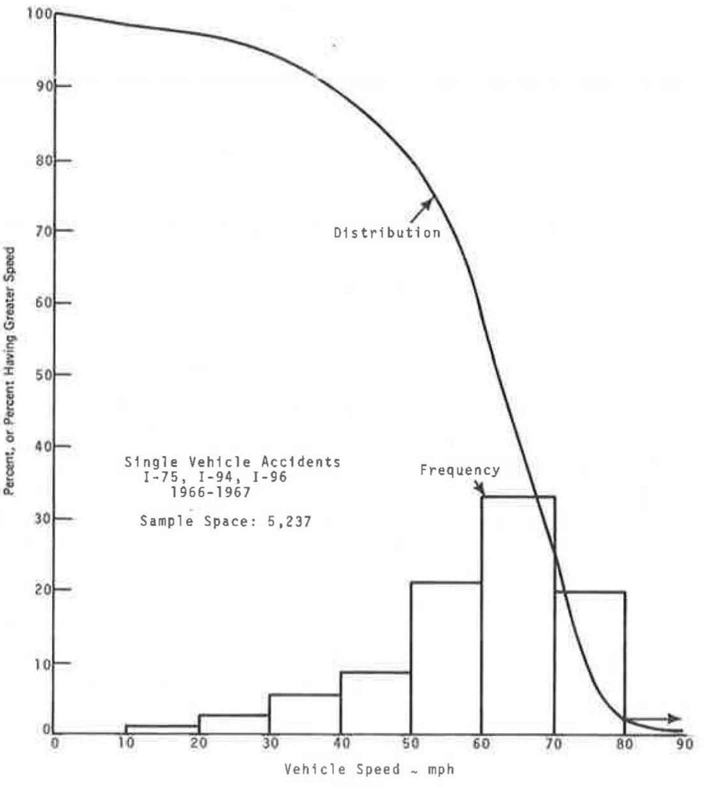


Figure 5. Encroachment angle distribution and frequency.

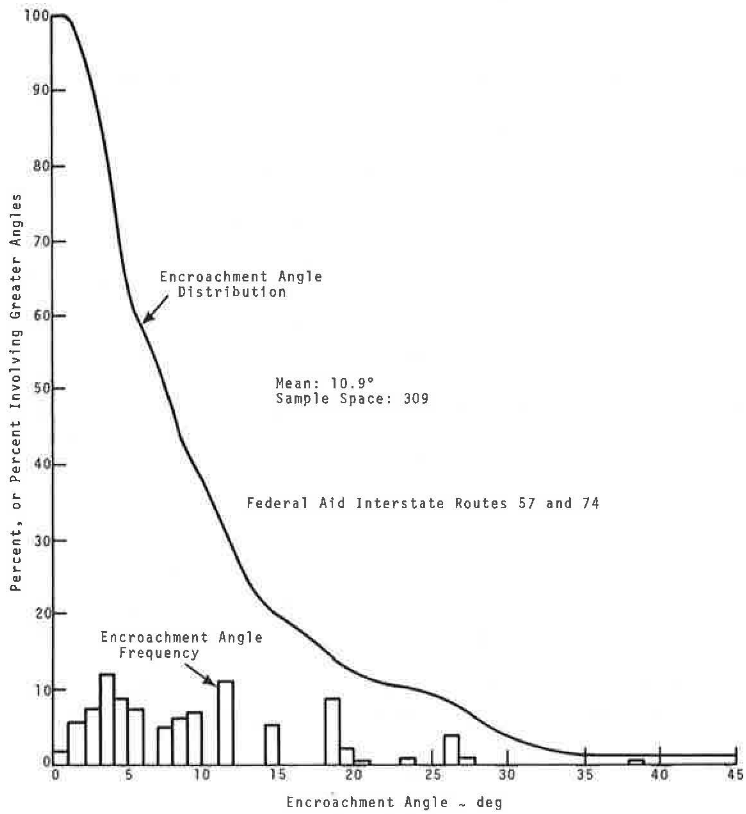


Table 1. Dike interaction sensitivity analysis (simulation exercise program).

Case	α (deg)	V (mph)	Lateral Position	Approach Slope	Soil Type	Approach Profile
1 (Baseline)	0	40	Center	1:6	Hard, frozen	Flat to dike
2	25	40	Center	1:6	Hard, frozen	Flat to dike
3	0	80	Center	1:6	Hard, frozen	Flat to dike
4	0	40	One wheel on flat, one on dike	1:6	Hard, frozen	Flat to dike
5	0	40	Center	1:10	Hard, frozen	Flat to dike
6	25	40	Center	1:6	Hard, frozen	Full median profile
7	0	40	Center	1:6	Soft, moist	Flat to dike
8	25	80	Center	1:6	Hard, frozen	Full median profile

The primary program addition for evaluating earthen dikes was the inclusion of a soft soil subroutine. Soft, moist soil is not uncommon near median dikes because the primary dike function is runoff control.

Most of the literature on tire-soil interaction is oriented toward military vehicles operating in swamp or sand environments. This emphasis usually implies track-laying vehicles traveling at low velocities (under 5 mph). Wheeled off-road vehicles, on the other hand, are characterized by tires with large diameters and low tire-soil contact pressures. Several investigators have claimed varying degrees of success in mathematically modeling these restricted situations, but few basic guidelines are generally agreed on. The most widely accepted theory is based on the low-speed, quasi-static analysis of Bekker (12, 13).

For stiff-tired passenger vehicles traveling over grassy medians at highway speeds, conditions are obviously different. Because the low-speed quasi-static theory is all that is available, an attempt was made to apply it to the preceding conditions. The results, although strictly conjectural, are intuitively reasonable for representative soil characterizing parameters.

The two basic phenomena to be modeled are tire sinkage and forward motion resistance. According to Bekker, the basic pressure-sinkage relationship for a continuous, homogeneous, isotropic soil can be stated as follows:

$$p = (k_c/b + k_\phi)z^n \tag{1}$$

where p is pressure and z is sinkage. The constants k_c, k_ϕ, and n are determined by driving a flat plate of dimension b into the soil measuring the necessary pressure to achieve a certain penetration. A graphic interpretation of test data for two sizes of plates yields the necessary constants.

If it is assumed that the wheel is rigid relative to the soil, the basic flat plate equation can be extended to a wheel of diameter D carrying a load W such that will sink.

$$z = 3W/[(3 - n)\ (k_c + bk_\phi)\ D^{1/2}] \tag{2}$$

Additional assumptions implicit in Eqs. 1 and 2 imply that predicted values become more valid as the soil sinkage approaches zero and the wheel diameter approaches infinity. Practical limits indicate adequate agreement with test data at low speeds for a miximum diameter of 20 in. and a maximum sinkage of one-sixth of the diameter.

As the tire sinks while moving forward, it must displace the soil in its path. The soil is partly compacted beneath the rolling tire surface and partly bulldozed to the side. These two effects are generally lumped together in calculating the forward motion resistance as follows:

$$R = (3W)^\epsilon/[(3 - n)^\epsilon\ (n + 1)\ k^{1/2n+1}\ D^{\epsilon/2}] \tag{3}$$

where

$\epsilon = (2n + 2)/(2n + 1)$ and
$k = k_c + bk_\phi$.

This relationship is derived by considering the ground reaction over the surface of the tire-soil interface and integrating over that area to obtain the equivalent resistance force.

The mathematical relations in Eqs. 1, 2, and 3 were incorporated into the variable terrain profile subroutine of the original simulation and are available on a user option basis.

SENSITIVITY ANALYSIS

The procedure for the sensitivity analysis consisted of making variations on a single standard case. The sensitivity of the vehicle-dike system to a particular parameter was then determined, in terms of the evaluation criteria, by varying only that parameter from the standard. This resulted in a series of two-point estimates of the true variation for each parameter.

The parameters and the respective values of each that was used in the sensitivity analysis are listed as follows:

1. Approach velocity: 40 mph, 80 mph;
2. Approach angle: 0 deg, 25 deg;
3. Dike approach slope: 1:6, 1:10;
4. Impact position along dike: center, one wheel on flat—one wheel on dike;
5. Approach profile: flat to dike, full median profile; and
6. Soil type: hard-frozen, soft-moist. The first value given for each of the preceding parameters was the standard case value.

The simulation exercise program for the specific cases that were examined is given in Table 1. Parameters and variables that were held constant for these runs are as follows:

1. A dike height equal to 18 in.;
2. A fixed steering-wheel position;
3. An unpowered vehicle;
4. Up to 75 parameters defining the dynamic properties of a 1963 Ford Galaxie, four-door, eight-cylinder sedan; and
5. The median profile as shown in Figure 1.

RESULTS

Study results were derived from kinematic data histories from the vehicle-dike simulation runs. Two samples of the kinematic data are shown in Figures 6 and 7.

Kinematic Data

Kinematic data for case 1 (Table 1) are shown in Figure 6. Vertical acceleration, vertical velocity, and center-of-gravity height are shown. Center-of-gravity height is measured with respect to a flat reference, with zero corresponding to the at-rest center-of-gravity position. The acceleration and velocity variables are measured with respect to a body fixed coordinate system. The arrows attached to the center-of-gravity height points represent the vehicle pitch attitude.

The dike profile is actually about 22 in. below the indicated position because the at-rest center-of-gravity height is taken as zero. The dike profile is also distorted because of the difference in vertical and horizontal scales.

Examination of the data reveals that the vehicle flies into the air to a maximum height of about 5 ft following initial contact with the dike. The vehicle pitch angle reaches an upper value of about 16 deg during this time. A maximum acceleration of about 17 g occurs at the landing point following the initial airborne phase. This acceleration is the peak of a fairly narrow spike, however, and the average acceleration during the 100-msec interval between the time marks within which the spike falls is about 6 g. During this period, the oscillation frequency of the acceleration trace is about 40 Hz. In general, this kind of acceleration would probably not cause injury to a seated passenger.

The maximum change in velocity, about 21 fps, occurs at the impact after the second airborne phase. This would probably cause injury to an unrestrained passenger in a "second colission" with the car interior.

Data for a second example, case 3, are shown in Figure 7. This case differs from case 1 only in that the velocity is 80 mph rather than 40 mph. Vehicle motions are, however, markedly different.

The vehicle travels more than 13 ft into the air following initial contact with the dike and 6 ft during the first rebound. Maximum pitch angle reaches 46 deg. This occurs during the second airborne phase and is responsible for the irregularity in the center-of-gravity trace near the 300-ft position point. The rear end of the vehicle strikes the ground at this location.

Figure 6. Case 1 kinematic data.

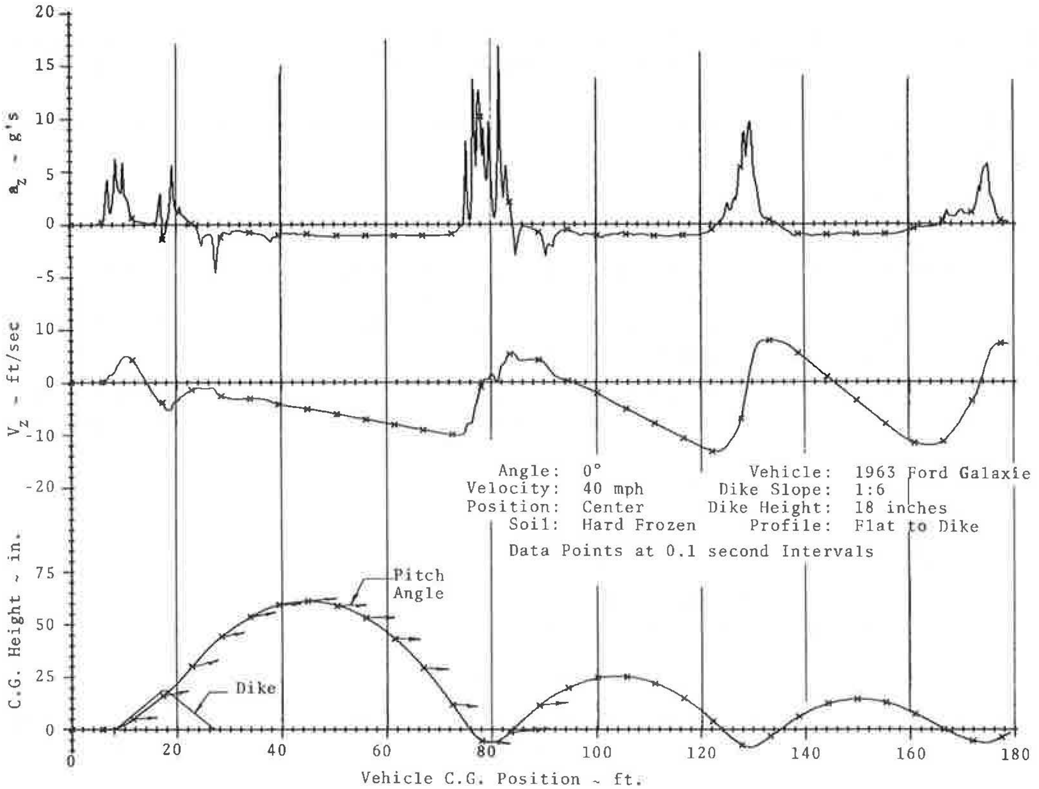
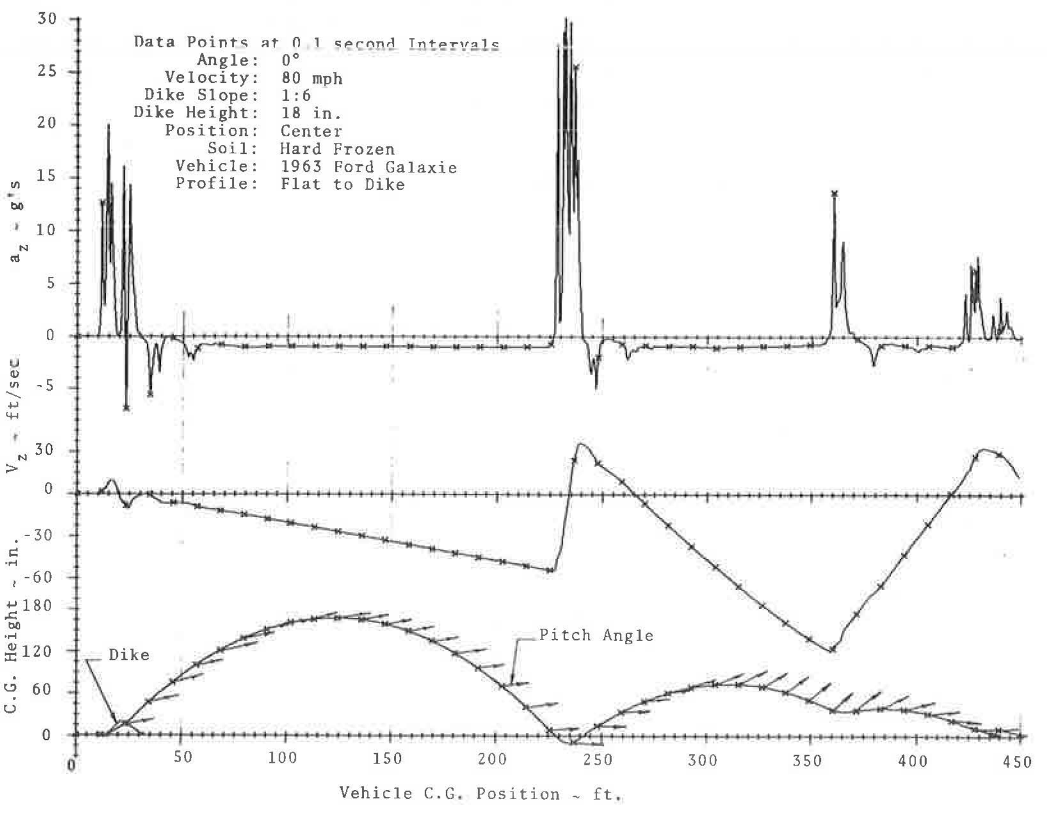


Figure 7. Case 3 kinematic data.



Maximum acceleration is again at the landing point following the initial airborn phase. Peak acceleration is more than 30 g, and the average is about 15 g over a 100-msec interval. The oscillation frequency is about 50 Hz. It is unlikely that an unrestrained passenger could withstand these accelerations without injury.

The maximum change in velocity is about 73 fps. This occurs at the initial landing when the vehicle strikes the ground and rebounds. This velocity change is not entirely vertical because it is measured with respect to a coordinate system fixed in the car. Large pitch angles of the vehicle tend to complicate the situation, with the result that some of the velocity change is a component of forward velocity. The vehicle attached coordinate system is realistic relative to passenger attitute, however, in that the passenger feels these velocity changes through a reorientation of his motion with respect to the vehicle interior. Needless to say, the indicated magnitude of velocity change would very probably cause injury.

Comparative Data

The sensitivity of the vehicle-dike system to a specific parameter was estimated by comparing the variation of selected evaluation measures as the parameter was varied. The measures were maximum vertical acceleration, maximum vertical velocity change, and maximum center-of-gravity height. The first two were compared with the threshold levels given in Table 1 as a means of estimating occupant injury.

Angle Effect—The effect of varying the approach angle to the dike is given in Table 2, in which cases 1 and 2 are compared with approach angles of 0 and 25 deg respectively. Interestingly, case 1 shows larger acceleration and greater center-of-gravity movement, whereas case 2 shows greater velocity change. The effects are due to the roll motion inherent in case 2 and tend to suggest that impact angle has a sizable effect on vehicle kinematics. Results in both cases are in the range of possible passenger injury.

Approach Velocity Effect—The effect of approach velocity on the vehicle-dike system is given in Table 3. Two sets of runs are compared with velocities of 40 and 80 mph. One set is for a 0-deg impact angle (cases 1 and 3), whereas the other is for a 25-deg angle with a full median approach profile (cases 6 and 8).

By examining the 0-deg approach angle first, one can observe that there are marked increases in all three measures when the speed is increased from 40 to 80 mph. Passenger injury is virtually certain in the 80-mph case.

One could get a different impression from the 25-deg approach angle data, however, because the increases here are not nearly as great. Except for the center-of-gravity height, this can be explained by the fact that the case 8 run ($V = 80$ mph, $\alpha = 25$ deg) was terminated just after impact with the dike when the vehicle had rolled over on its side. Therefore, the acceleration and ΔV_z values are not strictly comparable. Each of these would undoubtedly have been higher had the run continued. Center-of-gravity height is fairly representative, however, because the vehicle appeared to be near maximum height at the termination point.

Approach velocity has a large effect on all measures, then, except perhaps for center-of-gravity height at high approach angles. In the latter case, much of the energy that would normally cause the car to fly into the air is converted to roll motion.

Lateral Position Effect—The effect of impact position along the dike is given in Table 4, in which cases 1 and 4 are compared. In case 1, the vehicle was directed toward the center of the dike, whereas in case 4 the vehicle was positioned along the median side slope such that one wheel went over the dike while the other just missed. The height of the dike under the traversing wheel was about 10 in.

The data given in Table 4 make it quite clear that there is a dramatic decrease in vehicle loading for the off-center impact. Kinematic values are negligible by comparison, which indicates that position along the dike has a considerable effect on vehicle kinematics.

Dike Approach Slope—The system sensitivity to dike approach slope is given in Table 5. Data for cases 1 and 5 with slopes of 1:6 and 1:10 respectively are compared. In each case, values of acceleration, ΔV_z, and center-of-gravity height for the 1:10 case are roughly half those for the 1:6 case. Whereas the 1:6 slope might cause injury, the 1:10 slope would probably not. Dike slope is an important factor, then, in vehicle-dike interaction.

Soil Effect—The effect of soil variation on the system is indicated in Table 6, which compares cases 1 and 7. Evidently, soft soil causes a substantial reduction in vehicle acceleration and velocity change—in effect, altering the injury probability from likely to unlikely. The soil is quite soft, however, with the vehicle sinking in up to 8 in. at highway speeds.

As indicated earlier, the soft soil model used in the simulation is strictly an intuitive one. Both theoretical and experimental work are required to develop a truly valid high-speed soil model, and this has not been done. The model appears to be representative, however, and as a minimum gives an indication of the attenuating benefits of softer soil. Soil is therefore an important factor relative to vehicle kinematics.

Median Profile Effect—Case 2 involves a flat approach to the dike, and in case 6 the vehicle approaches over the full median profile. The approach angle in each case is 25 deg. Comparative data are given in Table 7.

Peak accelerations are slightly less for the full median case, whereas the maximum change in velocity is substantially less. Lower values for the full median case are due to the roll attitude of the vehicle as it travels down the median slope. Because the vehicle is approaching the dike at an angle, one front wheel strikes the dike before the other, which causes an initial rolling motion. The vehicle is already rolled by virtue of its traveling down the median slope, however, and the induced roll is less. Resulting impact loads on the front tire are also less. Although the difference in ΔV_z values is substantital, the general agreement is closer than in any of the other cases.

CONCLUSIONS AND RECOMMENDATIONS

Sensitivity analysis has shown that most of the vehicle-dike parameters investigated have a marked influence on vehicle dynamics. It also seems clear that, due to the general nonuse of seat belts, the standard dike profile, with 1:6 approach slope, is unsafe. Indeed, a casual examination of several dike installations indicates that dikes in general are rather nonstandard and that many have steeper slopes than 1:6. Thus, the problem is an acute one. Specific conclusions are listed as follows:

1. Possible injury to unrestrained passengers is indicated at all speeds above 40 mph when a vehicle strikes the middle of a dike similar to the current Michigan standard.
2. Approach velocity, angle, impact position, dike slope, and soil type have sizable effects on vehicle kinematics. Dike approach profile has a lesser effect.
3. An impact velocity of 80 mph produces about twice the passenger loading that is experienced at 40 mph.
4. Striking the dike in the middle is far more traumatic than hitting off to one side. This suggests that the hazardous portion of the dike may be limited to a relatively narrow region.
5. Striking a 1:10 slope reduces passenger loadings by a factor of about one-half when compared to a 1:6 slope.
6. Soft, moist soil attenuates passenger loading on the order of 50 percent when compared with rigid terrain.
7. Approaching the dike from the road shoulder appears to be less traumatic than approaching from a flat surface.

Now that the important interaction parameters have been identified, the next step is to proceed in developing an optimized cross section. This will require a full-scale test program and additional simulation activities.

Further investigation of high-speed, tire-soil interaction is also required. Since this investigation, the tire-soil work of Crenshaw (14) has been published, but further research is still needed.

ACKNOWLEDGMENT

The research reported in this paper was financed under the Highway Planning and Research Program and was sponsored by the Michigan Department of State Highways

Table 2. Approach angle effect on vehicle dynamics.

Case	V (mph)	α (deg)	$a_{z_{max}}$ (g)	$\Delta V_{z_{max}}$ (fps)	z_{max} (in.)
1	40	0	16.9	21.2	60.9
2	40	25	9.9	34.8	50.5

Table 3. Approach velocity effect on vehicle dynamics.

Case	V (mph)	α (deg)	Approach Profile	$a_{z_{max}}$ (g)	$\Delta V_{z_{max}}$ (fps)	z_{max} (in.)
1	40	0	Flat	16.9	21.2	60.9
3	80	0	Flat	30.3	72.6	168.1
6	40	25	Full median	8.2	17.8	50.4
8	80	25	Full median	12.7	59.3	59.1

Table 4. Lateral impact position effect on vehicle dynamics.

Case	V (mph)	α (deg)	Lateral Position	$a_{z_{max}}$ (g)	$\Delta V_{z_{max}}$ (fps)	z_{max} (in.)
1	40	0	Center	16.9	21.2	60.9
4	40	0	One wheel flat, one on dike	1.6	2.8	4.8

Table 5. Dike approach slope effect on vehicle dynamics.

Case	V (mph)	α (deg)	Approach Slope	$a_{z_{max}}$ (g)	$\Delta V_{z_{max}}$ (fps)	z_{max} (in.)
1	40	0	1:6	16.9	21.2	60.9
5	40	0	1:10	9.0	10.4	33.4

Table 6. Soil effect on vehicle dynamics.

Case	V (mph)	α (deg)	Approach Profile	$a_{x_{max}}$ (g)	$\Delta V_{z_{max}}$ (fps)	z_{max} (in.)
2	40	25	Flat	9.9	34.8	50.5
6	40	25	Full median	8.2	17.8	50.4

Table 7. Median profile effect on vehicle dynamics.

Case	V (mph)	α (deg)	Soil Type	$a_{z_{max}}$ (g)	$\Delta V_{z_{max}}$ (fps)	z_{max} (in.)
1	40	0	Rigid	16.9	21.2	60.9
7	40	0	Soft, moist	4.9	13.0	47.6

through a subcontract to the Highway Safety Research Institute from Wayne State University. The opinions, findings, and conclusions expressed in this paper are those of the authors and not necessarily those of the sponsoring agencies.

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