TENTATIVE CRITERIA FOR THE DESIGN OF SAFE SLOPING CULVERT GRATES

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Some highway drainage structures have a geometrical configuration that can cause an errant automobile to come to an abrupt stop or veer out of control. One such structure is the end culvert inlet with or without headwalls. In recent years, highway engineers have used sloping inlet and outlet grates that allow an automobile to traverse the culvert opening rather than come to an abrupt stop. Sloping grates are currently designed on the basis of judgment and experience because objective criteria are practically nonexistent. By using a mathematical simulation technique, we were able to investigate the dynamic behavior of a selected standard-size automobile traversing a median containing a crossover and a sloping culvert inlet grate. Twenty-three computer simulations were made. It was determined that 8:1 ditch side slopes and 10:1 culvert grate slopes produced tolerable automobile accelerations to an unrestrained occupant. Steeper combinations of side and grate slopes were found to produce severe accelerations and/or roll-over and should be avoided where possible. For purposes of structural design, it was found that the dynamic tire load on 8:1 and flatter grate slopes was about five times the automobile curb weight. For 6:1 and steeper grate slopes, the dynamic tire load reached values of about 10 times the automobile curb weight.

•AS discussed in a recent publication (1), some highway drainage structures are potentially hazardous and, if located in the path of an errant vehicle, can substantially increase the probability of an accident. These structures consist of cross drains and their appended culvert end structures, median and curb inlets, roadside channels or ditches, and other special drainage structures.

An objective for which the highway engineer should strive has been defined as follows:

> A traffic-safe drainage structure is one which does not inhibit the driver's ability to regain control of his vehicle—permitting him either to return to the traveled roadway or to stop safely without damage or injury (1).

General guidelines that aid the highway engineer in the design of a traffic-safe drainage structure have been presented elsewhere (1). These guidelines reflect the best knowledge available concerning those measures that have proved to be the most successful in minimizing the potential hazards associated with drainage structures and maintaining hydraulic efficiency.

A sloping inlet or outlet grate is a structure occasionally used in place of the abrupt culvert inlet with or without headwalls. Figure 1 shows a typical sloping grate installation. This study provides criteria for the design of a traffic-safe sloping culvert grate.

A mathematical simulation technique was used to study the traffic-safe characteristics of a sloping grate-slope configuration. The simulation provided information on the motion, forces, and accelerations of an automobile that could be expected during the event. Twenty-three different events were studied to identify important parameters

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Figure 1. Typical sloping culvert grate.

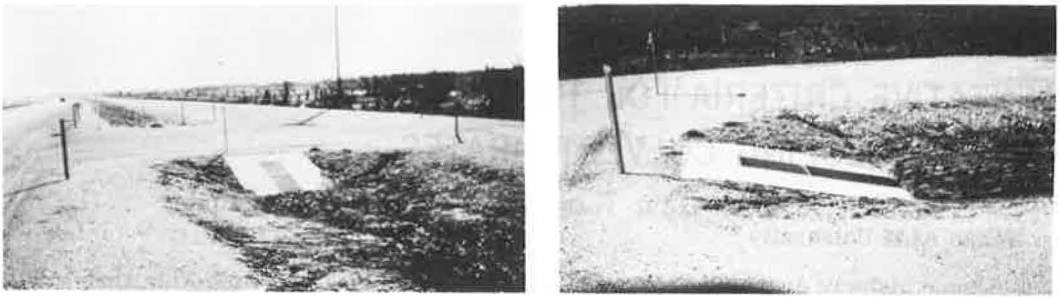


Figure 2. Idealization of automobile (2, 3).

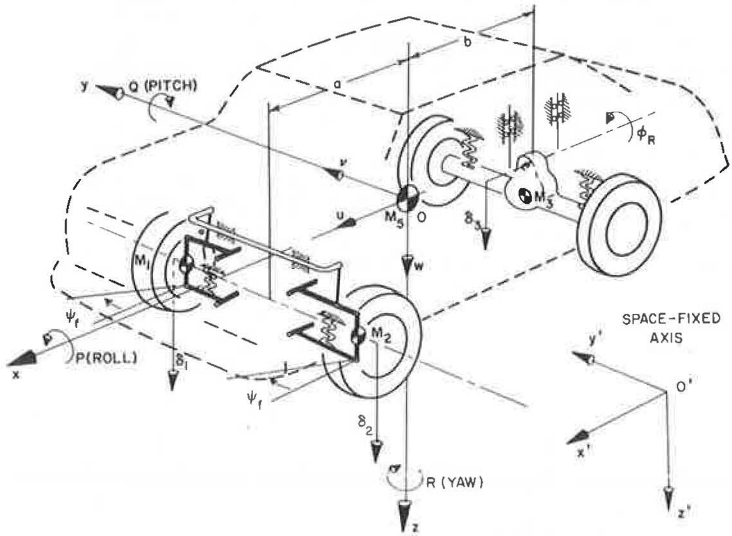
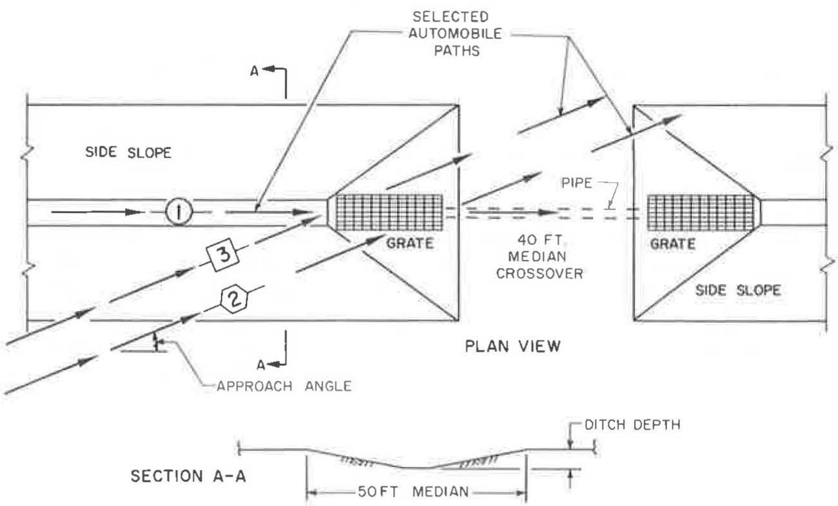


Figure 3. Simulated median terrain configuration and selected automobile paths.



and to make recommendations concerning grate design. The information provided, when used in conjunction with the data in Ref. 1, will help the highway engineer ensure that an errant automobile can safely traverse a defined side slope and adjoining grate slope configuration.

MATHEMATICAL MODEL OF AN AUTOMOBILE

In the evaluation and design of a roadway and its environment, it is important to understand the effects of various roadway geometric features on the dynamic response of an automobile and its occupants.

The mathematical model described here was used to investigate the dynamic response of an automobile negotiating various side slope and adjoining sloping grate terrain configurations. The model can also be used to investigate various other problems associated with the roadway environment, such as highway traffic barrier collisions, rapid lane change maneuvers, handling response on horizontal curves, and drainage-ditch cross sections.

The mathematical model was developed by Cornell Aeronautical Laboratory (CAL) (2, 3) and later modified for specific problem studies by the Texas Transportation Institute (TTI) (4). A conceptual idealization of the model is shown in Figure 2. The model is idealized as four rigid masses, which include (a) the sprung mass (M_s) of the body supported by the springs, (b) the unsprung masses (M_1 and M_2) of the left and right independent suspension system of the front wheels, and (c) the unsprung mass (M_3) representing the rear axle assembly. The 11 degrees of freedom of the model include translation of the automobile in three directions measured relative to some fixed coordinate axes system; rotation about the three coordinate axes of the automobile; independent displacement of each front wheel suspension system; suspension displacement and rotation of the rear axle assembly; and steering of the front wheels. A more detailed discussion of the mathematical model is given elsewhere (2, 3, 4).

The validity of the model is dependent to a large extent on the accuracy of the input parameters pertaining to the automobile selected. In this study, a 1963 Ford Galaxie four-door sedan was selected because of (a) the availability of data on the automobile parameters, (b) the excellent comparisons obtained by CAL (2, 3) between full-scale tests and mathematical simulation during a variety of maneuvers, and (c) its representativeness of a large population of automobiles with regard to size, weight, and suspension.

Very good comparisons were observed between full-scale ramp traversal tests and corresponding simulated tests conducted by CAL (3). The nature of a ramp traversal by an automobile is very similar to that experienced during traversal of a sloping grate.

Mathematical simulation provides a rapid and economical method to investigate the many parameters involved as an automobile traverses some defined ground forms. Once the limiting parameters are identified, it may be desirable to conduct a limited number of full-scale tests prior to final selection of a particular design. This approach, in contrast to a full-scale trial-and-error approach, will yield more meaningful results with considerably less resource expenditure.

The mathematical simulation was facilitated by the use of an IBM 360 computer. Approximately 1 min of computer time is required for 1 sec of event time. On the average, it takes 3 sec for an automobile departing the roadway at a speed of 60 mph and at an angle to traverse some defined side and sloping grate ground form. The computer cost for 3 min of time is approximately $25.

EVALUATION CRITERIA

The criteria used in this study to investigate the traffic-safe characteristics of a ground form in the vicinity of sloping grate culvert were (a) automobile stability, (b) automobile airborne distance, and (c) automobile acceleration severity index.

The stability criterion requires that an automobile, subsequent to becoming airborne on the sloping grate, remain in an upright position. Roll-over was considered sufficient to classify a terrain configuration as being not traffic-safe. Roll-over was observed to occur in one of two ways. First, side roll-over occurred about the X-axis of the automobile. Second, front-end roll-over occurred about an axis parallel to the Y-axis (pitch) upon contacting the terrain after being airborne.

The distance airborne criterion requires that the automobile, subsequent to becoming airborne on the sloping grate, land in a location that would not endanger the lives of motorists in the opposing traffic lanes of travel.

The acceleration severity index requires that the combined longitudinal, lateral, and vertical accelerations of the automobile at its center of mass have a severity index equal to or less than unity. A severity index of less than unity indicates that serious or fatal injuries will probably not occur. The equation used to determine the severity index is discussed in some depth elsewhere (5). The severity index equation is as follows:

$$SI = \sqrt{\left(\frac{G_{long}}{G_{XL}}\right)^2 + \left(\frac{G_{lat}}{G_{YL}}\right)^2 + \left(\frac{G_{vert}}{G_{ZL}}\right)^2}$$

where

G_{long} = actual automobile acceleration in longitudinal Z-axis, g;
G_{lat} = actual automobile acceleration in lateral Y-axis, g;
G_{vert} = actual automobile acceleration in vertical Z-axis, g;
G_{XL} = limit automobile acceleration in longitudinal X-axis, g;
G_{YL} = limit automobile acceleration in lateral Y-axis, g; and
G_{ZL} = limit automobile acceleration in vertical Z-axis, g.

The limit accelerations in the preceding equation were defined as the highest automobile accelerations that an occupant could sustain without serious or fatal injury. The limit acceleration values used in this study for an unrestrained occupant were G_{XL} = 7 g, G_{YL} = 5 g, and G_{ZL} = 6 g.

It is well known that the actual accelerations of an automobile can reach high values over a small time interval (from roughly 2 to 10 msec). Such accelerations are commonly referred to as "spikes." There is much discussion among highway and research engineers as to whether automobile acceleration spikes are actually felt by the occupants. In a recent publication (6), it was concluded that the accelerations of an automobile at its center of mass should be measured as an average over a time interval of 50 msec. The acceleration values reported in this study are in accordance with those findings (6).

MATHEMATICAL SIMULATION RESULTS

In this study, information is provided on a common type of culvert end structure protected by a sloping grate. This information was obtained from a mathematical simulation of a selected 1963 Ford Galaxie traversing various side and sloping grate ground forms at a median crossover.

A median width of 50 ft and, for all but one case, a ditch depth of 3 ft were selected to limit the number of parameters to be studied. The departure speed of the automobile from the roadway was taken as 60 mph, whereas the departure angle was treated as a variable. Figure 3 shows a typical roadway site terrain configuration. The results of this study also apply to at least two other roadway sites: (a) where two sloping grates collect and distribute water into a culvert pipe placed under the traveled roadway to a drainage ditch in the right-of-way as shown in Figure 4, and (b) where the culvert end structure is placed parallel to the traveled roadway under a driveway or roadway that abuts the main highway.

A total of 23 mathematical simulations was investigated in arriving at an optimum design for the median side slope and grate slope terrain configuration shown in Figure 3.

The first group, consisting of six mathematical simulations, was designed to determine the effect of the grate slope, ditch depth, and departure path on the automobile's response. A median side slope of 6:1 and a departure angle of 25 deg were maintained for each run. The slope of the culvert grate was varied from 4:1 to 10:1. Side rollover occurred in traversing 10:1 and steeper grate slopes for a path 2 departure

Figure 4. Modification of existing culvert crossover with headwalls (1).

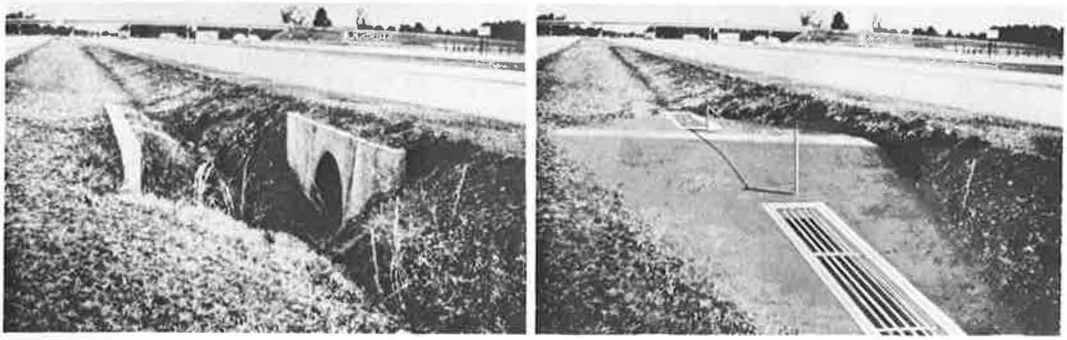
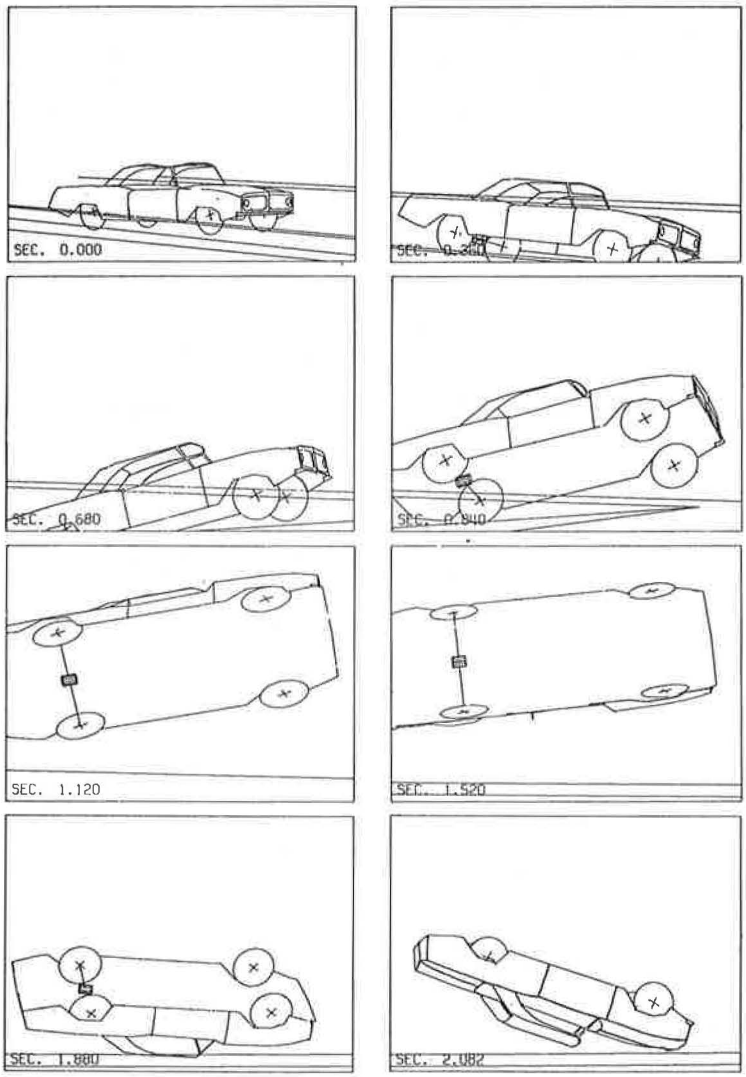


Figure 5. Simulation of automobile negotiating 6:1 side slope and 6:1 culvert grate slope at a speed of 60 mph and an angle of 25 deg.



(Table 1). Figure 5 shows the side roll-over of an automobile traversing path 2 after negotiating a 6:1 grate slope. Side roll-over did not occur when the automobile departure path (path 3, Fig. 3) from the roadway was such that the automobile encountered the flat ditch prior to traversing the grate slope. With regard to ditch depth, a change from 3 to 2 ft did not prevent roll-over. Ditch depths greater than 3 ft were not considered because of the limitations imposed by the 50-ft median width. Also, greater ditch depths on wider medians should not appreciably alter the relative angle between the side slope and the grate slope, so that a path similar to that which produced roll-over would be possible.

The second group, consisting of two simulations, involved a median side slope of 8:1 and a grate slope of 6:1. Side roll-over did not occur in either of these cases, but the magnitude of the accelerations was sufficient to probably inflict serious injuries. Also, for the 25-deg departure angle, the airborne criterion was not satisfied; the automobile landed in the opposing traffic lane.

The third group, consisting of four simulations, concerned head-on traversals in which the grate slope was varied from 4:1 to 10:1, and all other variables were held constant. The results obtained from the head-on simulations are given in Table 1 and shown in Figure 6. The steeper the grate slope is, the greater are the automobile accelerations, dynamic vertical tire loads, and height and distance airborne. At a grate slope of 6:1, the automobile, upon contacting the terrain after being airborne, rolled over about its front end (Fig. 7). For the path 1 traversals, the accelerations for a 10:1 grate slope are on the border line, and the severity index indicates that severe injuries can occur; whereas, for grate slopes steeper than 10:1, the severity index indicates that severe injuries will occur.

The fourth group, consisting of six simulations, was run to determine the feasibility of using a median side slope of 8:1 and a grate slope of 8:1. The departure angle of the automobile was treated as a variable. Roll-over occurred at a very shallow departure angle of 5 deg in traversing path 2 as shown in Figure 3. However, when the automobile encountered the flat ditch prior to traversing the grate slope (path 3, Fig. 3) at the same shallow departure angle of 5 deg, roll-over did not occur.

It appeared at this point that an 8:1 side slope and 10:1 grate slope would be a reasonable combination that would satisfy the safety criteria in addition to the economic and hydraulic requirements. The fifth and last group, consisting of five simulations, involved a median side slope of 8:1 and a grate slope of 10:1. The automobile departure angle was treated as the variable. The acceleration severity index of the automobile was unity or less for all cases. As mentioned earlier, however, the acceleration severity index slightly exceeded unity for a head-on 10:1 grate slope simulation, which indicates that severe injuries may occur. The terrain locations where the automobile will land after being airborne are shown in Figure 8. For departure angles of 20 deg or less, the automobile will land within the median on the other side of the 40-ft crossover; whereas, for a departure angle of 25 deg, the automobile will land on the outside edge of the opposite traffic lane shoulder. Simulations were not made for automobile departure angles of more than 25 deg because of the findings of Hutchinson (7), which show that only a small percentage (about 11 percent) of the median encroachments exceed 25 deg. In this study the maximum roll angle of 50 deg occurred at a shallow departure angle of 5 deg (Table 1).

This study also provides information on the dynamic loads imposed by the automobile tires on the culvert grate. Load impact factors, which are defined as the ratio of the dynamic tire loads to the static tire loads, were computed and are given in Table 1. In the absence of additional data it may be assumed that these load impact factors for a standard-size automobile would pertain to any automobile.

SUMMARY AND CONCLUSIONS

The objective of this study was to develop criteria for designing traffic-safe sloping grate configurations. To accomplish this task, we used a mathematical computer simulation technique to investigate the dynamic behavior of a standard-size automobile traversing various terrain configurations in the vicinity of a sloping culvert grate.

Figure 6. Head-on 60-mph simulations of automobile traversing various sloping grate configurations.

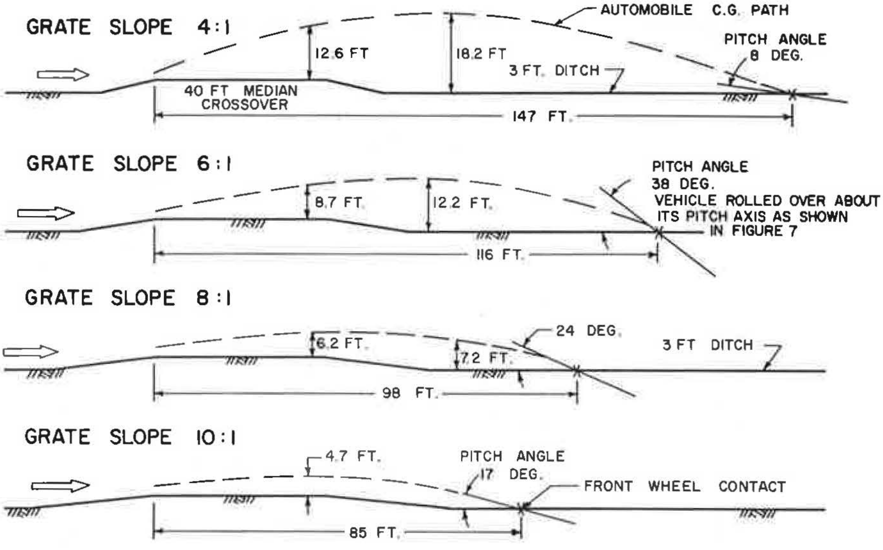


Figure 7. Head-on 60-mph simulation of automobile negotiating a 6:1 culvert grate slope.

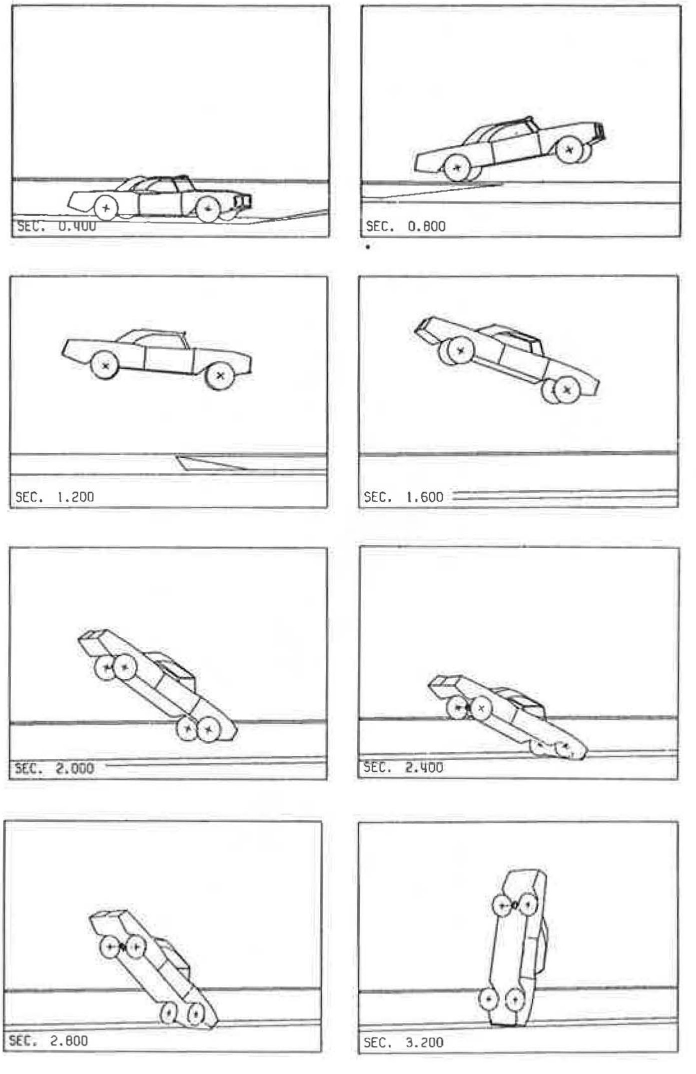
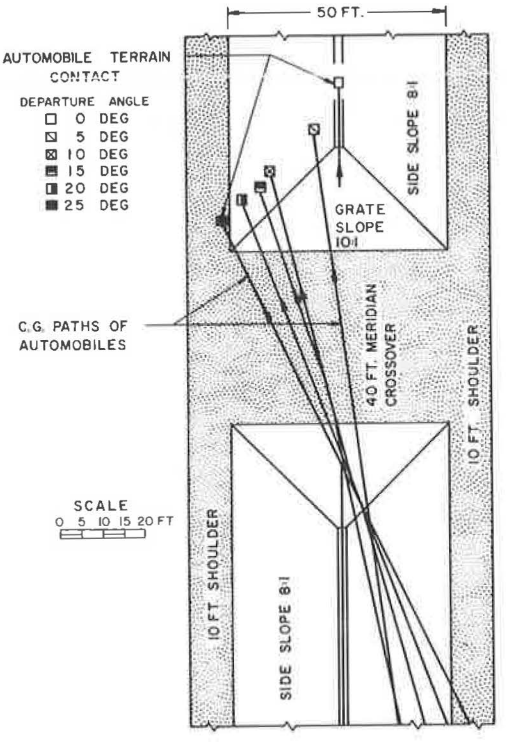


Table 1. Results of mathematical simulations of an automobile traversing various side and grate slope configurations at a speed of 60 mph.

Terrain			Automobile							Accelerations of More Than 50 msec							
										Grate Slope Contact				Terrain Contact After Airborne			
Ditch Depth (ft)	Side Slope	Grate Slope	Approach Angle (deg)	Path[a]	Max. Roll Angle (deg)	Rise of c.g. Above Terrain (ft)	Distance Airborne (ft)	Max. Vert. Tire Load on Grate (kips)	Impact Load Factor	G_{Long} (g)	G_{Lat} (g)	G_{Vert} (g)	Severity Index	G_{Long} (g)	G_{Lat} (g)	G_{Vert} (g)	Severity Index
3	6:1	4:1	25	2	RO[b]	11.8	93[d]	44.0	9.3	5.1	1.9	10.8	2.1	–	–	–	–
3	6:1	6:1	25	2	RO[b]	6.3	85[d]	34.2	7.2	3.5	1.1	6.8	1.3	–	–	–	–
3	6:1	8:1	25	2	RO[b]	5.8	58[d]	31.9	6.7	1.8	0.9	4.6	0.9	–	–	–	–
3	6:1	10:1	25	2	RO[c]	4.7	52	24.6	5.2	0.3	1.3	6.5	1.1	–	–	–	–
3	6:1	6:1	25	3	51	6.7	86	22.4	4.7	1.1	0.6	4.4	0.8	1.3	4.8	3.9	1.0
2	6:1	6:1	25	2	RO[b]	7.8	87[d]	52.3	11.0	1.9	1.1	7.1	1.3	–	–	–	–
3	8:1	6:1	25	2	7	8.8	101[e]	30.1	6.3	2.8	0.4	9.1	1.7	0.3	0.7	9.7	1.6
3	8:1	6:1	15	2	34	9.9	98	25.4	5.3	2.3	0.3	6.9	1.2	2.2	2.9	4.1	0.9
3	–	4:1	0	1	0	18.2	147	29.0	6.1	3.6	0.0	8.7	1.6	1.9	0.0	18.4	3.1
3	–	6:1	0	1	0	12.2	116[f]	22.1	4.7	1.3	0.0	5.3	0.9	8.4	0.0	7.7	2.1
3	–	8:1	0	1	0	7.2	98	19.3	4.1	0.6	0.0	3.7	0.6	4.5	0.0	6.6	1.4
3	–	10:1	0	1	0	4.7	86	14.9	3.1	0.1	0.0	3.1	0.5	3.0	0.0	5.9	1.1
3	8:1	8:1	5	3	50	6.6	82	23.9	5.0	0.2	0.4	3.6	0.8	2.9	5.4	2.7	1.1
3	8:1	8:1	5	2	RO[c]	6.1	97	18.9	4.0	0.2	0.5	3.6	0.6	–	–	–	–
3	8:1	8:1	10	2	40	6.4	78	21.2	4.5	0.9	0.3	4.4	0.8	2.2	3.7	2.9	0.8
3	8:1	8:1	15	2	50	6.3	68	22.7	4.8	1.2	0.4	4.4	0.8	1.9	3.2	2.0	0.7
3	8:1	8:1	20	2	21	6.2	78	21.2	4.5	1.4	0.3	6.3	1.1	1.2	1.2	2.4	0.5
3	8:1	8:1	25	2	12	6.2	81[e]	23.6	5.0	1.5	0.3	7.1	1.2	1.1	1.0	2.4	0.5
3	8:1	10:1	5	2	50	4.8	73	17.8	3.7	0.1	0.5	3.4	0.6	2.7	4.8	2.4	1.0
3	8:1	10:1	10	2	32	5.0	68	20.3	4.3	0.1	0.4	3.6	0.6	1.8	2.5	2.6	0.7
3	8:1	10:1	15	2	34	4.8	62	21.6	4.6	0.7	0.3	3.5	0.6	1.7	3.0	3.3	0.8
3	8:1	10:1	20	2	17	4.8	65	17.7	3.7	0.9	0.3	5.2	0.9	0.3	0.7	4.9	0.8
3	8:1	10:1	25	2	26	4.8	63	20.5	4.3	0.9	0.3	5.4	0.9	0.3	0.6	3.6	0.6

[a]See Figure 3 for illustration of path numbers.
[b]Roll-over occurs when automobile is airborne.
[c]Roll-over occurs when automobile contacts terrain after having been airborne.
[d]Approximate distance when top of automobile contacts terrain.
[e]Automobile lands in opposing traffic lane.
[f]Front-end roll-over occurs when automobile contacts terrain after having been airborne.

Figure 8. Locations where automobile contacts terrain after being airborne.



A typical roadway site was selected to limit the number of parameters studied. The site consisted of a divided roadway, a median crossover, and sloping inlet and outlet grates to allow water to flow under the crossover. A median width of 50 ft and, for all but one case, a ditch depth of 3 ft were selected. The speed at which the automobile departed from the roadway was taken as 60 mph.

Parameter studies were conducted to determine what influence departure angle and path, median side and grate slopes, and ditch depth had on the response of an automobile and occupant. Both head-on and angle departures were studied. For evaluation criteria, the configurations were judged on the basis of minimizing automobile accelerations as measured by a severity index, preventing roll-over, and minimizing the chance of the automobile landing in the opposite lane of traffic after being airborne. Specific findings of this study are as follows:

1. For side slope and grate slope traversals, the tendency of an automobile to roll over increases as the angle of departure from the roadway decreases;
2. For head-on traversals, the acceleration severity index for a grate slope of 10:1 may be questionable; whereas, for grate slopes steeper than 10:1, the severity index indicates that severe injuries would probably occur; and
3. When used in conjunction with 10:1 and steeper grate slopes, wide roll-over will occur on a 6:1 slope with ditch depths of 2 and 3 ft.

The simulation results further indicate that, during a departure angle of 25 deg or less, an automobile could safely traverse a terrain configuration having side slopes of 8:1 and a culvert grate slope of 10:1. Findings on the dynamic response of an automobile as it traverses this particular ground form are summarized as follows:

1. The acceleration severity index indicates that an unrestrained occupant would probably not be seriously injured;
2. The maximum roll angle of 50 deg occurred at a shallow departure angle of 5 deg;
3. The distance airborne was sufficiently low such that the automobile would land on the shoulder of the opposing traffic lane or median and hence probably not endanger traffic in the opposing lanes of travel; and
4. The dynamic vertical tire load on the sloping grate was about 5 times greater than the static weight of the automobile.

Guidelines that suggest that side slopes and culvert sloping grates should be 10:1 and flatter are presented elsewhere (1). The findings of this study tend to substantiate those guidelines.

ACKNOWLEDGMENT

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