in the paper are by no means definitely proven. They were intended as first approximations only, and no claim was made that they yielded good results in the region of traffic congestion. However, they do seem to yield better results than does the existing exposure theory. Forbes' calculation suggests that my theoretical head-on accident rate is too high for traffic of 850 vehicles per hour. But the standard exposure theory would indicate a rate about 50 percent higher still, if fitted to the lower volume data.

It is difficult to understand Forbes' remarks about a "one-variable theory" (especially in view of his efforts in behalf of the exposure theory). To examine the effects of speed and volume is hardly to deny the importance of cother fators. Speed may well be a major factor in determining accident rates, but we cannot yet measure its effect against that of, say, traffic signals or the emotional state of the driver.

In his concluding paragraph, Forbes advocates the application of statistical tests of goodness-of-fit to accident theories. This seems to me a rather premature suggestion. In the present rudimentary state of our theories, much progress must be made before one can reasonably hope for a close fit to actual accident occurrence. Furthermore, most of our accident records leave much to be desired, so that a negative statistical test might well result even for a perfectly sound theory. This weakness in the available data is a serious handicap to studies which would derive relationships from statistical analysis of the data. It may, therefore, be more profitable to work on the development of mathematical models from what seem to be reasonable a priori assumptions, and to be satisfied with rather modest agreement with the "facts."

# Speed Characteristics on Vertical Curves

B. A. Lefeve, *Director*
*Bureau of Highway Planning, New York State Department of Public Works*

There exist many miles of highways built 20, 30, and 40 years ago. These highways are obviously not designed for present day speeds. Critical points exist at vertical curves with restrictive stopping-sight distances. To determine the speed characteristics of today's passenger cars, at these points, the New York State Department of Public Works, in coöperation with the Bureau of Public Roads, made comprehensive speed observations at 20 such locations in New York State.

Conditions for site selection were: tangent length for at least 1,000 ft., each side of the vertical curve; full approach grade of a gradient to minimize its effect on average speed; no marginal influence; no speed zones; free-flowing traffic; traffic in lane adjacent to study lane at a minimum; good riding surface; and no-passing line markings where the sight distance was 500 ft. or less. Sight distance varied from 150 to 700 ft.

Field equipment included a constant-speed 20-pen recorder, electrically connected to 10 pneumatic detector units, 100 ft. apart. Seven detector units were laid on the approach to the vertical curve and three on the leaving grade. Speed for approximately 100 cars at each site was recorded. Three sight-distance criteria were studied: from 4½ ft. above the pavement to 4 in.; from 4½ ft. to 2 ft.; and from 4½ ft. to 4½ ft. above the pavement.

At each trap and for each site the following data was compiled and plotted: average speed; 85-percent speed; safe speed for the three sight distance criteria (according to AASHO policy for nonpassing minimum sight distances based on safe stopping distances); AASHO safe sight distance required for 85-percent speed; the percent of drivers exceeding the legal speed limit; and from the cumulative frequency distribu-

tion curves, the percent of drivers overdriving the safe speed for the three sight distance criteria.

The average speed of cars near the crest of the vertical curves was taken as the average speed of the highways. All sites with an average speed of 45 mph. or greater, near the crest of the vertical curve, were classified as high-speed two-lane roads and those with an average speed near the crest below 45 mph. were classified as normal-speed two-lane roads. The distribution of speeds near the crest of the vertical curves grouped by sight distance and driver performance near the crest of vertical curves for the three criteria of measuring sight distance are shown on charts and discussed. The AASHO recommended stopping sight distances for various speeds is used as a basis for comparison.

The accident record of the sites is discussed; percentile speeds versus AASHO safe speed for minimum sight distances, the relation between the three criteria of measuring sight distance grouped for minimum sight distance, and the percentage of drivers exceeding the legal speed limit are shown by charts and discussed. The appendix contains supporting field and technical data.

The summary of findings, applicable to free-moving passenger cars on vertical curves where the minimum sight distance is between 150 and 500 ft., indicate: (1) reduction of average speed as drivers approach vertical curves, (2) the relation between operating speeds at the crest of vertical curves and the minimum sight distances, (3) practical stopping sight-distance requirements on vertical curves for present day traffic and (4) the relation of driver performance on vertical curves, in terms of operating speeds, to the safe speed as determined by various design standards.

● YEAR by year our vast network of highways is extended and improved, and car manufacturers continue to incorporate modifications in vehicle design which will enable the driver to operate his car with greater comfort and safety and also at greater speed.

Much of this safety and comfort, as well as speed, furnished by the car manufacturer could not be realized without the continuing improvements which have been incorporated in the highway design and construction through the adoption of the present-day highway standards.

These standards have been determined after a detailed study of motor-vehicle operation and driver behavior. In line with the continued changes in highway construction techniques and practice and in motor-car design, such standards should be continually examined and reëxamined for possible improvements.

We must constantly ask ourselves, "Do drivers actually operate their vehicles in the way we think they do when we adopt specific design standards? Should these standards be modified?"

In view of our present-day trend toward more powerful engines and increased vehicle speeds,[1] sight distance is and will continue to be one of the most important factors to examine and consider. Consequently, the New York State Department of Public Works, in coöperation with the Bureau of Public Roads, has undertaken studies of passenger-car speeds where the highway nonpassing minimum sight distances, according to present AASHO policy,[2] are substandard. The study consisted of a series of observations taken since 1950 at 20 locations, at which the speeds of vehicles were recorded at several points on either side of the crest of selected vertical curves. In 1951, the study was extended to include a series of observations at 16 locations of speed on horizontal curves of various degrees of curvature and superelevation. This report will, however, discuss only the former.

[1] The average speed of passenger cars in 1951, 23 states reporting, was 50.2 mph. Half of the passenger-car speeds recorded were in excess of 50 mph, 14 percent were over 60 mph. This represents a new high and the first upturn of any account since 1948. July 1952 Traffic Speed Trends, Bureau of Public Roads.

[2] A Policy on Sight Distance for Highways, American Association of State Highway Officials, adopted February 17, 1940.

## STATEMENT OF THE PROBLEM

Ability to see the road for an adequate distance ahead is of the utmost importance in the safe and efficient operation of a motor vehicle. Vehicle speed is subject to the control of drivers whose training varies from almost none to practically perfection. With this conglomeration of drivers whose training, temperaments, and judgment differ within such a wide range, all occupying and using our highways at the same time, it is quite obvious that if the greatest amount of safety possible is to be built into our highways, they must be so built that the poorest of these drivers can see at least far enough ahead, at all times, to be able to bring his vehicle to a safe stop to avoid striking some unexpected object or obstacle on the road ahead of him.

In New York, and undoubtedly in most of the other states, there now exist many hundreds of miles of highways that were built 20, 30, or even 40 years ago and whose alignment and grade have not been appreciably changed since that time. These highways were obviously not designed for present-day speeds, since the design standards in use at that time were much lower than those now used. These highways have many locations where sight distance is restricted not only by vertical curves but by many other conditions. It is, therefore, important to find out how drivers act at these locations of restrictive sight distance. It follows that once this is known then something can be done to correct dangerous practices on these old roads and to revise present standards as needed in the light of this information. Judging from the present highway-finance situation as compared to the highway needs, it appears that these old highways may be with us for some time to come.

## OBJECTIVE OF STUDY

This particular study was conducted to determine: (1) the relation between the speeds at which drivers of passenger cars operate near the crest of vertical curves, with restricted stopping sight distance, and the existing sight distance for high-speed and normal-speed, two-lane, rural highways; (2) the method of measuring sight distance to which drivers of passenger cars are most likely to govern their speeds near the crest of vertical curves for high-speed and normal-speed, two-lane, rural highways; (3) necessary and practical stopping sight distance requirements on vertical curves for present-day traffic in order to provide safe operating conditions on two-lane, rural highways; and (4) legal-speed observance.

## SELECTION OF SITES

The selection of sites was confined to those sections of two-lane highways on tangent alignment where a vertical curve was, as far as practicable, the only factor controlling sight distance and having any influence on operating speed. Sections of highway with long, steep approach grades were avoided, since it is difficult to differentiate between the retarding effect of grade and that caused by limited sight distance. Five sites of the 20 studied do show approach grades over 4 percent. However, these grades are short and by actual test had no apparent effect on average speeds observed. Sections of highways on horizontal curves or at places where roadside development, such as gasoline service stations, intersecting roads, and the like, might influence speed also were avoided.

Specifications for the selection of sites are listed in the appendix. In general, approach grades varied from a minus 0.6 percent to a maximum of a plus 7.8 percent; leaving grades from a minus 0.7 percent to a minus 7.6 percent. Sight distances varied from 150 to 700 ft. Figure 1, shows the general location of the sites in central and eastern New York and Table 3 in the appendix indicates the specific location and geometric features of the individual sites. Figures 2 to 4, indicate the physical features of typical sites. Note the lane markings on each photograph. These paint-line lane markings exist on the sites as prescribed for vertical curves by the *Manual of Uniform Traffic Control Devices of the New York State Traffic Commission*—no-passing markings are applied at all locations where the actual sight distance is 500 ft. or less measured from 4½ ft. above the pavement to a point 4½ ft. above the pavement.

## METHODS AND CONDITIONS OF STUDY

Field equipment consisted of an Esterline-Angus 20-pen recorder, operated at a constant speed, electrically connected to 10 pneumatic detector units, 100 ft. apart, each consisting of a flexible rubber tube laid across the pavement with an air switch on each end.

Usually, seven detector units were laid on the approach to the crest of the vertical curve and three were on the leaving grade, beyond the crest of the vertical curve, in order to obtain a complete pattern of the speed of each car.

number of cars observed for each site are shown in Table B in the appendix.

The tubes of the 10 pneumatic detector units were fastened across the pavement, 100 ft. apart, providing nine traps. For identification purposes the road tubes were numbered from 1 to 10. The arrangement of the tubes on the study section, provided for Tubes 1 to 7 on the approach grade and Tubes 8 to 10 on

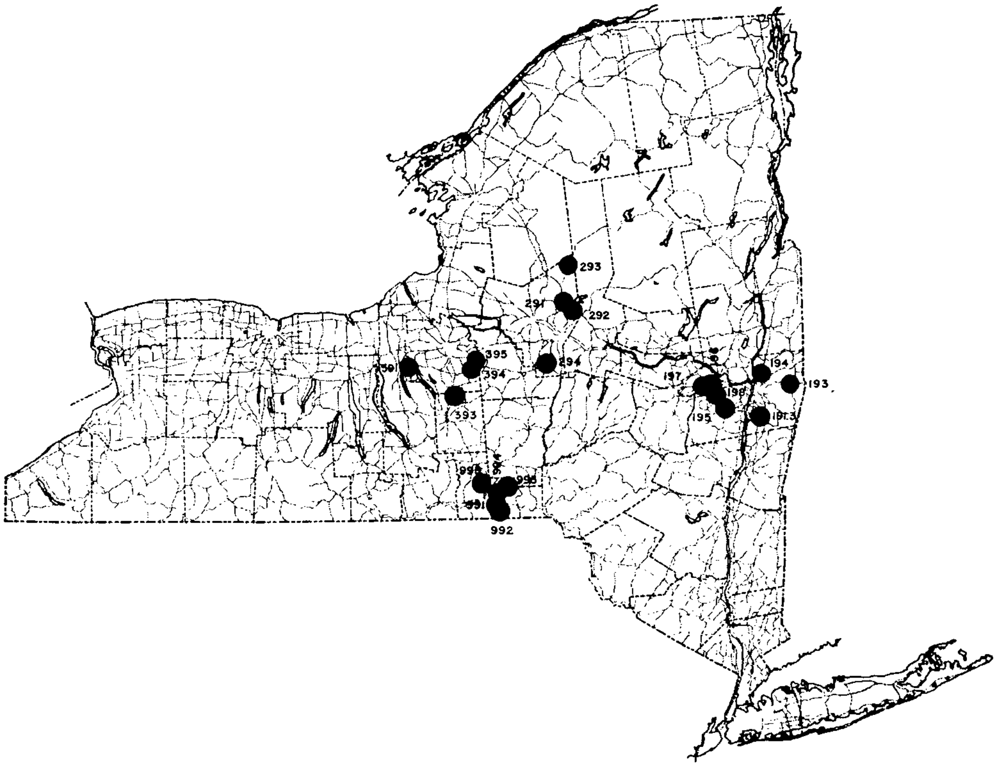


**Figure 1. Location of sites for vertical-curve study.**

Cars were selected on the basis of substantially free or uncontrolled movement in one direction through the site. Observations were taken when traffic in the opposite direction was at a minimum. At each site, the speeds for approximately 100 cars which appeared to be moving normally were recorded and used. Weather conditions during the observations in no way affected the normal operation of the vehicles so that, insofar as possible, variations in speed were due to the restrictive sight distances afforded. Time, date, and

the leaving grade with Tube 7 at the crest of the vertical curve. Corresponding pen numbers of the recorder were connected to the air switches at the end of the tubes.

The field data were recorded on the Esterline-Angus recorder. This graphic recorder utilized a roll of paper which moved at a constant rate of speed and upon which recording pens were placed. These pens made continuous lines which when interrupted by the passage of a car over the road tubes to which the individual pens were electrically connected, registered the interruptions on the chart. Measurement of the lines between interruptions provided the speed data at each trap.

Field stations were established at the study sections to tie in the physical data of the sites. In each instance, Station 10 was located at Tube 7.

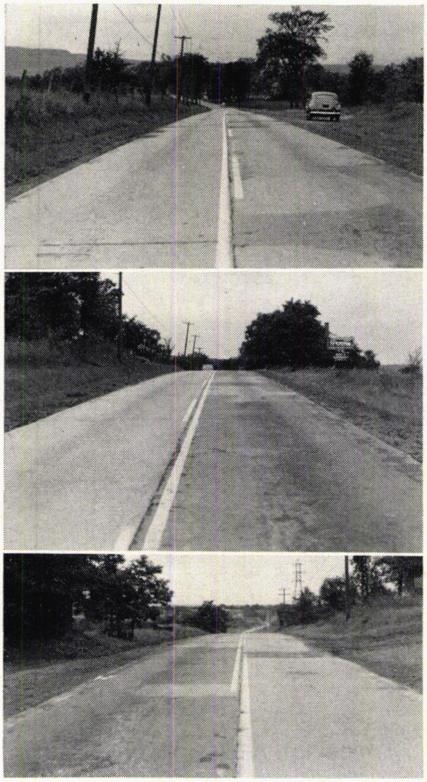

**Figure 2. Site 198: Top, approach grade looking west; middle, crest on leaving grade looking west; bottom, leaving grade looking east.**

Profile and sight distances for each site were obtained in the field. Three sight distance criteria were studied: from 4½ ft. above the pavement to a 4-in. object, the standard for a small object on the pavement; from 4½ ft. to a 2-ft. object, the height of a normal tail light; and from 4½ ft. to a 4½-ft. object, the height of an approaching or leading car.

Figure 5 shows the layout of detector units, pavement markings, and sight distance studied.

## DEVELOPMENT OF BASIC DATA

### *The Individual Site Analysis*

The following procedure was followed in the tabulation and analysis of data for each of the twenty sites observed.

*Speed Data.* The speeds for each passenger car at each trap were listed, as measured from the Esterline-Angus charts. From this listing the data (Table 1) for the plotting of the cumulative frequency distribution of free speeds at each trap (Fig. 6) was compiled.

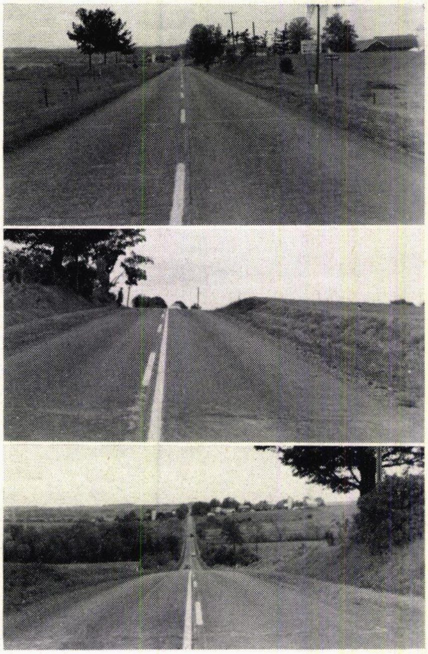

**Figure 3. Site 394: Top, approach grade looking east; middle, approach grade looking east; bottom, leaving grade looking west.**

The average speed at each trap was computed arithmetically and plotted on a chart (Fig. 8). From the speed-distribution curves the percent of cars traveling over 50 mph. and the 85-percentile speed, respectively, at each trap, was determined and registered on the chart (Fig. 8).

*Field Data.* The profile taken on the centerline of pavement, of the observation site, was plotted on the chart (Fig. 8) together with the values for the three sight-distance criteria, as measured in the field: 4½ ft. to a

4-in. object, 4½ ft. to a 2-ft. object and 4½ ft. to a 4½-ft. object.

*Safe Stopping Distances* (*AASHO Standards*). The safe stopping distances, used for the various speeds observed, were based on the AASHO standards. Thus, the safe stopping distances for 30, 40, 50, 60, and 70 mph. are 192, 275, 368, 484, and 614 ft., respectively. For intermediate speeds, a curvilinear interpolation was used (Fig. 7). These distances are those recommended by the AASHO as nonpassing minimum sight distances, using the 4-in. object as the criteria for measuring sight distance.

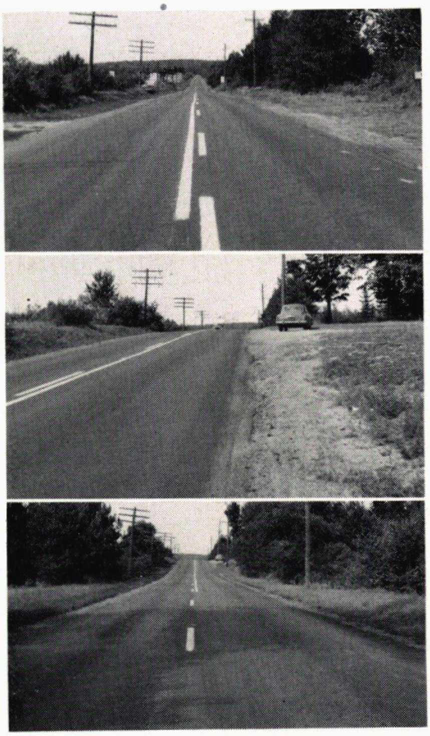

**Figure 4. Site 293: Top, leaving grade looking north; middle, crest on approach grade looking north; bottom, approach grade looking north.**

*Related Data.* The safe speed, at each trap, for each of the sight distance criteria, was determined by relating the respective sight distance measured at the trap, as stopping sight distance to the corresponding speed from Figure 7. These points were plotted on Figure 8 and are represented by the safe-speed curves.

The percentage of drivers of passenger cars exceeding the speed from which they could stop before reaching an object after it comes into view was termed percent overdriving. The percent overdriving, at each trap for each of the sight distance critera, was determined by taking the respective safe speed, at the trap, from the safe-speed curves and entering the cumulative frequency-distribution speed curve for the trap and taking off the percentage of cars exceeding that speed. Likewise, similar percentages were determined

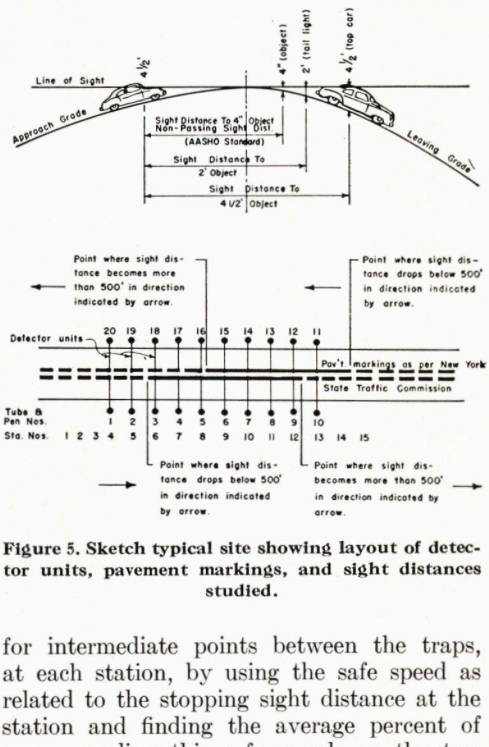


**Figure 5. Sketch typical site showing layout of detector units, pavement markings, and sight distances studied.**

for intermediate points between the traps, at each station, by using the safe speed as related to the stopping sight distance at the station and finding the average percent of cars exceeding this safe speed, on the two adjacent cumulative frequency-distribution curves of speeds. These percentages were plotted on the chart shown in Figure 8 and are represented by the percent-overdriving curves.

Sight distance required for 85-percent speed (AASHO Standards), at each trap, was determined by entering the cumulative-frequency distribution curve of speeds for the trap, taking off the speed of 85 percent

TABLE 1
SPEED DISTRIBUTION DATA—TYPICAL SITE

| Speed mph. | Trap 1–2 | | | Trap 2–3 | | | Trap 3–4 | | |
|---|---|---|---|---|---|---|---|---|---|
| | Units | Accum. Total | Percent | Units | Accum. Total | Percent | Units | Accum. Total | Percent |
| 65 | 2 | 142 | 100.0 | | | | | | |
| 64 | 5 | 140 | 98.6 | 1 | 142 | 100.0 | | | |
| 63 | 1 | 135 | 95.1 | | | | 1 | 142 | 100.0 |
| 62 | 2 | 134 | 94.3 | 3 | 141 | 99.3 | | | |
| 61 | | | | | | | 1 | 141 | 99.3 |
| 60 | 8 | 132 | 93.0 | 9 | 138 | 97.2 | 7 | 140 | 98.7 |
| 59 | | | | 1 | 129 | 90.8 | | | |
| 58 | 9 | 124 | 87.3 | 3 | 128 | 90.2 | 4 | 133 | 93.7 |
| 57 | 3 | 115 | 81.0 | 2 | 125 | 88.0 | 2 | 129 | 90.8 |
| 56 | 7 | 112 | 78.8 | 9 | 123 | 86.6 | 9 | 127 | 89.4 |
| 55 | 7 | 105 | 74.0 | 3 | 114 | 80.3 | 3 | 118 | 83.1 |
| 54 | 4 | 98 | 69.1 | 9 | 111 | 78.2 | 8 | 115 | 81.0 |
| 53 | 3 | 94 | 66.3 | 1 | 102 | 71.8 | 2 | 107 | 75.3 |
| 52 | 8 | 91 | 64.2 | 8 | 101 | 71.1 | 6 | 105 | 74.0 |
| 51 | 7 | 83 | 58.5 | | | | 2 | 99 | 69.7 |
| 50 | 16 | 76 | 53.6 | 17 | 93 | 65.5 | 13 | 97 | 68.3 |
| 49 | 4 | 60 | 42.3 | 6 | 76 | 53.6 | 4 | 84 | 59.2 |
| 48 | 8 | 56 | 39.5 | 11 | 70 | 49.4 | 18 | 80 | 56.4 |
| 47 | 3 | 48 | 33.8 | 5 | 59 | 41.6 | | | |
| 46 | 7 | 45 | 31.7 | 8 | 54 | 38.1 | 18 | 52 | 43.7 |
| 45 | 6 | 38 | 26.8 | 2 | 46 | 32.4 | 2 | 44 | 31.0 |
| 44 | 5 | 32 | 22.6 | 11 | 44 | 31.0 | 9 | 42 | 29.6 |
| 43 | 3 | 27 | 19.1 | 6 | 33 | 23.3 | 2 | 33 | 23.3 |
| 42 | 8 | 24 | 16.9 | 6 | 27 | 19.1 | 13 | 31 | 21.8 |
| 41 | 2 | 16 | 11.3 | 3 | 21 | 14.8 | 1 | 18 | 12.7 |
| 40 | 3 | 14 | 9.9 | 6 | 18 | 12.7 | 6 | 17 | 12.0 |
| 39 | 2 | 11 | 7.8 | 3 | 12 | 8.5 | | | |
| 38 | 5 | 9 | 6.3 | 5 | 9 | 6.3 | 6 | 11 | 7.8 |
| 37 | | | | | | | 1 | 5 | 3.5 |
| 36 | 3 | 4 | 2.8 | 3 | 4 | 2.8 | 3 | 4 | 2.8 |
| 35 | | | | | | | | | |
| 34 | 1 | 1 | 0.7 | 1 | 1 | 0.7 | 1 | 1 | 0.7 |
| 33 | | | | | | | | | |
| 32 | | | | | | | | | |
| 31 | | | | | | | | | |
| 30 | | | | | | | | | |

| Speed mph. | Trap 4–5 | | | Trap 5–6 | | | Trap 6–7 | | |
|---|---|---|---|---|---|---|---|---|---|
| | Units | Accum. Total | Percent | Units | Accum. Total | Percent | Units | Accum. Total | Percent |
| 65 | | | | | | | | | |
| 64 | | | | | | | | | |
| 63 | 1 | 142 | 100.0 | | | | | | |
| 62 | 3 | 141 | 99.3 | 7 | 142 | 100.0 | 2 | 142 | 100.0 |
| 61 | | | | 1 | 135 | 95.2 | | | |
| 60 | 6 | 138 | 97.2 | 2 | 134 | 94.4 | 4 | 140 | 98.6 |
| 59 | | | | 3 | 132 | 93.0 | 2 | 136 | 95.7 |
| 58 | 2 | 132 | 93.0 | 5 | 129 | 91.0 | 1 | 134 | 94.4 |
| 57 | 2 | 130 | 91.5 | 1 | 124 | 87.4 | 1 | 133 | 93.7 |
| 56 | 12 | 128 | 90.2 | 9 | 123 | 86.7 | 7 | 132 | 93.0 |
| 55 | 3 | 116 | 81.7 | 1 | 114 | 80.4 | | | |
| 54 | 5 | 113 | 79.6 | 4 | 113 | 79.6 | 7 | 125 | 88.0 |
| 53 | 4 | 108 | 76.1 | 2 | 109 | 76.8 | 2 | 118 | 83.1 |
| 52 | 6 | 104 | 73.3 | 10 | 107 | 75.4 | 7 | 116 | 81.7 |
| 51 | 4 | 98 | 69.1 | 1 | 97 | 68.3 | 5 | 109 | 76.8 |
| 50 | 8 | 94 | 66.3 | 9 | 96 | 67.6 | 10 | 104 | 73.3 |
| 49 | 3 | 86 | 60.6 | 5 | 87 | 61.3 | 1 | 94 | 66.3 |
| 48 | 16 | 83 | 58.5 | 12 | 82 | 57.7 | 10 | 93 | 65.5 |
| 47 | 4 | 67 | 47.2 | 3 | 70 | 49.3 | 7 | 83 | 58.5 |
| 46 | 13 | 63 | 44.4 | 13 | 67 | 47.2 | 11 | 76 | 53.6 |
| 45 | 2 | 50 | 35.2 | 4 | 54 | 38.0 | 5 | 65 | 45.8 |
| 44 | 12 | 48 | 33.8 | 12 | 50 | 35.2 | 14 | 60 | 42.3 |
| 43 | 2 | 36 | 25.4 | 6 | 38 | 26.8 | 7 | 46 | 32.4 |
| 42 | 12 | 34 | 23.9 | 8 | 32 | 22.5 | 10 | 39 | 27.5 |
| 41 | 3 | 22 | 15.5 | 6 | 24 | 16.8 | 4 | 29 | 20.4 |
| 40 | 5 | 19 | 13.4 | 1 | 18 | 12.7 | 7 | 25 | 17.6 |
| 39 | 2 | 14 | 9.9 | 6 | 17 | 12.0 | 1 | 18 | 12.7 |
| 38 | 7 | 12 | 8.5 | 5 | 11 | 7.8 | 6 | 17 | 12.0 |
| 37 | | | | | | | 1 | 11 | 7.8 |
| 36 | 1 | 5 | 3.5 | 2 | 6 | 4.2 | 3 | 10 | 7.5 |
| 35 | 3 | 4 | 2.8 | 2 | 4 | 2.8 | | | |
| 34 | 1 | 1 | 0.7 | 2 | 2 | 1.4 | 4 | 7 | 4.9 |
| 33 | | | | | | | 1 | 3 | 2.1 |
| 32 | | | | | | | 1 | 2 | 1.4 |
| 31 | | | | | | | 1 | 1 | 0.7 |
| 30 | | | | | | | | | |

| Speed mph. | Trap 7–8 | | | Trap 8–9 | | | Trap 9–10 | | |
|---|---|---|---|---|---|---|---|---|---|
| | Units | Accum. Total | Percent | Units | Accum. Total | Percent | Units | Accum. Total | Percent |
| 65 | | | | | | | | | |
| 64 | | | | | | | | | |
| 63 | | | | | | | 1 | 142 | 100.0 |
| 62 | 2 | 142 | 100.0 | 2 | 142 | 100.0 | 2 | 141 | 99.3 |
| 61 | 1 | 141 | 99.3 | 2 | 140 | 98.6 | 1 | 139 | 98.6 |
| 60 | 1 | 140 | 98.6 | 6 | 138 | 97.3 | 4 | 138 | 97.3 |
| 59 | 1 | 139 | 98.6 | 1 | 132 | 93.0 | | | |
| 58 | 5 | 138 | 97.3 | 2 | 131 | 92.2 | 3 | 134 | 94.4 |
| 57 | 1 | 133 | 93.7 | 1 | 129 | 91.0 | 5 | 131 | 92.2 |
| 56 | 6 | 132 | 93.0 | 8 | 128 | 90.2 | 6 | 126 | 88.7 |
| 55 | 1 | 126 | 88.7 | 2 | 120 | 84.5 | 1 | 120 | 84.5 |
| 54 | 6 | 125 | 88.0 | 9 | 118 | 83.1 | 5 | 119 | 83.8 |
| 53 | 1 | 119 | 83.8 | 2 | 109 | 76.8 | 7 | 114 | 80.4 |
| 52 | 10 | 118 | 83.1 | 3 | 107 | 75.4 | 8 | 107 | 75.4 |
| 51 | 3 | 108 | 76.1 | 6 | 104 | 73.3 | 4 | 99 | 69.7 |
| 50 | 9 | 105 | 74.0 | 11 | 98 | 69.1 | 11 | 95 | 66.9 |
| 49 | 1 | 96 | 67.6 | 4 | 87 | 61.3 | 3 | 84 | 59.2 |
| 48 | 11 | 95 | 66.9 | 12 | 83 | 58.5 | 14 | 81 | 57.1 |
| 47 | 5 | 84 | 59.2 | 4 | 71 | 50.0 | 4 | 67 | 47.2 |
| 46 | 15 | 79 | 55.6 | 8 | 67 | 47.2 | 10 | 63 | 44.4 |
| 45 | 2 | 64 | 45.1 | 5 | 59 | 41.6 | 2 | 53 | 37.3 |
| 44 | 15 | 62 | 43.7 | 11 | 54 | 38.0 | 12 | 51 | 35.9 |
| 43 | 6 | 47 | 33.1 | 7 | 43 | 30.3 | 6 | 39 | 27.4 |
| 42 | 10 | 41 | 28.9 | 12 | 36 | 25.4 | 7 | 33 | 23.3 |
| 41 | 2 | 31 | 21.8 | 2 | 24 | 16.8 | 6 | 26 | 18.3 |
| 40 | 9 | 29 | 20.4 | 6 | 22 | 15.5 | 7 | 20 | 14.1 |
| 39 | 4 | 20 | 14.1 | 4 | 16 | 11.3 | 4 | 13 | 9.2 |
| 38 | 4 | 16 | 11.3 | 2 | 12 | 8.5 | | | |
| 37 | 3 | 12 | 8.5 | 1 | 10 | 7.1 | 3 | 9 | 6.3 |
| 36 | | | | | | | 2 | 6 | 4.2 |
| 35 | | | | 4 | 9 | 6.3 | 2 | 4 | 2.8 |
| 34 | 2 | 9 | 6.3 | 3 | 5 | 3.5 | 1 | 2 | 1.4 |
| 33 | 4 | 7 | 4.9 | 1 | 2 | 1.4 | | | |
| 32 | 2 | 3 | 2.8 | | | | | | |
| 31 | 1 | 1 | 0.7 | 1 | 1 | 0.7 | | | |
| 30 | | | | | | | 1 | 1 | 0.7 |

of the cars and relating this speed to the corresponding AASHO safe stopping distance from Figure 7. These points were plotted on the chart in Figure 8 and are represented by

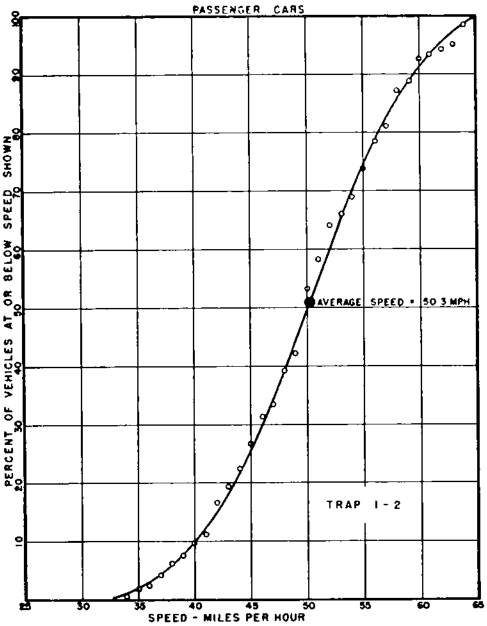


**Figure 6. Cumulative frequency distribution of free speeds at one trap.**

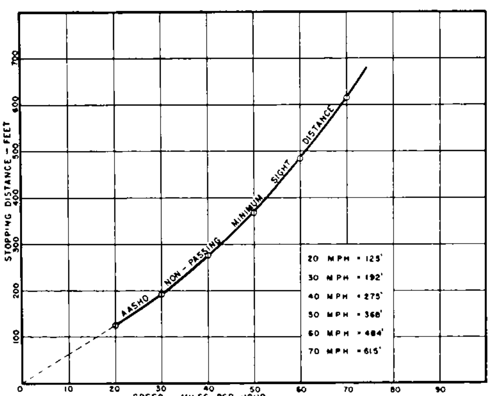


**Figure 7. AASHO safe stopping distance for speeds.**

the curve labeled, "Sight distance required for 85-percent speed (AASHO Standards)."

The information shown graphically, for each site furnishes a basis for composite analysis of the data.

### METHODS OF ANALYSIS

The data obtained at the different study locations, which have been illustrated by Figure 8, were combined so that driver behavior for similar situations involving vertical curves could be analyzed. The results of the analysis of the speed data at all points along the approach to each vertical curve indicated that the most-critical place on the curve, when considered in relation to the speed of the passenger cars, is at the point of minimum sight distance, or within about 100 ft. of this point in each case. Table A (appendix) shows the speed characteristics of the drivers together with other information for the most critical point at each study location.

Based on the combined data, the following analyses were made to obtain information which is vital to an understanding of driver behavior on vertical curves and which is, therefore, useful for the proper design of highways: (1) relation between minimum sight distances when measured to different heights of objects on the road; (2) decrease in vehicle speeds as a vertical curve is approached; (3) distribution of speeds near the crest of vertical curves as related to the minimum sight distance; (4) driver performance near crest of vertical curves as related to safe stopping distances on high-speed and normal-speed two-lane highways; (5) relation between driver performance and safe performance as determined by various standards; and (6) accident history at study locations.

The physical characteristics of each site and some of the speed data are shown by Table 2. Roads on which the average speed was 45 mph. or more at the critical point approaching the crest have been called high-speed roads for purposes of analysis, and other roads where average speeds were below 45 mph. have been called normal-speed roads. In interpreting the results of the analysis, it is pertinent that the highways on which study sites were selected also included other horizontal and vertical curves with minimum sight distances corresponding to the minimum sight distances at the vertical curves which were included in the study. The other vertical curves, some of which were even more critical, were omitted from the study because they did not meet the specifications which had been established for the selection of the study sites. Many of them had horizontal curves in combination with the vertical curves which would have increased the number of variables involved and made it practically impossible to segregate the effect of vertical sight distance restriction from the others.

between sight distances and object heights as shown by Figure 9.

It is, of course, possible to establish the relation between sight distance measured to various heights of objects when the profile is

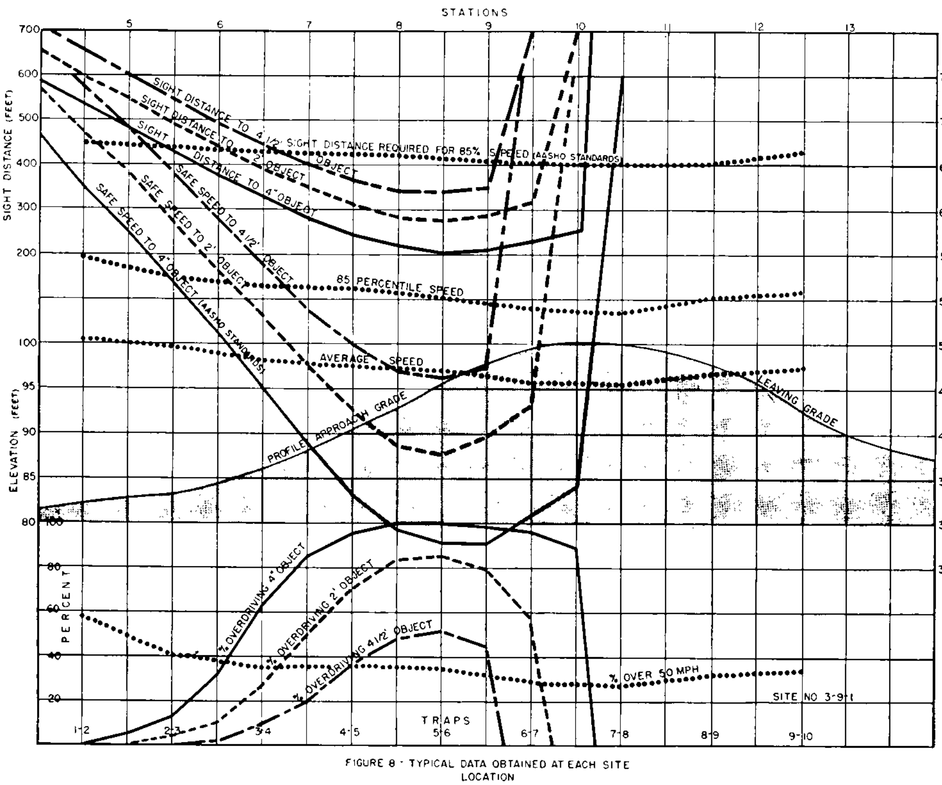


**Figure 8. Typical data obtained at each site location.**

## RELATION BETWEEN MINIMUM SIGHT DISTANCES AT VERTICAL CURVES WHEN MEASURED TO DIFFERENT HEIGHTS OF OBJECTS ON THE ROAD

For the proper interpretation of driver performance on vertical curves, it is necessary to establish the relation between minimum sight distances when measured to objects of different heights located on the road surface. At each of the sites included in this study, sight distances along the vertical curve were measured from $4\frac{1}{2}$ ft. (the height of a driver's eyes) to objects 4 in., 2 ft., and $4\frac{1}{2}$ ft. high located on the surface of the road. These data were then used to establish the relation known. Also, for a given vertical curve the relation will always be constant as long as a driver's eye and the object are on a uniform vertical curve. In this study, however, the relations between the different height objects as shown by Figure 9 are for conditions on existing curves that were not necessarily designed according to present-day standards. Figure 9 shows, for example, that on a vertical curve where the minimum sight distance measured to a 4-in. object is 200 ft., the sight distance measured to a 2-ft. object would be 275 ft., and the sight distance measured to a $4\frac{1}{2}$-ft. object would be 345 ft. Using the AASHO standards for safe stopping distance as shown by Figure 7, a sight distance of 200

TABLE 2
OBSERVED DATA AND CHARACTERISTICS OF SITES

| | High Speed Group | | | | | | | Normal Speed Group | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Site No. | | | | | | | Site No. | | | | | | | | | | | | |
| | 391 | 393 | 394 | 993 | 194 | 291 | 294 | 196 | 292 | 293 | 991 | 193 | 195 | 197 | 198 | 1913 | 395 | 992 | 994 | 995 |
| Average speed 1st trap, mph | 50.3 | 51.2 | 52.6 | 52.8 | 46.8 | 48.4 | 47.6 | 48.3 | 49.2 | 47.2 | 48.4 | 42.3 | 42.8 | 42.2 | 42.0 | 43.6 | 45.2 | 42.6 | 43.1 | 45.4 |
| Average speed at critical point, mph | 48.0 | 46.3 | 47.7 | 49.6 | 46.4 | 45.1 | 46.5 | 44.4 | 44.6 | 43.5 | 44.6 | 39.8 | 37.8 | 40.3 | 39.6 | 41.6 | 44.6 | 40.2 | 42.9 | 39.7 |
| Speed decrease at critical point, mph | 2.3 | 4.9 | 4.9 | 3.2 | 0.4 | 3.3 | 1.1 | 3.9 | 4.6 | 3.7 | 3.8 | 2.5 | 5.0 | 1.9 | 2.4 | 2.0 | 0.6 | 2.4 | 0.2 | 5.7 |
| Percent decrease | 4.6 | 9.6 | 9.3 | 6.1 | 0.9 | 6.8 | 2.3 | 8.1 | 9.4 | 7.8 | 7.8 | 5.9 | 11.7 | 4.5 | 5.7 | 4.6 | 1.3 | 5.6 | 0.5 | 12.5 |
| Percent exceeding 50 mph. at critical point | 34 | 33 | 34 | 49 | 30 | 19 | 26 | 21 | 15 | 13 | 19 | 9 | 3 | 7 | 7 | 13 | 20 | 3 | 19 | 4 |
| Approach grade, percent | 5.0 | 2.5 | −0.6 | 3.0 | 1.8 | 5.8 | 1.2 | 2.4 | 4.2 | 3.8 | 4.2 | 0.9 | 7.8 | 6.0 | 3.2 | 4.0 | 1.9 | 2.2 | −0.6 | 3.8 |
| Leaving grade, percent | 5.5 | 7.6 | 7.2 | 3.3 | 4.6 | 5.0 | 5.5 | 4.2 | 5.5 | 2.0 | 4.4 | 4.0 | 6.2 | 0.7 | 6.0 | 5.1 | 2.2 | 4.6 | 5.8 | 7.0 |
| Length of vertical curve, feet | 400 | 300 | 350 | 500 | 700 | 450 | 250 | 500 | 250 | 300 | 450 | 300 | 350 | 500 | 500 | 500 | 500 | 400 | 550 | 300 |
| Sight distance at critical point to 4-inch object | 210 | 170 | 255 | 310 | 510 | 225 | 205 | 300 | 150 | 225 | 225 | 260 | 190 | 255 | 235 | 235 | 450 | 275 | 360 | 160 |
| Pavement width, feet | 20 | 20 | 20 | 24 | 22 | 20 | 22 | 20 | 20 | 20 | 22 | 20 | 22 | 20 | 20 | 20 | 20 | 22 | 24 | 22 |
| Number of samples | 142 | 107 | 100 | 103 | 110 | 151 | 108 | 128 | 108 | 103 | 101 | 90 | 100 | 100 | 103 | 91 | 100 | 100 | 121 | 100 |

ft. is safe for a speed of 31 mph., a sight distance of 275 ft. is safe for 40 mph., and a sight distance of 345 ft. is safe for 48 mph. Therefore, if it is necessary for safety to come to a stop after a 4-in. object comes into view, the maximum safe speed is 31 mph. on a vertical curve with a minimum sight distance of 200 ft. as measured to a 4-in. object.

If, however, it is assumed that it is not necessary to be able to stop for objects less than 2 ft. high after they first come into view, 40 mph. is the safe speed on the same vertical curve. Similarly, if it is not necessary to come to a stop for any object less than 4½ ft. high

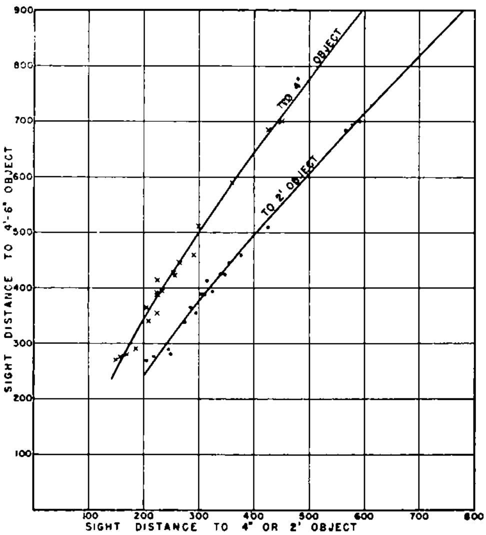


**Figure 9. Relation between minimum sight distances when measured to different heights of objects on the road.**

after it first comes into view, 48 mph. would be the safe speed on this vertical curve. It therefore follows that the safe speed on the curve could either be 31, 40, or 48 mph., depending on the criterion used for a safe condition.

## DECREASE IN SPEEDS AS A VERTICAL CURVE IS APPROACHED

One would normally expect drivers traveling at high speeds to slow down on vertical curves where sight distances are as short as those included in this study. This was consistently the case at the study locations, although in some cases the reduction in speed was not as great as one would expect.

The average decrease in speed as related to sight distance at the various vertical curves is shown by Figure 10. On an average, where the minimum sight distance was 150 ft., drivers decrease their speed 6 mph. before reaching the point of minimum sight distance. Where the minimum sight distance was 400 ft., the average decrease in speed was only 2 mph. Separate analyses for the high-speed roads and the normal-speed roads showed that the decrease in speed varied with the normal approach speeds, there being about the same percentage reduction in both cases as has been previously explained.

There were five sites where the approach grades were over 4 percent (Table 2), and other sites where the approach to the vertical curve

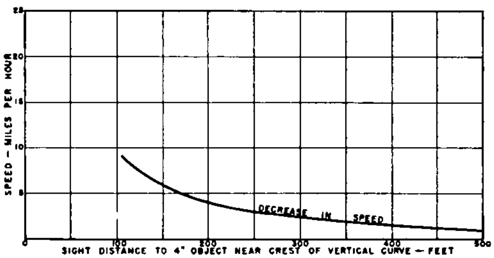


**Figure 10. Decrease in speed as vertical curve is approached.**

was about level. A comparison of the reduction in speed for these two conditions indicates that the reduction in speed was not a direct result of the grade, there being about the same reduction in speed for vertical curves where the approach was level as where the approach was on an appreciable grade. From this analysis, it is evident that drivers do reduce their speeds as they approach vertical curves with short sight distances. The magnitude of the reduction in speed, however, is not as great as is necessary to provide entirely safe operating conditions, as will be discussed later.

## DISTRIBUTION OF SPEEDS NEAR THE CREST OF VERTICAL CURVES AS RELATED TO THE MINIMUM SIGHT DISTANCE

It has been shown that average speeds of vehicles decrease as the point of minimum sight distance on a vertical curve is approached. On an average, there is also a greater decrease in speed on approaching the vertical curves with the shorter sight distances than on the other vertical curves where the sight distances are somewhat longer. In an effort to determine whether the decreases in average speeds as observed were sufficient to compensate for the short sight distances at the vertical curves, the speed distributions at the critical points on the curves have been related to the minimum sight distances as shown by Figure 11.

For Figure 11, 20 sites were first divided into two groups, the one group being roads where the speeds near the crest of the curve averaged less than 45 mph. and the other group roads where speeds near the crest of the curve were at least 45 mph. The first group,

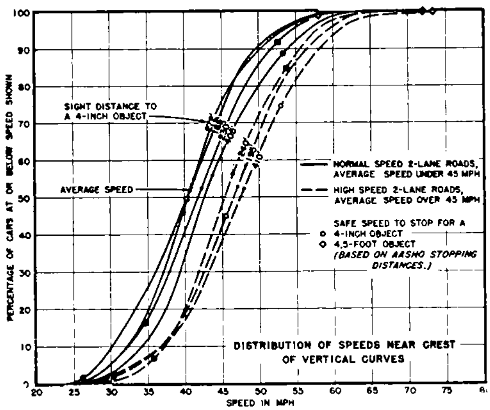


**Figure 11. Distribution of speeds near crest of vertical curves.**

as previously indicated, has been termed normal-speed roads, whereas the second group has been termed high-speed roads. Within these two groups, sites with critical points of similar minimum sight distances, as measured to a 4-in. object, were combined and the sight distances averaged for each combination. There resulted a total of seven different sight distance groups, four groups for the normal-speed roads and three groups for the high-speed roads. The cumulative distribution of passenger-car speeds, at the critical point for each site was tabulated and summarized for each sight-distance group and plotted in Figure 11.

Figure 11 shows that there is no consistent relation between the speed distributions and the minimum sight distance at the vertical curves, although there is some tendency for the higher speeds to occur at locations with the longer minimum sight distances. In general, the speed distributions, regardless of minimum sight distance, have the same general pattern. These patterns are similar to the normal speed distribution patterns at locations where sight distances are not restricted.

Three points have also been plotted on each of the speed distribution curves of Figure 11. The first point, a solid circle, represents the average speed. The second point, an open circle, represents the safe speed for the particular sight-distance condition, assuming that it is necessary for passenger cars to be able to stop for a 4-in. object after it first comes into view. The third point, an open square, represents the safe speed for the particular sight distance condition, assuming that it is not necessary for passenger cars to be able to stop for an object less than 4½ ft. high after it first comes into view. It may be observed that for most of the sight-distance conditions, a high percentage of the drivers exceeded the safe speed as determined by the sight distance to a 4-in. object, and in two cases about 50 percent of the drivers exceeded the safe speed as determined by the sight distance to a 4½-ft. object. It may also be observed that the average speed near the crest of the curve, as well as the speed-distribution pattern, bears no definite relation to the minimum sight distance. This confirms the observations made from Figure 10.

Using related information from Figures 9 and 11, Table 3 was compiled. This table shows, for both the high-speed and normal-speed roads, that 98 percent of the drivers exceed the speed from which they could stop before reaching a 4-in. object after it comes into view when the sight distance is less than 200 ft.; with a sight distance of 300 ft., about half of the drivers exceed the speed as determined by AASHO standards. A sight distance of about 400 ft., on main rural highways, is needed before driver behavior conforms with the AASHO standards.

### DRIVER PERFORMANCE NEAR CREST OF VERTICAL CURVES AS RELATED TO SAFE STOPPING DISTANCES

Since it has been found from the previous analyses that minimum sight distances at vertical curves bear no direct relation to the speeds at which drivers operate their vehicles, it is of interest to determine the percentage of drivers that exceed safe speeds on vertical curves, based on various criteria for determining safe speeds. It is also of interest to determine what criteria, if any, are used by drivers in governing their speeds on vertical curves. For this purpose, the data for the 20 study sites were classified into two groups corresponding to the same groups used for the high- and the normal-speed roads. Driver performance was then expressed in terms of the percentage of drivers unable to stop before reaching objects of various heights as the objects first came into view. Figure 12 shows this information for high-speed roads,

TABLE 3
RELATION BETWEEN THE PERCENT OF DRIVERS EXCEEDING SPEED AND VARIOUS SIGHT DISTANCES NEAR THE CREST OF VERTICAL CURVES

| Sight Distance in Feet Measured to 4″ Object | Speed, mph. | | | Percent Exceeding Speed | | |
|---|---|---|---|---|---|---|
| | When Sight Distance is Measured to | | | | | |
| | 4″ Object | 2′ Object | 4½′ Object | 4″ Object | 2′ Object | 4½′ Object |
| High speed roads: | | | | | | |
| 195 | 30.3 | 38.3 | 45.5 | 98.0 | 86.0 | 55.3 |
| 240 | 35.8 | 44.5 | 53.7 | 93.3 | 54.2 | 14.8 |
| 410 | 53.7 | 65.2 | 73.0 | 23.0 | 1.5 | 0 |
| Normal speed roads: | | | | | | |
| 165 | 26.0 | 33.4 | 40.1 | 98.7 | 79.3 | 51.0 |
| 230 | 34.6 | 44.0 | 52.0 | 83.9 | 39.0 | 9.3 |
| 272 | 39.7 | 50.0 | 58.0 | 54.2 | 10.5 | 0 |
| 405 | 53.3 | 64.5 | 72.7 | 11.3 | 0 | 0 |

whereas Figure 13 shows the same informa- for low-speed roads.

Considering first the high-speed roads, it may be seen from Figure 12 that on vertical curves where the minimum sight distance is 300 ft. as measured to a 4-in. object, 69 percent of the drivers would be unable to stop before reaching a 4-in. object after it first came into view in case this became necessary to avoid an accident. Likewise at this same location, 20 percent of the drivers could not have stopped before reaching a 2-ft. object after it first came into view. All but 3 percent of the drivers, however, could have stopped their vehicles before reaching a 4½-ft. object after it first came into view. These percentages are based on the AASHO standards for stopping distances from various speeds.

Figure 13 shows the driver performance on normal-speed roads in a manner similar to Figure 12 for high-speed roads. On vertical curves where the minimum sight distance is 300 ft. as measured to a 4-in. object, the percentage of drivers that would be unable to stop before reaching a 4-in., 2-ft. or 4½-ft. object would be 41, 5, and 0, respectively.

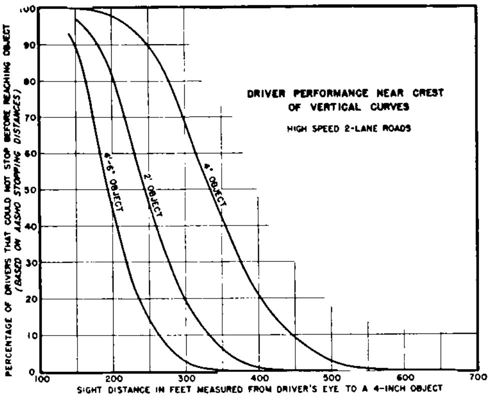


**Figure 12. Driver performance near crest of vertical curves on high-speed, two-lane roads.**

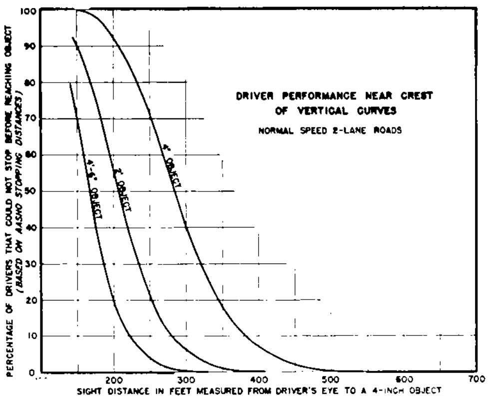


**Figure 13. Driver performance near crest of vertical curves on normal-speed, two-lane roads.**

In order to accommodate 85 percent of the drivers on high-speed, two-lane roads, the minimum sight distance measured to a 4-in. object must be 425 ft., and when using a 2-ft. object as the criterion for sight, the minimum sight distance measured to a 4-in. object must be approximately 315 ft., and when using a a 4½-ft. object as the criterion for sight, the minimum sight distance measured to a 4-in. object must be approximately 250 ft.

Similarly, to accommodate 85 percent of the drivers on normal-speed, 2-lane roads, where the average speeds under normal conditions do not exceed 45 mph., minimum sight distances measured to a 4-in. object, must be 360 ft. if the driver is to stop before reaching a 4-in. object after it first comes into view, 265 ft. if he is to stop before reaching a 2-ft. object after it first comes into view, and 210 ft. if he is to stop before reaching a 4½-ft. object after it first comes into view.

Whether or not a driver should be able to stop his vehicle before reaching either a 4-in., 2-ft., or 4½-ft. object after it first comes into view can be determined only by the accident experience at vertical curves with shorter sight distances than those listed in the above paragraph. Since there is such a large percentage of drivers exceeding safe speeds regardless of the criterion which is used, vertical curves with short sight distances must either have high accident rates or the possibility of a driver having to stop at such a location is very remote.

Table 4 summarizes this data as it appears on Figures 12 and 13.

TABLE 4
DRIVER PERFORMANCE NEAR CREST OF VERTICAL CURVES

| Sight Distance in Feet Measured to 4″ Object | Percentage of Drivers that Could Not Stop Before Reaching Object (Based on AASHO Stopping Distance) | | | | | |
|---|---|---|---|---|---|---|
| | High-Speed Roads, Height of Object | | | Normal-Speed Roads, Height of Object | | |
| | 4″ | 2′ | 4½′ | 4″ | 2′ | 4½′ |
| 200 | 98 | 82 | 45 | 92 | 56 | 20 |
| 300 | 69 | 20 | 3 | 41 | 5 | 0 |
| 400 | 21 | 1 | 0 | 7 | 0 | 0 |
| Minimum sight distance, in feet, measured to 4″ object needed to accommodate 85% of drivers... | 425 | 315 | 250 | 360 | 265 | 210 |

## RELATION BETWEEN DRIVER PERFORMANCE AND SAFE PERFORMANCE AS DETERMINED BY VARIOUS STANDARDS

To illustrate further the relation between driver performance and safe performance as determined by various standards, Figure 14 has been prepared. In this figure, for simplification, the driver performance has been combined for all 20 sites studied.

It will be noticed that there are three scales for the sight distance as measured to the three heights of object. The driver performance in miles per hour on the ordinate is plotted against sight distance to a 4-in. object on the abscissa. The relative sight distance shown by the three sets of figures on the abscissa were taken from Figure 9.

The almost horizontal curves for driver performance indicate a slight decrease in speed with a reduction in the minimum sight distance. However, the reduction in speed does not approach the reduction which would be necessary to comply with safe operation regardless of the standard used as a criterion for safe operation.

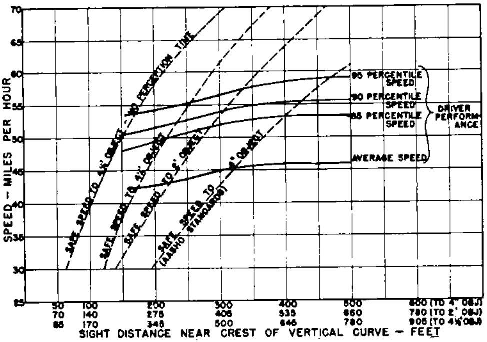


**Figure 14. Driver performance as related to safe performance as determined by various standards.**

Apparently drivers do not believe that critical situations will occur at vertical curves which require them to come to a stop or they believe they can stop in a much shorter distance than the distance which is actually required.

If critical situations do arise at vertical curves which might require a driver to come to a stop as an object comes into view, a minimum sight distance of approximately 325 ft. is required for the speed at which the average driver travels on a main rural highway, a sight distance of approximately 400 ft. is required to meet the needs of 85 percent of the drivers, a sight distance of approximately 425 ft. is required to meet the needs of 90 percent of the drivers, and a sight distance of approximately 470 ft. is required to meet the needs of 95 percent of the drivers. In other words, sight distances of less than 500 ft. to a 4-in. object on vertical curves have no place in modern highway design, except possibly on local or mountainous roads where the desired speeds are normally lower.

TABLE 5
ACCIDENT HISTORY AT VERTICAL CURVES OBSERVED

| Site No. | Report Period *from–to* | No. Cars Involved | Damages | | Date of Accident | Description of Accident |
|---|---|---|---|---|---|---|
| | | | P.D. Cars | P.I. Persons | | |
| 193 | 1943–1952 | 1<br>2<br>2<br>1 | 1<br>2<br>2<br>1 | 1<br>2<br><br>1 | July 47<br>Aug. 48<br>Apr. 50<br>Feb. 52 | Lost control, hit telephone pole<br>Side swiped car coming from drive<br>Side swiped car in passing<br>Lost control. Wet pavement |
| 194 | 1943–1952 | 2<br>2 | 2<br>2 | <br>3 | July 48<br>Sept. 50 | Collided head-on in passing<br>Collided head-on in passing |
| 195 | 1943–1952 | 2 | 2 | 5 | Sept. 50 | Collided head-on in passing |
| 196 | None | | | | | |
| 197 | 1943–1952 | 2<br>1<br>1<br>2<br>2<br>2<br>2 | 2<br>1<br>1<br>2<br>2<br>2<br>2 | <br><br><br><br>1<br><br> | Sept. 43<br>Sept. 46<br>Apr. 47<br>Jan. 51<br>Jan. 51<br>Dec. 51<br>Dec. 51 | Collided with car turning left<br>Lost control, hit telephone pole<br>Lost control. Blow out<br>Side swiped car in passing<br>Collided head-on in passing<br>Collided head-on in passing<br>Collided head-on in passing |
| 198 | 1943–1952 | 2<br>2 | 2<br>2 | 1<br> | June 49<br>Nov. 51 | Collided with oncoming car turning right<br>Collided with car turning left |
| 1-9-13 | None | | | | | |
| 291 | 1947–1952 | 1<br>1 | 1<br>1 | 1<br> | No record | Lost control<br>Lost control |
| 292 | 1947–1952 | 2 | 2 | 2 | No record | Ran into rear end of car ahead |
| 293 | 1947–1952 | 2<br>1 | 2<br>1 | 1<br> | No record | Ran into rear end of car ahead<br>Lost control |
| 294 | None | | | | | |
| 391 | None | | | | | |
| 393 | 1947–1952 | 2 | 2 | 1 | 1951 | Ran into rear end of car ahead |
| 394 | 1947–1952 | 2 | 2 | 1 | 1948 | Collided head-on in passing |
| 395 | None | | | | | |
| 991 | 1938–1952 | 2<br>3<br>2<br>1 | 2<br>3<br>2<br>1 | <br><br>3<br>1 | Dec. 38<br>Feb. 40<br>Jan. 49<br>Oct. 50 | Side swiped car in passing<br>Skidded on slippery pavement<br>Collided head-on in passing<br>Lost control, hit tree |
| 992 | 1938–1952 | 2<br>1<br>2<br>2 | 2<br>1<br>2<br>2 | 4<br><br>1<br> | July 39<br>Aug. 40<br>Nov. 40<br>Mar. 50 | Collided with car turning left<br>Lost control, hit tree<br>Collided head-on in passing<br>Ran into rear end of car ahead |
| 993 | None | | | | | |
| 994 | None | | | | | |
| 995 | 1938–1952 | 2<br>2 | 2<br>2 | | Feb. 40<br>Jan. 41 | Skidded on slippery pavement<br>Side swiped car backing out of drive |

### ACCIDENT HISTORY AT STUDY LOCATIONS

From the foregoing analyses, it is apparent that the majority of drivers of passenger cars do not decrease their speed appreciably when confronted with restrictive sight distance on vertical curves. The inference is that drivers either do not realize that critical situations may occur at vertical curves which will require them to come to a stop or they believe they can stop in a much shorter distance than is actually required. In any event, they are taking chances on roadway and traffic conditions affected by the limited sight distances afforded by the vertical curves.

A measure of the type and degree of the risks taken by drivers is reflected, in part, by the accident history at the sites studied. All available records of accidents for the sites of this study were collected and compiled in summary form as shown in Table 5. The periods covered in this compilation vary from 6 to 14 yr. for the individual sites. Thirty-three accidents were recorded at 13 of the sites involving property damage to 58 vehicles and personal injury to 29 individuals. There were no recorded accidents for seven of the sites. It appears from an analysis of the types of accidents that overdriving was one of the principal factors in the majority of the accidents.

As the outlook for the future indicates higher-powered passenger cars and increased speeds, adequate sight distance for safe driving conditions should be provided in new design to reasonably meet this anticipated speed demand. If it becomes necessary to design for less than that speed, proper signing and pavement markings should be used.

The limited accident data indicate that design and uniform pavement markings alone will not solve the problem of maximum highway safety. In addition, drivers must exercise good judgment consistent with existing highway facilities.

### SUMMARY OF FINDINGS

The findings in this report are based on driver-performance data recorded for free-moving passenger cars at the sites of 20 vertical curves on 2-lane, rural highways in New York. The findings are applicable to curves where the minimum sight distance is between 150 and 500 ft. The following are the major findings:

1. As drivers approach vertical curves with short sight distances, they invariably reduce their speeds to some extent. The reduction in speed, however, is far less than that required to provide safe operating conditions, regardless of the criterion used for determining safe conditions. Apparently, the drivers feel that the reduction in speed is greater than it actually is, or individual drivers so seldom encounter critical situations on vertical curves that they are not aware of the hazard involved.

2. No consistent relation exists between operating speeds at the crest of vertical curves and the minimum sight distances. The speeds at the vertical curves, regardless of the sight distance, are apparently governed by the normal speeds on the highway.

3. A minimum sight distance of 400 ft. to a 4-in. object is necessary to accommodate the driving habits of 85 percent of the drivers. Corresponding sight distances to accommodate 90 and 95 percent of the drivers are 425 and 470 ft. respectively. (This is based on present AASHO standards for safe stopping distances from various speeds.)

4. Driver performance on vertical curves in terms of operating speeds bears no relation to the safe speed as determined by various design standards.

### ACKNOWLEDGEMENT

This study was carried on by the Vehicle Operation Section of the Bureau of Highway Planning, New York State Department of Public Works with the coöperation of the Bureau of Public Roads. The procedure for analysis was developed in collaboration with O. K. Normann and A. Taragin of the Highway Transport Research Branch of the Bureau of Public Roads and progressed under the direction of C. E. Billion of New York's Bureau of Highway Planning.

## APPENDIX A

### *Definitions*

The definitions used for the various terms in this study are the same as presented in the *Highway Capacity Manual* and the American Association of State Highway Officials' *Policy on Sight Distance for Highways* as they pertain to passenger cars.

*Speed.* The rate of movement of passenger cars expressed in miles per hour.

*Average Speed.* The average of the speeds of all passenger cars at a specified point on a given roadway, during a specified period of time.

*Design Speed.* A speed selected for purposes of design and correlation of those features of a highway, such as curvature, superelevation, sight distance, upon which the safe operation of passenger cars is dependent. It is the highest continuous speed at which individual passenger cars can travel with safety upon a highway, when weather conditions are favorable, traffic density is low, and the design features of the highway are the governing conditions for safety.

*85-Percentile Speed.* The speed which 15 percent of the passenger cars exceed.

*Legal Speed.* The maximum speed permitted by law—50 mph. in New York State.

*Safe Speed to 4-in. Object (AASHO Standards).* The maximum speed at any point on the roadway which will provide safe stopping distance as measured by the nonpassing minimum sight distance at the point on the highway with vision approximately 4 ft. 6 in. above the pavement to an object 4-in. above the pavement.

*Safe Speed to 2-ft. Object.* Same as above except nonpassing minimum sight distance is measured to an object 2 ft. above the pavement.

*Safe Speed to 4½-ft. Object.* Same as above except nonpassing minimum sight distance is measured to an object 4½ ft. above the pavement.

*Percent Overdriving.* The percentage of drivers of passenger cars exceeding the speed from which they could stop, as measured by the AASHO standards for vehicle stopping distance, before reaching an object after it comes into view.

*Sight Distance.* The length of roadway visible to the driver of a passenger car at any point on the roadway when the view is unobstructed by traffic.

*Stopping Sight Distance.* The distance required by a driver of a passenger car, traveling at a given speed, to bring his car to a stop after an object on the roadway becomes visible.

*Restricted Stopping Sight Distance.* A sight distance shorter than the stopping sight distance for the design speed.

*Safe Stopping Distance to a 4-in. Object (AASHO Standards).* The distance required by a driver of a passenger car, traveling at a given speed, and whose eye is assumed to be 4.5 ft. above the pavement surface, to bring his car to a stop, after an object 4 in. above the pavement becomes visible. Same as AASHO Nonpassing Minimum Sight Distance.

*Sight Distance Required for 85-percent Speed (AASHO Standard).* The sight distance necessary to accommodate 85 percent of the passenger cars, in the sample, safely, according to AASHO standards for safe stopping distance.

*AASHO Nonpassing Minimum Sight Distance.* Nonpassing minimum sight distance is the sum of two distances: (1) the distance traversed by a vehicle from the instant the stationary object is visible to the instant the brakes are applied and (2) the distance required to stop a vehicle after the brakes are applied. The first of these two distances depends upon the speed of the vehicle and the sum of the perception time and the brake reaction time of the operator. The second distance depends on the speed of the vehicle, the characteristics and condition of brakes, tires and pavement surface, and the alignment and the grade of the highway. The sum of these two distances traversed to stop the vehicle is the safe stopping distance and therefore the nonpassing minimum sight distance. The factors adopted by the AASHO for perception and brake reaction time and braking distance computations to arrive at the approved nonpassing minimum sight distances for assumed design speeds, are listed in their policy. When using the 4-in. object as the criteria for measuring sight distance, these approved minimum sight distances are the basis for the AASHO nonpassing-minimum-sight-distance curve as shown in Figure 7.

## APPENDIX B

### *Specifications for Location of Sites*

In the establishment of each site for speed observance on vertical curves, the following roadway requirements were met:

1. Alignment. Vertical curve on tangent.
2. Grade. Approach grade on tangent length with a minimum of 1,000 ft. to the point of vertical intersection and of gradient to minimize effect on speed.
3. Rural. An open highway.
4. No impediments. No speed zones under 50 mph.
5. Good riding surface.
6. No access roads within 1,000 ft. of site.
7. Free-flowing traffic.
8. Minimum traffic in opposite direction of observations.

## APPENDIX C

### *Sampling Accuracy*

Generally speaking, sample calculations of the arithmetic mean of a group of observed speeds requires only 50 to 100 observations to assure dependable and accurate results. However, the important consideration in sampling regardless of size is to find the single value representative of the group of samples. This may be the arithmetic mean, the median, or the mode. From inspection of the speed distribution curve of a group of samples, the value which is most representative of the group may be selected as evidenced by the tendency of the other samples to group around it.

The scattering of the samples varied in each test of the study. This tendency toward scattering of the data is recognized by calculating an average value which is an estimate

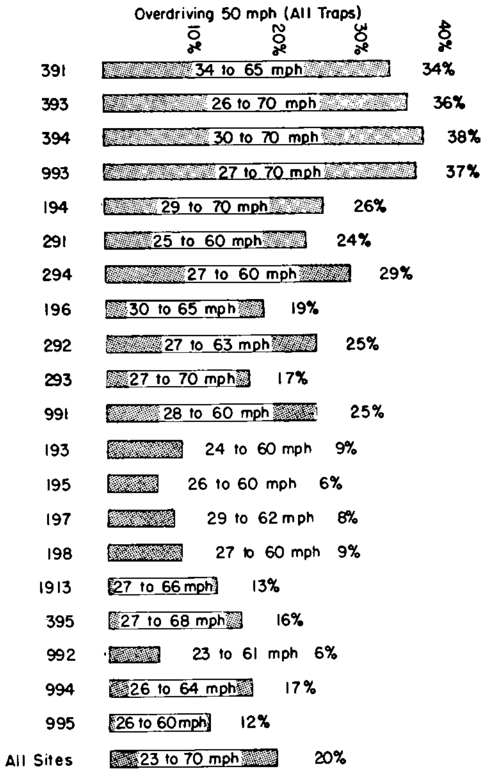


**Figure A. Legal-speed observance.**

of the so-called true value (in this study, the average value for speed of all traffic). The computed arithmetic mean of the samples was used as an estimate of the true average speed. The standard deviation is used as a measure of the scatterings to determine the adequacy of the samples.

The method of estimating standard deviation and sample error was applied to the observations grouped according to average speed near the crest of the vertical curves for high-speed and normal-speed roads with the following results:

| | Average Speed | Standard Deviation | Standard Error |
|---|---|---|---|
| High-speed roads, mph.... | 46.8 | 8.8 | 0.31 |
| Normal-speed roads, mph.. | 41.7 | 7.6 | 0.21 |

There are only 4.8 chances in 100 that the true average speed differs by 0.62 mph.(two standard errors) from the sample average.

TABLE A

DATA AT CRITICAL POINTS NEAR CREST OF VERTICAL CURVES

| Site | Sight Distance Measured to 4-Inch Object | Safe Speed | Driver Performance Speed, mph. | | | |
|---|---|---|---|---|---|---|
| | | | Average | 85% | 90% | 95% |
| 2-9-2 | 150 | 24 | 44.6 | 51.4 | 53.5 | 56.2 |
| 9-9-5 | 160 | 25.4 | 39.7 | 47.3 | 48.6 | 50.9 |
| 3-9-3 | 170 | 26.8 | 46.3 | 54.7 | 57.0 | 60.0 |
| 1-9-5 | 190 | 29.5 | 37.8 | 44.2 | 46.0 | 49.5 |
| 2-9-4 | 205 | 31.5 | 46.5 | 53.5 | 55.2 | 57.2 |
| 3-9-1 | 210 | 32.2 | 48.0 | 53.5 | 55.0 | 57.2 |
| 2-9-1 | 225 | 34.0 | 45.1 | 52.1 | 54.0 | 56.4 |
| 2-9-3 | 225 | 34.0 | 43.5 | 49.3 | 51.1 | 53.5 |
| 9-9-1 | 225 | 34.0 | 44.6 | 51.7 | 53.5 | 55.7 |
| 1-9-8 | 235 | 35.2 | 39.6 | 46.6 | 48.6 | 51.2 |
| 1-9-13 | 235 | 35.2 | 41.6 | 49.6 | 52.0 | 55.5 |
| 1-9-7 | 255 | 37.7 | 40.3 | 45.6 | 48.2 | 52.5 |
| 3-9-4 | 255 | 37.7 | 47.7 | 54.8 | 56.5 | 59.5 |
| 1-9-3 | 260 | 38.3 | 39.8 | 46.3 | 48.5 | 52.5 |
| 9-9-2 | 275 | 40.1 | 40.2 | 45.9 | 47.7 | 50.5 |
| 1-9-6 | 300 | 42.8 | 44.4 | 51.0 | 52.4 | 54.5 |
| 9-9-3 | 310 | 44.0 | 49.6 | 56.6 | 58.1 | 60.0 |
| 9-9-4 | 360 | 49.0 | 42.9 | 51.8 | 54.0 | 57.0 |
| 1-9-4 | 510 | 62.0 | 46.4 | 55.2 | 57.7 | 61.6 |
| 3-9-5 | 450 | 57.2 | 44.6 | 51.0 | 52.8 | 55.5 |

TABLE B

DATA ON SAMPLES

| District, Project, Site | Date and Time of Sampling | No. of Samples |
|---|---|---|
| 1-9-3 | Sat., Oct. 7, 12:45 P.M. 4:45 P.M. | 90 |
| 1-9-4 | Tues., Aug. 15, 11:30 P.M. 3:20 P.M. | 110 |
| 1-9-5 | Thurs., Aug. 24, 11:30 A.M. 3:30 P.M. | 100 |
| 1-9-6 | Wed., Aug. 23, 2:30 P.M. 3:50 P.M. | 128 |
| 1-9-7 | Wed., Aug. 23, 10:00 A.M. 12:30 P.M. | 100 |
| 1-9-8 | Thurs., Aug. 17, 1:40 P.M. 4:35 P.M. | 103 |
| 1-9-13 | Tues., Aug. 22, 8:30 A.M. 3:45 P.M. | 91 |
| 2-9-1 | Wed., Sept. 6, 9:30 A.M. 5:15 P.M. and Sat., Sept. 30, 3:30 P.M. 5:15 P.M. | 151 |
| 2-9-2 | Tues., Aug. 29, 3:10 P.M. 5:40 P.M. and Wed., Aug. 30, 10:50 A.M. 2:50 P.M. | 108 |
| 2-9-3 | Tues., Sept. 5, 3:30 P.M. 5:30 P.M. | 103 |
| 2-9-4 | Mon., Aug. 28, 12:15 Noon 2:30 P.M. and Tues., Aug. 29, 9:30 A.M. 10:50 A.M. | 108 |
| 3-9-1 | Mon., Oct. 2, 10:30 A.M. 1:30 P.M. | 142 |
| 3-9-3 | Fri., Sept. 29, 1:00 P.M. 5:00 P.M. | 107 |
| 3-9-4 | Wed., Sept. 27, 9:50 A.M. 3:50 P.M. | 100 |
| 3-9-5 | Wed., Oct. 18, 12:15 P.M. 3:30 P.M. | 100 |
| 9-9-1 | Mon., Sept. 18, 11:00 A.M. 2:15 P.M. | 101 |
| 9-9-2 | Mon., Sept. 18, 4:00 P.M. 6:20 P.M. | 100 |
| 9-9-3 | Wed., Sept. 20, 2:30 P.M. 6:10 P.M. | 103 |
| 9-9-4 | Wed., Sept. 20, 8:45 A.M. 12:15 P.M. | 121 |
| 9-9-5 | Tues., Sept. 21, 10:30 A.M. 3:30 P.M. | 100 |
| | Total | 2166 |

TABLE C
GEOMETRIC FEATURES AND LOCATION OF SITES

| District, Project, Site | S.H No. | Route | County | Road Width Feet | No. of Lanes | Direction Traffic Observed | Approach Grade, % | Leaving Grade, % | Length V.C. | Minimum Sight Distance 4½ ft. to 4" | 2'-0" | 4'-6" | 1950 12 hr. Aug. Count | Location of Site |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1-9-3 | 5478 | 2 | Rensselaer | 20 | 2 | Eastbound | +0.9 | −4.0 | 300′ | 260 | 355 | 460 | 2098 | V.C. on tangent. 2-lane P.C.C. pavement with surface treatment 0.80 mile west of Petersburg |
| 1-9-4 | 1425 | 40 | Rensselaer | 22 | 2 | Southbound | +1.8 | −4.6 | 700′ | 425 | 565 | 685 | 2469 | V.C. on tangent. 2-lane P.C.C. pavement 0.95 miles north of B. & M. R. R. overpass |
| 1-9-5 | 366 | 85 | Albany | 22 | 2 | Westbound | +7 | −6.2 | 350′ | 185 | 245 | 290 | 1655 | V.C. on tangent. 2-lane P.C.C. pavement with surface treatment. 2.1 miles east of intersection of Rts. 85 and 85A |
| 1-9-6 | 880 | US 7 | Schenectady | 20 | 2 | Westbound | +2.4 | −4.2 | 500′ | 290 | 375 | 460 | 4973 | V.C. on tangent. 2-lane P.C.C. pavement 1.75 miles west of W.S.R.R. underpass in South Schenectady |
| 1-9-7 | 5545 | US 7 | Schenectady | 20 | 2 | Westbound | +6.0 | −0.7 | 500′ | 255 | 340 | 425 | 4682 | V.C. on tangent. 2-lane P.C.C. pavement 0.70 miles east of intersection routes 7 and 20 at Duanesburg |
| 1-9-8 | 177 | 146 | Albany | 20 | 2 | Eastbound | +3.2 | −6.0 | 500′ | 235 | 325 | 395 | 1453 | V.C. on tangent. 2-lane P.C.C. pavement 0.20 miles east of Altamont Village line |
| 1-9-13 | 1874 | 150 | Rensselaer | 20 | 2 | Westbound | +4.0 | −5.1 | 500′ | 235 | 310 | 390 | 1027 | V.C. on tangent. 2-lane P.C.C. pavement 1.61 miles southwest of East Schodack |
| 2-9-1 | 1144 | 12 | Oneida | 20 | 2 | Northbound | +5.80 | −5.5 | 450′ | 225 | 295 | 355 | 5595 | V.C. on tangent. 2-lane P.C.C. pavement with surface treatment. 1.60 miles south of intersection of 28-B to Remsen |
| 2-9-2 | 5559 | 28 | Oneida | 20 | 2 | Southbound | +4.2 | −5.5 | 250′ | 150 | 205 | 270 | 2410 | V. C. on tangent. 2-lane bit. mac. pavement 1.80 miles southeast of Trenton Falls |
| 2-9-3 | 5248 | 28 365 | Oneida | 20 | 2 | Northbound | +3.8 | −2.0 | 300′ | 225 | 315 | 415 | 2350 | V. C. on tangent. 2-lane bit. mac. pavement 0.40 miles north of Woodgate traffic light |
| 2-9-4 | 8277 | 12 | Oneida | 22 | 2 | Southbound | +1.2 | −5.5 | 250′ | 205 | 285 | 365 | 2279 | V. C. on tangent. 2-lane bit. mac. pavement 3.20 miles south of Paris |
| 3-9-1 | 9037 | US 20 | Cayuga | 20 | 2 | Eastbound | +5.0 | −5.5 | 400′ | 210 | 275 | 340 | 5671 | V. C. on tangent. 2-lane bit. mac. pavement 1.50 miles west of Onondaga County line |
| 3-9-3 | 595 | US 11 | Cortland | 20 | 2 | Northbound | +2.5 | −7.6 | 300′ | 170 | 250 | 280 | 2458 | V. C. on tangent. 2-lane bit. mac. pavement 0.70 miles south of P.S.C. #5423 at Tully |
| 3-9-4 | 8391 | US 20 | Onondaga | 20 | 2 | Westbound | −0.6 | −7.2 | 350′ | 255 | 345 | 425 | 4072 | V. C. on tangent. 2-lane bit. mac. pavement 0.70 mile east of Pompey Center |
| 3-9-5 | 9025 | 20N 92 | Onondaga | 20 | 2 | Northbound | +1.9 | −2.2 | 500′ | 450 | 590 | 700 | 5946 | V.C. on tangent. 2-lane P.C.C. pavement 3.10 miles northwest of Madison Co. line |
| 9-9-1 | 834 | US 11 | Broome | 22 | 2 | Northbound | +4.2 | −4.4 | 450′ | 225 | 305 | 390 | 3708 | V.C. on tangent. 2-lane bit. mac. pavement 600 ft. north of Danceland |
| 9-9-2 | 834 | US 11 | Broome | 22 | 2 | Southbound | +2.2 | −4.6 | 400′ | 275 | 365 | 445 | 3640 | V.C. on tangent. 2-lane bit. mac. pavement 1000 ft. north of hwy. to Kirkwood Airport |
| 9-9-3 | 266 | US 7 | Broome | 24 | 2 | Southbound | +3.0 | −3.3 | 500′ | 300 | 425 | 510 | 2149 | V.C. on tangent. 2-lane bit. mac. pavement 1.4 miles south of intersection of county road to tunnel |
| 9-9-4 | 5242 | US 7 | Broome | 24 | 2 | Southbound | −0.60 | −5.8 | 550′ | 360 | 480 | 590 | 2516 | V.C. on tangent. 2-lane bit. mac. pavement 0.25 miles east of Port Crane and Route 369 |
| 9-9-5 | 267 | US 11 | Broome | 22 | 2 | Southbound | +3.50 | −7.25 | 300′ | 160 | 220 | 275 | 2632 | V.C. on tangent. 2-lane bit. mac. pavement 2.7 miles from No. Junction of Routes 11 and 12 on Route US 11 |