Effect of Grades on Service Volume

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The problem of determining effects of trucks or any slow-moving vehicle on the operating characteristics of a section of multilane road is discussed. The action of trucks in reducing the service volume of a road is described and is related to the number of trucks, speed of trucks (steepness of grade), and length of grade. Relationships between these factors are developed and presented in the form of a proposed design chart for determining equal service volumes which would be suitable for rural conditions for any combination of grade, autos, and trucks. The use of this chart in determining when additional lanes should be added and the effects of trucks on maximum capacity of a road are described.

•THE PURPOSE of this paper is to develop a level-of-service curve for multilane highways that will show the effect of grades and trucks on the service volume for a given level of service, and more particularly, for the level of service that has been adopted as design capacity for rural freeways by AASHO, i.e., 2,000 cars per hour on two lanes in one direction on a level grade.

The 1950 edition of the Highway Capacity Manual stated that one truck was equivalent to two passenger cars in level terrain, four passenger cars in rolling terrain, and eight passenger cars in mountainous terrain (1). This statement can be plotted in graphical

cars per hour on two lanes (1,000 veh/hr/lane). Thus, with 10 percent trucks in level terrain, the service volume would be 1,820 vph, consisting of 182 trucks and 1,638 autos, and in rolling terrain it would be 1,540 vph, consisting of 154 trucks and 1,386 autos. This was shown in Table 9 of the Highway Capacity Manual as 91 and 77 percent, respectively, of passenger car "capacity" on level terrain.

The Highway Capacity Manual truck equivalency factor (1) was a broad approximation and many design engineers have felt a need for capacity charts which were more sensitive to such measurable factors as length and steepness of grade. How long does a grade have to be to qualify as mountainous? Are the hills of the San Francisco Bay Area "rolling" and the Sierra Nevada "mountainous"? Trucks seem to have as much effect in the former as in the latter location. In fact, a large portion of the Interstate highway across the Sierra follows river grades and the trucks roll along at 50 mph there just the same as they do in level terrain.

Attempts have been made to determine truck equivalency factors by measuring time headways between vehicles which were classified as car-car, car-truck, truck-car, truck-truck, in each lane. These attempts, in which the author participated, were not successful because observations had to be at a precise (unobserved) combination of trucks and cars to help determine the locus of the graph shown in Figure 1. In Figure 1, truck equivalent is the slope of the line. If observations are made at any pair of ordinates except right on the sloping line, they do not have any quality which would help determine either the position or slope of the line. For example, the two points (x_1, y_1,) and (x_2, y_2) shown in Figure 1 are of no use in plotting the graph and really only show the traffic demand at the places and times of observation. Actual measurements at several points in California showed extreme variation in truck equivalents

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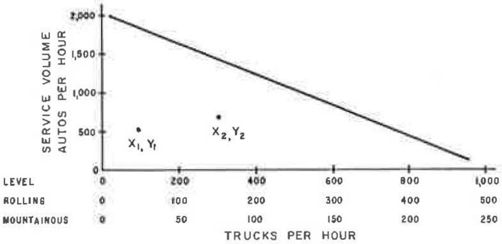


Figure 1. Effect of trucks on service volume, two lanes in one direction (1).

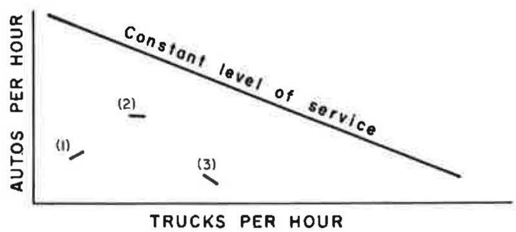


Figure 2.

and some absurdities such as a truck equivalent less than 1 on a plus 6 percent grade. These would plot on Figure 1 somewhat as shown in Figure 2.

The slopes shown at points 1, 2, and 3 of Figure 2 are only of small dimensions ($\Delta y/\Delta x$) but they were calculated for each observation and plotted (erratically, as indicated). A plus slope would indicate a truck equivalent of less than 1, and is perfectly possible to calculate from observed data, but as can be seen, this does not say anything useful about the "capacity" curve itself.

One of the problems involved relates to a clear understanding of what is meant by a "level of service," or what was formerly called "practical capacity." Basically it is a matter of probability. Figure 3 shows time-distance graphs of several vehicles in a stream of traffic on a short segment of two-lane one-way roadway.

It is seen that all the vehicles in Figure 3 enjoyed free movement except No. 8 which had to slow down and wait for No. 9 to gain an acceptable headway before it could move into L_2 and pass No. 7. There is a chance that this will happen no matter how low the volume is. The chance (probability) increases as each of the following increases:

1. Volume (number of vehicles per unit of time) of slow vehicles and of faster vehicles;
2. Difference in vehicle speeds (increased steepness of grade causing this to increase); and
3. Length of road under consideration (length of grade).

At some volume far below capacity, the chance of this happening is high enough that the traveling public decide they need a wider road. This is basically an economic decision. That is to say, the public appear to be willing to keep on building and paying for more highways as long as they encounter restrictions to free flow exceeding some amount. As interpreted by the American Association of State Highway Officials (AASHO), on rural highways this amount is not more than 30 hr/yr during which 2,000 passenger cars per hour or more pass a given point on two lanes in one direction on level grade.

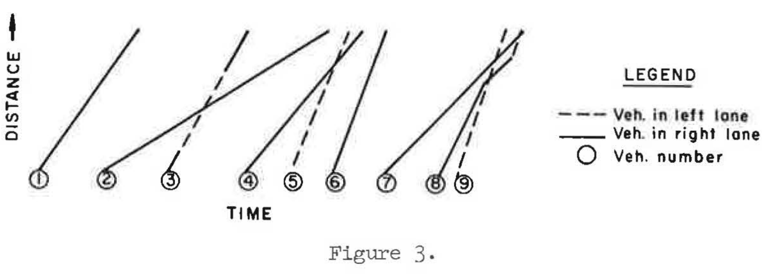


Figure 3.

DEVELOPMENT OF DESIGN CHART FOR RURAL CONDITIONS

Basically, we are concerned with finding an acceptable level of operation and relating it to length of grade, steepness of grade, and number of trucks. We assume that the acceptable flow rate is related to the frequency of passing opportunities that occur for vehicles overtaking a slow-moving vehicle. Passing opportunities are related to the three factors noted.

What do we mean by acceptable level of operation for a section of rural freeway with two lanes in one direction? In the design sense, we should expect pretty much free flow with little slowing in the left lane and very few autos caught in the right lane. We can say for sure we want no stoppages in the left lane. With our knowledge of traffic flow, what conditions bring this about?

Effects with Trucks in Right Lane Only

Since we are considering freeways, we assume good alignment and that slow-moving vehicles can be seen by an auto driver in the right lane for some distance before he would have to slow appreciably. This auto driver, on seeing the truck, would then simply merge into the left lane. He would have as much time to do this as he would normally have to merge into a freeway at any high-standard on-ramp.

We know from observation that the maximum auto rate-of-flow that can pass a single truck or series of trucks in the right lane varies from 1,800 to about 2,400 vph. And for smooth flow with no queuing upstream, the maximum passing rate is limited to 2,000 vph. As an example, if a flow rate greater than 2,000 vph is going by a truck and if a car caught behind the truck tries to merge into this stream, there is a high probability of breakdown in the left lane. Of course, there is a chance that this car would not try to pass but if there are several cars caught and the grade is of significant length, it is certain that some will attempt to pass, causing severe congestion.

When merging volumes at a good ramp are below 1,500 vph, there is little or no congestion and no ramp vehicles in queue. On a grade with trucks in the right lane, the same holds true and if total auto flow rate is less than 1,500 vph, there will be no [illegible] right lane. (If a lane is completely blocked and the public is aware of it, as they are aware of grades, 1,500 autos per hour can be handled in a two-lane to one-lane merge with little trouble or speed reduction.)

Based on this discussion, Figure 4 represents what we consider a rural design level of service with trucks in the right lane only. With no trucks, design volume is 2,000 vph (in two lanes). This is considered to be an acceptable volume giving free flow with little restrictions to desired speeds. With the introduction of a few trucks, the acceptable number of autos decreases, but fairly gradually. With just several trucks per hour, acceptable auto volume is still 1,900. Though flow around these trucks will involve some localized turbulence, this high auto flow is still considered acceptable because much of the auto traffic will not encounter the truck and the flow rate in the left lane passing the truck will take place over a very short space. In other words, the high flow rate passing the truck will be only for about ¼ mi. As the frequency of trucks increases, most traffic will encounter trucks and acceptable passing auto rates are reduced to 1,500 vph. Flow rates of 1,500 in the left lane still take place over a relatively short space, as many autos move back to the right lane on passing a truck. As truck flow rates increase even more, very few autos will go back to the right lane and most autos will be in the left lane for the entire length of grade. In this case, 1,500 vph in one lane is considered too high to maintain rural free-flow conditions and, therefore, acceptable auto flow rate decreases to 1,200 vph. (In actual practice, when trucks are this numerous, they will not stay in the right lane and acceptable auto rates are even lower.)

As long as trucks stay in the right lane, the length of grade is not a controlling factor. For example, even with a great number of trucks, if they are all in the right lane, a flow rate of 1,200 autos per hour in the left lane can be handled reasonably well for any length.

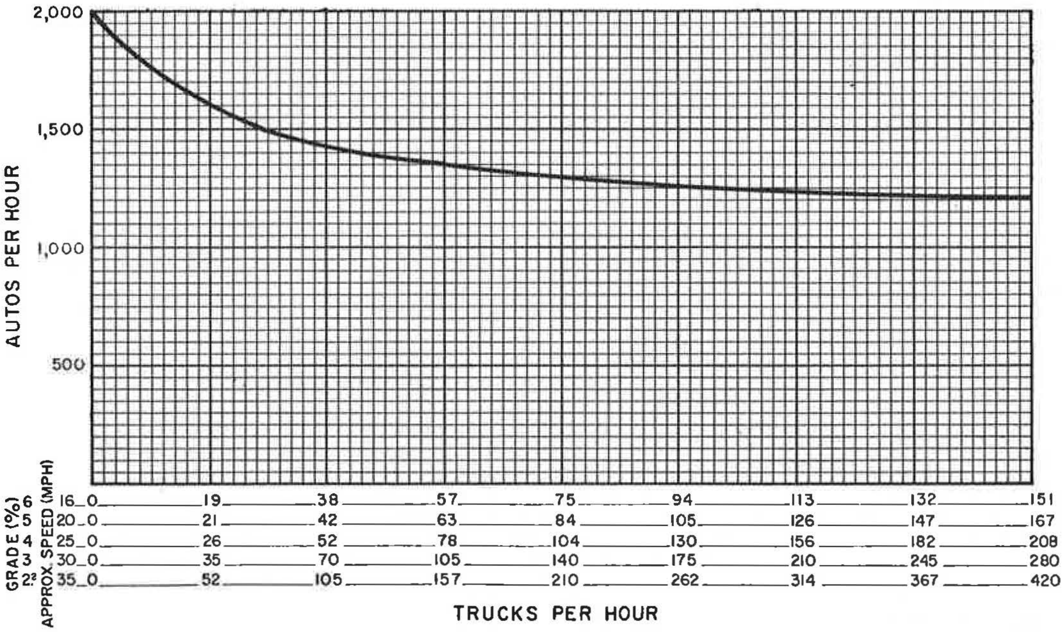


Figure 4. Effect of trucks on auto volume at given level of service if trucks remain in right lane.

The effects of different steepness of grade are indicated in Figure 4 by the different scales for each grade. Although the exact weighting of various grades was determined in connection with truck passing effects, it also represents fairly closely the degree of interference even with all trucks in the right lane. In other words, a flow rate of 1,200 autos per hour would encounter roughly the same number of slow vehicles in the right lane with 75 trucks per hour on a 6 percent grade, 84 trucks per hour on a 5 percent grade, 104 trucks per hour on a 4 percent grade, etc.

As an example of the use of this chart, assume a location with a predicted one-way peak volume of 1,300 vph including 10 percent trucks and the section contains a sustained 4 percent grade, 8,000 ft long. (A sustained grade is considered one where average truck speed is reduced to 35 mph or less.) Since the 130 trucks and 1,170 autos on a 4 percent grade plot below the capacity line, operation would generally be acceptable and a climbing lane would not be required.

Effects with Trucks in Left Lane

As the number of trucks and/or the length of grade and/or the steepness of grade increase, the chances of trucks overtaking and passing other trucks increase greatly. This becomes a much more important limitation on capacity. The number and duration of passing maneuvers can be estimated from the speed distribution of trucks, the number of trucks, and the length of grade. This number varies with the length of grade and with the square of the number of trucks and is related to the speed distribution of the trucks. (See Appendix A and B for a more detailed explanation.)

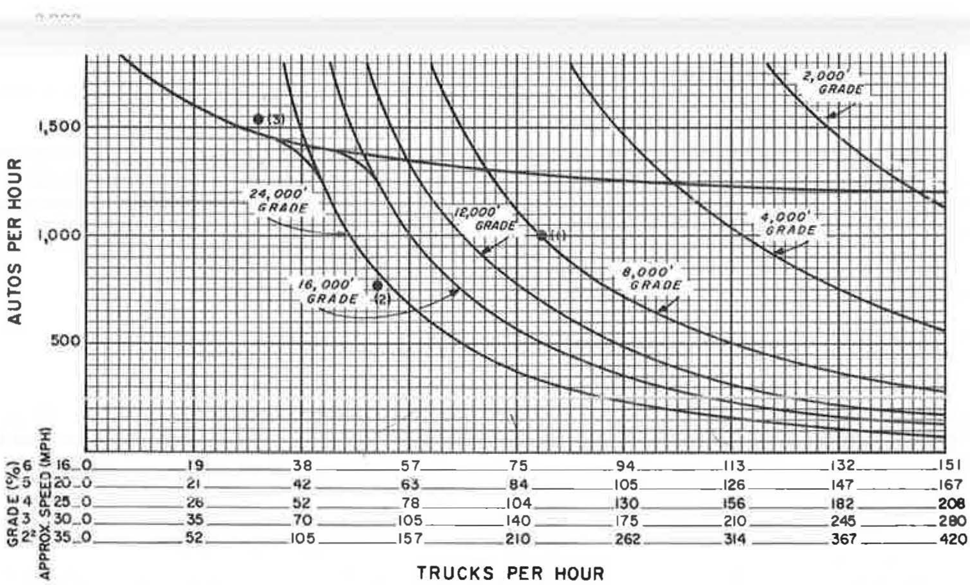
In other words for a given number and speed of trucks if the grade is twice as long, there will be twice as many passing maneuvers. For a given length of grade and speed of trucks, twice as many trucks will result in 4 times as many passings. For a given number of trucks and length of grade, the duration of passing maneuvers is related to the average speed of trucks as described in Appendix B; i.e., if trucks average 20 mph, slow trucks are in the left lane 1.55 times longer than if the trucks average 25 mph.

Figure 5 was drawn using these relationships such that any point on these curves will result in an equal amount of total delay to auto traffic, and level of operation is, therefore, assumed to be equivalent. In other words, on a given grade with 1,000 autos and 75 trucks, there will be a certain number of autos delayed by truck passing maneuvers. If there are 150 trucks, there will be 4 times as many passings, and if there are 250 autos in the stream, then the same number of autos will be delayed by trucks in the left lane. Therefore, 75 trucks and 1,000 autos are equivalent to 150 trucks and 250 autos.

The level of operation or position of the curves on the graph was determined subjectively by observing several grades. It was determined, for example, that on an 8,000-ft 3 percent grade with 150 trucks per hour, acceptable operation would result if auto flow did not exceed 1,000 per hour (Fig. 5). The curves, therefore, represent equal operation for any combination. Two other combinations of conditions subjectively determined to be acceptable also are shown and fit the curves fairly well.

This level of service is not exactly the same as with 2,000 vph on a level section without trucks. As long as there is even one truck in the left lane, there is a probability that some autos will be delayed. There is almost no probability of an auto being delayed this amount on a level section without trucks. It would be economically foolhardy to try to provide this service on a grade only several thousand feet long, and drivers do not require or expect it. The type of service provided in this chart is still high level and very few autos would be delayed. Some will be caught, but there will be no long queues. The percentage of autos delayed is not constant, though the amount of delay and absolute number of autos delayed is relatively constant.

Using the same example as previously to illustrate use of the chart, the 1,170 autos and 130 trucks would plot above the acceptable operation curve for an 8,000-ft grade and, therefore, operation would be less than desirable. A climbing lane should then be



(1)-Number of autos and trucks on an 8,000 ft. 3% 2 lane grade considered to give acceptable level of service for rural conditions. This point used to place the family of curves.

Independent subjective determination of acceptable conditions.
(2)-"Grapevine" 2 lane, 6%, 30,000', 50T, 750A.
(3)-"Waldo" 2 lane, 6%, 10,000', 30T, 1550A.

Figure 5. Effect of trucks on auto volume at given level of service when truck-passing-truck maneuvers control (superimposed on Figure 4 curve).

provided, although the chart also indicates that if 4,000 ft of passing lane were provided, operation on the remaining 4,000-ft section would be acceptable.

In effect, then, for a given combination of truck and grade conditions, we evaluate them using Figures 4 and 5, taking the lower of the two acceptable volume levels. Therefore, Figure 5 combines the two graphs. For convenience and practicality in constructing the final design chart, we round the corners where the truck passing control intersects nontruck passing control. Figure 6 shows the final chart.

USE OF DESIGN CHART FOR RURAL CONDITIONS

In using this chart, it should be recognized that the curves represent average conditions and there can be a great amount of variability. In other words, if trucks on a particular grade are faster than the normal speed distribution used in developing the chart, operation will not be as critical for a certain combination of autos, trucks and grade. Conversely, if the trucks are slower than normal, operation will be more critical.

Volumes indicated on the chart are full hour volumes. Therefore, this also introduces variability since volume rates can fluctuate significantly within an hour. For example, if an hour flow is 1,500 veh, there is a chance that the flow rate, when there are several trucks on the grade, could be 1,800 vph.

However, the curves in general take care of normal variability and if the conditions of the chart are satisfied, only in rare cases would severe congestion result. Actual capacity would never be exceeded.

The design chart is for two lanes only. When more lanes are available, we assume that trucks will still only use the right two lanes or could be required to by law, so that the additional lanes could handle, based on rural conditions, 1,000 autos per hour per lane. Therefore, assuming conditions of a grade were such that acceptable hour flow were 1,200 veh including 100 trucks in the two lanes, if three lanes were available, acceptable flow would be 2,200 veh including 100 trucks. If four lanes were available, the figure would be 3,200 with 100 trucks.

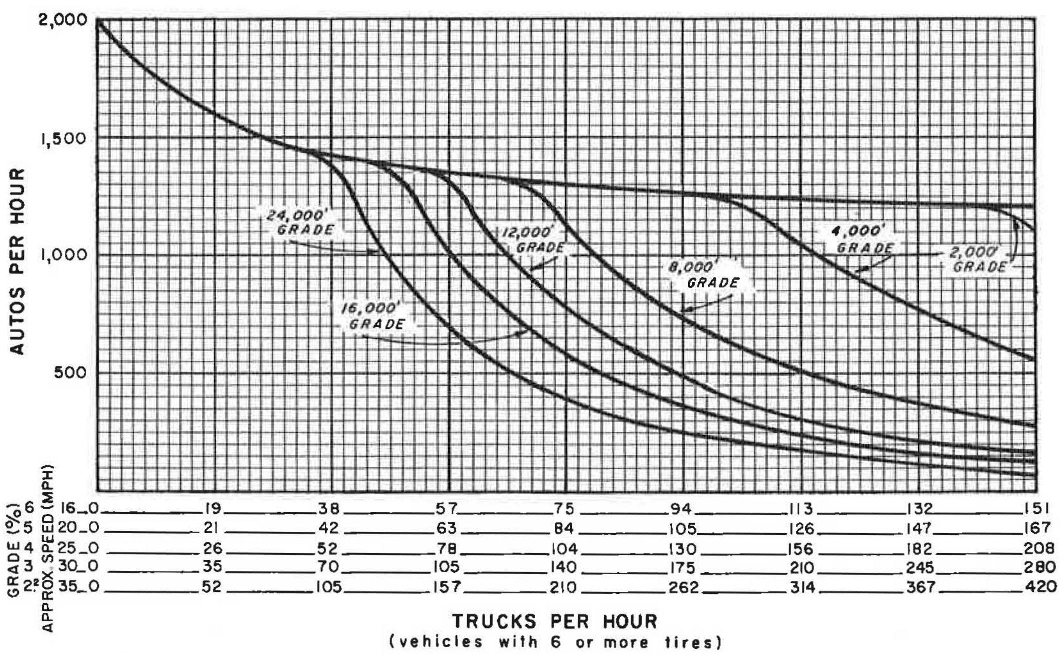


Figure 6. Equivalent service volumes relating trucks, grades, and autos on two-lane one-way roadways.

On grades less than 2 percent where truck speeds are not reduced to 35 mph, effects of trucks are generally based on the greater space occupied by trucks and slightly lower speeds maintained. In this case, reductions in free-flow volume of 2,000 autos per hour without trucks can be based on an equivalency of one truck equaling two autos.

One other point should be noted concerning the lengths of grade indicated in the chart. They represent sustained grades which are grades long enough to reduce average truck speed to 35 mph or less. The vertical curve or length of grade necessary to slow the trucks from 50 to 35 mph does not have to be considered. The length indicated on the chart is the length the trucks are at 35 mph or less. It takes about 2,000 ft for trucks to slow to 35 and then accelerate from 35 to 50 mph on a 6 percent grade compared to about 3,400 ft on a 3 percent grade (2). If we want to be more precise and were evaluating a 6 percent grade against a 3 percent grade, then the 8,000-ft grade curve, for example, would actually represent about 10,000 ft of 6 percent grade but 11,400 ft of 3 percent grade.

In summary, if predicted traffic conditions and grade conditions plot above the acceptable volume curves, an additional lane should be provided if flow on the grade is to be maintained at a quality roughly equivalent to the same flow on level or rolling terrain.

The chart, however, indicates that for some conditions, a climbing lane would not have to be added the full length of a grade to bring operating conditions to an acceptable level. For example, assume a 24,000-ft 6 percent grade with predicted traffic of 1,000 autos and 75 trucks. This plots well above the curve of acceptable operation for a 24,000-ft grade, and a climbing lane should be provided. But if only 16,000 ft of climbing lane were provided leaving 8,000 ft of two-lane 6 percent grade, then flow conditions would be acceptable since the traffic and grade conditions plot below the acceptable operation curve for an 8,000-ft grade. The physical picture this represents is that with 24,000 ft of two-lane grade, trucks will be in the left lane frequently enough to cause numerous delays to the auto stream. If the length of two-lane grade is only 8,000 ft, there is much less chance that trucks will catch up with each other; consequently, there will be fewer trucks in the left lane and infrequent delays to the auto

In general, if a truck lane is not provided the whole length of a grade, it should be used on the upper part of the grade. This will not require merging of slow trucks on the grade. It is important that a climbing lane be carried far enough so that trucks can accelerate to about 40 mph before entering the main lanes. Also, trucks that do not decelerate as slowly as normal do not need a truck lane at the beginning of the grade.

However, it is much safer to provide a truck lane the whole length. In the example, 16,000 ft of climbing lane increased auto design volume by 700. But 24,000 ft of climbing lane increases auto design volume by at least 1,000 and virtually insures that the grade will have as much capacity as the approach section.

URBAN FLOW CONDITIONS

The discussion and design chart presented deal strictly with rural conditions where most trips are long and essentially free-flow conditions are desired. Although we have not yet developed charts in this detail for urban conditions, some discussion is in order. In any section of freeway, the most important thing is to insure that enough lanes are provided so that demand will not exceed the capacity of the section. Capacity of a rural freeway is no different from that of an urban freeway.

Sustained grades of any slope (defined as a grade long enough and steep enough to reduce truck speeds to 35 mph or less) greatly reduce capacity and since most urban freeways will operate near capacity, as a general rule an added lane should be provided on all sustained grades in urban areas in which design hour volumes are within 1,000 vph of normal capacity on a level section.

For example, on a four-lane section (one-way) with estimated peak hour traffic of 5,000 veh, an extra lane should be provided on any sustained grade. Similarly, an extra lane should be provided for 3,500 veh on three lanes and 2,000 vehicles on two lanes. Even if truck volumes are relatively light, these lanes should still be provided.

Design hour volumes of 1,500 veh/lane cannot be handled without severe congestion on any sustained grade when there is a truck on this grade at 35 mph or less. And once a stoppage occurs, conditions become even worse because trucks which ordinarily would traverse the grade at a reasonable speed cannot, once they have been stopped, accelerate to this speed.

Several grades have been observed at maximum capacity. One four-lane one-way 5.5 percent grade, only 4,600 ft long, with 150 trucks and buses, had a maximum capacity of about 6,000 autos per hour. This is about 1,500 vph less than capacity of a level four-lane section. Another grade, 10,000 ft long, three lanes wide at 6 percent, with only 100 trucks and buses, had a maximum capacity of about 3,800 autos, about 1,700 to 1,800 vph less than capacity on a level three-lane section.

REFERENCES

1. U.S. Bureau of Public Roads. Highway Capacity Manual. U.S. Govt. Print. Office, 1950.
2. Calif. Div. of Highways Traffic Bull. No. 2.

Appendix A

DATA ON TRUCK CHARACTERISTICS AND EFFECTS OBTAINED AT CORDELIA GRADE (I-80)

To obtain more information on the behavior and effect of trucks, a study was made of operation on a grade located about midway between Sacramento and San Francisco

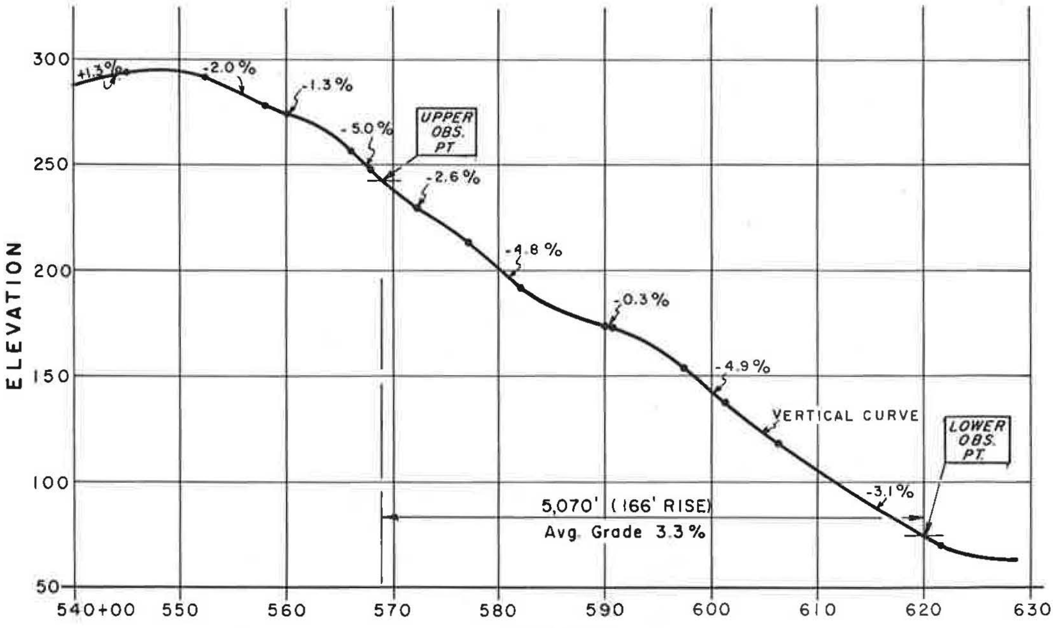


Figure 7. Cordelia grade, westbound lanes, I-80.

on the two westbound lanes of I-80. The location is rural and the nature of the traffic tends to make it high speed. Through vehicles have been on 50 mi of continuous freeway and expressway, although they passed through several construction zones. Figure 7 shows the profile of the grade and the observation points. The 1962 two-way ADT at this location was 26,000 veh with a seasonal peak of 33,500.

Data were gathered by time-lapse photography taken simultaneously at two points: (a) near the bottom of the grade, and (b) 5,000 ft up the grade. Photography was in color and a clock was framed in the picture at each camera. Thus, it was relatively simple to match vehicles and determine elapsed time between the two observation points. This was done for 100 percent of the trucks and about 60 percent of the autos. Matching of all trucks also made it possible to determine truck-passing-truck maneuvers. All analysis was made from the films.

Speeds shown or noted were always based on travel time between the two observation points because we believed effects on auto travel could best be determined in this manner. Spot speeds would not reflect delays at points not observed.

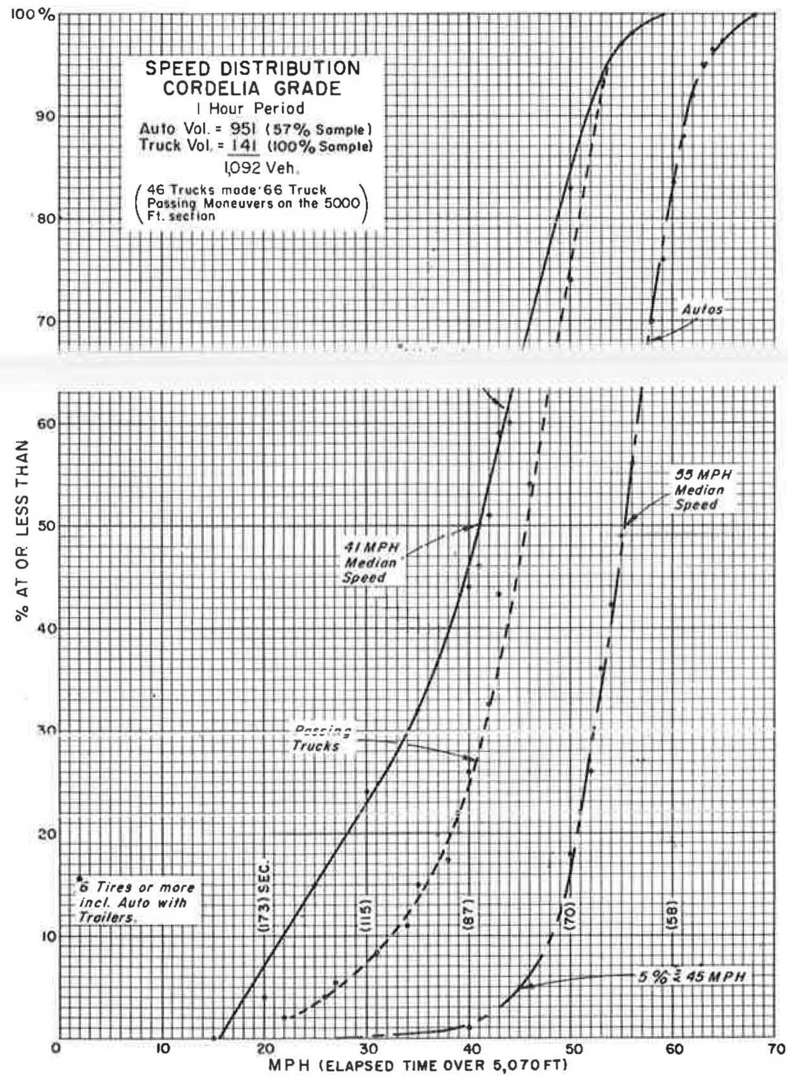


Figure 8.

The study was made in August 1963 for a 2-hr period. For the period studied, 5-min total flow rate varied from 875 to 1,580 vph. Truck rates (including buses and autos with trailers) varied from 85 to 225 trucks per hour.

Figure 8 shows that for a complete hour with 140 trucks (median speed of 41 mph with 66 truck-passing-truck maneuvers), 950 autos traveled through the section at a median speed of 55 mph, and 5 percent were at 45 mph or less. Figure 9 shows that for a separate 50-min period with a truck flow rate of 140 trucks per hour (median speed of 35 mph with 70 truck-passing-truck maneuvers per hour), 1,150 autos per hour traveled through the section at a median speed of 51 mph; 15 percent traveled at 45 mph or less.

For a 5-min period (Fig. 10) with 130 trucks per hour and 1,030 autos per hour, median auto speed was 57 mph with none less than 48 mph. There was only one truck-passing-truck maneuver during the 5-min period and average truck speed was 46 mph. Therefore, at this volume of trucks and autos, there was little or no delay to autos.

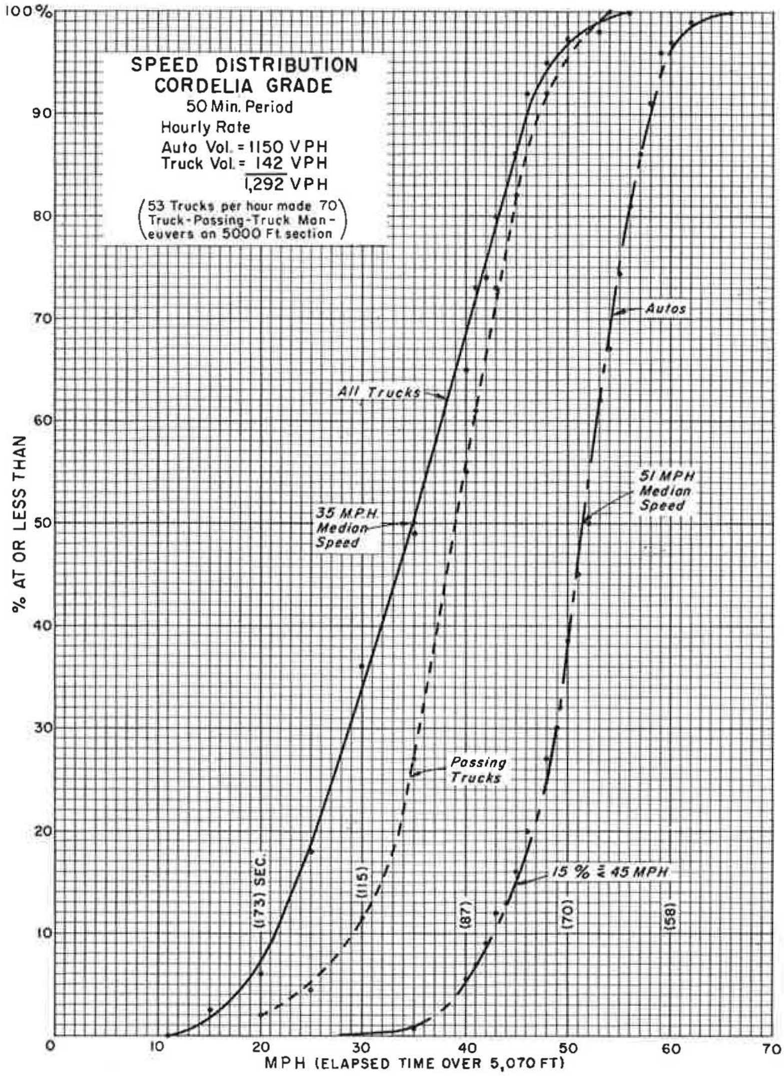


Figure 9.

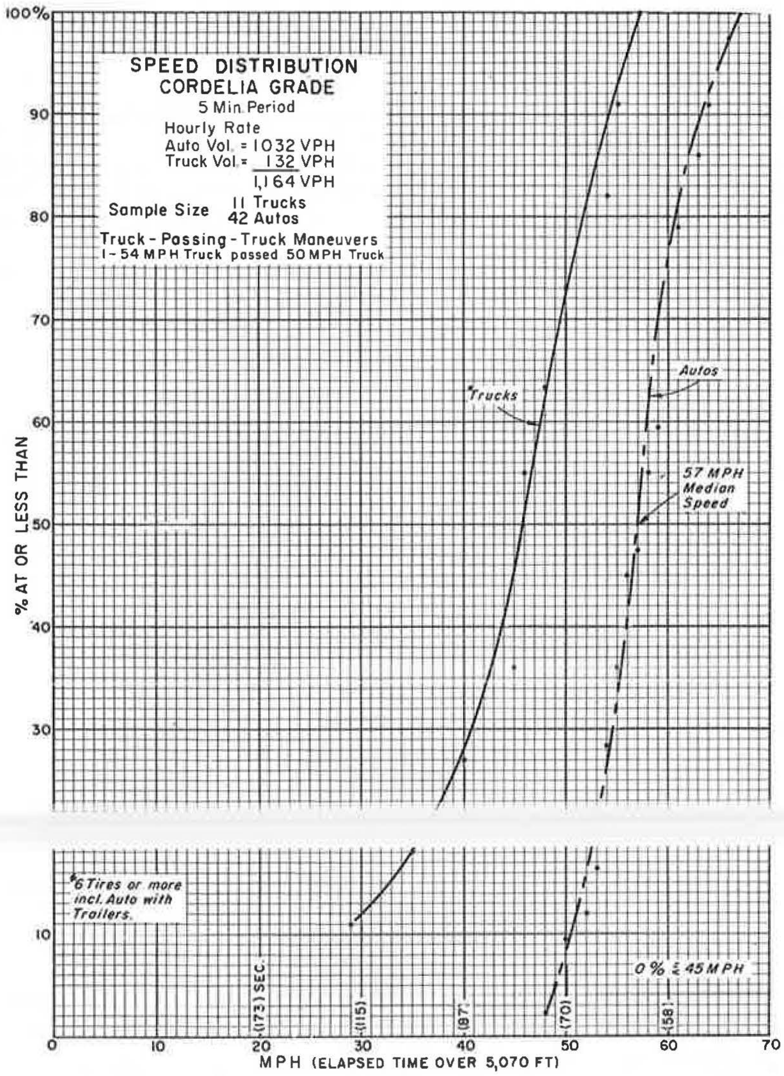


Figure 10.

Figure 11 shows that the average free-flow auto speed on all California freeways in 1962 was 56.7 mph.

In another 5-min period (Fig. 12) with 190 trucks per hour and 1,380 autos, median auto speed was again 57 mph. This also reflects little delay to autos in spite of a large number of trucks with a median speed of 34 mph and numerous truck-passing-truck maneuvers. However, on examining the truck passing maneuvers, it can be seen that the passing trucks were reasonably fast and the passed trucks were slow. Under these conditions, the duration of a passing maneuver tends to be minimized. This figure points out that, despite a large number of trucks, as long as the left lane is not seriously blocked there is little delay to autos when the auto flow rate is 1,400 vph.

During another 5-min period (Fig. 13) with 170 trucks per hour and 1,420 autos per hour, median auto speed was only 46 mph. Median truck speed was 32 mph. Although truck passings were not as numerous as in the period illustrated in Figure 12, the passing trucks were considerably slower. The effect with 1,420 autos per hour as reflected by the auto speeds is severe.

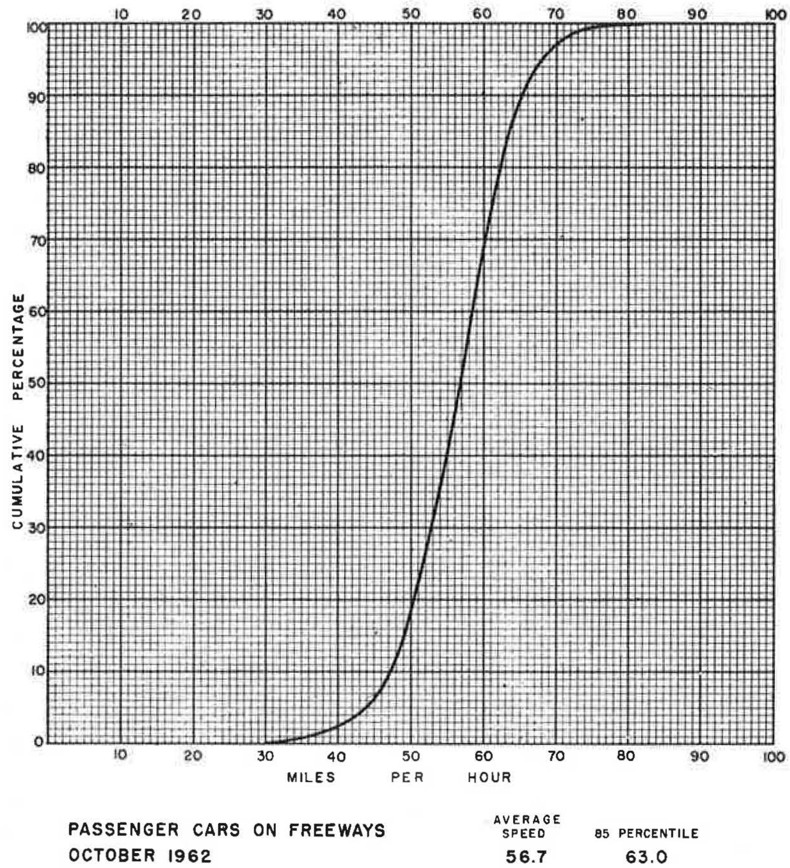


Figure 11. Free-flow speed curves for all California freeways, prepared by California Division of Highways, Traffic Department.

We can assume that the desired speed is about 57 mph or about 60 sec to traverse the study section. In this instance, the average car took 75 sec or a delay of 15 sec per car. Twenty-five percent of the cars took 87 sec or longer. These are serious delays and reflect undesirable operation with large speed differentials between autos even in the left lane. Actually when an average auto speed is, for example, 40 mph over the 5,000-ft section, the spot speed on the section could vary from zero to 60 mph. There were, in fact, complete stoppages in the left lane at times.

It can be seen that operation at these auto volume levels is not as dependent on total number of trucks as it is on the number and type in the left lane.

Figure 14 plots the number of truck-passing-truck maneuvers against total number of trucks. Theory of probability indicates that the number of trucks catching up with other trucks varies with the square of total number of trucks. Figure 14 indicates that passing maneuvers follow this same pattern. Other studies have shown this same trend.

In summary, study of this grade indicates the validity of the previous discussion that as long as there are no trucks (or no slow ones) in the left lane of a two-lane section, there will be little or no delay as long as auto volume is 1,500 vph or less. However, with an appreciable number of trucks, there will be enough truck-passing-truck maneuvers to lower auto capacity below 1,500 vph.

On this particular grade with an hour volume of 140 trucks, buses and trailers and 1,150 autos (Fig. 9), operation is less than acceptable for design purposes. With these

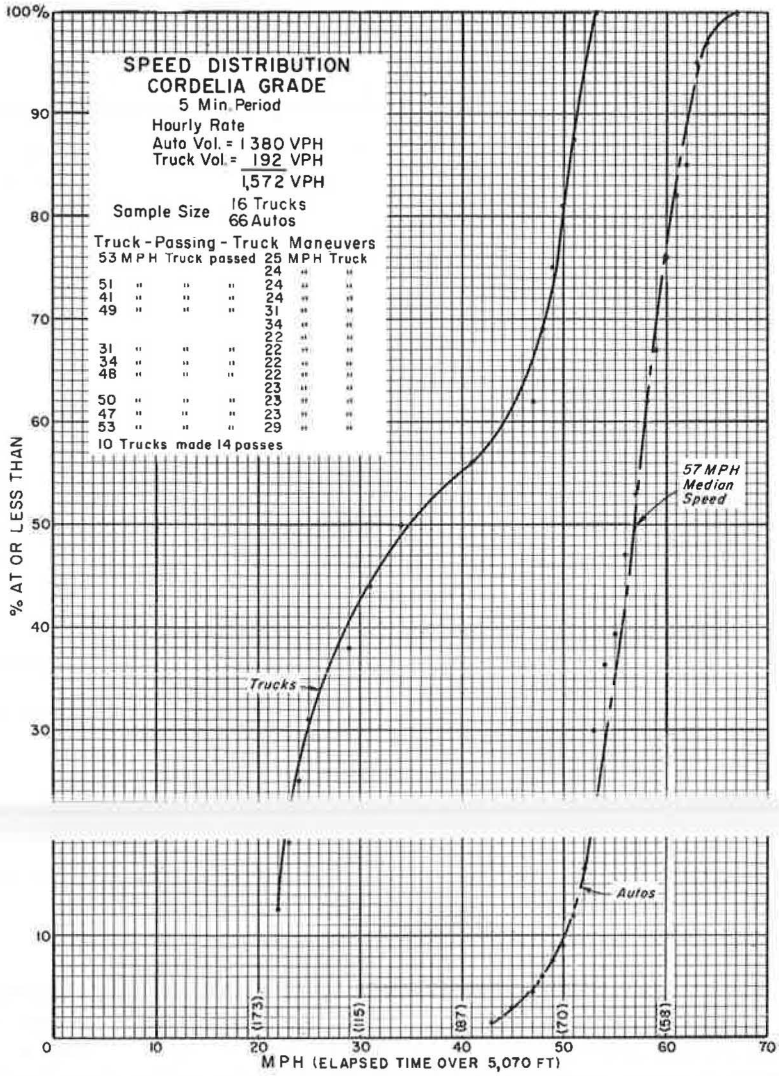


Figure 12.

conditions, median auto speed (over a 5,000-ft section of the grade) was 51 mph with 15 percent at or less than 45 mph. At times there were actual stoppages.

For the same number of trucks and 950 autos (Fig. 8), median auto speed was 55 mph, slightly less than the unrestricted speed of 57 mph. Only 5 percent were at or less than 45 mph. In this case this would probably be considered acceptable for design purposes under rural conditions.

Appendix B

DEVELOPMENT OF DESIGN CAPACITY CHART

This section describes the development of the relationships between truck frequency, length and steepness of grade shown in Figure 5 indicating limits of free-flow volumes for two lanes in one direction when truck-passing-truck maneuvers are the control.

To illustrate how truck passing maneuvers affect operation, we first stipulate that as soon as a truck catches another he will pass. (Our studies indicate this is generally true regardless of auto volumes.) We assume that a truck going 19 mph passing one going 10 mph would encroach on the left lane long enough to gain about 300 ft on the passed truck. This would take about 26 sec and he would travel about 680 ft in the left lane. (At this point it might be well to point out that though absolute numbers and arbitrary rules, such as gaining 300 ft, are used, they are used only in the sense of developing relationships. The numbers are not used to determine amounts of delay,

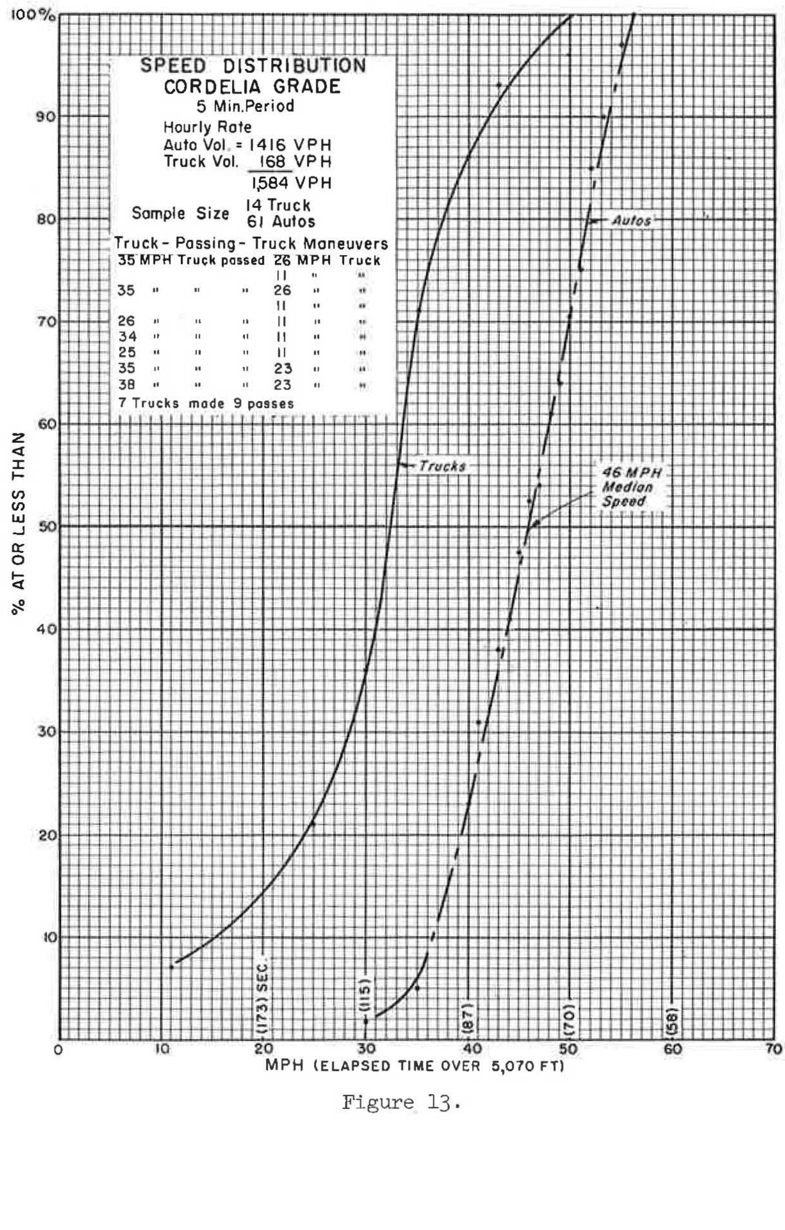


Figure 13.

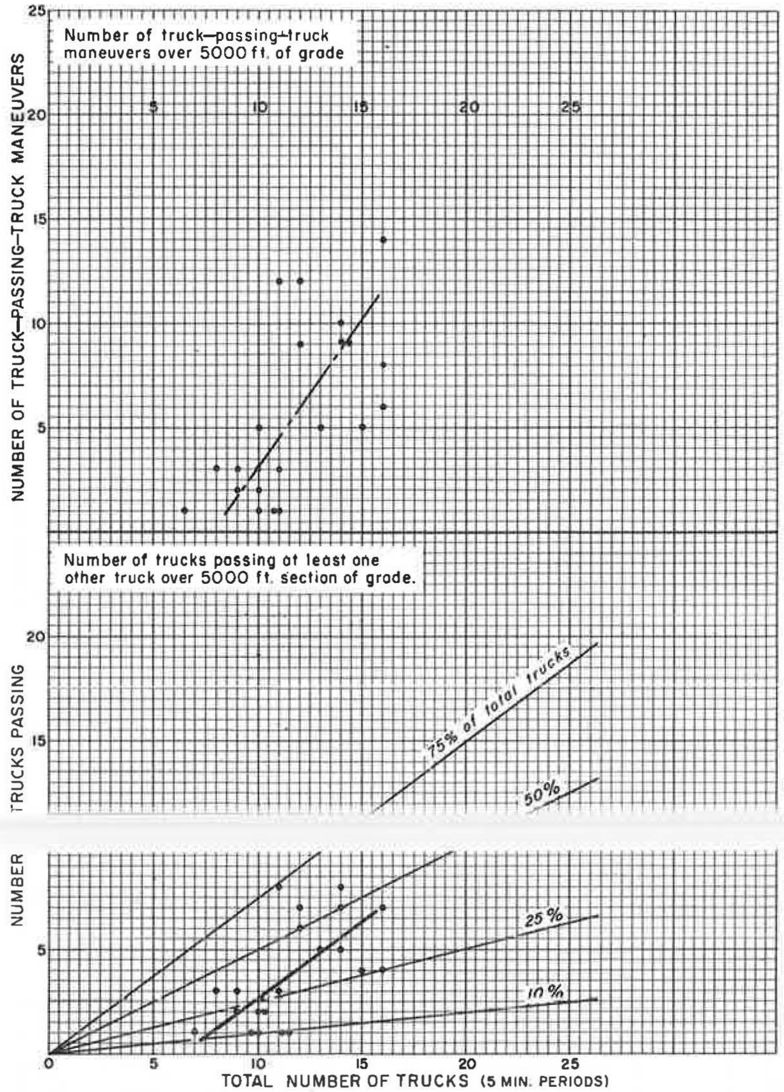


Figure 14.

etc., but only to obtain a relative effect. Changing the values would not change the relative effects significantly.) It would take a car about 9 sec to travel the same distance (680 ft). Thus, when a truck started the passing maneuver, a car would have to be 17 sec back in order to just catch the truck as he was getting back into the right lane. Five seconds are added so that the car will still be behind the truck a certain distance when the truck moves back to the right lane so that the auto will not slow in anticipation that the truck will not clear the left lane. This means that if no slowdown is to occur in the left lane, no car can arrive within 22 sec after the truck starts his passing maneuver. If the auto flow rate is 1,500 per hour, there is zero probability that no car will arrive at a point in a 22-sec period. There is a 42 percent chance that 10 cars or more will arrive. It is obvious then that if free flow is desired in the left lane, acceptable flow rates will have to be less than 1,500 vph if there are many truck-passing-truck maneuvers.

Knowing the speed distribution of trucks, number of trucks, and length of grade, the number of expected passing can be determined. Using this relationship, curves in Figure 5 were developed such that total delay for a given number of autos at a point on any curve will be equal. This equivalence is in relative terms and a particular amount of delay cannot be inferred from the curves.

Truck speed distributions obtained for the development of the truck acceleration curves in Traffic Bulletin No. 2 (2) were used as basic data. Figure 15 reproduces from this bulletin the average crawl speed on various grades of loaded as well as unloaded trucks.

Truck speeds were grouped as shown in Figure 16. For example, if the average speed of all trucks on a particular grade is 20 mph, 30 percent will be 15 mph or less. These groupings are used to calculate the relative number of truck passing maneuvers for different grades. These are given in Table 1 and are based strictly on the probability of trucks at various speeds overtaking trucks at the lesser speeds indicated. This was done by first assuming 100 trucks per hour at an average speed of 20 mph on a section of grade, 2,000 ft long. Thirty of the trucks will have an average speed of 10 mph (5 to 15 mph) and 22 an average of 18 mph (16 to 20 mph). It would take a 10-mph truck 137 sec to traverse the 2,000 ft. It would take an 18-mph truck 76 sec to traverse the same distance. Therefore, if the 18-mph truck arrives at the beginning of the 2,000-ft section within 137 - 76 or 61 sec after the 10-mph truck arrives, it will catch up. Since there are 22 trucks at 18 mph on the average they will cross a given point every 164 sec. Therefore, when a 10-mph truck passes the start of the section on the average (over many trials), 61/164 or 0.37 18-mph trucks will arrive soon enough to catch the 10-mph truck within 2,000 ft. Since there are 30 10-mph trucks, on the average 0.37 $\times$ 30 or 11 18-mph trucks will catch up with the 10-mph trucks at some point on the 2,000-ft section of grade during the hour.

It follows that if the section is twice as long, there will be twice as many 18-mph trucks catching 10-mph trucks. If the section is 4,000 ft long, the 10-mph truck takes 274 sec to traverse the grade and the 18-mph truck 152 sec. Therefore, any 18-mph truck arriving within 122 sec after the 10-mph truck will catch up. With 22 trucks per hour at 18 mph, each time a 10-mph truck arrives at the beginning of the section, on the average 0.74 18-mph will arrive. If there are 30 10-mph trucks, 22 18-mph trucks will catch 10-mph trucks on the 4,000-ft section or twice the number on the 2,000-ft

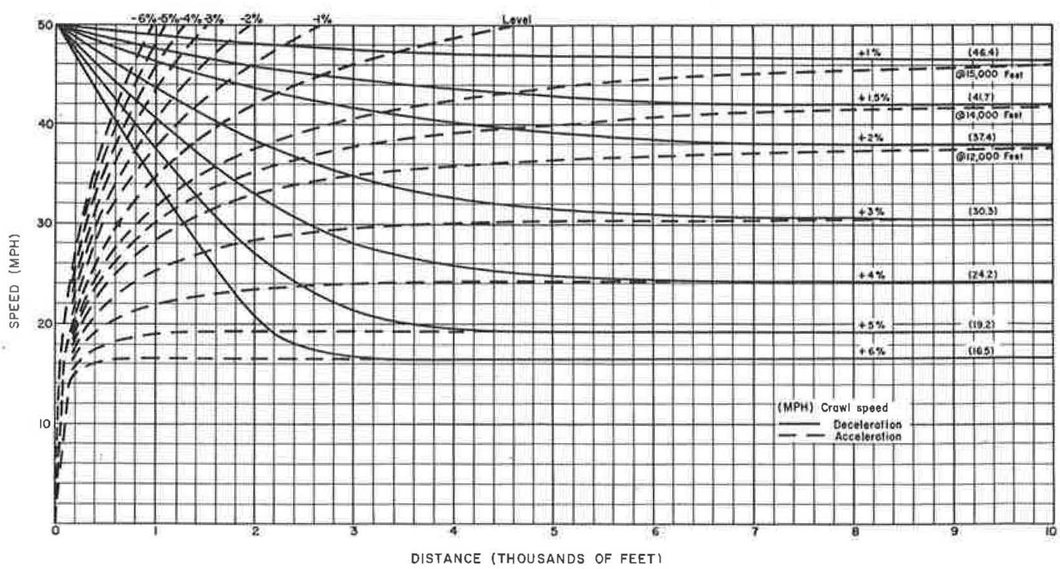
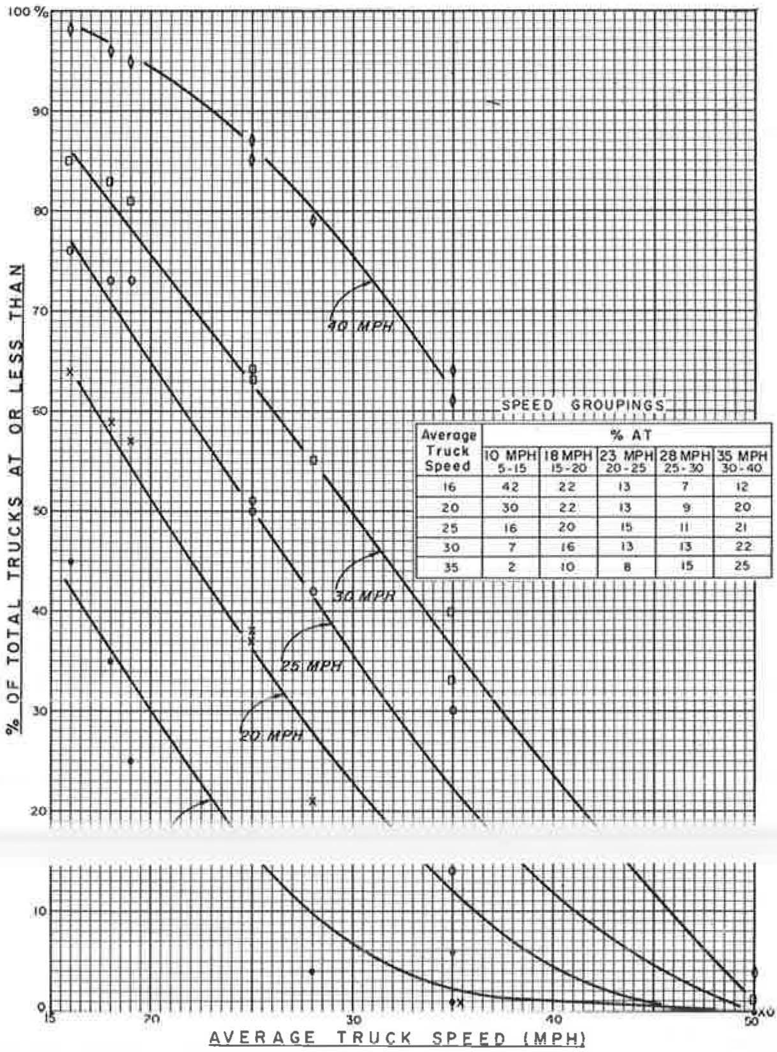


Figure 15. Truck acceleration and deceleration curves (2).



Average Truck Speed	% AT				
	10 MPH 5-15	18 MPH 15-20	23 MPH 20-25	28 MPH 25-30	35 MPH 30-40
16	42	22	13	7	12
20	30	22	13	9	20
25	16	20	15	11	21
30	7	16	13	13	22
35	2	10	8	15	25

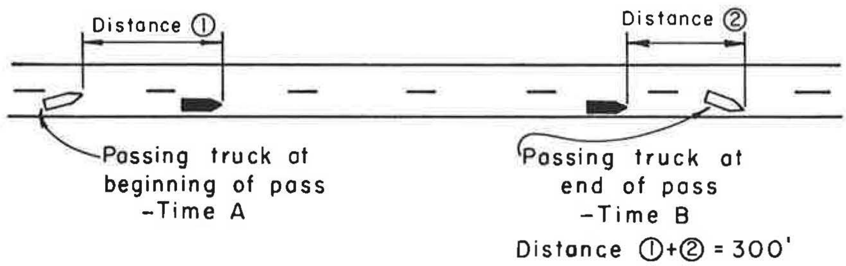
Figure 16. Truck speed distributions.

section. It also follows that if there are twice as many trucks there will be 4 times as many overtakings.

Development of Relative Scale for Different Truck Speeds

In calculating the number of seconds an auto must be behind a truck when the truck starts his passing maneuver so that the auto will not be delayed by the passing maneuver, the following procedure is used:

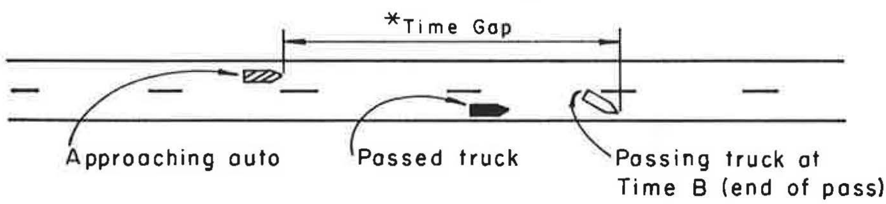
1. A basic stipulation is that the passing truck on the average will encroach on the left lane long enough to gain about 300 ft on the passed truck:



2. When the passing truck is completing his pass any approaching auto must still be a certain number of seconds behind the truck so that he will not have braked appreciably in anticipation that the truck will not clear the left lane (reaction time):

*Assume that at time B approaching auto, in order not to be delayed, must be -

5 seconds behind truck if truck is going 20mph
4 " " " " " " " 25mph
3 " " " " " " " 30mph
2 " " " " " " " 35mph



3. Using this criteria, Table 2 was prepared which gives the necessary time gap an auto must be behind various speed trucks when the truck starts its pass, if the auto is not to be delayed. The necessary gap also indicates in a relative way the amount of

TABLE 1

EXPECTED NUMBER OF TRUCKS OVERTAKING OTHER TRUCKS[a]

Type of Maneuver		Number Overtaking at Avg. Truck Speed				
		16 Mph	20 Mph	25 Mph	30 Mph	35 Mph
18-mph tr. catching	10-mph tr.	16	11	5	2	0.3
23-mph tr. catching	10-mph tr.	12	8	6	2	0.3
28-mph tr. catching	10-mph tr.	7	7	4	2	0.7
35-mph tr. catching	10-mph tr.	14	16	9	4	1.3
Total		49	42	24	10	3.0
23-mph tr. catching	18-mph tr.	1	1	1	1	0.5
28-mph tr. catching	18-mph tr.	1	1.5	2	1.5	1.0
35-mph tr. catching	18-mph tr.	3	4.5	4	3.5	2.5
Total		5	7.0	7	6.0	4.0
28-mph tr. catching	23-mph tr.	0.5	0.4	0.6	0.6	0.4
35-mph tr. catching	23-mph tr.	1	1.5	1.8	1.6	1.1
Total		1.5	1.9	2.4	2.2	1.5
35-mph tr. catching	28-mph tr.	0.2	0.4	0.5	0.6	0.8
Overall total		56	51	34	19	9

[a]Per 100 trucks per hour on 2,000-ft section of grade, based on grouping shown in Figure 16; number of overtakings proportional to length of grade and square of number of trucks.

TABLE 2

Type of Maneuver		Time for Pass. Truck to Gain 300 Ft (sec)	Dist. Traveled (ft)	Time for 55-Mph Auto to Travel Dist. (sec)	Reac. Time (sec)	Necessary Gap (sec)[a]
18-mph tr. passing	10-mph tr.	25.6	680	8.5	5	22
23-mph tr. passing	10-mph tr.	15.8	530	6.5	4	13
23-mph tr. passing	18-mph tr.	41.1	1,380	17.5	4	28
28-mph tr. passing	10-mph tr.	11.4	470	6.0	3	8
28-mph tr. passing	18-mph tr.	20.4	840	10.5	3	13
28-mph tr. passing	23-mph tr.	40.5	1,670	21.0	3	23
35-mph tr. passing	10-mph tr.	8.2	420	5.0	2	5
35-mph tr. passing	18-mph tr.	12.0	620	8.0	2	6
35-mph tr. passing	23-mph tr.	17.0	880	11.0	2	8
35-mph tr. passing	28-mph tr.	28.4	1,510	19.0	2	11

[a]Time for passing truck to gain 300 ft minus time for 55-mph to travel distance plus reaction time.

total delay time. For example, if an 18-mph truck passed a 10-mph truck and pulled out directly in front of an auto, that auto would be delayed approximately 22 sec. If a 28-mph truck passed a 23-mph truck directly in front of an auto, that auto would be delayed about 23 sec or about the same total amount. What this table does not indicate is that even though for this example the delay is the same, subjectively perhaps the delay behind the 10-mph truck is worse than delay behind the 28-mph truck.

4. From Table 1 and Step 3, Table 3 is derived which indicates the total time that no auto may arrive so that no delay will occur for a case with 100 trucks per hour and a 2,000-ft length. Although this table is not used directly the sums are used to weight relative effects of different grades when other conditions are equal.

This essentially relates the amount of delay which can be attributed to 100 trucks at various average speeds due to passing maneuvers. Since the number of passings is proportional to the square of the total number of trucks, if 100 trucks at 20 mph have

$$\left(\frac{x}{100}\right)^2 \times 716 = 582 = 100\sqrt{0.81} = $$

90 trucks at 16 mph = 100 trucks at 20 mph
124 trucks at 25 mph = 100 trucks at 20 mph
167 trucks at 30 mph = 100 trucks at 20 mph
250 trucks at 35 mph = 100 trucks at 20 mph

This gives the relative truck scale used at the bottom of Figure 6 in the text.

In summary, when truck passings control, equivalent service volume is related to the square of the number of trucks, proportional to length of grade, and is related to speeds of trucks as follows: 16 mph = 0.9; 20 mph = 1.00; 25 mph = 1.24; 30 mph = 1.67; 35 mph = 2.50. Therefore, if we say from subjective observation that on an 8,000-ft grade with 150 trucks per hour with an average speed of 30 mph, a volume of 1,000 autos per hour will result in good operation without undue delays to autos. We

TABLE 3

TOTAL TIME WHEN NO AUTO MAY ARRIVE[a]

Passing Maneuver		At Average Truck Speed														
		16 Mph			20 Mph			25 Mph			30 Mph			35 Mph		
		No. Passings	Requir. Gap	Time (sec)	No. Passings	Requir. Gap	Time (sec)	No. Passings	Requir. Gap	Time (sec)	No. Passings	Requir. Gap	Time (sec)	No. Passings	Requir. Gap	Time (sec)
18-mph tr. passing	10-mph tr.	16	22	352	11	22	242	5	22	110	2	22	44	0.3	22	7
23-mph tr. passing	10-mph tr.	12	13	156	8	13	104	6	13	78	2	13	26	0.3	13	4
23-mph tr. passing	18-mph tr.	1	28	28	1	28	28	1	28	28	1	28	28	0.5	28	14
28-mph tr. passing	10-mph tr.	7	8	56	7	8	56	4	8	32	2	8	16	0.7	8	6
28-mph tr. passing	18-mph tr.	1	13	13	1.5	13	20	2	13	26	1.5	13	20	1.0	13	13
28-mph tr. passing	23-mph tr.	0.5	23	13	0.4	23	9	0.6	23	13	0.6	23	13	0.4	23	9
35-mph tr. passing	10-mph tr.	14	5	70	16	5	80	9	5	45	4	5	20	1.3	5	7
35-mph tr. passing	18-mph tr.	3	6	18	4.5	6	27	4	6	24	3.5	6	21	2.5	6	15
35-mph tr. passing	23-mph tr.	1	8	8	1.5	8	12	1.8	8	14	1.6	8	13	1.1	8	9
35-mph tr. passing	28-mph tr.	0.2	11	2	0.4	11	4	0.5	11	6	0.6	11	7	0.8	11	9
Total				716			582			376			208			93

[a]So that no delay will occur for case with 100 trucks per hour and 2,000-ft length; total time = No. passings x required gap for each pass.

can then relate any combination of trucks, grade, and speed to this same level of operation or same amount of delay.

Example: Given conditions of 100 trucks per hour, a 12,000-ft grade, and speed of 25 mph, what is the auto capacity?

$$\text{Equiv. No. of trucks at 30 mph} = \frac{1.67}{1.24} \times 100 = 135$$

$$\text{Adjustment for No.} = \left(\frac{150}{135}\right)^2 \times 1,000 = 1,235 \text{ autos}$$

$$\text{Adjustment for length of grade} = \frac{8,000}{12,000} \times 1,235 = 825 \text{ autos per hour}$$