New Methods of Capacity Determination for Rural Roads in Mountainous Terrain

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●IN A comprehensive survey of highway needs, it is essential to establish a certain level of performance for each highway system in a state and then determine the construction, reconstruction, and improvements needed to bring the existing systems up to these performance levels. The levels of performance which are established must be feasible and based on the current desires of traffic to move safely and efficiently, with due consideration being given to the future demands of highway transportation since it is such an important factor in the national economy.

Performance levels may be measured, and also specified, in terms of safe operating speeds. Comprehensive studies as well as past practices have shown that drivers demand, and that it is more feasible to construct, facilities that will permit higher operating speeds in level terrain than in rough or mountainous terrain, on primary highways carrying most of the long-distance travel than on local roads where the average trip length is shorter, and for roads on the same system carrying the higher traffic volumes than for those carrying the lower traffic volumes. Although the type of service to be provided by a highway under construction is largely an administrative decision, this decision must be based on driver desires and traffic demand.

Once having established the type of service which a highway or a system of highways should provide, it is necessary to specify this service in terms of design speed and operating speed. The design speed is a speed determined for design and correlation of the physical features of a highway that influence vehicle operation. It is the maximum safe speed that can be maintained over a specified section of the highway when conditions are so favorable that the design features of the highway govern.[1] In short, it is the maximum safe speed that vehicles can safely travel over any section of the highway during extremely low traffic densities. In the design of a highway, the assumed design speed automatically establishes such items as the minimum stopping sight distance, the minimum sight distance at intersections, the maximum curvature, and the superelevation. Other features, such as widths of pavements and shoulders and clearances to walls and rails, are not directly related to design speed but they should be accorded higher standards for the higher design speeds.

The operating speed is the highest over-all speed exclusive of stops at which a driver can safely travel on a given highway under the prevailing traffic conditions without at any time exceeding the speed which is compatible with the design features of the highway. For this discussion it applies to the conditions during the 30th highest hourly traffic volume for the year under consideration. It is, therefore, a measure of the type of service which a highway provides during most of the hours of peak flow. The operating speed on an existing highway is affected by design speed, traffic volume, and number of lanes. Also, for two-lane roads, it is affected by the availability of sections on which the sight distance is of sufficient length to perform passing maneuvers safely. In the design of a new highway, it is the one factor which together with the traffic volume and assumed design speed determines the needed geometric features of a highway.

Drivers will accept as reasonable a somewhat lower operating speed, or a higher degree of congestion, on a highway that has been in existence for several years than they will accept or expect on a new highway or one recently reconstructed. Also, for a needs study to be realistic, there must necessarily be some overlap in the standards by which existing highways are judged for adequacy and those used for the construction of a new highway.

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[1]AASHO definition.

In the early stages of the West Virginia highway needs study the engineering committee, after reviewing the results of speed studies on highways throughout the state, agreed upon a set of tolerable conditions for judging the adequacy of existing highways in order to determine those in need of construction or reconstruction. A set of standards was also prepared for use on new construction. Both were in terms of operating speeds and design speeds. The tolerable conditions and the construction standards for highways carrying more than 1,800 vehicles per day are shown by Table 1.[2]

After these tolerable conditions and standards in terms of service to traffic had been agreed upon, it was relatively easy to establish the design requirements for new construction (Table 2A) from the information now contained in the AASHO policy on "Geometric Design of Rural Highways" and to prepare Table 3 from the results of traffic operation and capacity studies conducted during the past several years.

Table 3 shows the average daily traffic volumes that can be accommodated by a two-lane highway constructed to a given design speed with various percentages of the highway having slight distances in excess of 1,500 to 1,000 ft. These values are for the average conditions applicable in West Virginia which are:

1. The 30th highest hourly volume during the year is 12 percent of average daily traffic for that year.

TABLE 1

TOLERABLE CONDITIONS FOR EXISTING RURAL HIGHWAYS CARRYING OVER 1,800 VEHICLES PER DAY AND STANDARDS FOR NEW CONSTRUCTION OR RECONSTRUCTION IN TERMS OF THE SERVICE PROVIDED

Highway System	Terrain	Tolerable Conditions		Construction Standards	
		Operating Speed, mph	Design Speed, mph	Operating Speed, mph	Design Speed, mph
Interstate	Valley or level	45-50	60	50-55	70
	Rolling	40-45	50	45-50	60
	Mountainous	40-45	45	45-50	60
Other	Valley or level	45-50	60	50-55	70
	Rolling	40-45	50	45-50	60
	Mountainous	35-40	40	40-45	60

2. During the 30th highest hourly volume of a year, trucks with dual tires are 5 percent of the traffic.

3. In a capacity sense, the average dual-tired truck is equivalent to 2 passenger cars in valley or level terrain, to 4 passenger cars in rolling terrain, and to 8 passenger cars in mountainous terrain.

For highways where these average conditions do not exist or are not expected to be present during the year for which the highway is designed, appropriate corrections must be made in the capacities by the application of factors similar to those included in the discussion on capacities of existing highways.

DESIGN SPEEDS OF EXISTING HIGHWAYS

If the AASHO definition of design speed were applied to existing highways with profiles and alignments that were constructed prior to the time that this term came into common usage, it would be found that in many cases the average running speed of traffic would be several miles per hour above the design speed. Likewise, recent studies have shown that different highways constructed to modern standards may provide radically different operating conditions, even though their traffic volumes and their design

[2]As determined prior to the Federal-Aid Highway Act of 1956.

TABLE 2A

GEOMETRIC STANDARDS FOR NEW CONSTRUCTION FOR RURAL PRIMARY STATE HIGHWAYS

	TWO-LANE HIGHWAYS															FOUR-LANE HIGHWAYS		
	FUTURE AVERAGE DAILY TRAFFIC VOLUME GROUPS																	
	LESS THAN 500			500 TO 1800			1800 TO 3000			OVER 3000			INTERSTATE SYSTEM					
TERRAIN	VALLEY	ROLLING	MOUN-TAINOUS	VALLEY	ROLLING	MOUN-TAINOUS	VALLEY	ROLLING	MOUN-TAINOUS	VALLEY	ROLLING	MOUN-TAINOUS	VALLEY	ROLLING	MOUN-TAINOUS	VALLEY	ROLLING	MOUN-TAINOUS
DESIGN SPEED (MPH)	50	40	35	60	50	40	70	60	50	70	60	50	70	60	60	70	60	60
OPERATING SPEED (MPH)	40-45	35-40	30-35	45-50	40-45	35-40	45-50	45-50	40-45	50-55	45-50	40-45	50-55	45-50	45-50	50-55	45-50	45-50
MAXIMUM CURVATURE (Degrees)	9	14	20	6	9	14	4	6	8	3	5	7	3	5	5	3	5	5
STOPPING SIGHT DISTANCE (Feet)	350	275	225	475	350	275	700	525	400	700	525	400	700	525	525	700	525	525
LANE WIDTH (Feet)	10			11 1/			12			12			12			12 2/		
SHOULDER WIDTH (Feet) — IN CUT	5	3	3	6	4	4	8	6	4	8	8	4	8	8	4	8	8	4
SHOULDER WIDTH (Feet) — ON FILL	7	5	5	8	8	7	10	8	8	10	10	8	10	10	8	10	10	8
PASSING SIGHT DISTANCE (% Available) — 1500 Ft.	PERCENT FEASIBLE			10	5	—	10	5	—	10	5	—	10	5	—	NOT APPLICABLE		
PASSING SIGHT DISTANCE (% Available) — 1000 Ft.	PERCENT FEASIBLE			—	—	5	—	—	5	—	—	5 OR AS REQUIRED FOR CAPACITY				NOT APPLICABLE		
GRADE (Percent)	5 ADD 2% FOR GRADES UNDER 750 FT LONG	7	9	4 ADD 1% FOR GRADES UNDER 750FT. LONG	5	7	7% MAXIMUM UNLESS PERCENT AND LENGTH OF GRADE IS DETERMINED BY CAPACITY CALCULATION									7		
RIGHT OF WAY WIDTH 3/ (Feet)	60			80			100			120			120			200		
SURFACE TYPE	SURFACE TREATMENT			MEDIUM			HIGH			HIGH			HIGH			HIGH		
BRIDGES — LOADING	H15-S12 OR ONE H20 TRUCK, WHICHEVER PRODUCES THE GREATER STRESS									H20-S16 FOR INTERSTATE ROUTES AND OTHER PRIMARY ROUTES CARRYING HEAVY TRUCK TRAFFIC COMPARABLE TO INTERSTATE ROUTES								
BRIDGES — WIDTH	UNDER 50 FT. LONG — FULL ROADWAY WIDTH OVER 50 FT LONG — APPROACH PAVEMENT PLUS 4 FT									UNDER 50FT. LONG — FULL ROADWAY WIDTH OVER 50FT LONG — APPROACH PAVEMENT PLUS 4 FT AND MEDIAN ON FOUR-LANE HIGHWAYS								
BRIDGES — VERTICAL CLEARANCE	NOT LESS THAN 14 5 FEET																	

1/ ON NEW CONSTRUCTION OR RECONSTRUCTION 12FT. LANES SHOULD BE USED WITH VOLUMES ABOVE 1200 PER DAY WHEN TRUCK TRAFFIC IS MORE THAN 5 PERCENT.

2/ ALL FOUR-LANE HIGHWAYS SHALL BE DIVIDED   WHENEVER POSSIBLE THE MEDIAN SHALL BE AT LEAST 20 FT. WIDE, AND IN NO CASE LESS THAN THE 4-FOOT BARRIER TYPE.

3/ CONTROL OF ACCESS SHALL BE PROVIDED ON ALL NEW LOCATIONS ON THE INTERSTATE HIGHWAY SYSTEM AND ON OTHER PRIMARY HIGHWAYS CARRYING LARGE VOLUMES OF TRAFFIC

TABLE 2B

TOLERABLE CONDITIONS FOR RURAL PRIMARY STATE HIGHWAYS

		TWO-LANE HIGHWAYS														FOUR-LANE HIGHWAYS		
		AVERAGE DAILY TRAFFIC VOLUME GROUPS																
		LESS THAN 500			500 TO 1800			1800 TO 3000			OVER 3000			INTERSTATE SYSTEM					
TERRAIN		VALLEY	ROLLING	MOUN-TAINOUS	VALLEY	ROLLING	MOUN-TAINOUS	VALLEY	ROLLING	MOUN-TAINOUS	VALLEY	ROLLING	MOUN-TAINOUS	VALLEY	ROLLING	MOUN-TAINOUS	VALLEY	ROLLING	MOUN-TAINOUS
DESIGN SPEED (MPH)		40	35	30	50	40	35	60	50	40	60	50	40	60	50	45	60	50	45
OPERATING SPEED (MPH)		35-40	30-35	25-30	40-45	35-40	30-35	45-50	40-45	35-40	45-50	40-45	35-40	45-50	40-45	40-45	45-50	40-45	40-45
MAXIMUM CURVATURE (Degrees)		14	20	25	9	14	20	6	9	14	5	7	11	5	7	9	5	7	9
STOPPING SIGHT DISTANCE (Feet)		275	225	200	350	275	225	475	350	275	475	350	275	475	350	300	475	350	300
LANE WIDTH (Feet)		9			10	10 [1]		10			10			10			10		
SHOULDER WIDTH (Feet)	IN CUT	3	3	2	6	3	3	6	4	4	6	4	4	6	4	4	6	4	4
	ON FILL	3	3	3	6	4	4	8	6	4	8	6	4	8	6	4	8	6	4
PASSING SIGHT DISTANCE (% Available)	1500 Ft	NOT REQUIRED			NOT REQUIRED			10	5	—	10	5	—	10	5	—	NOT APPLICABLE		
	1000 Ft	NOT REQUIRED			NOT REQUIRED			—	—	5	—	—	5	—	—	5			
								OR AS REQUIRED FOR CAPACITY											
GRADE (Percent)		7	8	10	5	7	8	8	8	8	7	7	7	7	7	7	7		
		ADD 1% FOR GRADES UNDER 1000 FT LONG			ADD 1% FOR GRADES UNDER 750 FT LONG			MAXIMUM UNLESS PERCENT AND LENGTH OF GRADE IS DETERMINED BY CAPACITY CALCULATION											
SURFACE TYPE		SURFACE TREATMENT			SURFACE TREATMENT			MEDIUM [2]			MEDIUM [2]			MEDIUM [2]			MEDIUM [2]		
BRIDGES	LOADING	H 15 FOR ALL BRIDGES ON THE PRIMARY SYSTEM																	
	WIDTH	NOT LESS THAN WIDTH OF APPROACH SURFACE		NOT LESS THAN WIDTH OF APPROACH PAVEMENT PLUS 2 FEET															
	VERTICAL CLEARANCE	NOT LESS THAN 13 FEET																	

[1] LANE WIDTHS OF 9 FT. MAY BE ACCEPTED AS TOLERABLE UNDER 800 VEHICLES PER DAY WITH A SMALL PERCENTAGE OF TRUCKS.

[2] GOOD SURFACE CONDITION REQUIRED

CONTROL OF ACCESS NOT REQUIRED

speeds are identical. Average speeds, for example, will be much higher on a highway with few 5-degree curves and considerable tangent alignment than on a highway with many 5-degree curves and little tangent alignment. This is because above-minimum design values are utilized where feasible and drivers do vary their speeds to a considerable extent with the immediate geometric conditions rather than adopting one uniform speed for the entire length of a highway.

Conversely, for a given operating speed a highway with few curves and mostly tangent alignment will accommodate higher volumes of traffic than a similar highway with many curves of the same degree and less tangent alignment. In relating the operating speed of a highway to its capacity, therefore it is necessary to determine the "average highway speed," especially for existing highways.

Introduction of the term "average highway speed," which is in effect the average maximum safe speed, or the operating speed for a passenger car over a section of high-

TABLE 3

CONSTRUCTION STANDARDS FOR CAPACITIES OF 2-LANE HIGHWAYS,
12-FOOT LANES

(Based on 5 percent trucks during 30th highest hour factor of 12 percent ADT)

Percentage of Highway with Passing Sight Distance[a]		Average Daily Traffic Volume			
				Mountainous	
		Valley or Flat	Rolling	Interstate	Other
1,500 ft	1,000 ft	Oper. Speed 50-55 Design Speed 70	Oper. Speed 45-50 Design Speed 60	Oper. Speed 45-50 Design Speed 60	Oper. Speed 40-45 Design Speed 60
100	100	4,850	6,500	5,500	6,550
80	90	4,450	5,850	5,000	6,000
60	80	3,950	5,050	4,300	5,300
40	70	3,350	4,200	3,600	4,600
20	60	2,400	3,450	2,900	3,850
0	50	1,300	2,600	2,200	3,050

[a]Percentage of 1,500-ft passing sight distance is used for all operating speeds except those below 45 mph. The 1,000-ft values are applicable to all operating speeds.

way during extremely low traffic densities, is an approach which has not previously been employed in relating alignment and profile to capacities. It is an approach, however, which must be employed to obtain reasonable accuracy in capacity determinations, especially for existing highways.

The average highway speed of an existing highway may be determined by weighting the possible speeds of traffic on the individual sections during low traffic flows by the length of the sections. The possible speeds for various horizontal curves and stopping sight distance conditions may be determined by use of the AASHO tables relating these features to the design speed.

When preparing plans for a highway, the designer should base the geometric features on an assumed design speed over a substantial length of highway to obtain a balanced design. The lower the design speed, the greater is the likelihood of the occurrence of such sections. Invariably there are sections where the designer utilizes values that are adequate for higher speeds than the design speed assumed. As a result, the high-speed driver can travel over the section during low traffic densities at an average speed which exceeds the assumed design speed. This speed is the average highway speed and is equivalent to the low volume operating speed.

Figures 1 and 2 show how the operating speed on a 2-lane highway varies with the
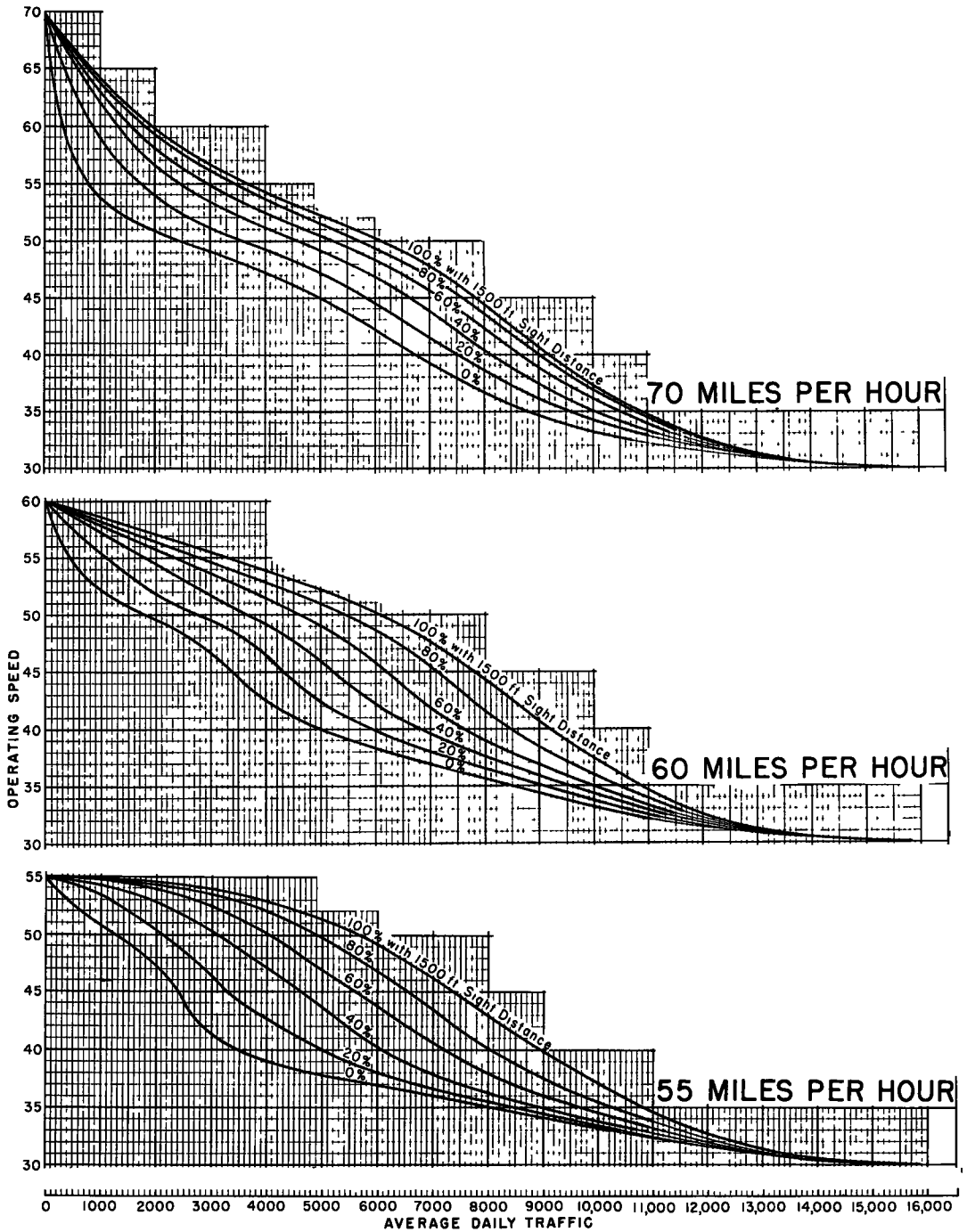
Figure 1. Effect of traffic volume and available passing sight distance of two-lane roads on operating speed for various average highway speeds. (Computed on basis of no grades exceeding 3 percent, 12-ft lanes, 12 percent design hour, 5 percent dual-tired commercial vehicles in the design hour, and a truck equivalent of 2).
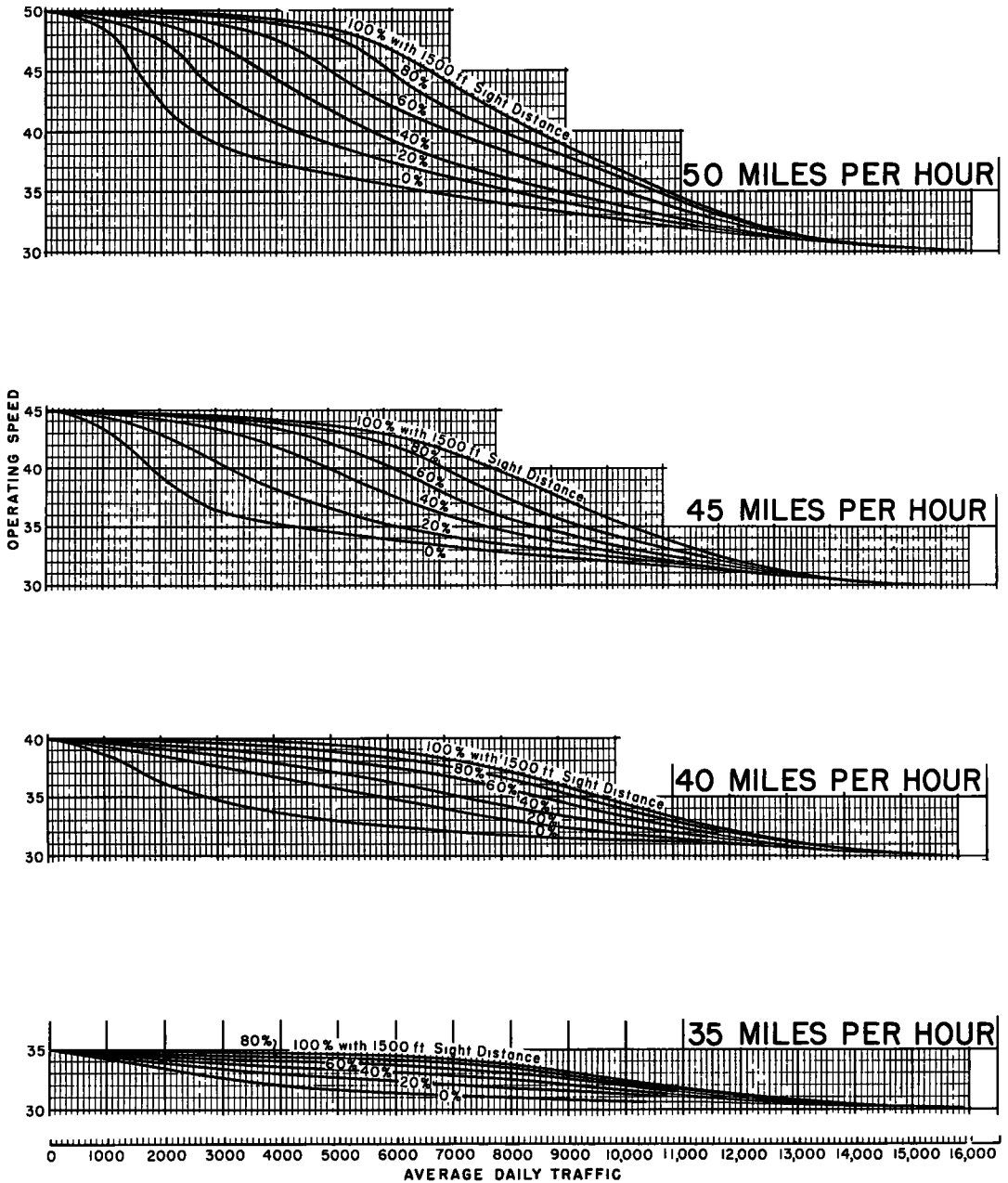
Figure 2. Effect of traffic volume and available passing sight distance of two-lane
roads on operating speed for various average highway speeds. (Computed on basis of
no grades exceeding 3 percent, 12-ft lanes, 12 percent design hour, 5 percent dual-
tired commercial vehicles in the design hour, and a truck equivalent of 2).

average highway speed, the percentage of highway having 1,500-ft passing sight dis-
tance, and the traffic volume. The average daily traffic volumes in these charts are
for (a) terrain which is essentially level, (b) 12-ft traffic lanes, (c) 5 percent dual-
tired vehicles with a passenger car equivalent of 2, and (d) a 30th highest hourly vol-
ume during the year of 12 percent of the average daily traffic. They were prepared for
the Tennessee programing study from the information contained in Table 4, which was
prepared for the 1953-54 West Virginia needs study. Table 4, in turn, was prepared

TABLE 4

AVERAGE DAILY CAPACITIES OF 2-LANE HIGHWAYS

(Level terrain, 5 percent dual-tired vehicles, truck factor 2.0[a]
30th highest hour factor of 12 percent ADT)

Operating Speed, mph	Percentage of Highway with Passing Sight Distance of		Average Daily Traffic at Average Highway Speed of					
	1,500 ft	800 to 1,000 ft	70 mph	60 mph	55 mph	50 mph	45 mph	40 mph
50 - 55	100	100	4,850	4,750	4,300			
50 - 55	80	92	4,450	4,150	3,750			
50 - 55	60	84	3,950	3,450	3,000			
50 - 55	40	76	3,350	2,700	2,250			
50 - 55	20	68	2,400	1,800	1,350			
50 - 55	0	60	1,300	900	550			
45 - 50	100	100	7,100	7,100	6,600	5,650		
45 - 50	80	90	6,800	6,400	5,750	5,050		
45 - 50	60	80	6,400	5,550	4,800	4,000		
45 - 50	40	70	5,750	4,600	3,900	2,800		
45 - 50	20	60	4,900	3,750	2,800	2,000		
45 - 50	0	50	3,800	2,800	2,000	1,250		
40 - 45	100	100	8,450	8,450	8,050	7,450	6,550	
40 - 45	80	87	8,250	7,700	7,300	6,700	5,800	
40 - 45	60	76	7,900	6,800	6,450	5,700	4,850	
40 - 45	40	64	7,350	5,900	5,300	4,600	3,700	
40 - 45	20	52	6,650	4,950	4,100	3,200	2,200	
40 - 45	0	40	5,850	3,950	2,700	1,950	1,250	
35 - 40	100	100	9,900	9,900	9,900	9,600	9,100	7,900
35 - 40	80	85	9,750	9,350	9,000	8,750	8,200	7,150
35 - 40	60	72	9,400	8,650	8,100	7,950	7,250	6,000
35 - 40	40	58	8,950	8,000	7,150	6,950	6,150	4,700
35 - 40	20	44	8,400	7,350	6,300	5,850	4,500	3,100
35 - 40	0	30	7,650	6,600	5,350	3,850	2,450	1,500

[a]For West Virginia; normally 2.5.

from the results of extensive highway capacity studies conducted by the Bureau of Public Roads in cooperation with the various state highway departments and include the results reported in the "Highway Capacity Manual," supplemented by more recent investigations.

Figures 1 and 2 contain curves representing roadways with sight distances that are continuously in excess of 1,500 ft to those that have no 1,500-ft sight distances. The relation between operating speed and traffic volume as shown by the curves is applicable, however, only when the percentage of the highway not having a 1,500-ft sight distance is fairly evenly distributed between the limits of 1,500 ft and the stopping sight distance for the design speed. This is the more usual condition.

It must be pointed out that most of the data on which Figures 1 and 2 are based were obtained by studies conducted during traffic volumes within the lower three-quarters of the range (below 12,000 ADT). Studies conducted on 2-lane highways during capacity volumes represent principally level tangent sections well removed from sharp horizontal or vertical curves. For this reason, all curves except the ones for 100 percent of 1,500-ft sight distance are shown as light lines above 11,000 vehicles per day. There is still considerable question as to whether all the curves for the same average highway speed meet at a common point on the right, or whether the possible capacity and the speed at this capacity are slightly lower for the highways with the poorer alignment

than for those with a continuous sight distance in excess of 1,500 ft. This, however, is
not too important a consideration because the practical capacities of 2-lane highways a
well within the range for which reliable data are available.

The charts may be used either to determine the operating speed for a given traffic
volume or the traffic volume which the highway will accommodate at a given operating
speed. When it is desired to determine the capacity at a given operating speed for lane
widths other than 12 ft, for 30th highest hourly factors other than 12 percent, for truck
percentages other than 5 percent, or for truck equivalents other than 2, the following
factors must be applied to adjust the capacity volumes to the prevailing or estimated
future conditions:

1. For 11-ft lanes multiply the volumes by 0.86; for 10-ft lanes, by 0.77.

2. When the 30th highest hour factor is other than 12 percent, multiply the volumes
by $\dfrac{12}{\text{actual percentage}}$.

3. When there is other than 5 percent trucks during the peak hour or the truck equiv-
alent is greater than 2, as it will be on grades and in rolling or mountainous terrain,
multiply the volumes by $\dfrac{105}{100 - P + PT}$, where P is the percentage of trucks and T is
the truck equivalent in terms of passenger cars.

The operating speed for a given traffic volume when conditions other than those used
for these charts are applicable may be determined by employing the reciprocal of these
correction factors to the given traffic volume before entering the chart.

The Appendix contains eight tables for the conditions most prevalent on 2-lane roads
in West Virginia. The number of charts or tables that can be prepared for other combi-
nations of the many variable conditions is almost unlimited. A similar set of tables ma
be prepared for the conditions prevailing within any state or area.

FOUR-LANE DIVIDED HIGHWAYS

Figure 3 shows the relation between operating speeds, average highway speeds, and
traffic volumes on 4-lane divided rural highways free from the influence of intersection
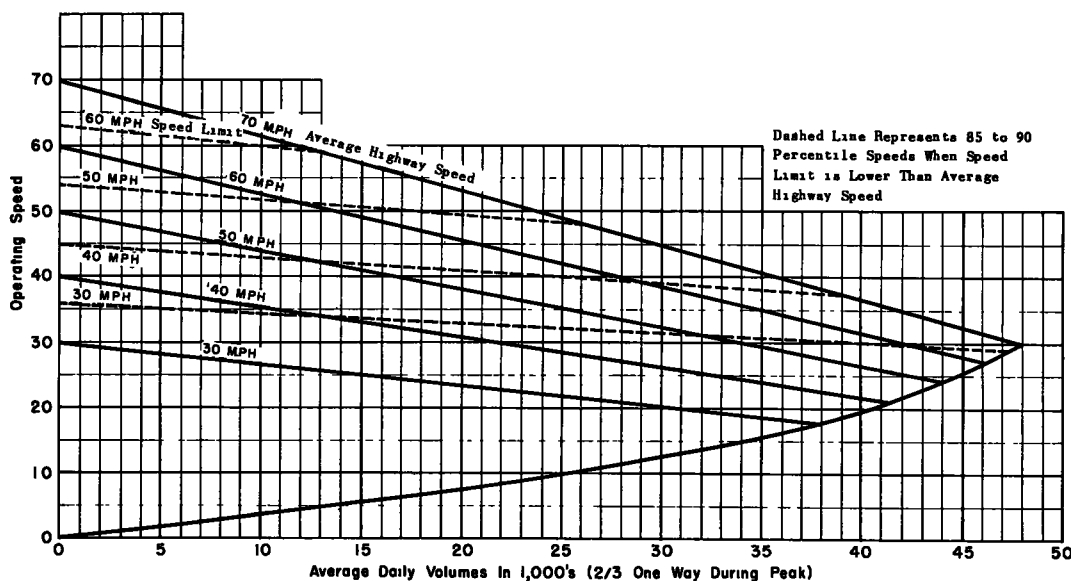The lowest curve represents the minimum speed at which traffic must flow to attain a

Figure 3. Operating speeds on 4-lane highways for various average highway speeds, in
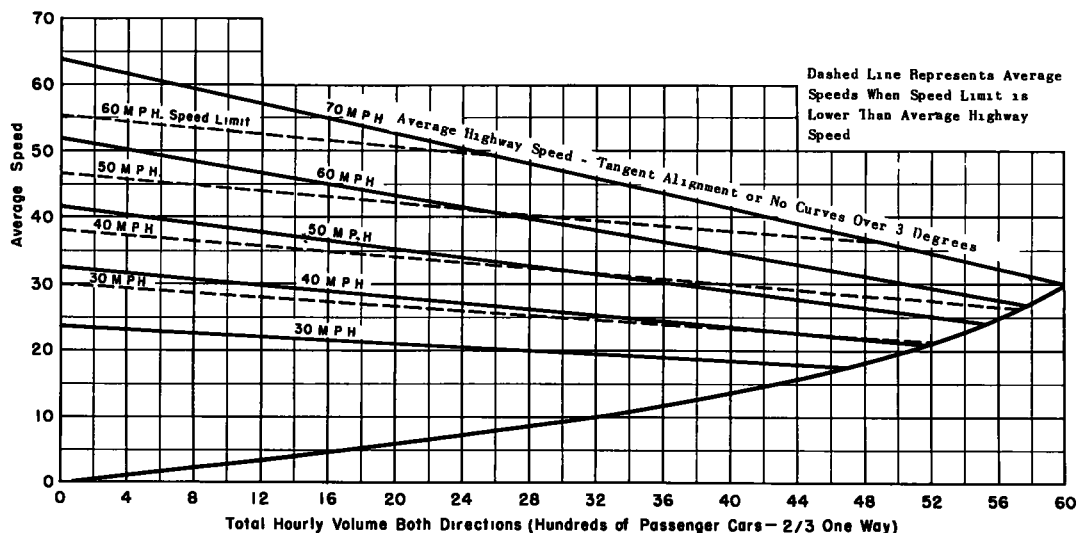direction of heavier travel.

Figure 4. Average speed on 4-lane highways for various average highway speeds, in direction of heavier travel.

given traffic volume. For example, traffic must be traveling at least 10 mph for a 4-lane highway to accommodate the 30th highest hourly volume when the average daily traffic is 25,000 vehicles.

The other solid lines of Figure 3 represent the normal operating speeds during various traffic volumes for different average highway speeds. Any point representing the speed-volume relationship must fall between the lower curve and the line representing the average highway speed.

The dashed lines show the effect of an enforced speed limit on the speed-volume relationship. A speed limit has an effect on the operating speed only when it is lower than the highway speed. Also, it has an effect only when the traffic volume is below that at which the dashed speed limit line intersects the solid line corresponding to the highway speed. At higher volumes, the solid lines show the normal speed-volume relationship, because at these volumes the speeds are governed by the traffic density rather than by the speed limits.

Figure 4 is similar to Figure 3 except that the average speed, rather than the operating speed, is related to the traffic volume. Figure 3 also shows the daily volumes based on a 30th highest hour factor of 12 percent and includes 5 percent trucks with a passenger car equivalent of two, whereas Figure 4 shows hourly volumes and includes no trucks.

These charts represent average conditions found on modern highways throughout the United States. In some areas, such as the central states where the terrain is level and speeds are higher than for the country as a whole, the speeds as shown by these charts will be somewhat low, especially for the low traffic volumes. For certain other areas they may be high, but in general any difference will not be great and the relative speeds for the different conditions will be accurate.

The traffic volumes or capacities at a given operating speed or at a given average speed are shown in terms of passenger cars in two 12-ft lanes for the one direction of travel. Daily and hourly volumes, or capacities for various percentages of trucks and a range of truck factors, may be determined by standard procedures.

The results for multilane highways, as shown by Figures 3 and 4, explain to a large extent the many variations in the speed volume relationship found by other investigators. Sometimes they have found that an increase in the traffic volume or density results in only a very slight or no drop in speeds. This would be the case, as shown by the dashed lines of Figures 3 and 4, when a speed limit or factors other than the traffic density are exerting a controlling influence on vehicle speeds.

The results of still other investigators show a curvilinear relationship, with the speeds dropping at an increasing rate as the traffic density increases. This would occur as the traffic volumes exceeded the range within which the speed limits were effective and especially when the volumes approached possible capacities. At volumes approaching possible capacities on multilane facilities (above 1,500 vehicles per lane), the safety factor for capacity, as indicated by the distance between the upper and lower curves of Figures 3 and 4, decreases rapidly, with the result that a slow driver or some other minor condition interrupting the normal flow of traffic can cause a sudden slowdown of all vehicles, with speeds decreasing from a point on one of the higher curves of Figures 3 and 4 to a point on the bottom curve, or to any intermediate point. The closer the possible capacity is approached, the greater is the possibility of such an occurrence.

The most baffling results obtained from speed-volume investigations are those which show an increase in speed with an increase in volume. Generally this occurs when a study is started during off-peak hours with light traffic and is continued through the peak or rush-hour volumes in the afternoon. As the traffic volume increases, the percentage of repeat drivers in a hurry to get home increases, with the result that speeds show little or no decline and oftentimes increase temporarily with the traffic volume. When capacity volumes are reached or closely approached, there is an abnormal decrease in speeds, producing the curvilinear relation between speed and traffic volume. Studies of this type do not show the true effect of increased volume or speeds, because there is a marked change in the character of traffic from off-peak to peak periods. The true effect of volume on speeds, as shown by Figures 3 and 4, can be obtained by simultaneous studies at different points where the geometric features of the highway are identical but the traffic volumes are different.

INFORMATION NEEDED FOR CAPACITY ANALYSIS

An engineering analysis of the ability of a highway to accommodate present or estimated future traffic volumes, in accordance with prescribed standards of service in terms of operating speeds, requires the following information:

1. Type of terrain through which the highway is located.
2. Average highway speed and frequency of occurrence of sharp curves that cause abnormally low speeds.
3. Percentage of the highway on which the passing sight distance exceeds 1,500 ft. On highways for which an operating speed of 40 mph or less has been specified, the percentage of highway with an 800- to 1,000-ft sight distance is required whenever there is a low percentage of the 1,500-ft sight distance.
4. The average truck factor and the truck factor on all long or steep grades.
5. Cross-section items, such as shoulder and surface type, width, and condition.

These five items were determined for all highways in West Virginia expected to carry annual volumes in excess of 1,800 vehicles per day within the next 20 years.

Terrain

Generally the alignment of an existing highway will be an indication of the surrounding terrain. Whether standards for level, rolling, or mountainous terrain should be applied to an existing road is largely a matter of engineering judgment. Nevertheless, the fact that the existing highway has many sharp curves and steep grades does not necessarily mean that a much better alignment and profile could not be obtained in the same general vicinity at a reasonable cost with modern equipment and methods. A large part of West Virginia has a terrain, however, through which it is extremely difficult and costly to build high-speed highways of modern design.

AVERAGE HIGHWAY SPEED

The average highway speed of each section of highway was determined by driving a passenger car over the highway at the maximum safe speed during extremely low traffic volumes to obtain a profile of the speed based on the geometric features of the highway. The safe speed was governed by sight distance, curvature, and possible marginal

interferences. All speed zones and speed limits were observed. Long tangent sections of highway were recorded as having a 60-mph highway speed, even though the test car was not necessarily operated at this speed. Such sections are, however, comparatively rare in West Virginia.

This method of determining the average highway speed and of obtaining a log of the sharp curves and other speed restrictions was employed because sufficiently detailed information was not available from any other source. Furthermore, this method as it was employed was sufficiently accurate and probably resulted in a more realistic appraisal than could have been obtained from detailed plans had they been available.

PASSING SIGHT DISTANCE

A second car with an accurate odometer was driven over each highway at a slow speed (about 30 mph) to determine the length and location of all sections with sight
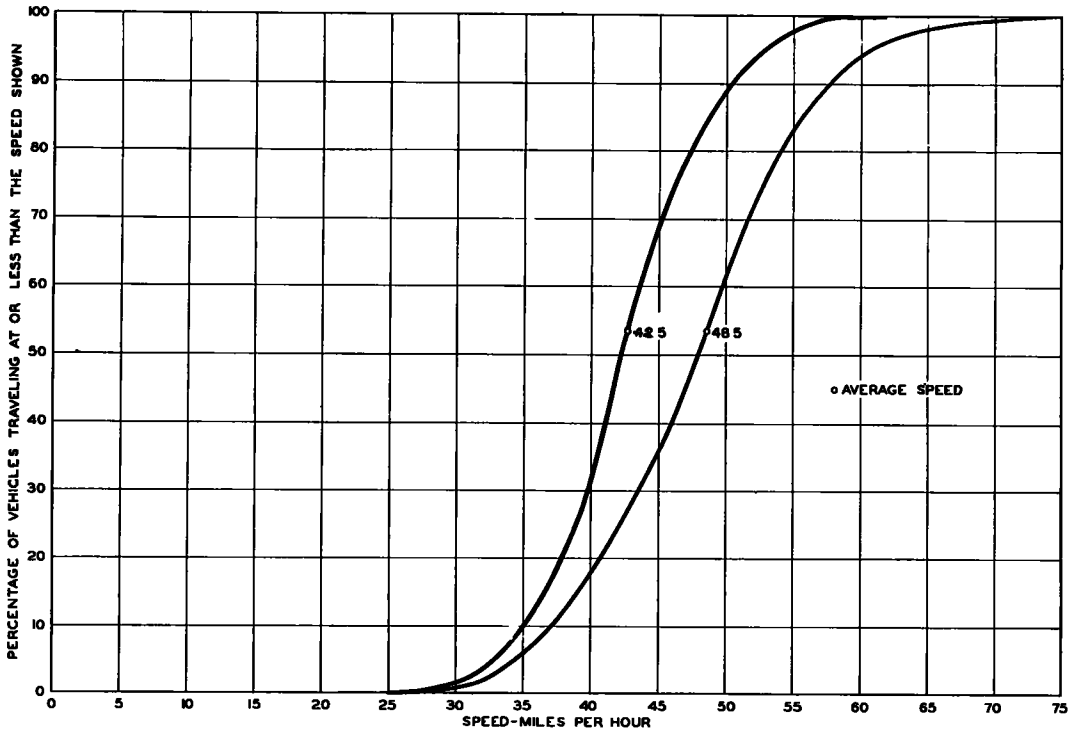

Figure 5. Distribution of normal passenger car speeds used for truck factors.

distances in excess of 1,000 ft and 1,500 ft, in lieu of more accurate and detailed sight distance information. The driver informed the passenger, who acted as the recorder, each time that there was a change in the sight distance from some value below 1,000 ft or 1,500 ft to a value above 1,000 or 1,500 ft. He also informed the recorder each time that the sight distance again became less than either of these values.

The recorder noted the odometer readings at these locations and at control points, such as crossroads, city limits, and major structures. It was possible to check the accuracy of the driver's estimate by this procedure as each reading was recorded, so that a sufficiently accurate estimate was obtained of the percentage of the highway with a sight distance in excess of 1,000 ft and the percentage in excess of 1,500 ft.

AVERAGE TRUCK FACTOR

Commercial vehicles with dual tires reduce the capacity of a highway in terms of vehicles per hour. In level terrain where commercial vehicles can maintain speeds that equal or approach the speeds of passenger cars, it has been found that the average

TABLE 5

TRUCK FACTOR FOR VARIOUS TRUCK SPEEDS AS RELATED TO
NORMAL PASSENGER CAR SPEEDS

| Truck Speed, mph | Truck Factor, pass. car equiv. | | |
	For Average Passenger Car Speed of 47.5 mph[a]	For Average Passenger Car Speed of 42.5 mph[b]	Adopted for Use in West Virginia Study
40	1.8	1.5	2
35	3.0	2.7	3
30	5.0	4.9	5
25	8.6	7.6	8
20	13.9	11.7	13
15	22.9	18.7	20
10	40.5	32.5	35
5	94.5	75.0	80

[a]Distribution as shown by curve A of Figure 3.

[b]Distribution as shown by curve B of Figure 3.

dual-tired vehicle is equivalent, in a capacity sense, to 2 passenger cars on multilane highways and to 2.5 passenger cars on 2-lane highways. The number of passenger cars that each dual-tired vehicle represents is termed the "truck equivalent" or the "truck factor."

The results of highway capacity studies have shown that the truck equivalent on long or steep grades increases with an increase in the difference between the normal speeds of passenger cars and the speeds of trucks. They have also shown that the truck equivalent changes very little, if at all, with a change in the percentage of trucks in the total traffic stream. (Studies have not been conducted at locations with more than 20 percent dual-tired trucks and have been confined principally to locations with less than 10 percent of these vehicles during the periods of peak flow. Further studies may indicate that for certain conditions the truck factor does change with a change in the percentage of trucks, but as yet there is no evidence to indicate whether it increases or decreases with an increase in the number or percentage of trucks.)

Truck equivalents are normally determined by obtaining detailed information on the speeds and headways of vehicles during various traffic volumes on highways with different alignments and profiles. An average truck factor is obtained for the dual-tired vehicles under each condition. If the study is of sufficient magnitude, it is possible to obtain a truck factor for each type of dual-tired vehicle, classified by speed groups.

The results of these studies have shown that the truck factors can also be calculated with a high degree of accuracy from the separate speed distributions of passenger cars and trucks recorded during light volumes when vehicles can travel at their normal speeds. The criterion used is the relative number of passings that would be performed per mile of highway if each vehicle continued at its normal speed for the conditions under consideration. That the results from such an analysis agree with those obtained by the more painstaking methods is not surprising. It is the difference between truck speeds and passenger car speeds on grades that causes trucks to reduce the capacity of a highway. The greater the speed difference, the greater is the reduction in capacity with a corresponding increase in the truck factor.

Table 5 shows how the truck factor varies with the truck speed for two different passenger car speed distributions, as shown by Figure 5. The higher the passenger car speeds, the higher are the truck equivalents. The factors in the right-hand column are the rounded values used for the West Virginia study and from which Figure 6 was plotted. The truck equivalent can be determined for any dual-tired vehicle by knowing its average speed under any highway condition such as a steep or long grade. The average truck factor can also be determined for any location or section of highway by
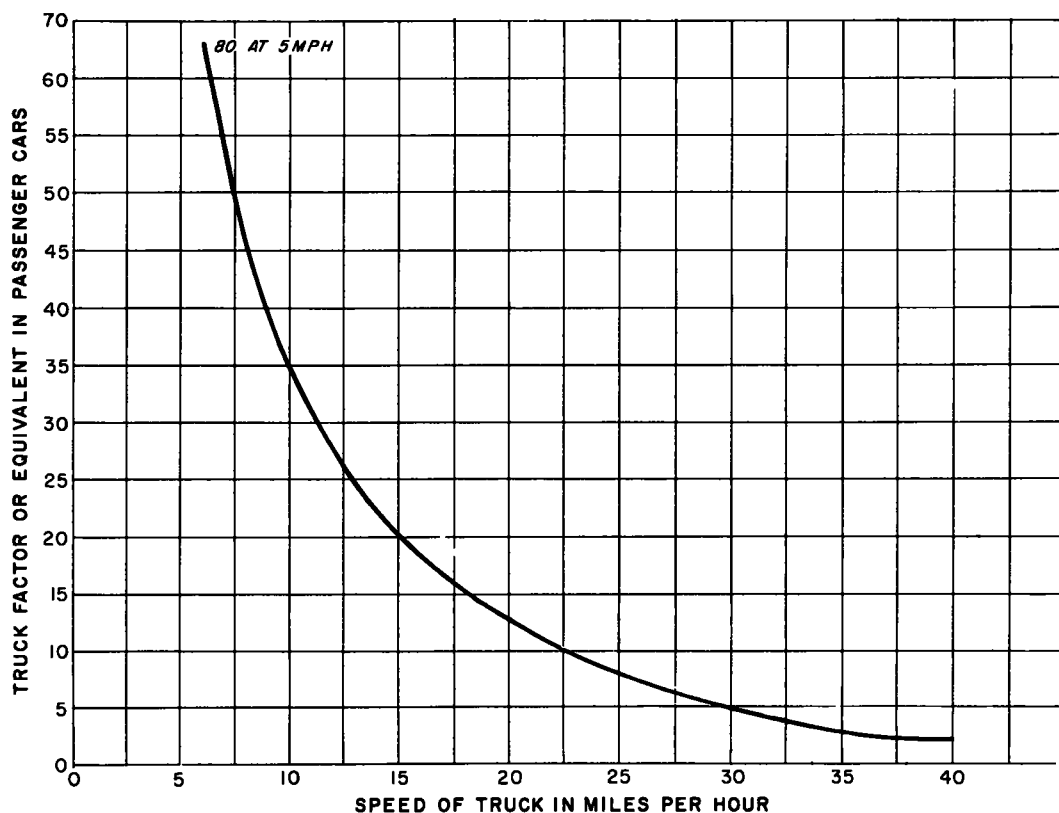
Figure 6. Truck factor for various average truck speeds.

knowing the average speed for all trucks if the passenger car speeds are within the limits of those shown by Figure 5. In this case there will be a slight error if there is a wide range in the truck speeds, because the curve of Figure 6 is not a straight line. The error will be slight, however, for most conditions.

CONTROL TRUCK USED FOR OBTAINING AVERAGE TRUCK SPEED

In flat or rolling terrain it is possible to conduct sufficient speed studies to determine the speeds of trucks for the typical and unusual profiles that are encountered on a high-way system. In mountainous terrain, however, this approaches an impossible task. This is especially true for West Virginia. Therefore, a unique method was employed to obtain the average truck factor for each section of highway and for each grade or combination of grades on all roads in West Virginia likely to carry more than 1,800 vehicles per day during the next 20 years. The method involved the selection of a typical truck with a typical load. This truck was driven over the highway system at its maximum safe speed consistent with normal truck operation to obtain a continuous speed profile. The speed of the truck and its odometer reading were recorded at the bottom and top of each grade, at crossroads or other control points, each time the gears were shifted, and each time there was a change of 5 mph in the speed of the truck. When the truck reached a crawl speed on long grades, the crawl speed was recorded to the nearest mile per hour. The truck was operated in both directions on the more import-ant roads to get a speed profile for each direction of travel.

The control truck and its load were selected to obtain a weight-power ratio of 325 lb per horsepower, so that its effect on highway capacity would be the same as the aver-age dual-tired vehicle. Its gross load was 40,000 lb, which was considerably lighter than the heaviest group of vehicles recorded during recent loadometer surveys, but

also heavier than the average dual-tired vehicle, including those with and without pay-loads. Because Figure 6 is not a straight line, the possible speed of the control truck on an upgrade was purposely somewhat lower than the average for all dual-tired trucks on the same grade. This was necessary so that the truck factor obtained for the speed of the control truck from Figure 6 would equal the average factor for all trucks.

As an example, the average truck factor for speeds of 35 and 15 mph is 11.5, or $(\frac{3 + 20}{2})$. A truck factor of 11.5 is represented by a speed of 21 mph rather than 25 mph (the average of 35 and 15).

Soon after placing the control truck in operation, its speeds on hills with known grad-ients were checked with the performance curves for vehicles under controlled test con-ditions and found to be in agreement. Trial runs on the same grade were also remark-ably consistent.

Speed studies of trucks on grades obtained at spot locations and also over the entire length of long grades by stopwatch studies showed that the average truck factor obtained by this procedure was somewhat lower than the truck factor obtained by using the speed of the control truck. The difference varied from 10 to 20 percent. Inasmuch as this was on the conservative side and would make a difference of less than 5 percent when used for estimating the capacities of existing roads, no adjustment or correction was made. Had it been desired to more accurately duplicate the average performance of presentday commercial vehicles as found in West Virginia, the load on the control truck should have been reduced about 5,000 lb.

The average speeds of the control truck on 3 to 7 percent uniform grades up to 6 miles long are shown by Figure 7 and Table 6. Figure 8 shows the speed of the truck at any point on these grades. The speeds as shown by the solid lines are based on the assumption that the truck enters the grade at 41 mph.
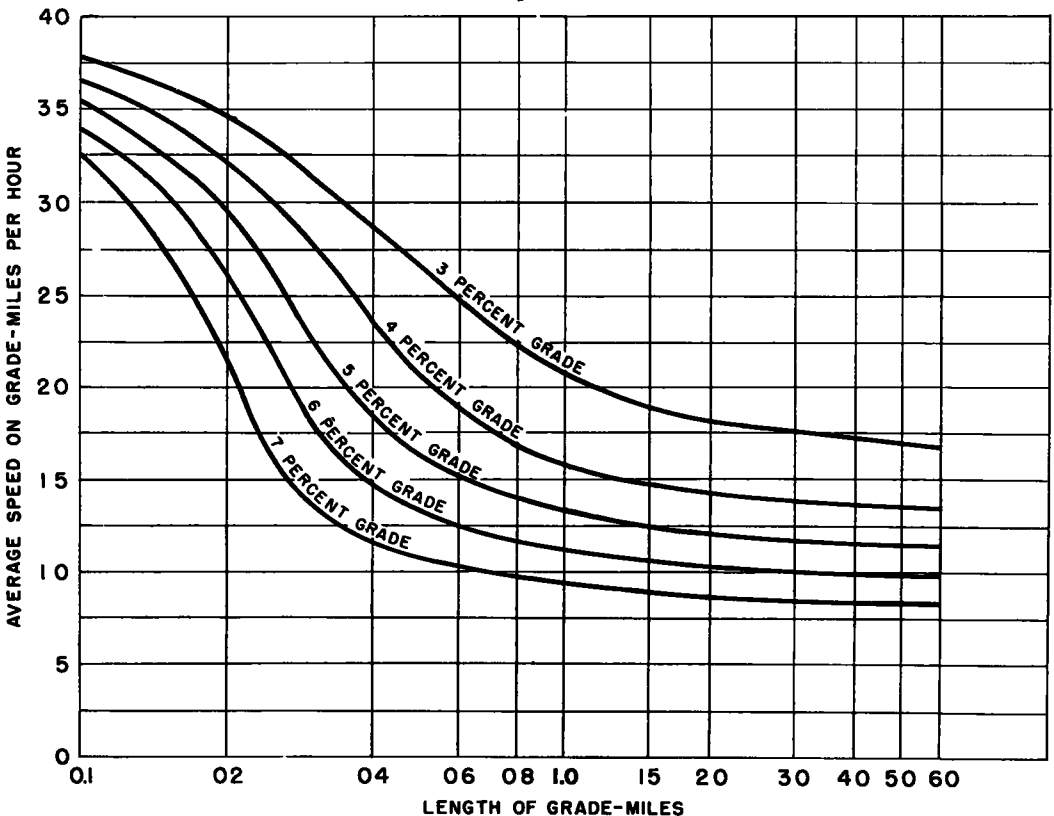

Figure 7. Average speed of control truck on grades.

These curves may also be used to determine the speed reduction due to any length and steepness of grade for other approach speeds. For example, if the approach is 40 mph (initial distance 85), the speed at the top of a 4 percent grade 1,000 ft long will be 26 mph (final distance 1,085). Similarly, if this same grade is approached at a speed of 30 mph, the speed at the top will be 17 mph.

The dashed curves emanating from 9 mph show the maximum performance of vehicles when the approach speed is so low that the vehicle must accelerate to eventually
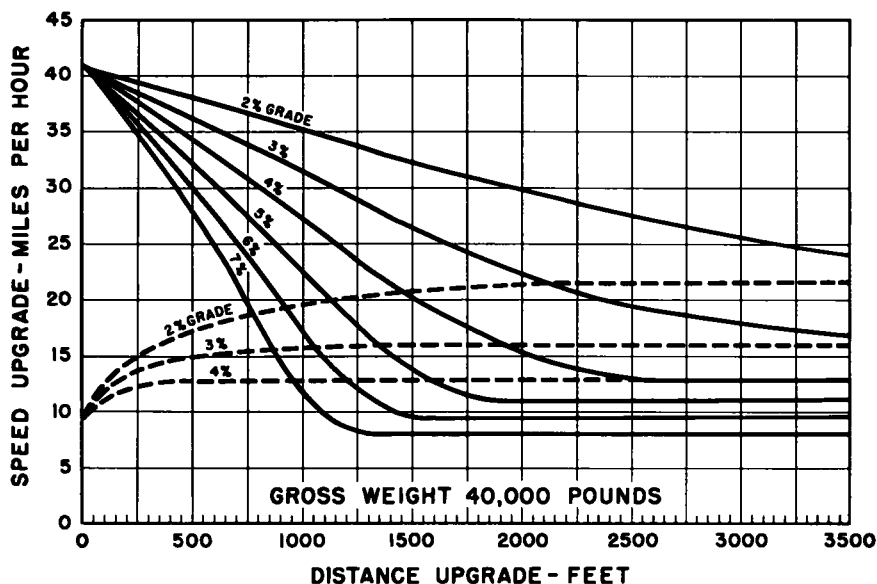
Figure 8. Effect of length of grade on the speed of medium motor vehicles.

TABLE 6

AVERAGE SPEED OF TYPICAL TRUCK ON GRADES, ENTERING SPEED 40 MPH

Length of Grade, mi	Average Speed, mph				
	3% Grade	4% Grade	5% Grade	6% Grade	7% Grade
0.1	37.3	36.1	35.2	34.0	32.6
0.2	34.6	31.7	29.3	25.8	21.4
0.4	28.4	23.4	18.2	14.5	11.8
0.6	24.6	18.5	14.9	12.4	10.2
0.8	21.9	16.6	13.7	11.5	9.5
1.0	20.4	15.7	13.1	11.0	9.2
1.5	18.7	14.6	12.3	10.5	8.8
2.0	17.9	14.1	11.9	10.2	8.5
3.0	17.3	13.6	11.6	10.0	8.4
4.0	16.9	13.4	11.5	9.8	8.3
5.0	16.7	13.3	11.4	9.8	8.2
6.0	16.6	13.2	11.3	9.7	8.2
Sustained Speed	16.0	12.8	11.0	9.5	8.0
Distance to reach sustained speed, mi	0.78	0.60	0.37	0.28	0.24

reach the sustained speed. These curves show that it takes exceedingly long distances to accelerate on grades when the approach speed is below that of the sustained speed. To change the speed on a 2 percent grade from 20 mph to the sustained speed of 21.5 mph, an increase of only 1.5 mph, the vehicle would have to travel 1,050 ft.

If needed, similar curves can be prepared for trucks with other weight-power ratios, or for other entering speeds, from the results of motor vehicle performance studies conducted by the Bureau of Public Roads and others (1, 2, 3, 4, 5, 6). This was not necessary for the West Virginia needs study because the truck was operated over all routes under consideration.

If the grades had been uniform and their lengths and gradients known, it would have been possible to determine the average truck factor by applying the data from Figure 7 to Figure 6. Driving the truck over the routes would have been unnecessary. This
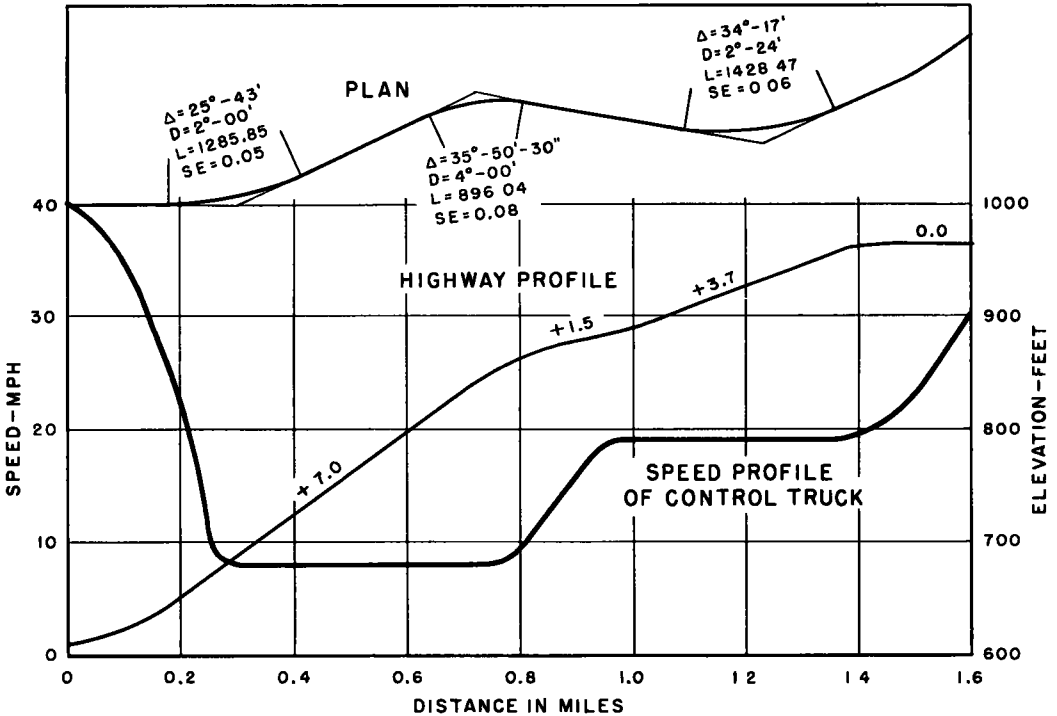
Figure 9. Speed profile of control truck.

method was employed in Kentucky and Tennessee. In West Virginia, however, the needed information for the grades was not available. Furthermore, in this state there are few uniform grades. Practically all have multiple gradients, for which it is possible but rather difficult and time-consuming to calculate truck speeds accurately. One such example is shown by Figure 9, which also gives the speed profile recorded for the control truck.

TRUCK CLIMBING LANES

Truck climbing lanes on the uphill side of long steep grades provide a means for improving the capacity of 2-lane roads through rough or mountainous terrain. It is on a long steep grade that the greatest difference occurs between the normal speed of passenger cars and the normal speed of trucks. The need for adequate passing opportunities is therefore greatest on the long steep grades, whereas the passing opportunities are generally less than on the level sections of a 2-lane highway. This results in higher truck factors and lower capacities for uphill sections of a 2-lane highway than

TABLE 7

SPEED CHARACTERISTICS OF CONTROL TRUCK ON UPGRADES[a]

Gradient, Percent	Crawl Speed[b]		Distance Upgrade, ft		
	Velocity, mph	Distance Upgrade, ft	34 mph (T.F.=3.0)	27 mph (T.F.=6.5)	19 mph (T.F.=13.8)
3	16.0	4,000	1,100	2,000	6,600
4	12.8	2,600	800	1,500	3,000
5	11.0	1,800	600	1,200	2,000
6	9.5	1,500	500	1,000	1,500
7	8.0	1,300	400	800	1,200

[a]When entering grade from level section at 40 mph.

[b]Speed which truck can maintain indefinitely.

for the level sections.

Where truck climbing lanes are provided, the truck factor becomes zero and the capacity of the normal section of the 2-lane highway is the same as though there were no trucks. Under certain conditions, therefore, truck climbing lanes will increase the practical capacity of an entire 2-lane highway to a value higher than that for the same alignment with no grades. This is because the provision of a climbing lane reduces the average truck factor and increases the percentage of the highway on which passing maneuvers may be performed.

Climbing lanes will also increase the capacity of multilane highways. In fact, an added lane for each direction of travel over the entire length of a multilane highway may often be avoided by providing an added lane on the uphill side of the long or steep grades. The quantitative effect that trucks have on the capacity of multilane highways with long steep grades is not as well known, however, as for 2-lane highways. For example, it is entirely possible that a few heavy trucks on a long steep grade of a multilane highway might have nearly as great an effect as a much larger number. The factors used at present are average values determined for less than 20 percent dual-tired vehicles (usually 5 to 10 percent).

APPLICATION OF UPHILL TRUCK LANES

The benefit to traffic by providing an uphill truck lane at a specific location depends on the following factors:

1. Traffic volume.
2. Percentage of trucks.
3. Length and steepness of grade.
4. Availability of passing sight distance.

Table 7 offers some guidance for the application of climbing lanes. Column 4, for example, shows the lengths of grade for an average truck speed of 34 mph or a truck factor of 3.0. At this average speed, even though about one-half of the trucks will be traveling at somewhat lower speeds, the speeds of passenger cars will not be affected sufficiently to greatly inconvenience the drivers. At traffic volumes approaching practical capacities for level sections of 2-lane highway, few passenger cars will overtake a truck on grades that are shorter than those shown in Column 4. For those that do, the necessary reduction in speed and the lost time in reaching the top of the grade when the passing sight distance is restricted, will not be appreciably greater than commonly necessary due to oncoming traffic on straight level sections. Truck climbing lanes cannot be justified, therefore, on grades shorter than those shown in Column 4, Table 7.

Columns 5 and 6, Table 7, show lengths of grade on which there is the same relative

TABLE 8

CAPACITIES OF 2-LANE HIGHWAYS ON GRADES

(Based on a 30th highest hour of 12 percent of the average annual volume)
5 Percent Trucks

Grade, Percent	Length of Grade, ft	Average Annual Traffic Volume, vehicles per day							
		Avg. Hwy. Speed 70 Oper. Speed 50-55		Avg. Hwy. Speed 60-70 Oper. Speed 50		Avg. Hwy. Speed 60-70 Oper. Speed 45-50		Avg. Hwy. Speed 50-70 Oper. Speed 40-45	
		Without Truck Lane	With Truck Lane	Without Truck Lane	With Truck Lane	Without Truck Lane	With Truck Lane	Without Truck Lane	With Truck Lane
3	1,100-2,000	4,300	4,700	4,850	5,500	5,150	6,000	6,500	7,000
	2,000-4,000	3,850	4,700	4,300	5,500	4,550	6,000	6,250	7,000
	Over 4,000	3,500	4,700	3,800	5,500	4,050	6,000	5,550	7,000
4	800-1,500	4,300	4,700	4,850	5,500	5,150	6,000	6,500	7,000
	1,500-3,000	3,850	4,700	4,200	5,500	4,400	6,000	5,800	7,000
	3,000-4,000	3,400	4,700	3,750	5,500	4,000	6,000	5,450	7,000
	Over 4,000	3,200	4,700	3,400	5,500	3,800	6,000	5,100	7,000
5	600-1,200	4,300	4,700	4,850	5,500	5,150	6,000	6,500	7,000
	1,200-2,000	3,500	4,700	3,800	5,500	4,050	6,000	6,150	7,000
	2,000-4,000	3,200	4,700	3,700	5,500	3,950	6,000	5,700	7,000
	Over 4,000	2,800	4,700	3,250	5,500	3,500	6,000	4,800	7,000
6	500-1,000	4,300	4,700	4,850	5,500	5,150	6,000	6,500	7,000
	1,000-1,500	3,500	4,700	3,800	5,500	4,050	6,000	6,150	7,000
	1,500-4,000	3,050	4,200	3,550	5,200	3,800	6,000	5,350	7,000
	Over 4,000	2,550	3,600	2,950	4,000	3,200	4,200	4,500	5,800
7	400-800	4,300	4,700	4,850	5,500	5,150	6,000	6,500	7,000
	800-1,200	3,500	4,700	3,800	5,500	4,050	6,000	5,550	7,000
	1,200-2,500	2,900	4,200	3,400	5,000	3,650	6,000	5,100	7,000
	2,500-4,000	2,600	3,600	3,000	4,000	3,300	4,200	4,600	5,800
	Over 4,000	2,000	3,000	2,400	3,400	2,650	3,600	3,700	4,600

need for a truck climbing lane. With a given traffic volume, for example, there is the same need for a climbing lane on a 3 percent grade 2,000 ft long as on a 7 percent grade 800 ft long.

The capacities of 2-lane highways on grades with and without truck climbing lanes are shown by Table 8 for the conditions applicable to West Virginia. The various groups shown for the length of grade (Col. 2) are purely arbitary, with the exception of the shortest length shown for each gradient. The grades could have been divided into a larger or smaller number of length groups with corresponding changes in the average annual traffic volumes. The number of groups used is believed to be consistent with the accuracy justified by the analyzed data.

Table 8 is based on the assumption that each climbing lane will be continuous from a point near the bottom of the grade to a point beyond the top of the grade where the sight distance becomes unrestricted and truck speeds again approach those of passenger cars. All steep grades of equal gradient longer than 4,000 ft have the same capacities. Prior to traveling 4,000 ft upgrade, most trucks will have reached their crawl speeds (Table 7).

For certain traffic and terrain conditions on exceedingly long grades, the use of passing bays may be an adequate and a more feasible solution than a continuous climbing lane (3, 4). With passing bays the capacity of a 2-lane road would be greater than without the passing bays and for certain conditions might equal the capacities shown in Table 8 for the 2-lane roads with a truck lane. The maximum capacities with continuous truck lanes are actually higher than most of the values in Table 8. For Table 8 it was assumed that the capacity on a grade with a truck lane could not exceed the capacity of a 2-lane level section. The capacity with a truck lane falls below the capacity of a level section only on the long grades greater than 5 percent where downhill speeds of trucks traveling in the lower gears affect capacities.

APPLICATION TO CAPACITY DETERMINATIONS

The tables and charts presented are the basic information needed for capacity determinations in connection with the West Virginia needs studies. From this information an almost unlimited number of special tables and charts can be prepared for specific conditions in either West Virginia or other states. The data can also be applied in many different ways, as will be explained by the applications made for the West Virginia, Kentucky, and Tennessee studies.

To determine the highway needs in West Virginia, it was necessary to have a vast amount of information concerning the roads and the traffic using them. For the capacity determination with which this report is concerned, only the factors that have been previously discussed were needed. Their effect on the capacities of 2-lane roads can be determined from Tables 1, 4, and 8, and Figure 6. Figure 7 was also needed for the Kentucky and Tennessee studies, because a control truck was not used to determine the truck factors in these states.

It is important that the conditions be similar over a length of highway for which a capacity determination is made. Section limits, for this reason, were usually defined by urban limits; or by a change in the traffic volume, surface width, average highway speed, or type of terrain; or by a marked change in the percentage of highway with a 1,500-ft passing sight distance. In addition, a county line was the end of one section and the beginning of another.

EXAMPLES OF APPLICATION TO WEST VIRGINIA HIGHWAYS

Five typical sections analyzed during the West Virginia studies will illustrate the procedures used to apply the capacity information. The basic information and the resulting calculations for each of these sections are given in Table 9.

Section 1 is located on U.S. 60 about 20 mi west of Charleston in Putnam County. It is 6.4 mi long with a 26-ft pavement in rolling terrain. It has an excellent passing distance as compared with most West Virginia roads, 59 percent of its length having a sight distance in excess of 1,500 ft. The average highway speed is 65 mph and the generally flat profile results in a truck equivalent of only 2. The average daily traffic

volume was 5,500 in 1955 with a design hour of 15 percent of the ADT having 7 percent trucks.

The capacity of this section is 5,800 vehicles daily at an operating speed of 45 to 50 mph, or is 7,150 vehicles daily at a tolerable operating speed of 40 to 45 mph. Because U.S. 60 is one of the most important highways in the state, it is desirable to provide conditions conducive to a high operating speed.

For an operating speed of 45 to 50 mph the existing traffic volume is practically equal to the capacity of the section. As it would be impractical to attempt to increase the capacity of the existing road by improving passing sight distances, the only recourse to accommodate expected future traffic volumes is to add additional lanes by constructing another one-way roadway and using the existing lanes for the other direction of travel.

Section 2, on U.S. 21 in Jackson County, is also on one of the more important roads in the state although the traffic volume is not high. The 6.2-mi section is located in rolling terrain about 20 mi north of Charleston. Both the alignment and profile are poor, resulting in a low design speed and almost no places where the sight distance is adequate

TABLE 9

CAPACITY ANALYSIS OF TYPICAL SECTIONS IN WEST VIRGINIA

Item	Sect. 1	Sect. 2	Sect. 3	Sect. 4	Sect. 5
(a) Known Conditions					
Location	U.S. 60	U.S. 21	U.S. 60	U.S. 50	U.S. 50
Length, mi	6.37	6.21	7.00	4.13	11.46
Terrain	Rolling	Rolling	Rolling	Rolling	Rolling
Avg. highway speed, mph	65	40	53	57	53
1.500-ft S.D., %	59	2	10	9	15
Surface width, ft	26	18	22	22	20
30th-hr factor, %	12	12	12	13	14
Truck speed, mph	40	32	29	25	24
Commercial veh, %	7	5	5	5	5
1955 ADT	5,500	2,300	2,400	2,400	2,600
Long grades	None	None	0.40 mi, 8%	0.50 mi, 7.5% 0.35 mi, 4% 0.60 mi, 2.5%	0.5 mi, 6.5% 1.2 mi, 5.0% 2.5 mi, 2.5%
Sharp curves			1 at 30 mph 1 at 35 mph 1 at 45 mph 2 at 50 mph	None	1 at 40 mph 1 at 45 mph 3 at 50 mph
(b) Determined Values					
Tolerable operating speed, Table 1, mph	40-45	40-45	40-45	40-45	40-45
Tolerable design speed, Table 1, mph	50	50	50	50	50
Tolerable capacity, Table 4, ADT	7,300	None	3,070	3,800	3,405
Width factor	1.00	0.70	0.86	0.86	0.77
30th-hr factor	1.00	1.00	1.00	0.92	0.86
Truck equivalent	2.0	4.0	5.0	8.0	9.0
Truck factor*	0.98	0.91	0.88	0.78	0.75
Corrected tolerable capacity, ADT	7,150	None	2,300	2,350	1,700

$$* \quad \frac{105}{(100-\% \text{ tr}) + (\% \text{ tr} \times \text{tr equiv})}$$

for passing. Pavement width is 18 ft and the truck equivalent is 4. The traffic volume during 1955 was 2,300 vehicles per day with the design hour being 12 percent of the ADT with 5 percent trucks.

The road as it exists today does not meet the tolerable standards for this class of highway. Inasmuch as its average highway speed is only 40 mph, it cannot carry traffic at the tolerable speed of 50 mph during low volumes nor at 40 to 45 mph during the 30th highest hourly volume of the year. It therefore has no capacity for these speeds.

Some improvement in alignment could be made to increase the average highway speed and the amount of passing sight distance. By providing a 1,500-ft sight distance over 10 percent of the length and raising the average highway speed to 45 mph, the capacity would be increased to 2,200 vehicles per day at an operating speed of 35 to 40 mph, or to 1,050 vehicles per day at 40 to 45 mph.

Widening the entire section to 24 ft would increase the capacities at the 35 to 40 and 40 to 45 mph operating speeds to 3,100 and 1,600 vehicles per day, respectively.

The tolerable operating speed for this highway is 40 to 45 mph, therefore the 35- to 40-mph operating speed would be inadequate and undesirable. The capacity at a minimum desirable operating speed with the alignment and sight distances improved to the extent possible on the existing location is still considerably less than the existing traffic volume. The conclusion is, therefore, that the only lasting solution is a complete redesign of the highway.

Section 3 is located on U.S. 60 in Greenbrier County about 100 mi east of Charleston. The terrain is rolling over this 7.0-mi section, the average highway speed is 53 mph, about 10 percent of the highway has a 1,500-ft sight distance, and the truck equivalent is 5.

Tolerable operating speed for this highway is 40 to 45 mph. At this speed the capacity of the section is 2,300 vehicles per day.

Several possibilities are available for increasing the capacity of the section, including removal of some or all of the five substandard curves, the addition of truck lanes on grades, and minor improvements in the sight distance by removal of trees, daylighting curves, etc.

Reducing curvatures would increase the average highway speed to about 55 mph, resulting in a tolerable capacity of about 2,600 vehicles per day.

Passing sight distance might be increased an additional 5 percent by miscellaneous measures, such as brush removal, curve daylighting, etc. This would further increase capacity to about 2,800 vehicles per day.

The next alternative is the provision of truck lanes. The existing grades would require about 1 mi of truck lanes to be added, resulting in a decrease in the over-all truck equivalent from 5 to 3. Minor improvement in the alignment would also provide additional passing sight distance so that a 1,500-ft sight distance would be available over approximately 20 percent of the highway. All these improvements would increase the capacity of the highway to about 3,380 vehicles per day at an operating speed of 40 to 45 mph. At the normal rate of traffic growth this volume would not be exceeded for a period of 6 to 7 years. Thereafter it would be necessary to undertake major changes in the alignment or to provide a 4-lane highway in order to maintain the desired operating speed.

Section 4 has 11-ft traffic lanes and is located on U.S. 50 in Wood County. It is 4.1 mi long through rolling terrain. The alignment is fairly good, as the average highway speed is 57 mph and 9 percent of the highway has a 1,500-ft sight distance. The traffic volume in 1955 was 2,400 vehicles per day with a design-hour factor of 13 percent of the ADT including 5 percent trucks.

For the tolerable speed of 40 to 45 mph, the capacity is 2,350 vehicles per day. This is slightly lower than the present volume.

Building a truck lane 1 mi long on a critical grade would reduce the truck equivalent to 3 and would increase the 1,500-ft passing sight distance from 9 percent to about 18 percent of the length. As a result the capacity would be increased to 3,250 vehicles per day at an operating speed of 40 to 45 mph.

Some additional 1,500-ft sight distance could be obtained by increasing the sight on the inside of several curves by simply removing such obstructions as brush and low

banks on the right-of-way. When the obstruction is off the right-of-way, additional right-of-way must be purchased or an agreement reached with the property owner to keep it cleared. An additional 5 percent of 1,500-ft sight distance can be obtained in this manner. This would increase the capacity at the desired operating speed to 3,450 vehicles per day, which represents an increase of nearly 60 percent over the present traffic volume, or to approximately the volume expected in 1970.

Section 5 is located on U.S. 50 in Hampshire County in the northeastern part of the state. The section is 11.5 mi long with uniform design characteristics in the rolling terrain. The average highway speed is 53 mph, the surface width is 20 ft, and 15 percent of the highway has a 1,500-ft sight distance. The truck equivalent is 9. The present ADT is 2,600 per day with a design factor of 14 percent including 5 percent trucks. Under these conditions, the capacity at an operating speed of 40 to 45 mph is 1,700 vehicles per day.

Several possibilities exist for improving the capacity. These include reducing the sharpness of five substandard curves, widening the surface, the addition of truck lanes on grades, and minor improvement in the sight distance.

Widening from 20 ft to 24 ft would increase the capacity to 2,200 vehicles per day. Removal of the substandard curves will increase the average highway speed to about 55 mph and would increase the passing sight distance 1 to 2 percent. These improvements, including the widening, would result in increasing the capacity to 2,550 vehicles per day.

The addition of 2.5 mi of truck lanes would increase the sections on which passings could be performed to about 25 percent of the highway and reduce the truck equivalent to 3. The total resulting capacity would be 3,600 vehicles per day, or 38 percent above the present volume.

These five examples are rather typical of the way the capacity information was applied in West Virginia to determine highway sufficiency. Its use was found especially helpful in pointing out the changes that could be made to improve capacity. Altering some highway features will have little effect on the capacity at a desired operating speed others, such as the provision of truck lanes and substantially improving the passing sight distances, will have a major effect.

APPLICATIONS TO CONDITIONS IN KENTUCKY AND TENNESSEE

The principles employed for capacity determinations in West Virginia have general application wherever curvatures and grades create special highway capacity problems. This was the case throughout most of Kentucky and Tennessee, where highway needs studies were started during the period that the West Virginia study was being completed.

The two special features needed in the refinement of the capacity analysis, which were the average highway speed and the truck equivalent, could have been obtained in the same manner as described for West Virginia. Utilizing the experience gained in the West Virginia study, however, it was found desirable and more feasible to derive these data from existing records, rather than from test vehicle operation.

Kentucky and Tennessee lacked data on actual truck operations which would be consistent with probable future conditions. Following many years of severe restrictions on truck size and weight, Tennessee had just revised its law so as to be in substantial agreement with AASHO recommendations. Truck operations, however, had not as yet changed to conform with the higher limits. Kentucky still retained its low limits, but it was anticipated that a more realistic position would be adopted, as it was in 1956, bringing that state in line with Tennessee and the other states. Without actual data on vehicle weights for the revised weight limits, it was assumed that future conditions in Kentucky and Tennessee would be similar to those on which the West Virginia study was based.

In both Kentucky and Tennessee, geometric design data were available, mile by mile, in the Highway Planning Division records, or were easily obtainable from plans. Thus, actual curvature was known, and curve lengths could be obtained or sampled from the plans. In both states, the gradient and the length of the grades on each section of highway were available from the plans. This was not the case for most roads in West Virginia

Determining Average Highway Speed

Operation of a test car, as in West Virginia, accounted for several factors that would affect the average highway speed, but horizontal curvature was by far the most significant. From available data, therefore, it was possible to approximate the average highway speed of control sections in the other states by concentrating the analysis on the combined effect of horizontal curves and tangents.

Vehicle speeds are affected ahead and beyond a curve for a distance which varies with the degree of curvature. That is, a vehicle on a tangent approaching a sharp curve must begin to slow down before reaching the curve in order to reduce its speed to the allowable speed on the curve. After traveling around the curve, an additional time and distance is required to accelerate back to the normal tangent speed. It was necessary, therefore, to determine the following information for each section of highway requiring a separate capacity analysis:

1. The possible safe speed, or design speed, of each curve.
2. The length of each curve.
3. The distance before and after each curve that the speed was affected, together with the average speed while decelerating and accelerating.
4. The average speed weighted by the length of the tangents, the curves, and by the deceleration and acceleration distances. This speed was used as the average highway speed.

The safe speeds for curves of various degrees (or radii) were determined from the tables in the AASHO policy on "Geometric Design of Rural Highways." The length of each curve was obtained from the highway plans or from planning survey information. Comfortable rates of acceleration and deceleration as shown in the AASHO policies were used to determine the length of speed transitions between the curves and tangents.

A special study conducted by sampling the curves on level sections from Kentucky highway plans showed that, regardless of curvature, the average total effect of a curve on the speed of a vehicle was equivalent to a travel distance of about 800 ft at the safe speed for the curve. For example, the 9-deg curves good for a design speed of 45 mph had an average length of 667 ft. Decelerating and accelerating from the 65-mph tangent speed required a total of 485 ft. On an average, a vehicle would be affected for a total distance of 1,152 ft, but the time lost was the same as if the speed was 45 mph for 915 ft and the tangent speed of 65 mph on the rest of the section. Likewise, for the 40-deg curves the equivalent distance at 20 mph was 691 ft. The equivalent distances varied from curve to curve, but the average was 780 ft with values much greater or less than the average being comparatively rare. An equivalent length of 800 ft, or 0.15 mi, for all curves was therefore used to determine the average highway speeds for the highway sections in Kentucky and Tennessee.

Tangent sections and curves as sharp as 3 deg were assumed to have a highway speed of 70 mph if there were no curves as sharp as 4 deg on the highway. If any curves on the highway were as sharp as 4 deg, the tangent sections and the curves of 4 deg or flatter were assumed to have a highway speed of 65 mph. These assumptions are in accordance with the AASHO definition of design speed as related to the travel speeds found on main rural highways during low traffic densities.

The following example illustrates the method used in estimating the average highway speed of a 2-lane section of highway 10 mi long:

Curvature, deg	Safe Speed, mph	Number of Curves	Total Length, mi	Col. 2 x Col. 4
6	55	1	0.15	8.25
10	43	2	0.30	12.90
12	40	8	1.20	48.00
20	35	4	0.60	21.00
30	25	1	0.15	3.75
0	65	-	7.60	494.00
Total		16	10.00	587.90

Average highway speed = $\dfrac{587.90}{10}$ = 59 mph.

If weighted by travel time, the average highway speed would be 56 mph. Within the limits of reasonable accuracy, however, either method should be satisfactory. For the needs studies conducted in Ontario, Canada, weighting to obtain the average highway speed was done on the basis of time involved rather than length.

DETERMINING TRUCK EQUIVALENT

Attention was called earlier to the fact that driving a test truck to establish a speed profile would be unnecessary if gradient and length were known, because available test data are adequate to establish truck speeds on known grades (Fig. 8).

With grade data available in Kentucky and Tennessee, determining the truck equivalent in terms of passenger cars, for capacity computations, made use of Figures 7 and 6, in that order.

It was first assumed that the entering speed of trucks approaching a grade was 40 mph. It is recognized that momentum from downgrades, and actual level speeds, may frequently be greater, but in the mountainous terrain where this analysis was especially pertinent, horizontal curvature is such that higher speeds are seldom encountered. For example, the speed profile of the test truck on U.S. 50 in West Virginia shows a maximum of only 45 mph for short distances at only three locations in a 50-mi section.

It was also assumed for the purposes of this study, that average truck speed was 40 mph on level terrain, on all grades of less than 3 percent, and on grades of 3 percent less than 500 ft long.

For all other grades, the average truck speed was determined from Figure 7 for each grade or average compound grade, in one direction only.

For the control section, or a long subsection, the average truck speed was determine by weighting by distance the speeds on level terrain and the several grades.

Finally, the weighted average truck speed was entered on Figure 6 to determine from the curve the truck equivalent in terms of passenger cars. Capacity analysis then was completed as previously described.

Descriptions of working procedures and the application of these data in estimating the requirements for truck lanes or other design modifications are discussed also in the "Manual of Engineering Procedure for Determining Needs of the Rural State Highway System," published by the state highway departments of Kentucky and Tennessee in 1954

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Appendix

TABLE A

TOLERABLE CAPACITIES OF EXISTING TWO-LANE ROADS, FLAT TERRAIN, OPERATING SPEED 45 TO 50 MPH, 5 PERCENT TRUCKS

Percent of Highway with Passing Sight of		Average Annual Volume, Vehicles per Day															
		12-ft Lanes				11-ft Lanes				10-ft Lanes				9-ft Lanes			
		passenger car speed (average highway speed) at low volume															
1,500 ft	1,000 ft	70 mph	60 mph	55 mph	50 mph	70 mph	60 mph	55 mph	50 mph	70 mph	60 mph	55 mph	50 mph	70 mph	60 mph	55 mph	50 mph
100	100	7,100	7,100	6,600	5,650	6,100	6,100	5,700	4,850	5,450	5,450	5,100	4,350	4,950	4,950	4,600	3,950
80	90	6,800	6,400	5,750	5,050	5,850	5,500	4,950	4,350	5,250	4,950	4,450	3,900	4,750	4,500	4,000	3,550
60	80	6,400	5,550	4,800	4,000	5,500	4,750	4,150	3,450	4,950	4,250	3,700	3,100	4,500	3,900	3,350	2,800
40	70	5,750	4,600	3,900	2,800	4,950	3,950	3,350	2,400	4,450	3,550	3,000	2,150	4,000	3,200	2,750	1,950
20	60	4,900	3,750	2,800	2,000	4,200	3,200	2,400	1,700	3,750	2,900	2,150	1,550	3,450	2,600	1,950	1,400
0	50	3,800	2,800	2,000	1,250	3,250	2,400	1,750	1,050	2,900	2,150	1,550	950	2,650	1,950	1,400	850

TABLE B

TOLERABLE CAPACITIES OF EXISTING TWO-LANE ROADS, FLAT TERRAIN OPERATING SPEED 40 TO 45 MPH, 5 PERCENT TRUCKS

Percent of Highway with Passing Sight of		Average Annual Volume, Vehicles per Day															
		12-ft Lanes				11-ft Lanes				10-ft Lanes				9-ft Lanes			
		passenger car speed (average highway speed) at low volume															
1,500 ft	1,000 ft	60 mph	55 mph	50 mph	45 mph	60 mph	55 mph	50 mph	45 mph	60 mph	55 mph	50 mph	45 mph	60 mph	55 mph	50 mph	45 mph
100	100	8,450	8,050	7,450	6,550	7,250	6,900	6,400	5,650	6,500	6,200	5,750	5,050	5,900	5,650	5,200	4,600
80	87	7,700	7,300	6,700	5,800	6,600	6,300	5,750	5,000	5,950	5,600	5,150	4,450	5,400	5,100	4,700	4,050
60	76	6,800	6,450	5,700	4,850	5,850	5,550	4,900	4,150	5,250	4,950	4,400	3,750	4,750	4,500	4,000	3,400
40	64	5,900	5,300	4,600	3,700	5,050	4,550	3,950	3,200	4,550	4,100	3,550	2,850	4,150	3,700	3,200	2,600
20	52	4,950	4,100	3,200	2,200	4,250	3,550	2,750	1,900	3,800	3,150	2,450	1,700	3,450	2,850	2,250	1,550
0	40	3,950	2,700	1,950	1,250	3,400	2,300	1,700	1,100	3,050	2,100	1,500	950	2,750	1,900	1,350	900

TABLE C

TOLERABLE CAPACITIES OF EXISTING TWO-LANE ROADS, ROLLING TERRAIN OPERATING SPEED 45 TO 50 MPH, 5 PERCENT TRUCKS

Percent of Highway with Passing Sight of		Average Annual Volume, Vehicles per Day															
		12-ft Lanes				11-ft Lanes				10-ft Lanes				9-ft Lanes			
		passenger car speed (average highway speed) at low volume															
1,500 ft	1,000 ft	70 mph	60 mph	55 mph	50 mph	70 mph	60 mph	55 mph	50 mph	70 mph	60 mph	55 mph	50 mph	70 mph	60 mph	55 mph	50 mph
100	100	6,500	6,500	6,050	5,150	5,600	5,600	5,200	4,450	5,000	5,000	4,650	3,950	4,550	4,550	4,250	3,600
80	87	6,200	5,850	5,250	4,600	5,350	5,050	4,500	3,950	4,750	4,500	4,050	3,550	4,350	4,100	3,700	3,200
60	76	5,850	5,050	4,400	3,650	5,050	4,350	3,800	3,150	4,500	3,900	3,400	2,800	4,100	3,550	3,100	2,550
40	64	5,250	4,200	3,550	2,550	4,500	3,600	3,050	2,200	4,050	3,250	2,750	1,950	3,700	2,950	2,500	1,800
20	52	4,500	3,400	2,550	1,800	3,850	2,950	2,200	1,550	3,450	2,600	1,950	1,400	3,150	2,400	1,800	1,250
0	40	3,450	2,550	1,850	1,150	3,000	2,200	1,600	1,000	2,650	1,950	1,400	900	2,400	1,800	1,300	800

TABLE D

TOLERABLE CAPACITIES OF EXISTING TWO-LANE ROADS, ROLLING TERRAIN
OPERATING SPEED 40 TO 45 MPH, 5 PERCENT TRUCKS

Percent of Highway with Passing Sight of		Average Annual Volume, Vehicles per Day																
		12-ft Lanes				11-ft Lanes				10-ft Lanes				9-ft Lanes			
		passenger car speed (average highway speed) at low volumes															
1,500 ft	1,000 ft	60 mph	55 mph	50 mph	45 mph	60 mph	55 mph	50 mph	45 mph	60 mph	55 mph	50 mph	45 mph	60 mph	55 mph	50 mph	45 mph
100	100	7,700	7,350	6,800	6,000	6,600	6,300	5,850	5,150	5,950	5,650	5,250	4,600	5,400	5,150	4,750	4,200
80	85	7,050	6,650	6,100	5,300	6,050	5,700	5,250	4,550	5,450	5,100	4,700	4,100	4,950	4,650	4,250	3,700
60	72	6,200	5,900	5,200	4,400	5,350	5,050	4,450	3,800	4,750	4,550	4,000	3,400	4,350	4,150	3,650	3,100
40	58	5,400	4,850	4,200	3,400	4,650	4,150	3,600	2,900	4,150	3,750	3,250	2,600	3,800	3,400	2,950	2,400
20	44	4,500	3,750	2,900	2,000	3,850	3,200	2,500	1,700	3,450	2,900	2,250	1,550	3,150	2,600	2,050	1,400
0	30	3,600	2,450	1,800	1,150	3,100	2,100	1,550	1,000	2,750	1,900	1,400	900	2,500	1,700	1,250	800

TABLE E

TOLERABLE CAPACITIES OF EXISTING TWO-LANE ROADS, ROLLING TERRAIN
OPERATING SPEED 35 TO 40 MPH, 5 PERCENT TRUCKS

Percent of Highway with Passing Sight of		Average Annual Volume, Vehicles per Day																
		12-ft Lanes				11-ft Lanes				10-ft Lanes				9-ft Lanes			
		passenger car speed (average highway speed) at low volumes															
1,500 ft	1,000 ft	55 mph	50 mph	45 mph	40 mph	55 mph	50 mph	45 mph	40 mph	55 mph	50 mph	45 mph	40 mph	55 mph	50 mph	45 mph	40 mph
100	100	9,050	8,750	8,300	7,200	7,800	7,500	7,150	6,200	7,000	6,750	6,400	5,550	6,350	6,100	5,800	5,050
80	83	8,200	8,000	7,500	6,500	7,050	6,900	6,450	5,600	6,300	6,150	5,800	5,000	5,750	5,600	5,250	4,550
60	67	7,400	7,250	6,600	5,500	6,350	6,250	5,700	4,750	5,700	5,600	5,100	4,250	5,200	5,100	4,620	3,850
40	51	6,500	6,350	5,600	4,300	5,600	5,450	4,800	3,700	5,000	4,900	4,300	3,300	4,550	4,450	3,920	3,000
20	36	5,750	5,350	4,100	2,850	4,950	4,600	3,500	2,450	4,400	4,100	3,150	2,200	4,000	3,750	2,900	2,000
0	20	4,900	3,500	2,250	1,400	4,200	3,000	1,950	1,200	3,800	2,700	1,750	1,100	3,450	2,450	1,600	1,000

TABLE F

TOLERABLE CAPACITIES OF EXISTING TWO-LANE ROADS, MOUNTAINOUS TERRAIN
OPERATING SPEED 45 TO 50 MPH, 5 PERCENT TRUCKS

Percent of Highway with Passing Sight of		Average Annual Volume, Vehicles per Day																
		12-ft Lanes				11-ft Lanes				10-ft Lanes				9-ft Lanes			
		passenger car speed (average highway speed) at low volumes															
1,500 ft	1,000 ft	70 mph	60 mph	55 mph	50 mph	70 mph	60 mph	55 mph	50 mph	70 mph	60 mph	55 mph	50 mph	70 mph	60 mph	55 mph	50 mph
100	100	5,500	5,500	5,150	4,400	4,750	4,750	4,450	3,800	4,250	4,250	3,950	3,400	3,850	3,850	3,600	3,100
80	87	5,300	5,000	4,450	3,900	4,550	4,300	3,850	3,350	4,100	3,850	3,450	3,000	3,700	3,500	3,100	2,750
60	76	5,000	4,300	3,750	3,100	4,300	3,700	3,200	2,650	3,850	3,300	2,900	2,400	3,500	3,000	2,600	2,150
40	64	4,450	3,550	3,050	2,200	3,850	3,050	2,600	1,900	3,450	2,750	2,350	1,700	3,100	2,500	2,150	1,550
20	52	3,800	2,900	2,200	1,550	3,250	2,500	1,900	1,350	2,950	2,250	1,700	1,200	2,650	2,050	1,550	1,100
0	40	2,950	2,200	1,550	950	2,550	1,900	1,350	800	2,250	1,700	1,200	750	2,050	1,550	1,100	650

TABLE G

TOLERABLE CAPACITIES OF EXISTING TWO-LANE ROADS, MOUNTAINOUS TERRAIN
OPERATING SPEED 40 TO 45 MPH, 5 PERCENT TRUCKS

Percent of Highway with Passing Sight of		Average Annual Volume, Vehicles per Day														
		12-ft Lanes				11-ft Lanes				10-ft Lanes				9-ft Lanes			
		passenger car speed (average highway speed) at low volumes														
1,500 ft	1,000 ft	60 mph	55 mph	50 mph	45 mph	60 mph	55 mph	50 mph	45 mph	60 mph	55 mph	50 mph	45 mph	60 mph	55 mph	50 mph	45 mph
100	100	6,550	6,250	5,800	5,100	5,650	5,350	5,000	4,400	5,050	4,800	4,450	3,950	4,600	4,350	4,050	3,550
80	85	6,000	5,700	5,200	4,500	5,150	4,900	4,450	3,850	4,600	4,400	4,000	3,450	4,200	4,000	3,650	3,150
60	72	5,300	5,000	4,450	3,750	4,550	4,300	3,850	3,200	4,100	3,850	3,450	2,900	3,700	3,500	3,100	2,600
40	58	4,600	4,100	3,600	2,900	3,950	3,550	3,100	2,500	3,550	3,150	2,750	2,250	3,200	2.850	2,500	2,050
20	44	3,850	3,200	2,500	1,700	3,300	2,750	2,150	1,450	2,950	2,450	1,900	1,300	2,700	2,250	1.750	1,200
0	30	3,050	2,100	1,500	950	2,600	1,800	1,300	800	2,350	1,600	1,150	750	2,150	1,450	1,050	650

TABLE H

TOLERABLE CAPACITIES OF EXISTING TWO-LANE ROADS, MOUNTAINOUS TERRAIN
OPERATING SPEED 35 TO 40 MPH, 5 PERCENT TRUCKS

Percent of Highway with Passing Sight of		Average Annual Volume, Vehicles per Day														
		12-ft Lanes				11-ft Lanes				10-ft Lanes				9 ft Lanes			
		passenger car speed (average highway speed) at low volumes														
1,500 ft	1,000 ft	55 mph	50 mph	45 mph	40 mph	55 mph	50 mph	45 mph	40 mph	55 mph	50 mph	45 mph	40 mph	55 mph	50 mph	45 mph	40 mph
100	100	7,700	7,450	7,050	6,150	6,600	6,400	6,050	5,300	5,950	5,750	5,450	4,750	5,400	5,200	4,950	4,300
80	83	7,000	6,800	6,350	5,550	6,000	5,850	5,450	4,750	5,400	5,250	4,900	4,250	4,900	4,750	4,450	3,900
60	67	6,300	6,200	5,650	4,650	5,400	5,350	4,850	4,000	4,850	4,750	4,350	3,600	4,400	4,350	3,950	3,250
40	51	5,550	5,400	4,800	3,650	4,750	4,650	4,150	3,150	4,250	4,150	3,700	2,800	3,900	3,800	3,350	2,550
20	36	4,900	4,550	3,500	2,400	4,200	3,900	3,000	2,050	3,750	3,500	2,700	1,850	3,450	3,200	2,450	1,700
0	20	4,150	3,000	1,900	1,150	3,550	2,600	1,650	1,000	3,200	2,300	1,450	900	2,900	2,100	1,350	800