Capacity Analysis of Two-Lane Highways

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The general terrain procedure for two-lane highways in the Highway Capacity Manual contains two flaws which could be significantly improved by changing the definition for when a vehicle is delayed. The first problem is that, even under the best roadway and traffic conditions, any two-way flow rate greater than 43 percent of capacity falls in levels of service D or E. Furthermore, levels of service D and E are too broad to provide definitive information about the flows within these levels. By changing the definition for when a vehicle is being delayed from a headway of 5 seconds, as given by the Manual, to a headway of 3.5 to 4.0 seconds, more useful level-of-service categories result. The second problem is that the general terrain procedure does not yield results compatible with the specific grade procedure. Given otherwise identical traffic and roadway conditions, a two-lane highway will often be categorized as having a better level of service on a specific grade than on a level or rolling terrain segment. This is opposite of what one would expect. By reducing the delay definition to 3.5 or 4.0 seconds, this inconsistency is not completely eliminated but is greatly reduced. Cases could be made for defining the delayed headway as any value from 2.0 to 6.0 seconds. For the purposes of the *Highway Capacity Manual*, a value between 3.5 and 4.0 seconds would provide more reasonable and consistent results.

The 1985 edition of the Highway Capacity Manual (*1*) has introduced a major revision to the procedures for analyzing uninterrupted flow on two-lane highways. New criteria are given for establishing the levels of service, and separate criteria are used for general terrain segments and specific grades.

For general terrain segments, any two-way flow rate greater than 43 percent of capacity is in level of service D or E, even under the very best roadway and traffic conditions. By comparison, for similar best conditions on a freeway it takes 77 percent of one-way capacity to be in level of service D; on other multilane highways it takes 71 percent.

Because different procedures are used for defining the levels of service for general terrain segments and specific grades, a serious inconsistency in the level of service can arise between a general terrain segment and a specific grade. Under identical traffic conditions, the level of service on a specific grade can often be better than the level of service on flat terrain.

The purpose of this paper is to examine the level-of-service criteria for general terrain segments and to offer possible alternatives. These alternative criteria would increase the boundary between levels of service C and D from the current 43 percent of capacity to between 53 and 60 percent under the best conditions. It will also be shown that the proposed alternatives reduce the inconsistency in the level of service between a general terrain segment and a specific grade.

GENERAL TERRAIN SEGMENTS

The Highway Capacity Manual (*1*) uses "percent time delay" as the primary measure of level of service for general terrain segments on two-lane highways. Average travel speed and capacity utilization are secondary measures. Percent time delay is defined as the average percent of time that all vehicles are delayed while traveling in platoons due to the inability to pass. Motorists are defined to be delayed when traveling behind a platoon leader at speeds less than their desired speed and at headways less than 5 seconds. As a surrogate for percent time delay, the percent of vehicles traveling at headways less than 5 seconds can be used. This surrogate is more easily measured in a field study than the percent of the time that all vehicles are delayed. The cut-off values for levels of service A, B, C, and D are respectively defined by the values 30, 45, 60, and 75 for percent time delay. Table 1 [table 8-1 from the Manual (*1*)] shows that for level terrain and 0 percent no passing zones the volume to capacity (*v/c*) ratio associated with level of service C is 0.43. As terrain becomes more severe and the restrictions on passing become greater, the *v/c* ratio for each level of service decreases.

Neither the Manual (*1*) nor the research document (*2*) which formed the basis for the chapter on two-lane highways offer an explanation as to why the cut-off values between the levels of service were selected as 30, 45, 60, and 75 percent time delay. Also, strong reasons are not given as to why 5 seconds was selected as the definition for being delayed. Reference is made in the research document (*2*) to another study (*3*) in which 6 seconds was suggested as the definition for being delayed. However, in a recent paper covering a study in the Netherlands, Botma (*4*) found that a preliminiary analysis of the data determined that no preference could be deduced from using 4, 5, or 6 seconds. Because 5 seconds appears to have been arbitrarily selected, it may be that a smaller value could be selected as long as it leads to reasonable *v/c* ratios for the various levels of service and as long as safety is not sacrificed.

It is the purpose here to offer two alternatives to the *v/c* ratio values given in table 1 for the level-of-service criteria for general terrain segments. The alternatives are based on the same percent time delay values used in the Manual (*1*) and on two different definitions for being delayed: 4 and 3.5 seconds.

First an argument will be offered as to why the 5-second headway may be too conservative a value by which to define a vehicle as being delayed and why 4 or 3.5 seconds might be more practical. It should be noted that at 60 mph the head-to-head spacing between two vehicles traveling at 5-seconds

TABLE 1 LEVEL-OF-SERVICE CRITERIA FOR GENERAL TWO-LANE HIGHWAY SEGMENTS (*1*, Table 8-1)

		v/c RATIO[a]																			
		LEVEL TERRAIN							ROLLING TERRAIN							MOUNTAINOUS TERRAIN						
	PERCENT TIME	AVG[b]	PERCENT NO PASSING ZONES						AVG[b]	PERCENT NO PASSING ZONES						AVG[b]	PERCENT NO PASSING ZONES					
LOS	DELAY	SPEED	0	20	40	60	80	100	SPEED	0	20	40	60	80	100	SPEED	0	20	40	60	80	100
A	≤ 30	≥ 58	0.15	0.12	0.09	0.07	0.05	0.04	≥ 57	0.15	0.10	0.07	0.05	0.04	0.03	≥ 56	0.14	0.09	0.07	0.04	0.02	0.01
B	≤ 45	≥ 55	0.27	0.24	0.21	0.19	0.17	0.16	≥ 54	0.26	0.23	0.19	0.17	0.15	0.13	≥ 54	0.25	0.20	0.16	0.13	0.12	0.10
C	≤ 60	≥ 52	0.43	0.39	0.36	0.34	0.33	0.32	≥ 51	0.42	0.39	0.35	0.32	0.30	0.28	≥ 49	0.39	0.33	0.28	0.23	0.20	0.16
D	≤ 75	≥ 50	0.64	0.62	0.60	0.59	0.58	0.57	≥ 49	0.62	0.57	0.52	0.48	0.46	0.43	≥ 45	0.58	0.50	0.45	0.40	0.37	0.33
E	> 75	≥ 45	1.00	1.00	1.00	1.00	1.00	1.00	≥ 40	0.97	0.94	0.92	0.91	0.90	0.90	≥ 35	0.91	0.87	0.84	0.82	0.80	0.78
F	100	< 45	—	—	—	—	—	—	< 40	—	—	—	—	—	—	< 35	—	—	—	—	—	—

[a] Ratio of flow rate to an ideal capacity of 2,800 pcph in both directions.
[b] Average travel speed of all vehicles (in mph) for highways with design speed ≥ 60 mph; for highways with lower design speeds, reduce speed by 4 mph for each 10-mph reduction in design speed below 60 mph; assumes that speed is not restricted to lower values by regulation.

headway is 440 feet. This represents a per lane density of 12 vehicles per mile, the value associated with level of service A on freeways. At 4 and 3.5 seconds, the spacings are 352 and 308 feet, and the per lane densities are 15 and 17 vehicles per mile. Both of these conditions are associated with level of service B on a freeway.

From an operational standpoint, a vehicle being delayed by another slower moving vehicle follows at some distance until an opportunity to pass becomes available. A typical following headway just before the beginning of a pass could not be verified from the literature, but the research document (*2*) states that some headways as small as three-quarters of a second were observed during a two-lane highway study in Canada. An analysis of following in which the reaction time for the following driver is 1 second, the braking rates of the leader and follower are equal, and the "safety gap" after stopping is 5 feet, leads to a required following headway of less than 1.5 seconds for all initial speeds over 40 mph if both vehicles are cars. If the lead vehicle is a WB-50 truck, the required following headway is less than 2.2 seconds.

For purposes of this argument, a more conservative following headway of 2.5 seconds will be used to establish a definition for being delayed. It is assumed that the following vehicle has a desired speed of 60 mph and that it will always have a headway greater than 2.5 seconds behind the slower leading vehicle. It is further assumed that the following vehicle does not use the brakes to maintain this headway but that braking is achieved only by removing the driver's foot from the gas pedal. The definition for being delayed is, therefore, established to be the action of removing the foot from the gas pedal to maintain a headway of at least 2.5 seconds. Table 2 gives the headways associated with having to remove the foot from the gas pedal for various speeds of the leading vehicle and for various rates of deceleration in order that the following vehicle always trails by at least 2.5 seconds.

Consider as an example the case of the lead vehicle traveling at 45 mph, the following vehicle at 60 mph, and a deceleration rate of 1.5 ft/sec/sec. Based on the 45 mph speed and the minimum headway of 2.5 seconds, the following vehicle should have a head-to-head spacing of 165 feet. To achieve the speed change from 60 to 45 mph at a braking rate of 1.5 ft/sec/sec, the following vehicle decelerates for 14.67 seconds during which time the spacing between the two vehicles decreases by 61 feet. Therefore, the original spacing when the foot must be removed from the gas pedal must be 326 feet. This spacing is associated with a headway of 3.7 seconds based on the speed of 60 mph.

Table 2 shows that for the range of speeds and braking rates given the worst condition occurs when the lead vehicle has a speed of 45 mph and the deceleration rate is 1.5 ft/sec/sec. At speeds in the 40 to 60 mph range, the deceleration due to removing the foot from the gas is generally higher and in the 2.5 to 3.0 ft/sec/sec range (*5*, p. 24). Therefore, it appears that 3.5 seconds or a more conservative 4 seconds may be reasonable definitions for being delayed as alternatives to the 5 seconds used in the Manual (*1*).

To obtain *v/c* ratios for the 4- and 3.5-second definitions for being delayed, the procedures used to develop the ratios given in table 1 for the 5-second definition were examined. The research document (*2*) describes how a simulation model was used to establish the flow rates and, hence, the *v/c* ratios. The distribution of vehicle headways used as input to the

TABLE 2 HEADWAY TO CONSTITUTE DELAY

SPEED OF LEADING VEHICLE (mph)	HEADWAY AT WHICH DECELERATION MUST START (sec) at DECELERATION RATE (ft/sec/sec)				
	1.5	1.8	2.0	2.5	3.0
55	2.5	2.5	2.5	2.5	2.5
50	2.9	2.8	2.7	2.6	2.5
45	3.7	3.4	3.3	3.0	2.8

Desired speed of following vehicle = 60 (mph)

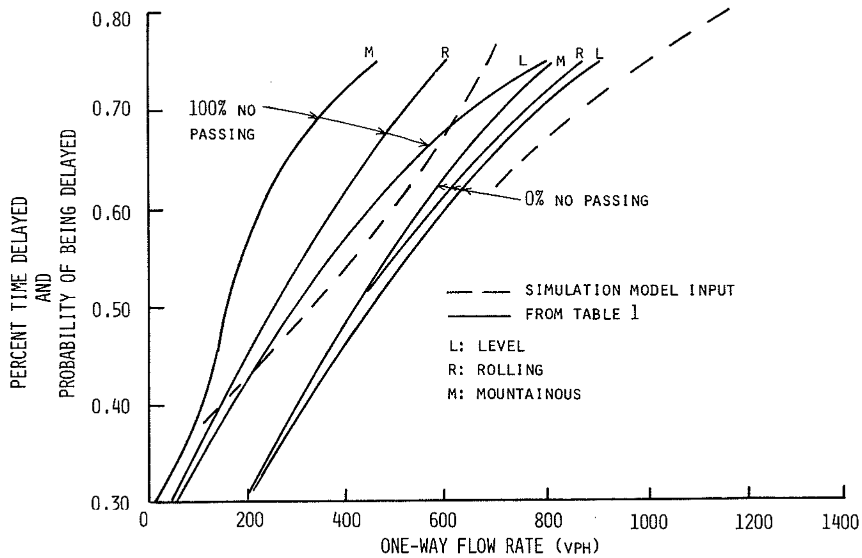

FIGURE 1 Delay–flow relationship for 5-second definition of delay.

simulation model is presented in the research document (*2*). For the 5-second definition for being delayed, the input to the simulation model, given as the probability of being delayed, is shown as the dashed lines in figure 1. The solid lines are the flow rates for 0 percent and 100 percent no passing on level, rolling, and mountainous terrain. These lines were obtained from the *v/c* ratios given in table 1 using an assumed one-way capacity of 1,400 vehicles per hour. This value is the one-way capacity associated with a 50-50 directional distribution on level terrain. Note that the three lines for 0 percent no passing fall between the two dashed lines and that the lines for 100 percent no passing fall to the left of the left dashed line.

The development of *v/c* ratios for other definitions for being delayed was based on an equation calibrated with the *v/c* ratios for the 5-second definition. The form of the equation was taken as:

$$P\,(h<t) = 1 - A\,\exp(-B\cdot t/T) \quad (1)$$

This is the probability of a headway (h) less than t seconds. The average headway is T seconds. A and B are constants to be determined based on the 5-second definition for being delayed. The probability of being delayed was taken to be the percent time delay associated with each level of service.

A curve fitting program was used to determine a separate set of constants A and B for each value of percent no passing for each type of terrain. The calibrated equations were then used to determine the values of T, and, hence, the *v/c* ratios, for t equal to 4 and 3.5 seconds. The resulting *v/c* ratios are shown in tables 3 through 5. These tables also include the ratios for the 5-second definition for being delayed so a comparison can be made.

Because the research document (*2*) describes the equations used to produce the input ot the simulation model, the input for 4 and 3.5 seconds was obtained and is shown as the dashed lines on figures 2 and 3. The solid lines on these figures again show the one-way flows for 0 and 100 percent no passing as obtained from the *v/c* ratios for the 4- and 3.5-second defi-

TABLE 3 LEVEL-OF-SERVICE CRITERIA FOR GENERAL TWO-LANE HIGHWAY SEGMENTS—LEVEL TERRAIN

LOS	DEFINITION OF DELAY (sec)	v/c RATIO — Percent No Passing Zones: 0	20	40	60	80	100
A	5	0.15	0.12	0.09	0.07	0.05	0.04
	4	0.19	0.15	0.12	0.09	0.06	0.05
	3.5	0.22	0.18	0.13	0.10	0.07	0.06
B	5	0.27	0.24	0.21	0.19	0.17	0.16
	4	0.34	0.30	0.27	0.24	0.22	0.21
	3.5	0.39	0.34	0.30	0.27	0.25	0.24
C	5	0.43	0.39	0.36	0.34	0.33	0.32
	4	0.53	0.49	0.46	0.44	0.42	0.41
	3.5	0.60	0.56	0.53	0.50	0.48	0.47
D	5	0.64	0.62	0.60	0.59	0.58	0.57
	4	0.81	0.78	0.76	0.74	0.73	0.72
	3.5	0.92	0.89	0.86	0.84	0.83	0.82
E	ALL	1.00	1.00	1.00	1.00	1.00	1.00

TABLE 4 LEVEL-OF-SERVICE CRITERIA FOR GENERAL TWO-LANE HIGHWAY SEGMENTS—ROLLING TERRAIN

LOS	DEFINITION OF DELAY (sec)	v/c RATIO Percent No Passing Zones					
		0	20	40	60	80	100
A	5	0.15	0.10	0.07	0.05	0.04	0.03
	4	0.19	0.14	0.10	0.08	0.06	0.05
	3.5	0.22	0.16	0.12	0.09	0.07	0.06
B	5	0.26	0.23	0.19	0.17	0.15	0.13
	4	0.33	0.28	0.24	0.20	0.18	0.17
	3.5	0.38	0.32	0.27	0.23	0.21	0.19
C	5	0.42	0.39	0.35	0.32	0.30	0.28
	4	0.51	0.46	0.41	0.37	0.35	0.33
	3.5	0.59	0.53	0.47	0.43	0.40	0.37
D	5	0.62	0.57	0.52	0.48	0.46	0.43
	4	0.79	0.73	0.67	0.62	0.59	0.56
	3.5	0.90	0.83	0.77	0.71	0.67	0.64
E	ALL	0.97	0.94	0.92	0.91	0.90	0.90

TABLE 5 LEVEL-OF-SERVICE CRITERIA FOR GENERAL TWO-LANE HIGHWAY SEGMENTS—MOUNTAINOUS TERRAIN

LOS	DEFINITION OF DELAY (sec)	v/c RATIO Percent No Passing Zones					
		0	20	40	60	80	100
A	5	0.14	0.09	0.07	0.04	0.02	0.01
	4	0.18	0.13	0.09	0.05	0.03	0.01
	3.5	0.20	0.15	0.10	0.06	0.03	0.02
B	5	0.25	0.20	0.16	0.13	0.12	0.10
	4	0.31	0.25	0.20	0.16	0.13	0.11
	3.5	0.35	0.28	0.23	0.18	0.15	0.12
C	5	0.39	0.33	0.28	0.23	0.20	0.16
	4	0.48	0.41	0.35	0.30	0.26	0.23
	3.5	0.54	0.46	0.40	0.34	0.30	0.26
D	5	0.58	0.50	0.45	0.40	0.37	0.33
	4	0.73	0.64	0.57	0.50	0.45	0.41
	3.5	0.83	0.73	0.65	0.57	0.52	0.47
E	ALL	0.91	0.87	0.84	0.82	0.80	0.78

nitions for being delayed. Note that on both figures the lines for 0 percent no passing fall between the two dashed lines and that the 100 percent no passing lines fall to the left of the left dashed line. This relationship repeats that noted on figure 1 associated with the 5-second definition for being delayed.

The *v/c* ratios (tables 3 through 5) associated with the 4- and 3.5-second definitions for being delayed are approximate alternatives for the alues given in the Highway Capacity Manual (*1*) for the 5-second definition. They should be considered approximate because they were not obtained using the simulation model. The comparison between figure 1 and figures 2 and 3 indicates that these *v/c* ratios are reasonable. The results indicated that for level terrain and 0 percent no passing zones (table 3), the *v/c* ratios for level of service C are 0.53 and 0.60 respectively for the 4- and the 3.5-second definitions compared to 0.43 for the 5 seconds. A more complete comparison will be discussed later in relation to an example.

SPECIFIC GRADES

The level-of-service criteria for specific grades on two-lane highways is not based on percent time delay but on the average speed of all the vehicles in the upgrade direction. Table 6 [table 8-2 of the Manual (*1*)] gives the speeds associated with each level of service. Based on this, the *v/c* ratios for grades from 3 to 7 percent are given in table 8-7 of the Manual (*1*) and repeated here for 3 and 7 percent grades in table 7.

As a result of having two different level-of-service criteria, one for general terrain segments and one for specific grades,

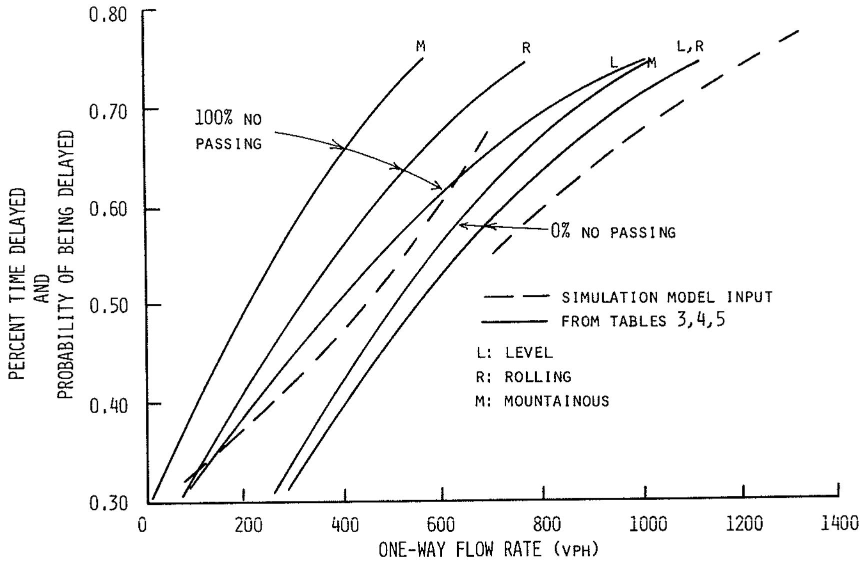

FIGURE 2 Delay–flow rate relationship for 4-second definition of delay.

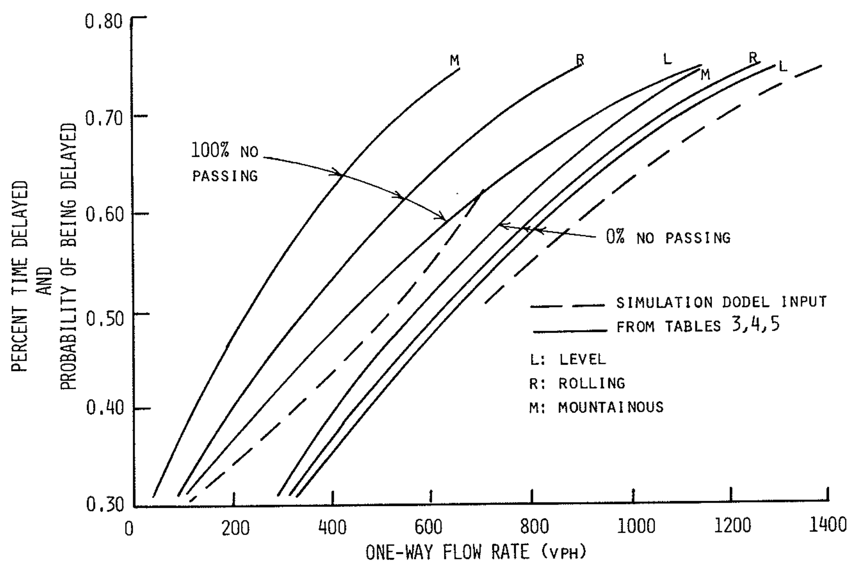

FIGURE 3 Delay–flow relationship for 3.5-second definition of delay.

it is possible for an inconsistency to occur in the level of service between level or rolling terrain segments and a moderate grade. This will be demonstrated by an example.

COMPARATIVE EXAMPLE

Consider a high-design, two-lane highway with design speed of 60 mph, 12 foot lanes, and usable shoulders at least 6 feet wide. The percent of no passing zones is taken as zero for level terrain, 10 percent for rolling terrain, and 20 percent for the 1-mile-long specific grades of 4 or 6 percent. The only no passing zone on the specific grades is near the top. The directional distribution of the traffic stream is 60–40 (for the specific grade, 60 percent is in the upgrade direction) and the only heavy vehicles are 12 percent trucks. The two-way service flows as computed by the procedures described in the Manual (*1*) and associated with each level of service are given in table 8 for the three definitions of being delayed.

The first four columns on figure 4 show the results obtained using the Manual's 5-second definition for being delayed for the general terrain segments and for the two specific grades. For the general terrain segments, levels of service A through C cover service flows up to about 990 and 720 vehicles per hour (vph), respectively, for level and rolling terrain. However, for the two specific grades, these first three levels of service cover service flows to about 1,630 and 1,100 vph for 4 and 6 percent grades, respectively. Notice that a service

TABLE 6 LEVEL-OF-SERVICE CRITERIA FOR SPECIFIC GRADES (*1*, Table 8-2)

LEVEL OF SERVICE	AVERAGE UPGRADE SPEED (MPH)
A	> 55
B	> 50
C	> 45
D	> 40
E	> 25 - 40 *

* The exact speed at which capacity occurs varies with the percentage and length of grade, traffic compositions, and volume.

TABLE 7 VALUES OF *v/c* RATIOS FOR SPECIFIC GRADES (*1*, Table 8-7)

		v/c RATIO					
		Percent No Passing Zones					
LOS	PERCENT GRADE	0	20	40	60	80	100
A	3	0.27	0.23	0.19	0.17	0.14	0.12
	7	0.00	0.00	0.00	0.00	0.00	0.00
B	3	0.64	0.59	0.55	0.52	0.49	0.47
	7	0.34	0.27	0.22	0.18	0.15	0.12
C	3	1.00	0.95	0.91	0.88	0.86	0.84
	7	0.77	0.65	0.55	0.46	0.40	0.35
D	3	1.00	1.00	1.00	1.00	1.00	1.00
	7	0.93	0.82	0.75	0.69	0.64	0.59

TABLE 8 EXAMPLE: TWO-LANE HIGHWAY SERVICE FLOWS

		GENERAL TERRAIN		SPECIFIC GRADE	
		LEVEL	ROLLING	4%-1mi	6%-1mi
	% NO PASS. =	0%	10%	20%	20%
LOS	DEFINITION OF DELAY (sec)				
A	5	350	240	200	50
	4	450	320		
	3.5	520	370		
B	5	620	440	850	440
	4	780	540		
	3.5	900	620		
C	5	990	720	1630	1100
	4	1220	860		
	3.5	1380	1000		
D	5	1500	1060	1890	1460
	4	1900	1350		
	3.5	2160	1540		
E	ALL	2350	1700	1950	1600

NOTE: 12 Percent trucks

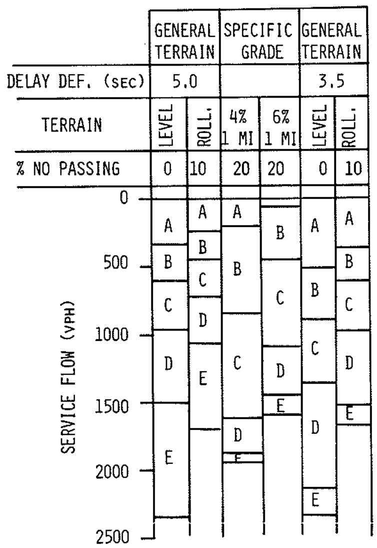

FIGURE 4 Example comparison—5.0- and 3.5-second definitions of delay.

flow in the range 1,500 to 1,630 vph is in level of service E for the level terrain segment, but in level C for the 4 percent grade. Even the 6-percent grade has a higher service flow for level C than the level terrain segment. From an examination of figure 4, one might conclude that a two-lane highway built as a series of 1-mile grades in the range of 4 to 6 percent would provide a better level of service than a level road with no passing restriction. This conclusion is not in keeping with traditional thinking about two-lane highway grades.

The last two columns on figure 4 give the service flows for the 3.5-second definition for being delayed. It can be seen that this definition expands the range of service flows for levels of service A through D and reduces the range in level E compared to the 5-second definition. Service flows up to 1,380 vph on level tererain and 1,000 vph on rolling terrain are now in level of service C instead of near the limits of level D for the 5-second definition. In addition to expanding the range of service flows within the acceptable levels of service, the 3.5-second definition is also less inconsistent with the 4 percent specific grade than the 5-second definition. There is still an inconsistency at the boundary between levels of service C and D, but it is less severe than that associated with the 5-second definition.

CONCLUSIONS

The selection of 5 seconds as the definition for being delayed is not strongly supported in the 1985 edition of the Highway Capacity Manual (*1*), and any value between 2 and 6 seconds may be reasonable. Using 5 seconds as the definition for being delayed also produces an inconsistency in the level of service between certain general terrain segments and specific grades. The selection of 4 or 3.5 seconds as the definition for being delayed would ameliorate these problems.

A field study should be carefully designed and conducted to determine at what headway drivers begin to feel delayed by a leading vehicle. The study should determine if a driver's perception of being delayed is dependent on roadway parameters, such as design speed or posted speed, and the traffic volume conditions.

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