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Operational Effectiveness of
Passing Lanes on Two-Lane Highways

Midwest Research Inst., Kansas City, MO

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Research, Development and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, Virginia 22101

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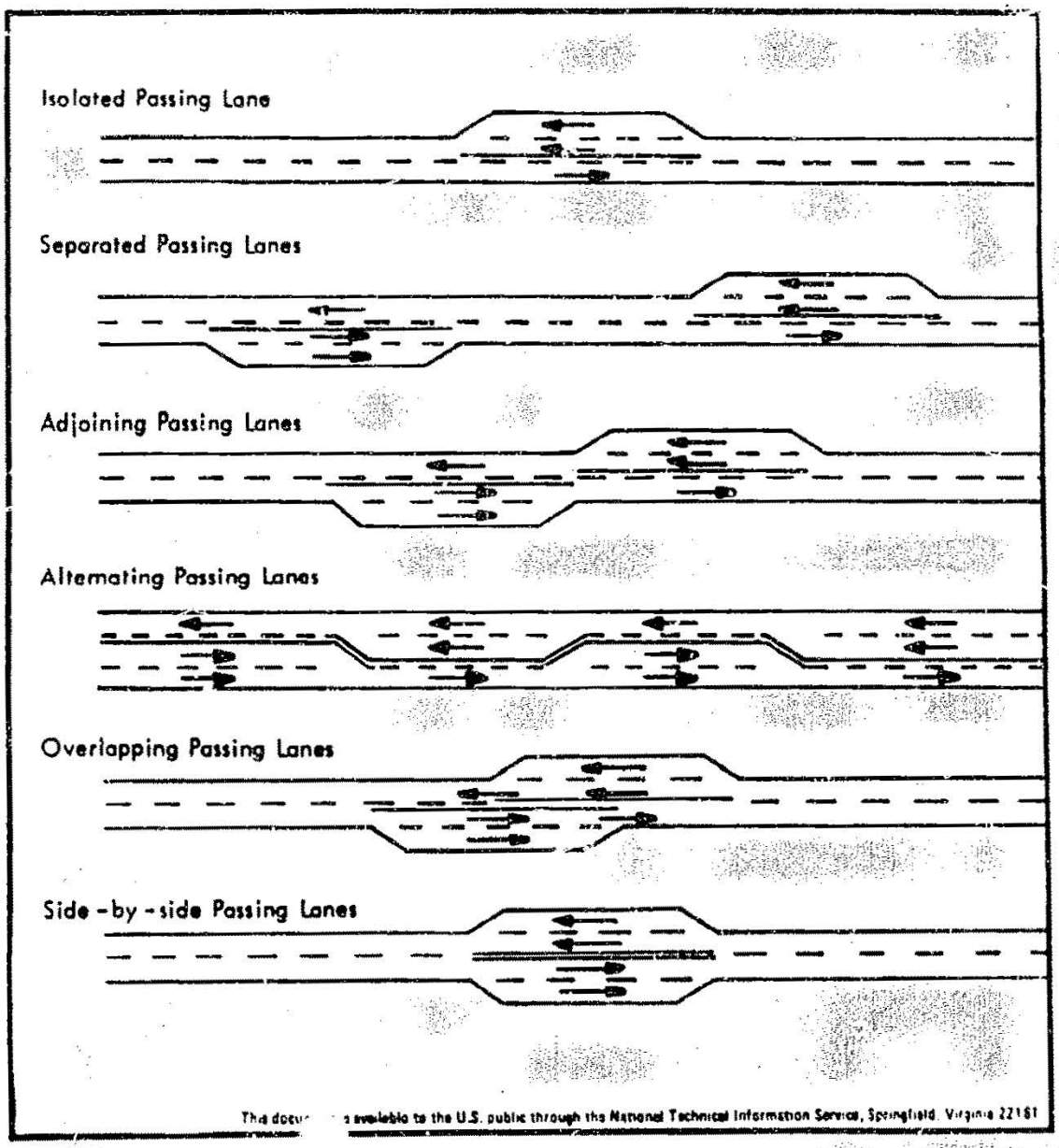

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16. Abstract

This report presents an evaluation of the operational effectiveness of passing lanes on two-lane highways in level and rolling terrain. Passing lanes are defined as added lanes in one or both directions of travel on a two-lane highway to provide additional passing opportunities. Passing lanes at intervals on a two-lane highway are a lower-cost alternative to construction of extended sections of four-lane highway.

The operational evaluation of passing lanes was performed with a computer simulation model of traffic operations on two-lane highways with and without passing lanes. This model, known as TWOPAS, was validated against traffic operational field data for passing lanes.

The TWOPAS model was used to evaluate the effectiveness of passing lanes in improving traffic operations on two-lane highways. The evaluation found that the operational effectiveness of passing lanes is a function of traffic flow rate and passing lane length. Quantitative estimates in the reduction of traffic platooning due to provision of passing lanes are presented in the report. Passing lanes were found to impact traffic operations for effective lengths of 3 to 8 mi (5 to 13 km) of highway, including both the passing lane and the conventional two-lane highway downstream of the passing lane. A case study evaluation of alternative passing improvements was performed using the TWOPAS simulation model; this case study and a benefit-cost evaluation of the results are presented in the report.

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TABLE OF CONTENTS

		Page
1.	Introduction	1
2.	Passing Lanes	1
3.	Computer Simulation of Traffic Operations in Passing Lanes	4
	3.1 Development of the TWOPAS Simulation Model	4
	3.2 Comparison of the TWOPAS Model Results with Field Data	5
4.	Simulated Road and Traffic Conditions	9
	4.1 Primary Experiment	9
	4.2 Supplementary Studies	11
	4.3 Measures of Effectiveness	11
5.	Operational Effectiveness of Passing Lanes	12
	5.1 Travel Speed and Percent Time Delay Over an Extended Road Length	13
	5.2 Downstream Effect of a Passing Lane	13
	5.3 Concept of Effective Length of a Passing Lane	16
	5.4 Optimal Design Length for Passing Lanes	18
	5.5 Changes in Spot Platooning Over the Length of a Passing Lane	20
6.	Conclusions and Recommendations	24
7.	References	2
Appendix -	Simulation Case Study of Passing Improvements	30

1. INTRODUCTION

Many highway agencies in the United States have regarded the construction of a four-lane divided highway as the most desirable response to operational problems on two-lane highways. Such improvements are expensive, however, and funds for road upgrading are very limited in many jurisdictions. This has led to a growing backlog of rural roads requiring improvement. In this situation it is possible to provide major upgrading on only a small proportion of the network, while many other candidate road sections continue to operate unsatisfactorily.

An alternative approach is to provide lower-cost improvements on existing two-lane rural roads, thus covering a much larger proportion of the roads in need of upgrading. Both international research,[1,2] and U.S. research and experience[3,4,5,6] have shown that the provision of passing lanes, turning lanes, localized alignment improvements, and other relatively low-cost measures can be highly cost-effective in improving both traffic operations and safety on existing two-lane rural roads. These options are also most appropriate for roads with lower traffic volumes which do not warrant major improvement projects and on recreational or other routes with high seasonal demand.

This report provides an evaluation of the operational effectiveness of passing lanes on two-lane highways in level and rolling terrain. The results of a simulation case study of passing lane improvements is presented in the Appendix. Further guidance on the use of passing lanes and other two-lane highway operational improvements such as turnouts, continuous paved shoulders, intersection turn lanes, shoulder bypass lanes at T-intersections, and two-way left-turn lanes is provided in the FHWA Informational Guide entitled, "Low-Cost Methods for Improving Traffic Operationals on Two-Lane Roads."[7]

2. PASSING LANES

A passing lane is an added lane provided in one or both directions of travel on a conventional two-lane highway to improve passing opportunities. This definition includes passing lanes in level or rolling terrain, climbing lanes on grades, and short four-lane sections. The length of the added lane can vary from 1,000 ft (305 m) to several miles. Figure 1 illustrates plan views of several typical passing lane sections. Figure 2 presents photographs of some typical examples of passing lanes. As illustrated in the photographs, passing lanes may be operated so that vehicles traveling in the opposite direction are either permitted to pass where sight distance is adequate or generally prohibited from passing.

Passing lanes are often constructed at regular intervals on two-lane highways to improve overall traffic operations by breaking up traffic platoons and reducing delays caused by inadequate passing opportunities over substantial lengths of highway. Passing lanes on a two-lane highway are often much more cost-effective than continuous four-laning for providing passing opportunities because locations with high construction costs (e.g., major earthwork, expensive structures) can be avoided.

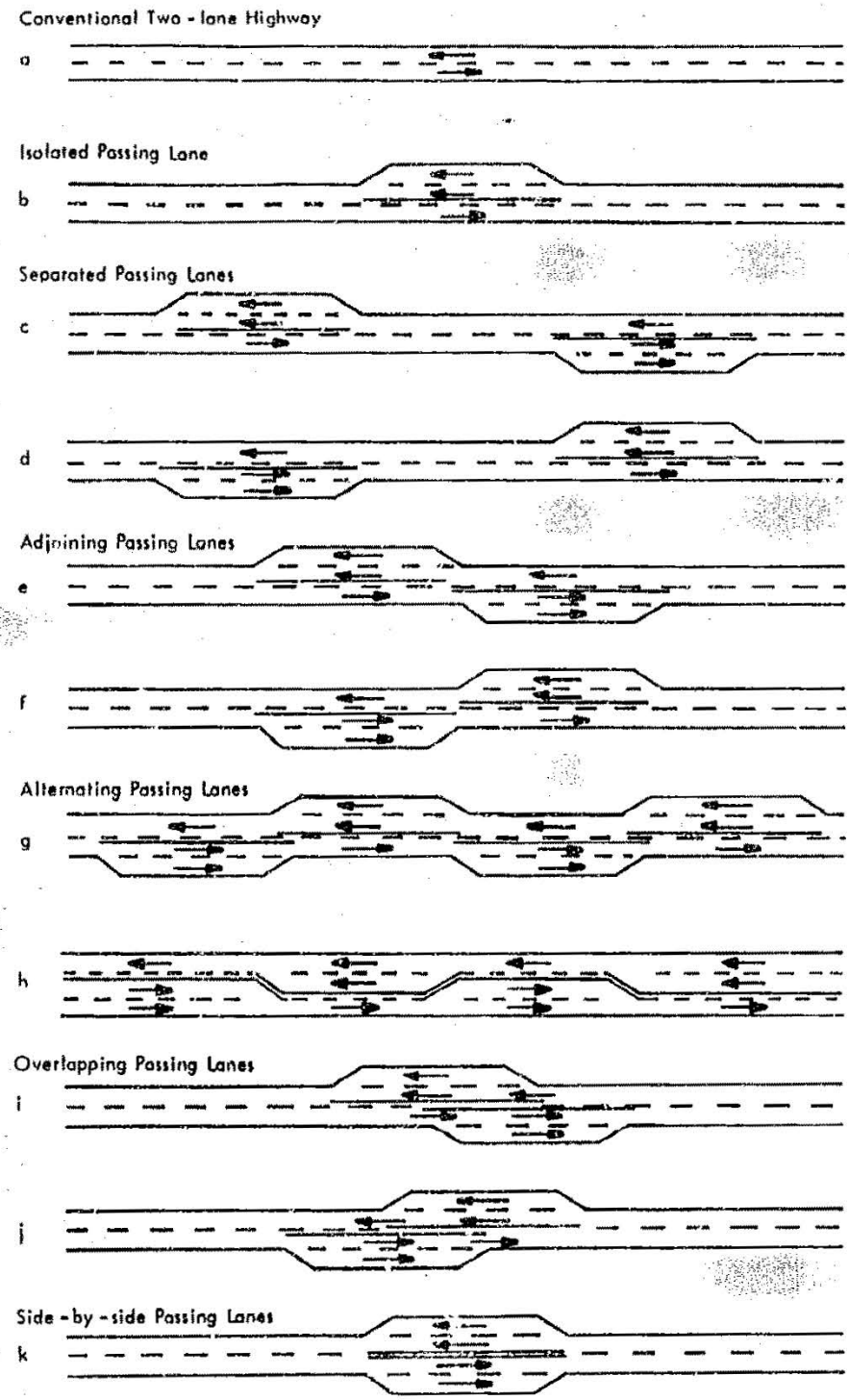
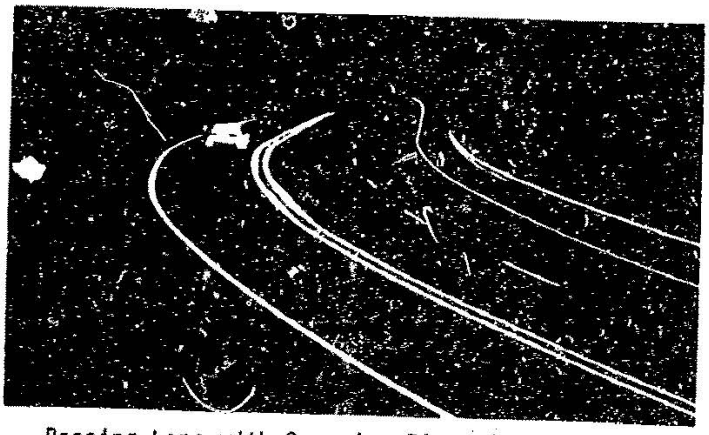


Figure 1 - Alternative Configurations for Passing Lanes[1]



Passing Lane with Opposing Direction Passing Prohibited

Passing Lane with Opposing Direction Passing Permitted

Passing Lanes in Both Direction (short four-lane section)

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Figure 2 - Typical Passing Lane and Short Four-Lane Sections Used on Two-Lane Highways

3. COMPUTER SIMULATION OF TRAFFIC OPERATIONS IN PASSING LANES

This section of the report discusses the computer simulation model, known as TWOPAS, developed to evaluate traffic operations in passing lanes on two-lane highways. The important features of the TWOPAS model are described and the model results are compared with fixed data.

3.1 Development of the TWOPAS Simulation Model

The TWOPAS computer simulation model is a modified version of TWOWAF simulation model that was used in the development of Chapter 8 of the 1985 HCM.[8,9]. However, TWOPAS has the added capability to simulate passing lanes on two-lane highways. The following features of TWOWAF were added or modified in the development of TWOPAS:

- Simulation of passing lane operations, including:
  - -- structural changes to incorporate passing lanes in either direction of travel at any location along the simulated road.
  - -- operation of the lane addition transition area so that the initial lane choice of a driver entering a passing lane reflects: the geometrics of the lane addition; the speed, performance capabilities, and size of the vehicle; and, the traffic situation at the time the vehicle approaches the lane addition. The lane choice probabilities are based on field data collected by Harwood and St. John.[3]
  - -- realistic lane changing with passing lane sections based on the lane changing behavior in multilane highway sections as represented in the multilane HILLCLIMB model.[10]
  - -- operation of the lane drop transition area based upon driver behavior at the lane drops of passing lane sections studied in the field.
  - -- passing maneuvers by opposing direction vehicles where those vehicles are permitted to pass.
- Generation of entering traffic headways based on the Borel-Tanner distribution for platoon sizes (used in the Australian TRARR model[11]) and the negative exponential distribution for interplatoon headways.
- Modification of the car-following model to mimic the KLD-Pitt car-following model used in TWOWAF without the large oscillations in vehicle acceleration and deceleration observed in that model.

- Modification of printed output to include operational data at up to 20 user-specified stations and 10 user-specified subsections on the simulated roadway.

A more detailed description of the model is provided in the TWOPAS User's Guide[12] and the TWOPAS Programmer's Guide.[13]

3.2 Comparison of the TWOPAS Model Results with Field Data

The original development of the TWOWAF model to simulate conventional two-lane hignways was based on traffic operational field data collected in NCHRP Project 3-19.[14] Its ability to realistically simulate two-lane highway traffic was validated against field data both in the original development and after its modification by KLD Associates for use in the 1985 HCM development.[3] In the current study, the simulation of conventional two-lane highways was accepted as valid, but further validation was performed to test the ability of the TWOPAS model to simulate the operational effects of passing lanes. This validation was performed through comparison of the traffic operational field data for passing lanes collected by Harwood and St. John to the results obtained from computer simulation of traffic operations at the same sites using the TWOPAS model.

Two field sites in Oregon were used for validation purposes. These sites are designated Sites R02 and R11; the site codes, locations, and characteristics are documented in the Harwood and St. John report.[3] Site R11 is a passing lane on a conventional two-lane highway, while Site R02 is a short four-lane section with passing lanes in both directions at the same location. Both validation sites are in level to moderately rolling terrain.

Two hours of traffic operations with slightly different traffic flow rates were simulated at each site. Two replicated runs with the TWOPAS model were made for each set of conditions tested. The simulation runs were each compared with averaged results for 2 or 3 hr of traffic operational field data for the same level of flow rate. The flow rate levels considered in the validation runs ranged from 150 to 500 veh/hr in each direction of travel.

Traffic platooning: The primary measure of effectiveness for the validation study was traffic platooning. The TWOPAS model provides both spot platooning measures (percentage of vehicles delayed in platoons, based on vehicle headways) and section platooning measures (e.g., percent time delay). However, the only measure of traffic platooning obtained in the field study was a spot platooning measure, the percentage of vehicles following in platoons at headways of 4 sec or less. Therefore, this measure was used in the validation study.

Figures 3 and 4 show excellent agreement between the simulation model and field measures of spot platooning both upstream and downstream of passing lanes. It should be noted that the spot platooning level at the entrance to the simulated roadway is specified in the user input data for

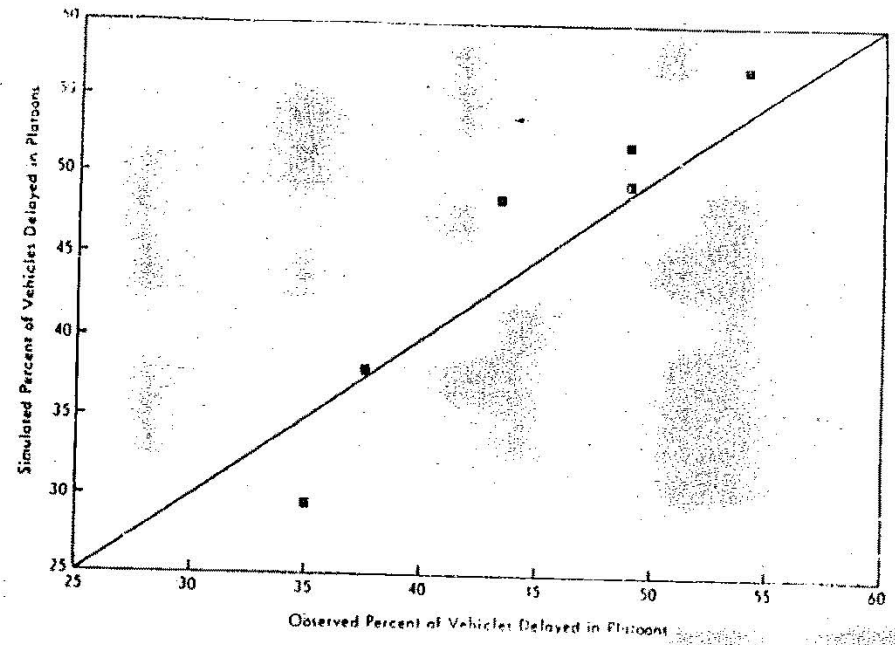


Figure 3 - Comparison of Simulation and Field Results for Percent of Vehicles Delayed in Platoons Upstream of a Passing Lane

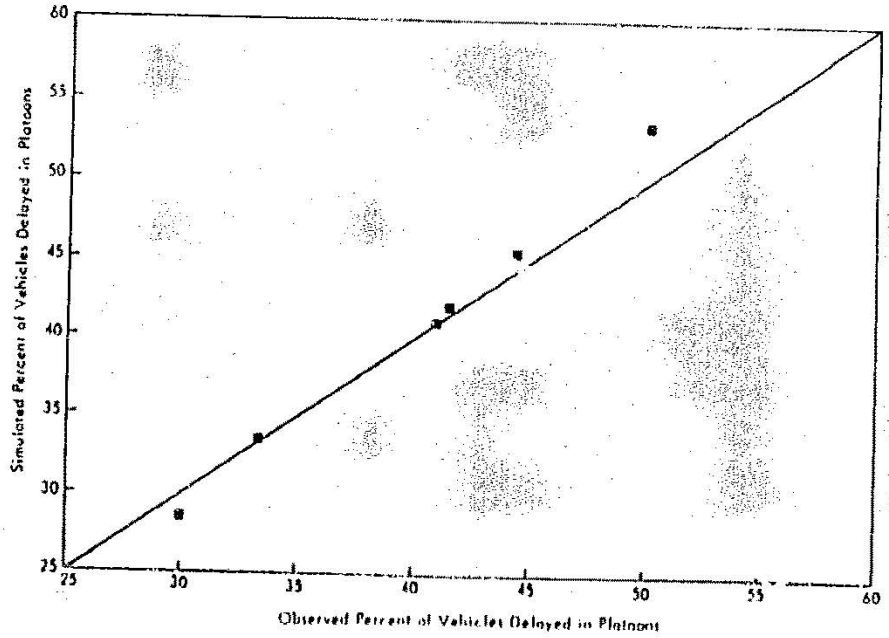


Figure 4 - Comparison of Simulation and Field Results for Percent of Vehicles Delayed in Platoons Downstream of a Passing Lane

the TWOPAS model and the beginning to the simulated roadway in the treated direction was located only 1,000 ft (300 m) upstream of the beginning of the passing lane. Thus, the good agreement between the simulation and field results in Figure 3 confirms the ability of the TWOPAS model to reproduce the specified input conditions.

The data in Figure 4 demonstrate that the TWOPAS model provides an extremely realistic representation of the effect of a passing lane on traffic platooning. This capability is the single most important model element for validation, since the 1985 HCM procedures for two-lane highways are based on traffic platooning as a measure of effectiveness.

The level of traffic platooning within a passing lane section also showed good agreement with field results. In general, the level of traffic platooning within a passing lane section is approximately one-half of the level of platooning upstream of the passing lane.

Traffic speed: Figure 5 illustrates the ability of the TWOPAS model to simulate traffic speeds. The figures present comparisons between simulated and field values of mean traffic speed for spot locations upstream of, within, and downstream of passing lanes.

The figure shows good agreement between the simulation and field results, since all of the plotted points lie relatively close to the diagonal line representing perfect agreement. Both simulation and field results show that average traffic speeds increase slightly within a passing lane section, indicating that TWOPAS corresponds well to observed traffic behavior.

Passing rate: Figure 6 presents a comparison of the simulation and field results for passing rates with passing lane sections. The passing rates are presented as the number of completed passes per hour per mile. The figure shows very poor agreement between the simulation and field results. Most of the plotted points lie well above the diagonal line in Figure 6, indicating that the simulated passing rates are much higher than the passing rates observed in the field. There is no obvious explanation for the poor agreement between model and field results for passing rates, but it appears that the model predictions for passing rates are not reliable. Further investigation of this aspect of the model is needed to assure that leap frog passes or some similar other instability are not producing artificially high passing rates. It is possible that the high passing rates result from a definitional problem within the TWOPAS model that counts multiple passes from the interactions of individual pairs of vehicles over short time periods. Nevertheless, this deficiency of the model does not appear to limit its ability to simulate the traffic platooning measures of primary importance on two-lane highways.

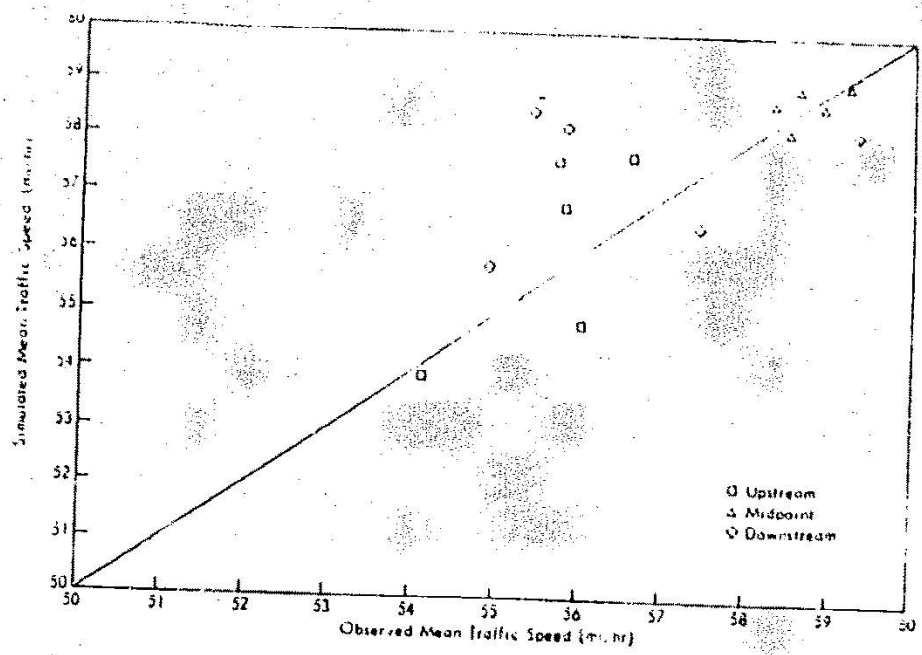


Figure 5 - Comparison of Simulation and Field Results for Mean Traffic Speeds

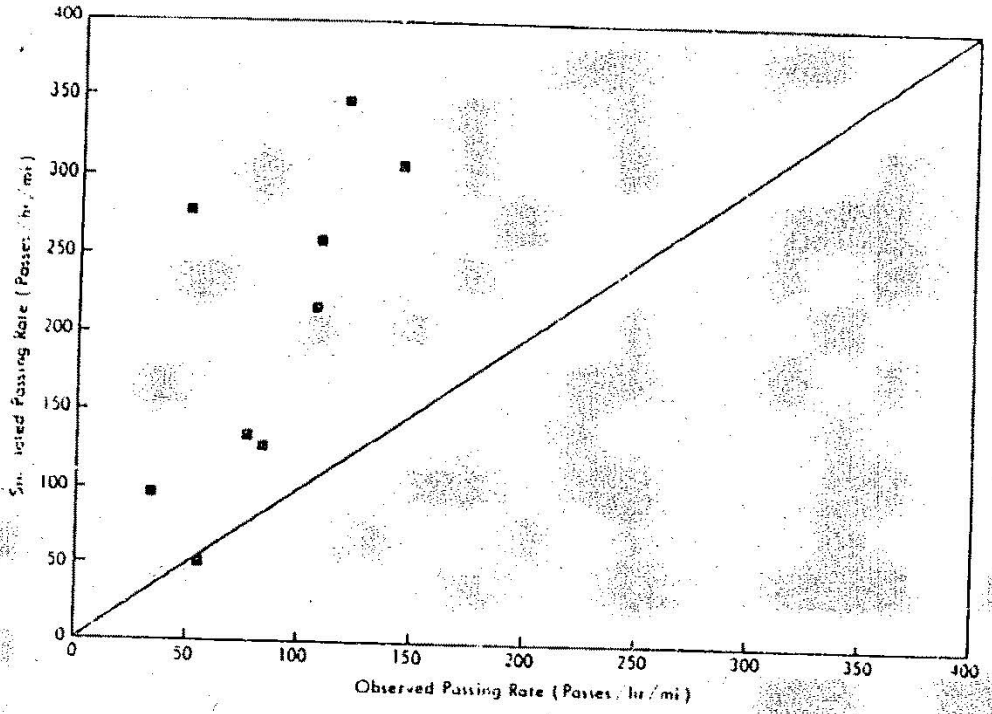


Figure 6 - Comparison of Simulation and Field Results for Passing Rate Within a Passing Lane

4. SIMULATED ROAD AND TRAFFIC CONDITIONS

This section of the report describes the simulated road and traffic conditions considered in the assessment of the operational effectiveness of passing lanes with the TWOPAS model.

4.1 Primary Experiment

The operational effectiveness of passing lanes was evaluated primarily from the results of 152 runs with the TWOPAS computer simulation model for an 8-mi road section with and without passing lanes. The road section used for the primary experiment was a hypothetical two-lane road in nearly level terrain with the characteristics shown in Table 1.

TABLE 1

CHARACTERISTICS OF ROAD SECTION USED IN PRIMARY EXPERIMENT

- 25 percent no-passing zones
- Nearly level terrain (maximum grade: ±1.5 percent)
- Moderate horizontal curvature
- Passing lane length: 0 (no passing lane); 0.25 mi; 0.50 mi; 0.75 mi; 1.00 mi; 1.50 mi; 2.00 mi
- Passing lane addition: no preference between right and left lanes
- Passing lane drop: right lane drop
- Flow rates: 100, 200, 400, and 700 veh/hr in each direction of travel
- Directional split: 50/50
- Vehicle mix: 5% trucks, 5% RVs
- Percentage of vehicles platooned upstream of passing lane: "average" (see Table 2)

Table 3 illustrates the distribution of the 56 simulation runs used for the primary experiment over the selected levels of passing lane length and flow rate. Two replicate runs were performed in each of the 26 cells shown in Table 3.

TABLE 2

UPSTREAM TRAFFIC PLATOONING LEVELS USED IN TWOPAS SIMULATION RUNS

Flow Rate[a] (veh/hr)	Upstream Platooning Level[b]		
	Low	Average	High
100	10	20	35
200	20	35	50
400	35	50	65
700	50	65	70

[a] In one direction of travel.
[b] Percentage of vehicles delayed in platoons upstream of passing lane.

TABLE 3

DISTRIBUTION OF TWOPAS SIMULATION RUNS FOR PRIMARY EXPERIMENT IN CELLS DEFINED BY FLOW RATE AND PASSING LANE LENGTH

Passing Lane Length (mi)	NUMBER OF SIMULATION RUNS				TOTALS
	One-Way Flow Rate (veh/hr)				
	100	200	400	700	
Conventional Two-Lane	2	2	2	2	8
0.25	2	2	2	2	8
0.50	2	2	2	2	8
1.75	2	2	2	2	8
1.00	2		2	2	8
1.30	2	2	2	2	8
2.00	2	2	2	2	8
TOTALS	14	14	14	14	56

Note: 1 mi = 1.609 km

4.2 Supplementary Studies

Three supplementary sets of simulation runs were performed. The first set of supplementary runs was used to evaluate the operational effect of variations in the level of traffic platooning upstream of a passing lane. The primary variables in this evaluation were upstream platooning level and flow rate. The upstream platooning level was defined as low, average, or high as a function of flow rate based on the criteria shown in Table 2. The same four levels of flow rate considered in the primary experiment were evaluated in the supplementary studies: 100, 200, 400, and 700 veh/hr in each direction of travel. The supplementary studies evaluated only two of the seven levels of passing lane length considered in the basic runs: 0 (conventional two-lane highway) and 1.00 mi. Two replicate runs were performed for each condition studied.

A second set of supplementary simulation runs were performed to investigate the effect of vehicle mix on the operational effectiveness of passing lanes. The primary experiment was performed with a vehicle mix including 10 percent heavy vehicles: 5 percent trucks and 5 percent recreational vehicles (RVs). A set of supplementary runs was performed to compare the primary runs for conventional two-lane highways and 1.0-mi (1.6-km) passing lanes to identical geometric situations with two contrasting vehicle mixes: 5 percent trucks and 20 percent RVs; and, 20 percent trucks and 5 percent RVs.

Finally, a third set of supplementary runs runs was performed to determine the effect of differences in terrain on the operational effectiveness of passing lanes. The runs for the primary experiment were made in nearly level terrain with maximum grades of ±1.5 percent. Additional runs were made to compare selected runs from the primary experiment to the identical highway with the grades increased to ±4 percent to produce rolling terrain.

4.3 Measures of Effectiveness

The primary measures of effectiveness were used in this study to assess the operational benefits of passing lanes on two-lane highways were traffic speed and traffic platooning. Field studies generally provide spot measures of traffic speed and vehicle platooning. An advantage of the evaluation of passing lanes with a computer simulation model is that measures of traffic speed and vehicle platooning over a highway section can also be obtained, and section measures of this type are generally used in capacity and level of service evaluations.

The measure of traffic platooning used in this study and also in the 1985 HCM procedure for two-lane highways is the percent of time vehicles are delayed by other traffic. The percent time delay is the proportion of total travel time represented by vehicles which are following in platoons.

The percent time delay for a highway section can be determined from the output of the TWOPAS computer simulation model. During traffic

simulation, the model "reviews" the position and trajectory of each vehicle at 1-sec intervals, selects a new speed for the vehicle based on vehicle, driver, and traffic characteristics, and advances the vehicle accordingly. Percent time delay is determined in the model for all vehicles within a specified highway section as the percentage of vehicle reviews where the vehicle reviewed is following so closely behind another vehicle that its speed selection is constrained by that vehicle.

The percent time delay can be approximated in field studies by counting the percentage of vehicles traveling at headways of 5 sec or less at a given point on the road. This 5 sec headway criterion is recommended in the 1985 HCM.[8] Other researchers have recommended various headway criteria for platooning, with the majority of recommendations being between 4 and 6 sec.[3,9,15,16] Theoretically, the probability of platooning at a given spot on the highway is proportional to the percent distance delayed, rather than to the percent time delayed. Since a vehicle travels farther in a given time when unimpeded than when following another vehicle, spot measures will always underestimate the percent time delayed. Consider, for example, a vehicle which travels 5 miles at its free speed of 60 mi/hr (time = 5 min) and 5 miles at a following speed of 50 mi/hr (time = 6 min). This vehicle spends 50 percent of its travel distance delayed in platoons, but its percent time delayed is 54.5 (6/11*100). Spot field measures will tend to reflect the lower value.

Two measures of spot platooning are available on the TWOPAS output for user-specified sections. The first measure is the spot equivalent of percent time delay (or its complement, percent unimpeded); this measure is the percentage of vehicles passing a selected highway location that are following so closely that their speed selection is constrained by the leading vehicle. The second measure is the percentage of vehicles following in platoons based on a 4 sec headway criterion. The first measure described above was chosen as the measure of spot platooning for the passing lane effectiveness analyses presented below in Section 5 because: (1) it was more sensitive to the presence of a passing lane than the second measure; (2) it produced statistical models of the operational effectiveness of passing lanes (see Section 5.4) with higher correlation coefficients than the second measure; and (3) it is consistent with the definition of percent time delay used in the 1985 HCM.

5. OPERATIONAL EFFECTIVENESS OF PASSING LANES

The assessment of the operational effectiveness of passing lanes based on the TWOPAS model results is presented in the following discussion. The primary assessment of passing lane effectiveness is provided in a discussion of passing lane effectiveness over an extended road length, including both the passing lane itself and the downstream section of conventional

two-lane highway where traffic operations are strongly affected by the passing lane. The determination of the effective length of a passing lane, including this downstream portion, is then discussed. The determination of optimum design length for the passing lane itself is illustrated based on a cost-effectiveness analysis. Finally, a procedure for predicting changes in spot platooning over the length of a passing lane is presented.

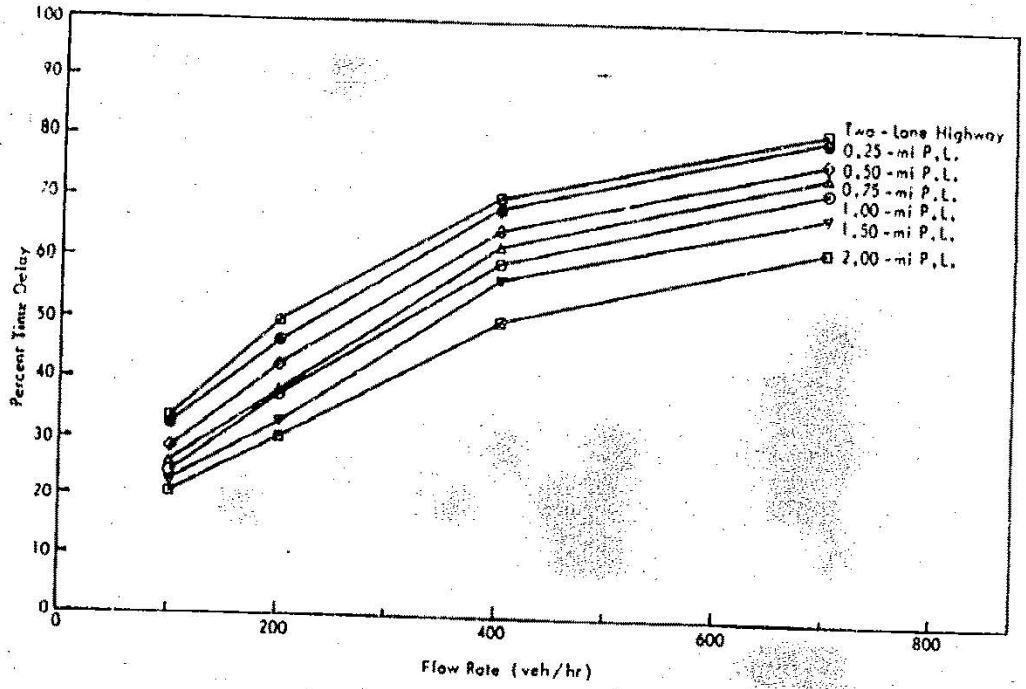
5.1 Travel Speed and Percent Time Delay Over an Extended Road Length

Figure 7 illustrates the effectiveness of passing lanes of various lengths in improving traffic operations on two-lane highways. Figure 7 is based on results obtained with the TWOPAS simulation model for the 56 runs for the primary experiment identified in Table 3.

The curves presented in Figure 7, for passing lanes of varying lengths, represent their effectiveness in increasing traffic speeds and decreasing the percent of time vehicles spend delayed in platoons on a two-lane highway in moderately rolling terrain. The vehicle speed and platooning measures in Figure 7 are averages over an 8-mi (13-km) highway section with the passing lane located at the beginning; thus, these curves represent the combined effects of improved traffic operations in the passing lane and downstream of the passing lane. Figure 7 illustrates that passing lanes produce relatively small increases in vehicle speeds, but can dramatically decrease vehicle platooning. Further simulation of passing lanes with the TWOPAS model has enabled the development of the predictive equations for passing lane effectiveness presented below.

5.2 Downstream Effect of a Passing Lane

Figure 8 illustrates the downstream effects of passing lanes of various lengths on vehicle platooning for flow rates of 400 and 700 veh/hr in each directon of travel. Figure 8 is based on the same TWOPAS simulation runs as Figure 7 for the flow rates considered. However, Figure 8 presents the percentage of vehicles delayed in platoons at specific spot locations on the highway, as opposed to Figure 7, which is based on the percentage of time vehicles are platooned over a section of highway. For a flow rate of 400 veh/hr, the effects of passing lanes can still be substantial 7 mi (11 km) downstream of the beginning of the passing lane, especially for longer passing lanes. At the higher flow rate of 700 veh/hr, nearly all of the operational benefits of the passing lane are gone within 5 mi (8 km), although there is a small residual effect even at 7 mi (11 km) downstream. The length of the passing lane has a strong influence on the improvement in traffic operations immediately downstream of the passing lane, but this differential between passing lane lengths largely disappears further downstream.



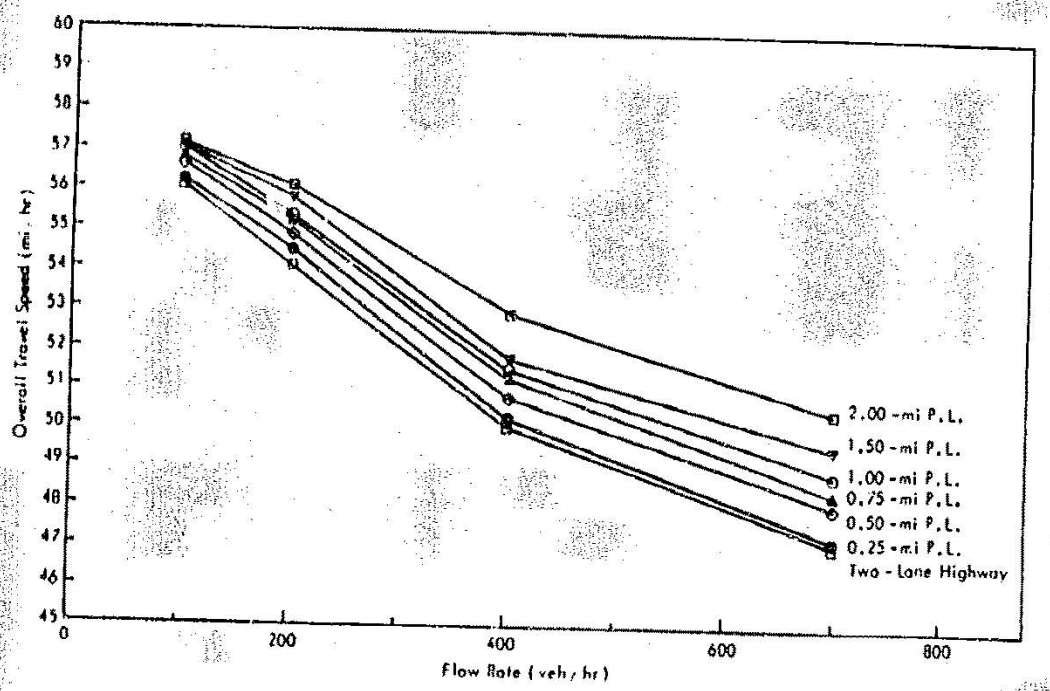
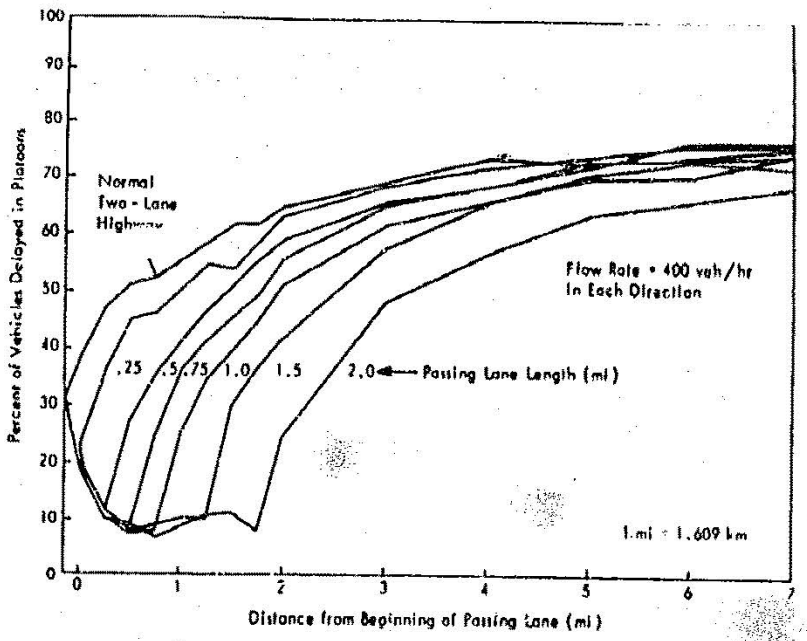


Figure 7 - Computer Simulation Results for Operational Effectiveness of Passing Lanes



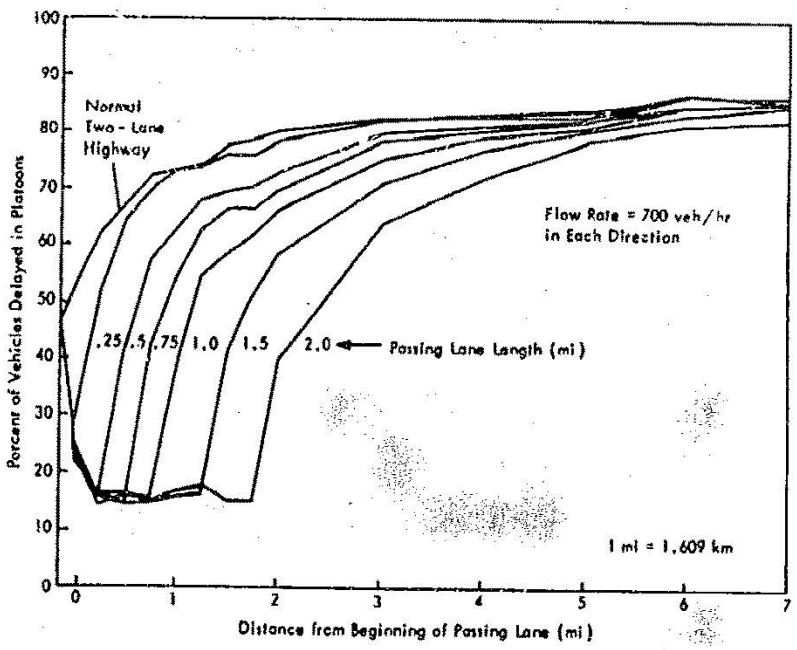


Figure 8 - Gradual Increase in Percentage of Vehicles Delayed in Platoons Downstream of Passing Lanes

5.3 Concept of Effective Length of a Passing Lane

The "effective length" of a passing lane includes both the passing lane itself and the downstream section of two-lane highway where platooning is lower than it would have been without the passing lane. Table 4 presents the estimated reductions in percent time delay for three different effective lengths -- 3, 5, and 8 mi (5, 8, and 13 km) -- as well as for different lengths of passing lane. The data in Table 4 for an effective length of 8 mi (13 km) are based directly on the results obtained from the TWOPAS model. The data for effective lengths of 3 and 5 mi (5 and 8 km) are estimates of the percent time delay that would be required within the effective length of the passing lane to produce the observed simulation results for the 8 mi (13 km) section. The estimates were based on the assumption that, if the effective length of a passing lane is 5 mi (8 km), then the percent time delay in the highway section between 5 and 8 mi (8 and 13 km) downstream of the beginning of the passing lane will be the same as the values tabulated in Table 4 for a conventional two-lane highway with no passing lane. The percent time delay for an effective length (L) other than 8 mi (13 km) can be estimated with the following equation:

$$PTD_L = \frac{(8)(PTD_8) - (8-L)(PTD_o)}{L} \qquad (1)$$

where: PTD_L = Percent time delay for an 8-mi (13-km) section containing a passing lane with an effective length of L.

PTD_8 = Percent time delay for an 8-mi (13-km) section containing a passing lane with an effective length of 8 mi (13 km).

PTD_o = Percent time delay for an 8-mi (13-km) section of conventional two-lane highway without passing lanes (i.e., the column of Table 4 for a passing lane length of zero).

L = Effective length of passing lane (mi).

The percent time delay for passing lanes in Table 4 is limited to a minimum of half of the percent time delay of a two-lane highway at the same flow rate.

It should be noted that the base values of percent time delay for a normal two-lane highway in Table 4 are significantly higher than those specified in the HCM for ideal conditions. This is because the simulated results were derived for non-ideal conditions of terrain, no-passing zones, and traffic composition. Since these conditions can vary from one case to another, it is recommended that Table 4 be entered using a given base value of percent time delay, rather than the traffic flow. In other words, the estimated two-lane highway percent time delay should be used to select the appropriate row of Table 4, regardless of traffic flow. Linear interpolation in Table 4 is acceptable.

TABLE 4

EFFECT OF PASSING LANES ON PERCENT TIME DELAY OVER AN EXTENDED ROAD LENGTH

One-Way Flow Rate (veh/hr)	PERCENT TIME DELAY						
	Passing Lane Length (mi)						
	0[a]	0.25	0.50	0.75	1.00	1.50	2.00
Effective Length = 0 mi[b]							
100	33	32	28	26	24	22	20
200	50	46	42	38	37	33	30
400	70	69	65	62	60	57	50
700	82	81	77	75	72	68	63
Effective Length = 5 mi							
100	33	31	25	22	19	17	17
200	50	44	37	31	29	25	25
400	70	68	62	57	54	49	38
700	82	80	74	71	66	60	52
Effective Length = 3 mi							
100	33	30	20	17	17	17	17
200	50	39	29	25	25	25	25
400	70	67	57	49	43	35	35
700	82	79	69	63	55	45	41

a/ Conventional two-lane highway with no passing lane
b/ As plotted in Figure 5

Note: 1 mi = 1.609 km

The results in Figure 8 indicate that the effective length of a passing lane could vary from 3 to 8 mi (5 to 13 km) depending on passing lane length, traffic flow and composition. Geometric and traffic control features of the downstream roadway that restrict passing opportunities and encourage formation of platoons, such as steep grades, narrow lanes, and no-passing zones, may reduce the effective length of a passing lane.

The concept of effective length is used for analysis purposes in Table 4 to determine the overall effect of a passing lane on level of service over an extended highway section. For most cases, effective length can be estimated from Figure 8, with adjustments for factors which might hasten or slow the downstream overtaking or catch-up process. If the two-lane highway downstream of the passing lane has few passing opportunities, for example, the effective length determined from Figure 8 should be reduced.

In some cases, the effective length of a passing lane is constrained by other road features, such as small towns, four-lane sections, or additional passing lanes a few miles downstream. In these situations, the distance to the downstream constraint should be used as the effective length for analysis purposes, if this is less than that estimated from Figure 8.

5.4 Optimal Design Length for Passing Lanes

The optimal design length for a passing lane can be determined through a cost-effectiveness analysis. This can be illustrated by the cost-effectiveness data in Table 5. This table presents the percent time delay over an effective length of 8 mi (13 km) for passing lanes of various design lengths, the difference between the percent time delay for each design length and a conventional two-lane highway, and the ratio of this difference to the design length. This ratio represents the effectiveness of passing lanes in reducing vehicle platooning per unit length. The use of design length in the denominator of the cost-effectiveness ratio represents the cost of constructing passing lanes, which can vary widely depending on terrain. The passing lane lengths used to compute the cost-effectiveness ratios in Table 5 have been increased by 600 ft (180 m), half of the combined length of typical lane addition and lane drop tapers, to account for the cost of constructing these transition areas.

Table 5 shows that for flow rates of 200 veh/hr or less in one direction of travel, the highest cost-effectiveness per unit length is obtained for passing lanes with design lengths between 0.5 and 0.75 mi (0.8 and 1.2 km). Passing lanes shorter than 0.5 mi (0.8 km) or longer than 0.75 mi (1.2 km) are not as desirable because they provide less operational benefit per unit length.

As flow rate increases above 200 veh/hr, the optimal design length for a passing lane also increases. At a flow rate of 400 veh/hr in one direction of travel, the optimal design length for a passing lane is 0.75 to 1.0 mi (1.2 to 1.6 km). At very high flow rates, such as 700 veh/hr in one direction of travel, the optimal design length of passing lanes ranges from 1.0 to 2.0 mi (1.6 to 3.2 km). However, the use of passing lanes longer than 1.0 mi (1.6 km) in length may not be desirable, even for highways with peak flow rates of 700 veh/hr in one direction of travel, because longer passing lanes would be suboptimal throughout the remainder of the day when traffic volumes are lower.

Cost-effectiveness analysis indicates that short passing lanes are usually more effective per unit length, and therefore per dollar spent on construction, than long passing lanes. Thus, the overall level of service on a highway can often be improved more by constructing three 0.5-mi (0.8-km) passing lanes spaced at intervals than by constructing one 2-mi (3.2-km) passing lane. The optimal design length for passing lanes on a specific section of two-lane highway should be based on the highest hourly flow rate that occurs frequently (e.g., on a daily basis) on that specific highway section. The design hour volume, which occurs in only a few hours out of each year, may be too high to serve as the basis for the choice of a cost-effective passing lane length.

TABLE 5

EFFECTIVENESS OF PASSING LANES PER UNIT LENGTH IN REDUCING PERCENT TIME DELAY

Passing Lane Length (mi)	Percent Time Delayed a/	Reduction from Conventional Two-Lane Highway	Reduction Per Unit Length of Passing Lane b/
FLOW RATE = 100 veh/hr			
None	33	—	—
0.25	32	1	2.8
0.50	28	5	8.2
0.75	26	7	8.1
1.00	24	9	8.1
1.50	22	11	6.8
2.00	20	13	6.2
FLOW RATE = 200 veh/hr			
None	50	—	—
0.25	46	4	11.1
0.50	42	8	13.1
0.75	38	12	14.0
1.00	37	13	11.7
1.50	33	17	10.6
2.00	30	20	9.5
FLOW RATE = 400 veh/hr			
None	70	—	—
0.25	69	1	2.8
0.50	65	5	8.2
0.75	62	8	13.1
1.00	60	10	9.0
1.50	57	13	8.1
2.00	50	20	9.5
FLOW RATE = 700 veh/hr			
None	82	—	—
0.25	81	1	2.8
0.50	77	5	8.2
0.75	75	7	8.1
1.00	72	10	9.0
1.50	68	14	8.7
2.00	63	19	9.0

a/ Based on effective length of 8 mi

b/ Unit length increased by 600 ft. to account for cost of constructing lane addition and lane drop tapers

Note: 1 mi = 1.609 km
1 ft. = 0.305 m

5.5 Changes in Spot Platooning Over the Length of a Passing lane

The effectiveness of a passing lane in improving traffic operations on a two-lane highway was also assessed by using the TWOPAS model to compare the percentage of vehicles delayed in platoons at a spot location immediately downstream of a passing lane with the percentage of vehicles that would have been delayed in platoons at the same location had the passing lane not been present. If the traffic flow on a conventional two-lane highway in level or moderately rolling terrain has reached an equilibrium condition, the percentage of vehicles delayed in platoons will not change markedly over a relatively short length of highway, so the comparison described above is roughly equivalent to a comparison between the percentage of vehicles delayed in platoons at spot locations upstream and downstream of a passing lane.

Effect of passing lane length and flow rate: A model was desired to predict the passing lane effectiveness as a function of design length and flow rate. A preliminary examination of the results of the 56 simulation runs with the TWOPAS model for the primary experiment (identified in Table 3) produced the results shown in Figure 9. The effectiveness of a passing lane in reducing vehicle platooning was found to increase with increasing passing lane length; however, the slope of the relationship between platooning reduction effectiveness and passing lane length, shown in the upper portion of Figure 9, decreases with increasing length. This finding confirms the hypothesis developed in earlier research by Harwood and St. John[3] that the effect of passing lane length on traffic platooning is nonlinear. The relationship between platooning reduction effectiveness and passing lane length illustrated in Figure 9 was found to be best explained in statistical models by a logarithmic transform of the passing lane length.

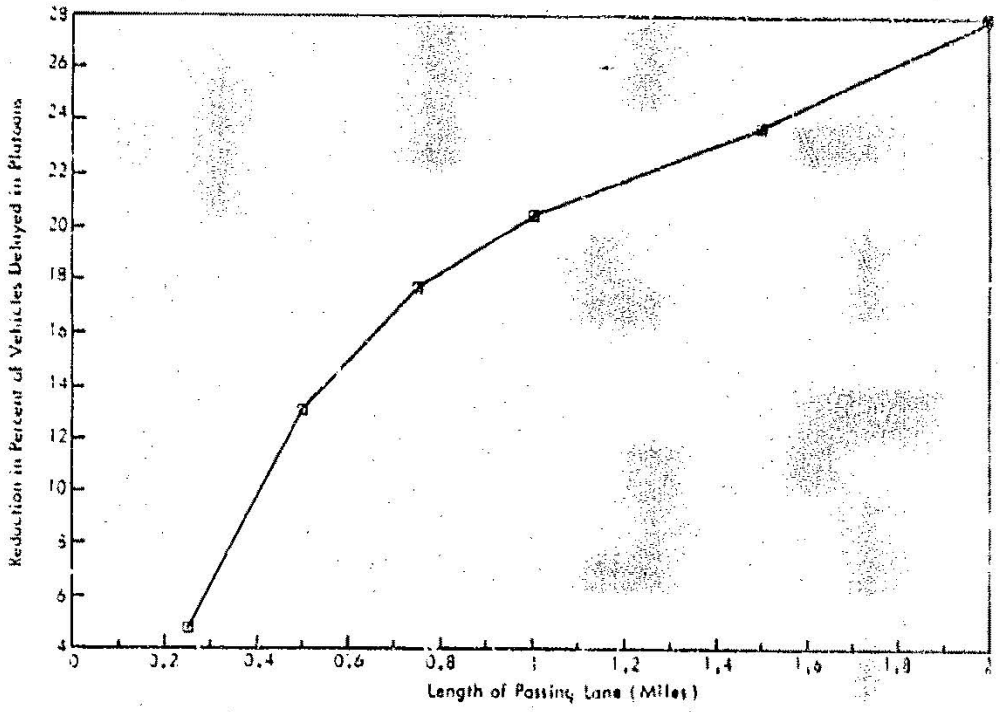
As illustrated in the lower portion of Figure 9, platooning reduction effectiveness tends to increase with flow rate at low volumes and decrease with flow rate at high volumes. This effect was found to be best explained in statistical models by the linear sum of two terms, one term representing the flow rate and a second term representing the reciprocal of the flow rate.

The following multiple regression model was found to best represent the combined effects of passing lane length and flow rate on platooning reduction effectiveness:

$$RPD = 34.2 + 10.8 \ln (LEN) - 0.0153\ FLOW - \frac{1800}{FLOW} \qquad (2)$$

where,

RPD = reduction in percentage of vehicles delayed in platoons due to the passing lane;
LEN = length of passing lane not including tapers (mi);
FLOW = flow rate in one direction of travel (veh/hr).



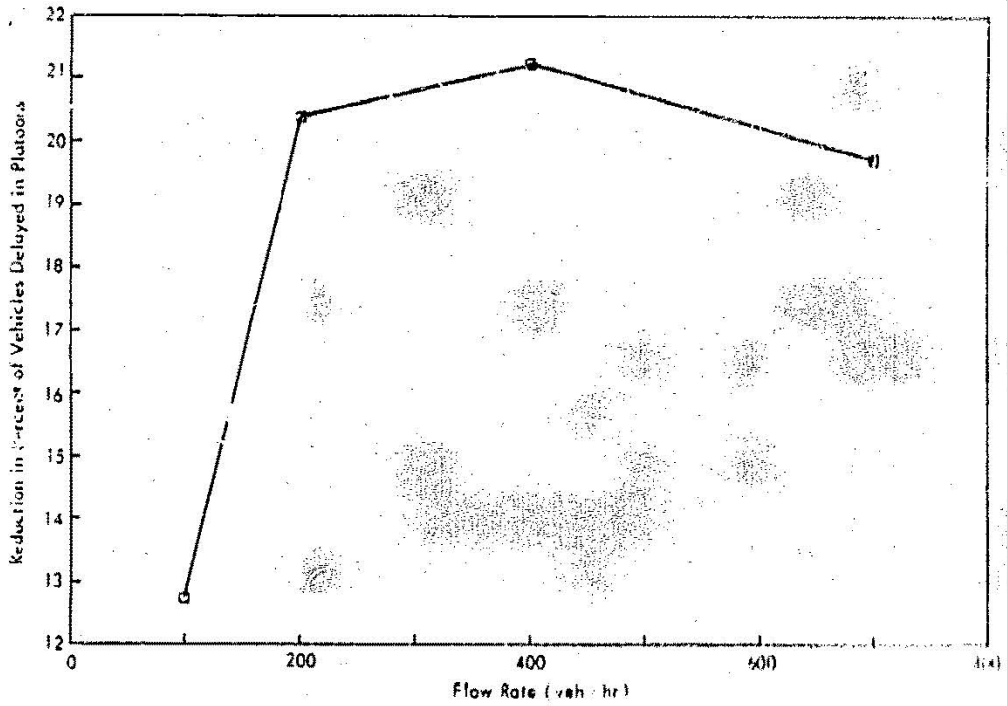


Figure 9 - Effect of Passing Lane Length and Flow Rate on Operational Effectiveness of Passing Lanes

The model presented in Equation (2) explains 90 percent of the variation in platooning reduction effectiveness (i.e., $R^2 = 0.90$).

Effect of upstream platooning: The percent of vehicles platooned on the conventional two-lane highway upstream of a passing lane represents the upstream level of service. A set of supplementary runs were conducted with the TWOPAS model to determine the effect of the level platooning upstream of a passing lane on its platooning reduction effectiveness. The results of these runs indicate that platooning reduction effectiveness increases with upstream platooning at low flow rates and decreases with upstream platooning at high flow rates. This effect was incorporated in a regression model of the combined effects of passing lane length, flow rate, and upstream platooning on the platooning reduction effectiveness of a passing lane:

$$RPD = -6.84 + 10.9\,\ell n\,(LEN) + 0.0823\,FLOW - \frac{471}{FLOW} + 9.59\,\ell n(PUD) - 0.0247\,FLOW*\ell n(PUD) \qquad (3)$$

where,

PUD = percentage of vehicle delayed in platoons upstream of passing lane;

and the other variables are as defined above.

The model presented in Equation (3) explains 89 percent of the variance in platooning reduction effectiveness (i.e., $R^2 = 0.89$). The multiplicity of terms in the model illustrates the complexity of the relationships and interactions that influence the effectiveness of passing lanes. Equation (3) is valid for the range of passing lane lengths from 0.25 to 2.00 mi (0.4 to 3.2 km), for the range of flow rates from 100 to 700 veh/hr, and for the range of upstream percentage of vehicles delayed in platoons from 20 to 70 percent. Equation (3) can be used for passing lanes on highways with up to 25 percent heavy vehicles in the traffic stream in level, moderately rolling, or severely rolling terrain. However, Equation (3) is not applicable to climbing lanes in mountainous terrain.

Table 6, which is based directly on Equation (3), provides a more convenient method to determine the effectiveness of passing lanes in reducing vehicle platooning. When entered with appropriate values for the length of a passing lane, the flow rate and the upstream percentage of vehicles delayed, Table 6 indicates the percent reduction in vehicle platooning resulting from immediately upstream to immediately downstream of a passing lane. Table 6 incorporates the assumption that the percentage of traffic delayed in platoons downstream of a passing lane will always be at least 10 percent. Linear interpolation in Table 6 is acceptable.

TABLE 6 -

REDUCTION IN PERCENTAGE OF VEHICLES DELAYED IN PLATOONS DUE TO PASSING LANE INSTALLATION

One-Way Flow Rate (Veh/Hr)	PASSING LANE LENGTH (MILES) 3/							
	.25	.50	.75	1.00	1.25	1.50	1.75	2.00
UPSTREAM: 20% DELAYED								
100	2.9	10.0	10.0	10.0	10.0	10.0	10.0	10.0
200	6.1	10.0	10.0	10.0	10.0	10.0	10.0	10.0
300	7.7	10.0	10.0	10.0	10.0	10.0	10.0	10.0
400	8.9	10.0	10.0	10.0	10.0	10.0	10.0	10.0
UPSTREAM: 30% DELAYED								
100	5.8	13.3	17.8	20.0	20.0	20.0	20.0	20.0
200	8.0	15.5	19.9	20.0	20.0	20.0	20.0	20.0
300	8.6	16.1	20.0	20.0	20.0	20.0	20.0	20.0
400	8.8	16.4	20.0	20.0	20.0	20.0	20.0	20.0
500	8.9	16.4	20.0	20.0	20.0	20.0	20.0	20.0
600	8.9	16.4	20.0	20.0	20.0	20.0	20.0	20.0
700	8.8	16.4	20.0	20.0	20.0	20.0	20.0	20.0
UPSTREAM: 40% DELAYED								
100	7.8	15.4	19.8	22.9	25.4	27.4	29.0	30.0
200	9.3	16.9	21.3	24.4	26.9	28.8	30.0	30.0
300	9.2	16.8	21.2	24.3	26.8	28.7	30.0	30.0
400	8.7	16.3	20.7	23.8	26.3	28.3	29.9	30.0
500	8.1	15.6	20.1	23.2	25.6	27.6	29.3	30.0
600	7.4	14.9	19.3	22.5	24.9	26.9	28.6	30.0
700	6.6	14.1	18.6	21.7	24.1	26.1	27.8	29.2
UPSTREAM: 50% DELAYED								
100	9.4	17.0	21.4	24.5	27.0	29.0	30.6	32.1
200	10.3	17.9	22.3	25.5	27.9	29.9	31.6	33.0
300	9.7	17.3	21.7	24.8	27.2	29.[illegible]	30.9	32.4
400	8.7	16.2	20.6	23.8	26.2	28.[illegible]	29.9	31.3
500	7.5	15.0	19.4	22.6	25.0	27.[illegible]	28.7	30.1
600	6.2	13.7	18.2	21.3	23.7	25.[illegible]	27.4	28.9
700	4.9	12.4	16.8	20.0	22.4	24.4	26.1	27.5
UPSTREAM: 60% DELAYED								
100	10.7	18.3	22.7	25.8	28.3	30.3	31.9	33.4
200	11.2	18.7	23.2	26.3	28.7	30.7	32.4	33.9
300	10.1	17.7	22.1	25.2	27.6	29.6	31.3	32.8
400	8.6	16.2	20.6	23.7	26.1	28.1	29.8	31.3
500	7.0	14.5	18.9	22.1	24.5	26.5	28.2	29.6
600	5.2	12.8	17.2	20.3	22.8	24.8	26.4	27.9
700	3.5	11.0	15.4	18.6	21.0	23.0	24.7	26.1
UPSTREAM: 70% DELAYED								
100	11.8	19.4	23.8	26.9	29.4	31.3	33.0	34.5
200	11.9	19.5	23.9	27.0	29.5	31.4	33.1	34.6
300	10.4	18.0	22.4	25.5	28.0	30.0	31.6	33.1
400	8.6	16.1	20.5	23.7	26.1	28.1	29.8	31.2
500	6.5	14.1	18.5	21.6	24.1	26.1	27.7	29.2
600	4.4	12.0	16.4	19.5	22.0	24.0	25.5	27.1
700	2.3	9.8	14.2	17.4	19.8	21.8	23.5	24.9

Note: 1 mi = 1.609 km

3/ Passing Lane Length Not Including Length of Lane Addition and Lane Drop

Effect of vehicle mix: An investigation of the effect of vehicle mix on the platooning reduction effectiveness of passing lanes was conducted using the results from the supplementary simulation runs described in Section 4.2. These runs considered the operational effects of three alternative vehicle mixes: (1) 5 percent trucks and 5 percent recreational vehicles (RVs), the vehicle mix on which Equations (2) and (3) are based; (2) 5 percent trucks and 20 percent RVs; and (3) 20 percent trucks and 5 percent RVs.

The effect of the different vehicle mixes on passing lane effectiveness over a range of flow rates is illustrated in Figure 10. There is no consistent trend in the vehicle mix effect. A regression analysis found no statistically significant effect of vehicle mix on platooning reduction effectiveness. Therefore, the findings represented by Equations (2) and (3), based on 10 percent heavy vehicles in the traffic stream, are presumed to be applicable to a range of vehicle mixes with up to 25 heavy vehicles in the traffic stream.

Effect of terrain: A similar analysis to that for vehicle mix was conducted to determine whether terrain has an effect on the platooning reduction effectiveness of passing lanes using results from the supplementary simulation runs described in Section 4.2. The terrains considered were nearly level terrain with ±1.5 percent grades used in the development of Equations (2) and (3) and more severely rolling terrain with ±4 percent grades.

The effect of the different terrains on passing lane effectiveness over a range of flow rates is illustrated in Figure 11. The differences between the operational effects of the two terrain types illustrated in Figure 11 are minimal and there is no consistent trend. A regression analysis found no statistically significant effect of vehicle mix on platooning reduction effectiveness. Therefore, the findings represented in Equations (2) and (3) based on moderately rolling terrain are presumed to be applicable to a range of terrain from level through severely rolling.

6. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions can be drawn from the research findings presented in this report:

1. The findings of this study confirm the findings of previous research that traffic platooning measures are more sensitive to flow rate on two-lane highways than traffic speed measures. Furthermore, traffic platooning measures were also found to be more sensitive to the presence of a passing lane than traffic speed measures. These findings confirm the choice of a traffic platooning measure, percent time delay, as the level of service criterion for two-lane highways in Chapter 8 of the 1985 HCM.

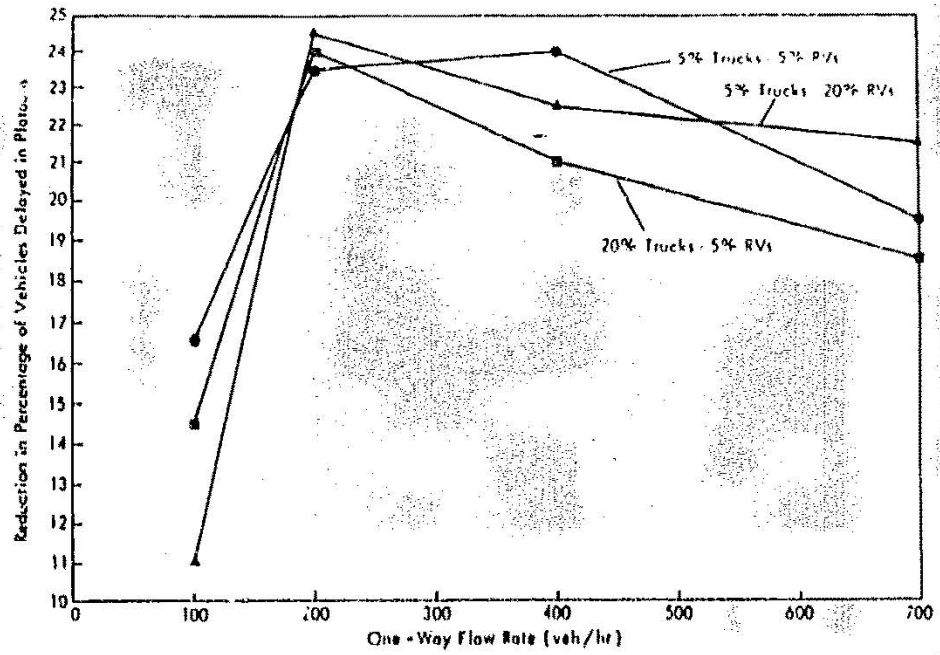


Figure 10 - Comparison of Effect of Vehicle Mix on Platooning Reduction Effectiveness of Passing Lanes Over a Range of Flow Rates

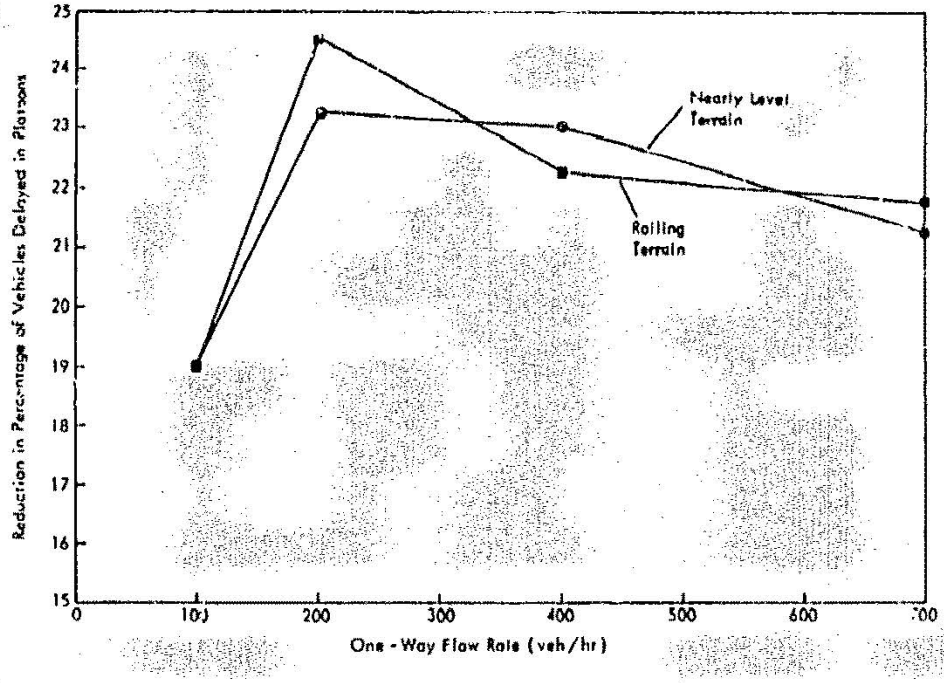


Figure 11 - Comparison of Effect of Terrain on Platooning Reduction Effectiveness of Passing Lanes Over a Range of Flow Rates

2. Passing lanes are effective in improving the level of service and reducing the percent time delay on two-lane highways by providing passing opportunities and breaking up traffic platoons.

3. The effectiveness of passing lanes in reducing percent time delay on two-lane highways can be determined from Table 4 of this report as a function of traffic flow rate and passing lane length.

4. Passing lanes provide traffic operational benefits on two-lane highways over an effective length from 3 to 8 mi (5 to 13 km). This effective length includes both the passing lane itself and a portion of the conventional two-lane highway downstream of the passing lane. The effective length of a passing lane is primarily a function of flow rate, with shorter effective lengths at higher flow rates. Other geometric and traffic control features that encourage the formation of platoons, such as steep grades, narrow lanes, and no-passing zones may also reduce the effective length of a passing lane.

5. Short passing lanes are generally more highly utilized and more cost-effective per unit length in improving traffic performance than extended sections of four-lane highway for two reasons. First, the traffic entering the passing lane from a normal two-lane section is more highly platooned, and thus "primed" to make the most of the extra lane. Second, the benefits of platoon break-up in the passing lane carry over as rediced delay on the downstream two-lane highway, until new pltoons form over a number of miles. A road with regular passing lanes thus has a cyclic pattern of platooning, with zones of build-up, passing, and improved downstream operations. This cycle makes best use of a relatively small highway investment, and provides an intermediate quality of traffic operations between those of a two-lane and four-lane highway.

6. A nonlinear relationship was found between the length of a passing lane and its operational effectiveness. As demonstrated in Table 5, the optimal length of a passing lane generally varies from 0.5 to 1.0 mi (0.8 to 1.6 km) depending on flow rate. Passing lanes of 0.5 to 0.75 mi (0.8 to 1.2 km) in length are optimal at flow rates of 200 veh/hr or less in one direction of travel. At 400 veh/hr, the optimal passing lane length is 0.75 to 1.0 mi (1.2 to 1.6 km). At very high flow rates, such as 700 veh/hr in one direction of travel, the optimal length of a passing lane is 1.0 mi (1.6 km).

7. The level of spot platooning downstream of a passing lane was determined to be a function of flow rate, passing lane length, and the level of traffic platooning upstream of a passing lane. Relationships to predict these effects are presented in Equations (2) and (3) in Section 5.5 of this report. No effect of terrain or vehicle mix on the level of spot platooning downstream of a passing lane was found.

The following recommendations for further research on two-lane highway operations and passing lane effectiveness were developed in the research.

1. A capacity and level of service analysis procedure for two-lane highways with passing lanes should be developed and incorporated in Chapter 8 of the 1985 HCM. The operational effectiveness data on passing lanes in Section 5 of this report provide a foundation for this development effort.

2. Climbing lanes on two-lane highways have different operational characteristics than passing lanes in level or rolling terrain. Research is needed to quantify these differences, expanding on the work of Botha,[17] and develop a procedure for incorporating climbing lane effects in Chapter 8 of the 1985 HCM.

3. Further research is needed in the variation of percent time delay and spot platooning over lengths of two-lane highway as a function of flow rate, availability of passing opportunities, and geometrics. Ideally, a macroscopic input/output model of two-lane highway sections is needed where upstream traffic characteristics and highway section characteristics can be used to predict downstream platooning. This research can be performed with traffic simulation, but should be validated in field studies.

4. The TRARR model developed by the Australian Road Research Board has capabilities similar to TWOPAS. A formal comparison between TRARR and TWOPAS should be made to determine their similarities and differences and select one model for further two-lane highway research.

5. The TWOPAS computer simulation model provides an excellent tool to examine the operational effectiveness of passing lanes. The model provides a very realistic representation of the effects of passing lanes on traffic platooning. However, the unusually high values of passing rate within passing lane sections simulated by TWOPAS should be investigated to determine the source and impact of this problem.

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APPENDIX

SIMULATION CASE STUDY OF PASSING IMPROVEMENTS

This appendix presents a case study of six alternative operational improvements for a typical section of two-lane highway. Where a single isolated operational improvement, such as a passing lane, is installed on a two-lane highway, the procedures presented in Section 5 of this report provide a method to estimate its operational effectiveness. Where several improvements are used in series along the same highway section, the interactions between the individual improvements can be complex and may best be examined with a computer simulation model.

Two existing computer models have the ability to simulate traffic operations on two-lane highways with and without passing lanes. These are TWOPAS model, developed for the Federal Highway Administration by Midwest Research Institute, and the TRARR model, developed by the Australian Road Research Board. The TWOPAS model is an updated version of the TWOWAF model, which was used to develop the capacity and level of service procedures in Chapter 8 of the 1985 HCM. The TRARR model[11] has been developed over a period of years in Australia and now includes the capability to simulate both passing lanes and turnouts.

The following discussion illustrates the application of the TWOPAS computer model to evaluate alternative operational improvements for a typical two-lane highway section in a midwestern State.

Study Site

The case study focuses on a 36-mi (58-km) section of conventional two-lane highway on State Route 25 between Town A and Town B, illustrated on the map in Figure 12. At the west end of the site, Route 25 connects with a four-lane divided freeway near Town A; this freeway serves a major metropolitan area located 40 mi (64 km) north of Town A. At the east end of the site near Town B, Route 25 connects with two-lane highways serving a vacation and resort area and serving a medium-sized metropolitan area located 80 mi (129 km) south of Town B. Towns A and B each have between 5,000 and 10,000 residents; there are no other sizeable towns and no junctions with State primary highways on Route 25 between Towns A and B.

Route 25 currently carries approximately 7,000 veh/day with 1,000 veh/hr in the design hour in both directions of travel. The peak flows generally occur for traffic going to and from the resort area to the east of the site on Friday and Sunday evenings. At these times, the site experiences long platoons of vehicles in the peak direction of travel and much lighter flows in the opposing direction. The traffic mix typically includes 5% trucks and 15% recreational vehicles.

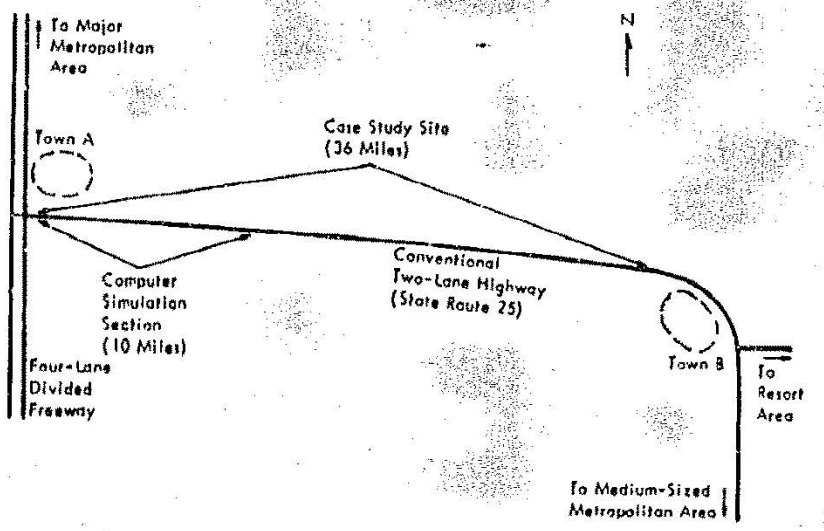

Figure 12 - Sketch Map of Case Study Site

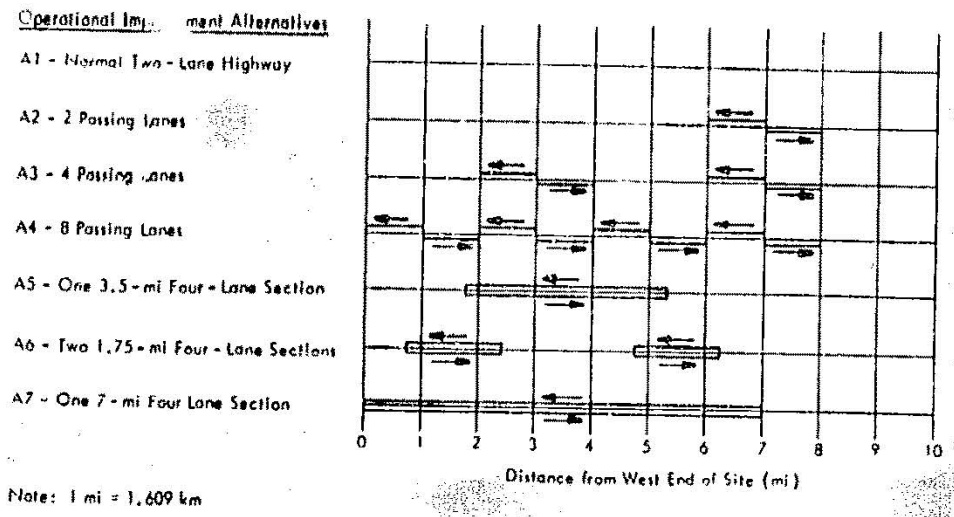

Figure 13 - Locations of Operational Improvement Alternatives for Simulation Case Study

The site is located in level to gently rolling terrain with maximum grades of 2 percent. The land use along the site is primarily agricultural with a few residences and roadside businesses.

Computer Simulation Approach

A computer simulation study was used to investigate the operational effects of improvement alternatives for the westernmost 10 mi (16 km) of the case study site. The purpose of this computer simulation study was to select the most appropriate operational improvements for the selected 10-mi (16-km) section and to indicate the general approach that should be used to improve the remainder of the site.

Computer simulation of the study site was performed using the TWOPAS model. The traffic volume and geometric data (including grades, horizontal curves, sight distances, and locations of passing and no-passing zones) used as input to the model are based on an actual two-lane highway site in a midwestern State that is currently under consideration for improvement.

The case study site was simulated for three levels of traffic flow rate (400, 800, and 1,000 veh/hr in both directions of travel combined) and two direction splits (70/30 and 30/70). The percentage of vehicles platooned entering the study section at the upstream end of the site in each direction of travel was selected to be appropriate for the flow rate. Relatively low levels of platooning were specified for entering traffic in the eastbound direction, since this traffic has just left a multilane freeway. Relatively high levels of platooning were specified for westbound traffic because this traffic has traversed an extended length of two-lane highway.

Operational Improvement Alternatives

Six alternative improvements were considered in the computer simulation study and were compared to the existing two-lane highway. These alternatives were:

- Two passing lanes (one in each direction);
- Four passing lanes (two in each direction);
- Eight passing lanes (four in each direction);
- One 3.5-mi (5.6-km) four-lane section;
- Two 1.75-mi (2.8-km) four-lane sections; and
- One 7-mi (11-km) four-lane section.

All of the passing lanes considered in the computer simulation study were 1.0 mi (1.6 km) in length. The alternative with eight passing lanes provides continuous alternating passing lanes over 8 mi (13 km) of highway.

The locations of the six improvement alternatives are illustrated in Figure 13.

Operational Effectiveness

Figures 14 and 15 illustrate summarize the results of the operational analysis performed with the TWOPAS model for the normal two-lane highway and the six improvement alternatives.

Figure 14 presents the effectiveness of the improvement alternatives at decreasing platooning over the 10-mi (16-km) study section. The table shows that the improvement alternatives are all effective in reducing percent time delay, especially at higher traffic volumes. In one case, the most effective improvement alternative decreased percent time delay from 76.7 to 30.2, an improvement from Level of Service E nearly to Level of Service A.

Figure 15 presents the effectiveness of the improvement alternatives on overall travel speeds on the 10-mi (16-km) section. The results show that these alternatives have a relatively modest effect on travel speeds. The greatest speed increase found for any alternative was 6.8 mi/hr (10.9 km/hr). These results indicate that percent time delay is more sensitive than speed to the presence of a passing lane or four-lane section, just as percent time delay was found to be more sensitive than speed to variations in flow rate in the 1985 HCM.

Safety Effectiveness

The safety effectiveness of each improvement alternative was determined on the basis of percentage accident reduction estimates for passing lanes and short four-lane sections. Passing lanes were estimated to reduce accident rates by 25 percent and four-lane sections were assumed to reduce accident rates by 34 percent based on the results of a safety evaluation by Harwood and St. John.[3] Estimated accident reductions were based on a typical two-lane highway accident rate of 1.75 accidents per million veh-mi (1.09 accidents per million veh-km) and were assumed to consist of 2 percent fatal accidents, 48 percent injury accidents, and 50 percent property-damage-only accidents.

Benefit-Cost Analysis

The operational improvement alternatives were compared through a benefit-cost analysis. In this analysis, both the traffic operational and safety benefits and the improvement construction costs are quantified in

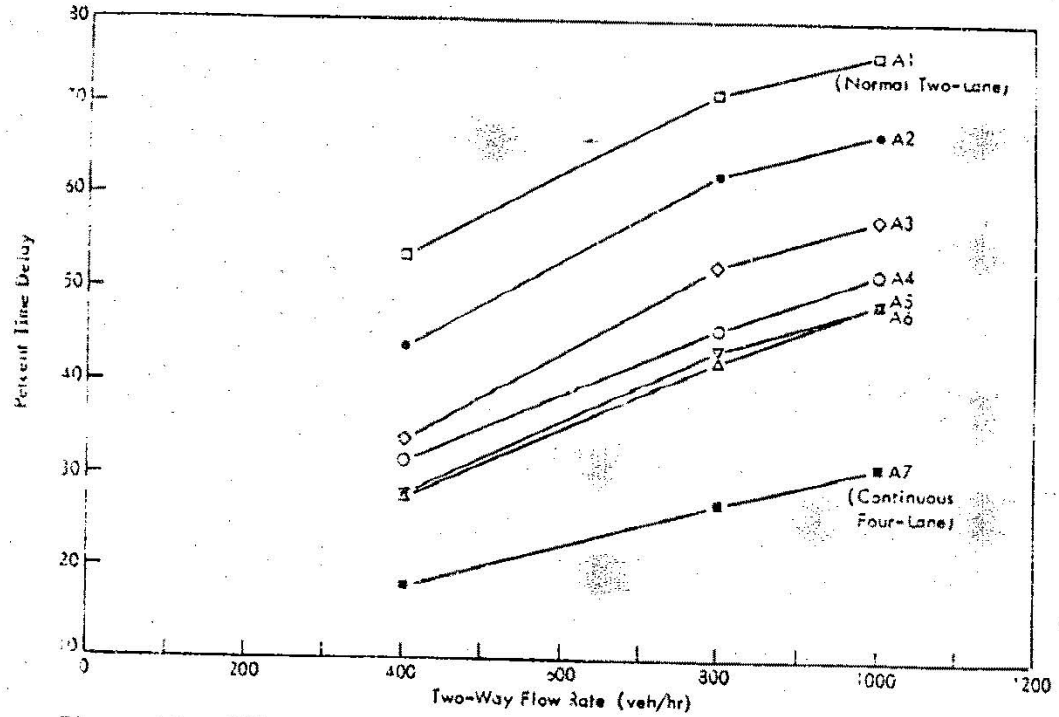

Figure 14 - Effect of Alternative Improvements on Traffic Platooning in Simulation Case Study

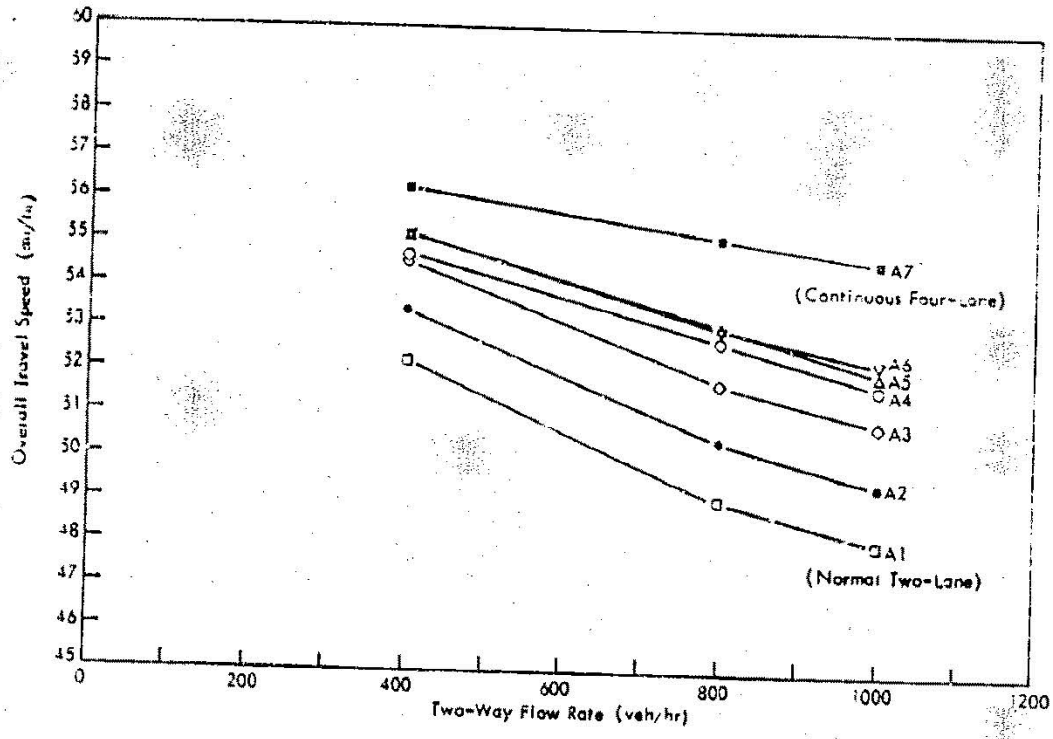

Figure 15 - Effect of Alternative Improvements on Overall Travel Speeds in Simulation Case Study

dollar terms. Benefit-cost analysis is necessary to evaluate the results of the case study, because none of the other evaluation methods, including cost-effectiveness analysis, provide a method to combine both traffic operational and traffic safety benefits.

Table 7 presents estimates of construction costs, annual delay reduction, and annual accident reduction for use in the benefit-cost analysis. The construction costs for the six design alternatives are based on the following estimates:

- Low-cost passing lanes: $ 500,000/mi
- Low-cost short four-lane sections: $1,100,000/mi
- Extensive four-laning: $1,500,000/mi

The difference between the construction costs for short four-lane sections and extensive four-laning arises because the locations of short four-lane sections can be selected to minimize construction costs.

Both the delay reduction and accident reduction benefits presented in Table 7 were estimated for the current traffic volume level of 7,000 veh/day. The effect of the alternative improvements on traffic speeds presented in Figure 15 were developed through computer simulation of specific hourly flow rates. The annual delay reductions or travel time savings in Table 7 were determined from the speed differences in Figure 15 and the following daily traffic distribution:

Two-Way Flow Rate (veh/hr)	No. of Hours per Day	No. of Vehicles per Day
1,000	1.0	1,000
800	2.0	1,600
400	8.0	3,200
100	12.0	1,200
0	1.0	0
	24.0	7,000

This daily traffic distribution is assumed to repeat itself each day, 365 days per year.

TABLE 7

CONSTRUCTION COSTS AND EXPECTED ANNUAL BENEFITS OF ALTERNATIVE IMPROVEMENTS IN SIMULATION CASE STUDY

	Operational Improvement Alternative	Construction Cost ($)	Expected Annual Delay Reduction (veh-hr)	Expected Annual Accident Reduction
A1	Normal two-lane	0	0	0
A2	2 passing lanes	1,115,000	10,100	2.3
A3	4 passing lanes	2,230,000	19,500	4.5
A4	8 passing lanes	4,460,000	26,900	9.0
A5	1 3.5-mi four-lane section	3,975,000	24,000	5.4
A6	2 1.75-mi four-lane sections	4,100,000	26,700	5.4
A7	1 7-mile four-lane section	10,670,000	39,000	10.7

Note: 1 mi = 1.609 km

TABLE 8

EFFECTIVENESS OF ALTERNATIVE IMPROVEMENTS IN REDUCING TRAVEL TIME AND TRAFFIC PLATOONING

	Operational Improvement Alternative	Annual Delay Reduction (veh-hr)	Annual Delay Reduction (veh-hr) per Lane-mi	Reduction in Percent Time Delay	Reduction in Percent Time Delay per lane-mi
A2	2 passing lanes	10,100	4,530	8.8	3.9
A3	4 passing lanes	19,500	4,380	18.9	4.2
A4	8 passing lanes	26,900	3,020	28.4	3.2
A5	1 3.5-mi four-lane section	24,000	3,320	26.6	3.7
A6	2 1.75-mi four-lane section	26,700	3,580	29.6	4.0
A7	1 7-mi four-lane section	39,000	2,740	46.2	3.3

Note: 1 mi = 1.609 km

A weakness of benefit-cost analysis for application to two-lane highway improvements is that, in order for the traffic operational benefits to be quantified in dollar terms, they must be quantified as a delay reduction or travel time savings based on increased traffic speeds. It has been established in the 1985 HCM that percent time delay is a more satisfactory measure of service for two-lane highways than speed. However, there is no accepted method to convert traffic operational benefits expressed as a reduction in percent time delay into dollar terms.

The operational benefits of the improvement alternatives are illustrated in Table 8, which shows the effectiveness of each improvement alternative and the cost-effectiveness per lane-mi in reducing travel time and traffic platooning (i.e., percent time delay). The travel time savings in Table 8 represent the combined effect of all traffic volume levels considered in the analysis. The reduction in percent time delay in Table 8 represents one particular traffic volume level -- 800 veh/hr -- which is typical of the entire range of flow rates. The improvement lengths used to compute the effectiveness per lane-mi in Table 8 have each been increased by 600 ft (180 m) to account for the cost of constructing the lane addition and lane drop tapers.

Table 9 presents the benefit-cost analysis of the six design alternatives, arranged in order of increasing construction cost. As in Table 8, both the traffic operational and safety benefits in Table 9 are appropriate for the current traffic volume level.

The operational benefits in Table 9 were estimated at $9.75 per veh-hr of delay reduced, as estimated by Chui and MacFarland.[18]

The safety benefits were estimated at $725,000 per fatal accident reduced, $54,600 per injury accident reduced, and $3,500 per property-damage-only accident reduced. These estimates are based on 1975 cost estimates for fatalities, injuries, and property damage in traffic accidents developed by the National Highway Traffic Safety Administration.[19] These NHTSA cost estimates were converted from involvement costs to accident costs with estimates of the number of fatalities per fatal accident, number of injuries per fatal accident and per injury accident, and amount of property damage per accident on rural highways. The resulting accident cost estimates were then updated to 1985 levels to account for inflation.

The improvement construction costs in Table 9 have been expressed on an annualized basis using an estimated service life of 20 years for the operational improvements and a discount rate (minimum attractive rate of return) of 4 percent. The improvement construction costs have been annualized so that they are expressed on a comparable basis with the annual delay reduction and safety estimates.

TABLE 9

BENEFIT-COST ANALYSIS OF ALTERNATIVE IMPROVEMENTS IN SIMULATION CASE STUDY

Operational Improvement Alternative	Expected Annual Benefits ($) Operational	Safety	Total	Annualized Construction Cost ($)	B/C Ratio	Marginal B/C Ratio
A2 2 passing lanes	98,500	97,700	196,200	82,500	2.38	2.38
A3 4 passing lanes	190,100	191,200	381,300	165,000	2.31	2.24
A5 1 3.5-mi four-lane section	234,000	229,500	463,500	294,100	1.58	0.64
A6 2 1.75-mi four-lane sections	260,300	229,500	489,800	303,400	1.61	0.78
A4 8 passing lanes	262,300	382,500	644,800	329,000	1.96	1.61
A7 1 7-mi four-lane section	380,200	454,700	834,900	789,600	1.06	0.41

Note: 1 mi = 1.609 km

The benefit-cost ratio for each improvement alternative shown in Table 9 is computed as the ratio of the total traffic operational and safety benefits to the annualized construction cost. The marginal benefit-cost ratio is computed for each incremental expenditure as the ratio of the additional traffic operational and safety benefits from a more expensive improvement to the additional cost of constructing that improvement.

Interpretation of Results

Table 9 shows that, at the current traffic volume level, all six of the improvement alternatives have benefit-cost ratios of 1.0 or more and are therefore considered cost-effective. The benefit-cost ratios for the improvement alternatives range from 2.38 for construction of two passing lanes to 1.06 for continuous four-laning of the western-most 7 mi (11 km) of the study site.

Review of the marginal benefit-cost ratios in Table 9 indicates an obvious choice among the six improvement alternatives at the current traffic volume level. The first alternative (two passing lanes) would cost $1,115,000 to construct and would be cost-effective with a benefit-cost ratio of nearly 2.4. The second alternative (four passing lanes) would cost an additional $1,115,000 to construct, but provides an additional traffic operational and safety benefit of $185,100 per year. The additional expenditure required to construct four passing lanes rather than two has a marginal benefit-cost ratio of 2.24 and is therefore economically justified. Similarly, the continuous passing lane alternative has a marginal benefit-cost ration of 1.61, indicating that the additional expenditures to construct eight passing lanes rather than four is cost-effective. The other improvement alternatives, which involve four-lane sections of varying length, have marginal benefit-cost ratios less than 1.0 and are therefore not economically

justified. However, these alternatives might become cost-effective in the future as traffic volumes increase.

The benefit-cost analysis results indicate that when the 10-mi (16-km) study site is considered in isolation, the most desirable operational improvement alternative is to construct eight passing lanes, two in each direction, at a cost of $4,460,000. It should be noted, however, that the construction of four passing lanes has a substantially higher marginal benefit-cost ratio than the construction of eight passing lanes. Thus, it would be more cost-effective to construct only four passing lanes in the 10-mi (16-km) study site and use the funds saved to construct additional passing lanes elsewhere on the same route. The recommended alternative has the advantage requiring over $8,000,000 less in construction expenditure than continuous four-laning; four passing lanes will provide 46 percent of the benefit of continuous four-laning for only 21 percent of the cost.

The benefit-cost analysis results in Table 9 indicate that the expected safety benefits are as important, or more important, than the traffic operational benefits in providing the justification for the construction of passing lanes at this site. This finding should be kept in mind because passing lanes may be even more cost-effective at sites with higher than average accident rates.

While the benefit-cost ratios for many of the design alternatives considered in this example are only slightly above 1.0, it should be kept in mind that greater speed increases from operational improvements would be expected at sites in more difficult terrain or with higher speed variance; furthermore, the traffic operational benefits might appear larger if the analysis were not constrained to consider speed rather than percent time delay as the measure of effectiveness.

The conclusion that passing lanes are preferable to four-lane sections at this site is based the current traffic volume of 7,000 veh/day and is valid at sites where little or no traffic growth in future years is projected. At the case study site, however, the responsible highway agency projects that over the next 20 years the traffic volume will more than double to 14,680 veh/day with a design hour volume of 2,350 veh/hr. This anticipated traffic volume growth calls for further consideration of the benefit-cost analysis results. Simple engineering economics indicate that, if the traffic operational and safety benefits increase linearly as traffic volumes grow by a factor of 110 percent, the annual traffic operational and safety benefits over a 20-year period will increase by an average of 45 percent. Thus, all of the improvement alternatives would become more cost-effective.

The projected design hour volume of 2,350 veh/hr is at or above the capacity of most two-lane highways, even with added passing lanes. Thus, if the projection of traffic volume growth is correct, the ultimate design for this facility should be a continuous four-lane highway. In that case, the passing lane alternative adopted should be consistent with the ultimate four-lane design. If the ultimate design is a four-lane undivided highway, then short four-lane sections should be considered now to increase passing

opportunities. If the ultimate design is a four-lane divided highway, passing lanes in one direction at a time could be installed now with the three-lane pavement eventually being converted to one roadway of a divided highway.

If the short four-lane alternative is adopted, the benefit-cost results in Table 9 indicate that the most cost-effective among the four-lane alternatives is two 1.75-mi (2.8-km) four-lane sections. It is especially important to note that two separate four-lane sections spaced 2 mi (3 km) apart are more effective than a single four-lane section of comparable length.

The findings of the benefit-cost analysis indicate that a staged construction approach should be used. Passing lanes or short sections of four-lane highway should be constructed at intervals along the highway. The funds saved by not constructing a continuous four-lane highway section at the westernmost end of the study site could be used to provide passing lanes or short four-lane sections through more of the 36-mi (58-km) study site. These sections can become part of a continuous four-lane highway if and when traffic volumes warrant. The staged construction approach not only maximizes the immediate traffic operational and safety benefits per dollar spent, but also provides the option to delay or cancel future construction of a continuous four-lane highway if the anticipated traffic volume growth does not occur.

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