Traffic Performance and Design of Passing Lanes

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A study of traffic performance and design of passing lanes on two-lane, two-way rural highways emphasized four major research areas. Field studies of traffic performance and design of five California passing lanes provided an operational assessment and focused attention on the other three research efforts. A before-and-after field study of two passing-lane entrance designs demonstrated that the modified design significantly increased the proportion of traffic that would enter the passing-lane section in the basic lane. Field observations of passing maneuvers clearly indicated that the number of passes per passing-lane length was a good measure of effectiveness of passing lanes. Equations were developed for estimating the number of passes as a function of traffic flow level for each of the five data sets. A sensitivity analysis through simulation identified that passing lanes from 0.25 to 0.75 mi long appeared to be the most effective and that spacing of 2 to 5 mi between such passing lanes appeared appropriate depending on downstream roadway and traffic conditions. The number of passes that would likely occur at three of the field sites under various traffic flow levels and vehicle composition mixes was estimated.

During the past several years, the Institute for Transportation Studies has performed research on two-lane, two-way rural highways; particular attention has been given to the traffic performance and design of passing lanes. This research has been sponsored by the California Department of Transportation (Caltrans) and FHWA. A number of reports have been prepared, including a final project report (*1,2*). This paper summarizes the results and conclusions of this research project, emphasizing four major substudies.

Field studies at five passing-lane locations in northern California assessed traffic performance in passing lanes. These five locations included short, medium, and long passing lanes in level, rolling, and mountainous terrain. Traffic performance measures included lane flows, traffic composition, travel times, spot speeds, passing-lane use, percent time delay, time headway distribution, and platoon structure.

The results of the field studies drew attention to the design of the entrance to passing-lane sections and suggested a possible modification in which traffic would be directed to the rightmost lane rather than to the passing lane. A before-and-after study at one of the five field study locations assessed this type of entrance design modification. Traffic performance measures for this assessment included passing-lane use, spot speeds, percent time delay, time headway distribution, and platoon structure.

The results of the earlier field studies identified weaknesses in the traffic performance measures used to assess the effectiveness of passing lanes. Because the purpose of passing lanes is to permit faster vehicles to pass slower vehicles, the number of passes in the passing lane might be a good traffic performance measure. The video records permitted reanalysis so that the number of vehicle passes under different flow levels by type of vehicle could be obtained.

The previous analyses were limited to five passing-lane locations with specific passing-lane designs and under existing traffic conditions. A simulation permitted extensive sensitivity analysis for situations that were not studied in the field. The simulation assessed the effect of passing-lane length, the effect of passing lanes on downstream conditions, and the effect of flow level and vehicle composition. The TRARR simulation model was used for this assessment, and was calibrated for the existing field study conditions.

FIELD STUDY RESULTS

The field study assessed site characteristics and measured traffic performance measures for the five passing-lane locations. This information for all five sites is presented in Tables 1 and 2.

Short Passing Lane in Level Terrain

The short passing lane studied was on State Route 70 in level terrain with good horizontal and vertical alignment. The average hourly flow in the direction of the passing lane during the 6-hr study period was approximately 300 vehicles per hour (vph). The traffic stream consisted of 90 percent four-tire vehicles, 4 percent trucks, and 6 percent recreational vehicles. Spot speed studies revealed average speeds of 57, 62, and 58 mph in the opposing, passing, and basic lanes, respectively.

Traffic performance measures included percent time delay, time headway distribution, and platoon size distribution. The percent time delay was estimated in the field as the percentage of vehicles traveling at headways of 5 sec or less. The percent time delay actually increased from 47 to 48 percent when traffic entering was compared with traffic leaving the passing lane. Traffic with 2-sec headways actually increased from 20 to 23 percent. Single-vehicle platoons also increased from 58 to 60 percent. These traffic performance measures did not indicate user benefits from the passing lane.

Short Passing Lane in Rolling Terrain

The short passing lane studied was on State Route 41 in rolling terrain with good horizontal alignment and on a 5-percent

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TABLE 1 FIELD STUDY RESULTS

Route Number	Passing Lane Length (miles)	Terrain (percent grade)	Directional Average Hourly Flow	Vehicle Composition (%)			Spot Speeds (mph)		
				Four-tired Vehicles	Trucks	Recreational Vehicles	Opposing Lane	Passing Lane	Basic Lane
70	short (0.5)	level (0-1)	300	90	4	6	57	62	58
41	short (0.5)	rolling (5)	200	88	5	7	59	57	54
49	short (0.4)	rolling (4)	150	96	1	3	N/A	58	55
140	medium (0.9)	rolling (4)	100	95	1	4	N/A	58	56
299	long (1.5)	mountain-ous (5-8)	150	87	1	12	54	59	53

N/A - Not Available

TABLE 2 FIELD STUDY PERFORMANCE MEASURES

Route Number	Passing Lane Length (miles)	Terrain (percent grade)	Percent Time Delay*		Percent Two-Second Headways		Percent One-Vehicle Platoons*	
			At Entrance	At Exit	At Entrance	At Exit	At Entrance	At Exit
70	short (0.5)	Level (0-1)	47	48	20	23	58	60
41	short (0.5)	Rolling (5)	52	49	26	19	58	63
49	short (0.4)	Rolling (4)	48	42	20	15	55	64
140	medium (0.9)	Rolling (4)	25	23	10	4	75	80
299	long (1.5)	Mountain-ous (5-8)	44	25	18	8	58	78

* Based on four second headway threshold value.

upgrade (*3*). The average hourly flow in the direction of the passing lane during the 6-hr study period was approximately 200 vph. The traffic stream consisted of 88 percent four-tire vehicles, 5 percent trucks, and 7 percent recreational vehicles. Spot speed studies revealed average speeds of 59, 57, and 54 mph in the opposing, passing, and basic lanes, respectively.

The percent time delay in the passing lane section decreased from 52 to 49 percent, and the percent of traffic with 2-sec headways decreased from 26 to 19 percent. Single-vehicle platoons increased from 58 to 63 percent. These traffic performance measures indicated slight improvements in user benefits due to the passing lane.

Short Passing Lane in Rolling Terrain

The short passing lane studied was on State Route 49 in rolling terrain with good horizontal alignment and on a 4-percent upgrade (*4*). The average hourly flow in the direction of the passing lane during the 6-hour study period was approximately 150 vph. The traffic stream consisted of 96 percent four-tire vehicles, 1 percent trucks, and 3 percent recreational vehicles. Spot speed studies revealed average lane speeds of 58 and 55 mph in the passing and basic lanes, respectively.

The percent time delay in the passing lane section decreased from 48 to 42 percent, and the percent of traffic with 2-sec headways decreased from 20 to 15 percent. Single-vehicle platoons increased from 55 to 64 percent. These traffic performance measures indicated slight improvements in user benefits due to the passing lane. These results were somewhat similar to those for State Route 41.

Medium-Length Passing Lane in Rolling Terrain

The medium-length passing lane studied was on State Route 140 in rolling terrain with good horizontal alignment and on a 4-percent upgrade. The average hourly flow in the direction of the passing lane during the 6-hour study period was approximately 100 vph. The traffic stream consisted of 95 percent four-tire vehicles, 1 percent trucks, and 4 percent recreational vehicles. Spot speed studies revealed average lane speeds of 58 and 56 mph in the passing and basic lanes, respectively.

The percent time delay in the passing lane section decreased from 25 to 23 percent, and the percent of traffic with 2-sec headways decreased from 10 to 4 percent. Single-vehicle platoons increased from 75 to 80 percent. These traffic performance measures indicated slight improvements in user benefits due to the passing lane. These results were somewhat similar to the results for the previous two passing lane sites. The increased potential benefits due to the longer passing lane, however, appeared to be offset by a lower hourly flow level.

Longer Passing Lane in Mountainous Terrain

The longer passing lane site studied was on US-299 in mountainous terrain on a grade varying from 5 to 8 percent. The average hourly flow in the direction of the passing lane during the 6-hour period was approximately 150 vph. The traffic stream consisted of 87 percent four-tire vehicles, 1 percent trucks, and 12 percent recreational vehicles. Spot speed studies revealed average lane speeds of 54, 59, and 53 mph in the opposing, passing, and basic lanes, respectively.

The percent time delay in the passing lane section decreased from 44 to 25 percent, and the percent of traffic with 2-sec headways decreased from 18 to 8 percent. Single-vehicle platoons increased from 58 to 78 percent. All of these measures of effectiveness indicated significant improvements and the largest improvement of all sites studied. The longer passing lane combined with the steeper grades and high percentage of recreational vehicles most likely accounted for these larger improvements.

Summary of Field Study Results

The results, particularly for the shorter passing lanes, raised three questions that shaped the later work on the project:

- What impact does entrance design have on the potential benefits derived from passing lanes, particularly short passing lanes in level terrain?
- What measures of traffic flow performance can best evaluate user benefit as affected by the passing lane?
- Where should measurements be taken in reference to the physical passing lane in order to best evaluate its effectiveness?

It was observed at the different sites that the entrance design and pavement markings did not encourage drivers to go immediately into the basic nonpassing lane. Hence, the effective length of the passing lane might be reduced. This reduction was most evident in the case of short passing lanes and where the differential speed between vehicles passing and being passed was small. After discussions with Caltrans engineers, it was decided to do a before-and-after study at the State Route 70 site; the change was restriping of the pavement markings to direct entering traffic into the basic nonpassing lane upon entrance to the passing-lane section.

Percent time delay, time headways, and percent of vehicles in single platoons were used in the field studies as measures of user benefits due to the passing lane. Results were inconclusive for short passing lanes, especially in level terrain. Several additional measures were considered, and those that could be expressed as a function of passing-lane length were preferred. It was decided that the number of passes per length of passing lane would be analyzed. Fortunately, the videotapes could be reanalyzed to obtain this measure of performance, although it was a tedious and time-consuming effort.

Almost all measurements obtained in the field study were taken within the passing-lane section. Further review of the results of this study, related references, and initial work with simulation models suggested that measurements some distance upstream and downstream of the passing-lane section might more completely indicate the user benefits as affected by the passing lane. Unfortunately, because of time and funding limitations, it was not possible to restudy upstream and downstream sections at the five field sites. Plans had already been developed to perform experiments with simulation, so this effort was shifted to computer simulation.

EFFECT OF PASSING-LANE ENTRANCE DESIGN

The field study of Route 70 with the existing passing-lane entrance design was conducted in October 1988. The pavement markings were modified in the early fall of 1989, and the field study of Route 70 with the modified passing-lane entrance design was conducted in November 1989.

The existing and modified passing-lane entrance design is shown in Figure 1. The lower sketch shows the existing design and pavement markings. The entrance flare widens at an approximate 1:25-ft ratio. Striping starts at the point where two full 11.5-ft lanes become available. The striping consists of a white dashed line that divides the passing section into two southbound lanes.

The upper sketch shows the modified design and pavement markings. Yellow striping was added at the entrance to the passing lane section with the intent of directing traffic into the basic lane. Neither the geometric design features nor the signing was changed. After the study area was restriped, drivers were given approximately 3 weeks to become familiar with the changes before the after study was initiated.

The after study was conducted under similar conditions of the before study. Both studies occurred on the same day of the week during almost identical daylight hours. Both days were sunny and roadway and traffic conditions were as similar as possible. The studies used identical field measurement techniques, including video cameras, tach vehicles, traffic counters, and radar speed guns.

The entrance design study results are summarized in Table 3 for both the before (existing design) and the after (modified design) studies. The traffic flow levels for the two studies were almost identical (305 versus 309 vph). There were slightly more trucks in the after study (4 to 5 percent) and fewer recreational vehicles (6 to 3 percent). The single most significant difference between the two studies was the lane distribution between the passing lane and the basic lane. Whereas 80 percent of the entering traffic in the before study moved directly into the passing lane, 80 percent of the entering traffic in the after study moved directly into the basic lane. The shift in this direction was expected, but the magnitude was far greater than expected. Unfortunately, this redirection of traffic into the basic lane was not accompanied by significant improvement in user benefits, at least considering the measures of effectiveness described in the following paragraph.

Lane speeds increased slightly, as expected, but not significantly. Changes in percent time delay within the passing-

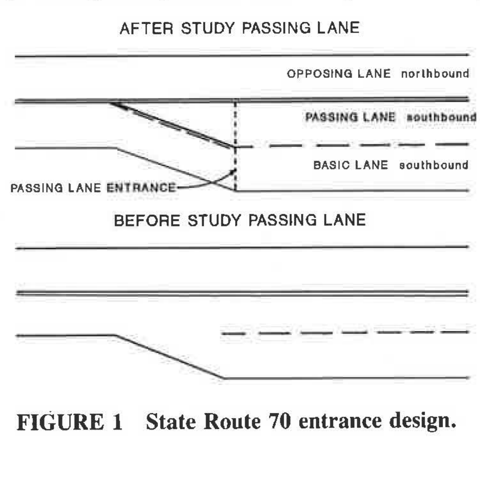

FIGURE 1 State Route 70 entrance design.

TABLE 3 ENTRANCE DESIGN STUDY RESULTS

RESULTS	Entrance Design	
	Existing	Modified
Flow Level		
- No. of Vehicles Observed	1828	1854
- Duration of Study (hrs)	6	6
- Hourly Flow (veh/hr)	305	309
Vehicle Composition (percent)		
- Four-tired Vehicles	90	92
- Trucks	4	5
- Recreation Vehicles	6	3
Lane Distribution (percent)		
- Passing Lane	80	20
- Basic Lane	20	80
Lane Speeds (mph)		
- Passing Lane	62	63
- Basic Lane	58	57
Percent Time Delay (percent)		
- At Entrance	53	50
- At Exit	54	52
1-2 Second Time Headways (%)		
- At Entrance	25	30
- At Exit	27	25
>10 Second Time Headways (%)		
- At Entrance	33	36
- At Exit	33	35
1-Vehicle Platoons (percent)		
- At Entrance	51	53
- At Exit	52	56
2-Vehicle Platoons (percent)		
- At Entrance	20	21
- At Exit	19	18

lane section were similar. The modified design did appear to reduce the percent of vehicles with small headways (1 to 2 sec), but large headways (more than 10 sec) were unaffected. There was a slightly greater increase in single-vehicle platoons and a slightly greater decrease in two-vehicle platoons with the modified entrance design, but neither difference was significant.

In summary, although the modified entrance design significantly changed the lane distribution at the beginning of the passing lane section, none of the measures of effectiveness showed significant improvements. Obviously this is an area for further research.

FIELD OBSERVATIONS OF PASSING MANEUVERS

A major conclusion from the field study results was the identification of the need for additional measures of effectiveness, particularly for short passing lanes in level terrain. Qualitative review of field study videotapes, review of the TRARR simulation model outputs, and discussions with Caltrans engineers led to the consideration of using the number of passes in the passing-lane section as a new measure of effectiveness. Another advantage of this measure of effectiveness is the ability to compare various lengths of passing lane by normalizing the number of passes by dividing by the length of the passing lane.

Videotapes of the field study sites were reanalyzed to determine levels of passing activity at each site. Each field site had been filmed for 6 hr, and approximately one-half of these films were analyzed. The quality of the film and the position of cameras at the Route 49 site did not permit the inclusion of this site in the study of passing activity. On the other hand, both the before and the after study tapes of the Route 70 site were included.

Assistants first matched a distinctive vehicle found in the passing-lane entrance videotape to the same vehicle in the videotape of the same passing-lane exit. From there, teams of two assistants noted the type and order of vehicles entering the passing lane. The order of the same vehicles was noted at the exit to the passing lane. The net number of passes occurring within the passing lane length was determined. The number of passes determined in this manner is considered the minimum number of passes that took place. Intermediate-type passes, such as one vehicle overtaking another but then being passed by the initially overtaken vehicle, are considered two passes and would have not been counted using this method. With this data collection scheme, it was possible to relate the number of passes to the entering traffic flow rate and to identify the types of vehicles passing and being passed. The next two subsections deal with these two issues, namely, the passing maneuver frequencies related to traffic flow levels and the passing maneuver frequencies related to vehicle types. This analysis included five data sites: Route 70 (existing design), Route 70 (modified design), Route 41, Route 140, and Route 299.

Passing Maneuver Frequencies Related to Traffic Flow Levels

The passing maneuver results related to traffic flow levels for the five data sets are summarized in Table 4. The passing-lane design features are again identified, and the traffic composition for each data set is given, with Route 41 having the highest percent of vehicles other than automobiles. The number of 5-min samples varied from 35 to 43, and the total number of vehicles observed and number of passes recorded are shown. The 5-min hourly flow levels for each data set varied from a low of 20 vph at the Route 140 site to a high of 530 vph at the Route 70 site (existing design). The 5-min hourly passing rates for each data set varied from a low of zero passes per hour at the Route 41, 140, and 299 sites to a high of 410 passes per hour at the Route 70 site (existing design).

The number of passes in the passing lane was plotted against the number of vehicles entering the passing lane. Inspection of these plots suggested that a linear fit was as appropriate as various nonlinear formulations. Linear regression analysis was performed with each of the five data sets, and the resulting linear relations are shown in Figure 2. The numerical results of the linear regression analysis are shown in Table 4.

The X-intercept values ranged from $+3.8$ to $+11.3$ vehicles in a 5-min period entering the passing lane. This range of

TABLE 4 PASSING MANEUVER FREQUENCY RELATED TO FLOW LEVELS

RESULTS	ROUTE NUMBER				
	70	70M	41	140	299
Passing Lane Design					
- General Length	short	short	short	medium	long
- Length (miles)	0.5	0.3	0.5	0.9	1.5
- Terrain	level	level	roll-ing	roll-ing	moun-tainous
- Percent Grade	1	1	5	4	5-8
- Entrance Design	exist-ing	modi-fied	exist-ing	exist-ing	exist-ing
Traffic Composition (%)					
- Four-tired Vehicles	94	92	87	96	95
- Trucks	2	4	5	0	1
- Recreation Vehicles	4	4	8	4	4
Sample Size					
- No. of 5-minute Intervals	39	39	35	43	39
- No. of Vehicles Observed	1059	1015	525	422	412
- No. of Passing Maneuvers	458	413	189	94	206
5-minute Hourly Flow					
- Lowest	190	180	50	20	40
- Average	330	310	180	120	130
- Highest	530	480	490	240	360
5-minute Hourly Passing Rate					
- Lowest	10	20	0	0	0
- Average	140	130	70	30	60
- Highest	410	330	310	120	310
Linear Regression Results					
- X-intercept	+7.7	+11.3	+5.5	+5.4	+3.8
- Y-intercept	-4.6	-8.0	-3.0	-2.7	-3.0
- Slope	+0.60	+0.71	+0.55	+0.50	+0.78
- R^2 Value	0.31	0.45	0.76	0.49	0.66

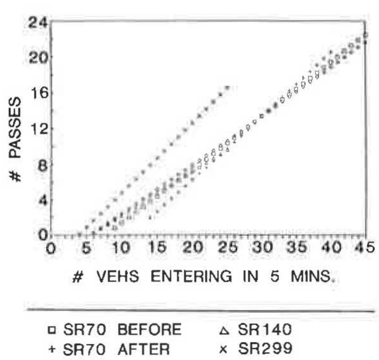

FIGURE 2 Passing activity: regression analysis comparison.

values indicates that when averaging time headways of vehicles entering the passing lane are about 1 min, the likelihood of vehicles passing is negligible. There appeared to be a pattern in that longer passing lanes had lower *X*-intercept values.

The *Y*-intercept values ranges from −8.0 to −2.7 passes in a 5-min period in the passing-lane section. This range of values indicates that the relationships are nonlinear and concave upward as traffic flow levels approach zero because the curve should go through the origin. Again a pattern appeared in that longer passing lanes had higher *Y*-intercept values. The no-intercept model and the nonlinear model were also considered for these data, but were not tested because of time constraints.

The slopes of the regression lines varied from +0.50 to +0.78. The slopes for the lines representing Routes 70 (existing design), 41, and 140 were quite similar; the slopes for the lines representing Routes 70 (modified design) and 299 had similar but higher values. A higher value might be expected for the Route 299 site because of its longer length, but the Route 70 site with the modified design would be expected to have a slope similar to Routes 70 (existing design), 41, and 140.

The regression correlation coefficients varied from 0.31 to 0.76. Although several of the higher valued coefficients might be considered to be in the acceptable range, the poor fit of Route 70 (existing design) (0.31) caused concern. The plot of data points for this data set revealed that six data points were significantly higher or lower than what the regression curve would indicate. In an attempt to explain the considerable variations, the videos for these six data points were reanalyzed to determine whether there had been a data analysis error.

Three situations contributed to significant changes in passing patterns:

- Vehicles entered the passing lane at uniform and large headways, and fewer passes were observed than expected;
- Vehicles in the sample were all passenger vehicles traveling at approximately the same speed, and although the flow level was high, fewer passes were observed than expected; and
- Vehicles entered in bunches with a nonauto as the platoon leader. Although the flow level was relatively low, there were more passes observed than expected.

Returning to Figure 2, the resulting linear regression lines for three of the five sites are almost identical. The Route 299 regression line is significantly different and shifted to the left. This difference is not unexpected because Route 299 had the longest passing lane and was located in the most mountainous terrain. In summary, for the shorter passing-lane locations in level to rolling terrain, the following observations were noted:

- The number of passes in a passing lane is negligible when the hourly 5-min rate of flow is less than 120 vph;
- The ratio of the number of passes to the number of vehicles entering (expressed as a percentage) increases from approximately 30 to 50 percent as the hourly 5-min rates of flow increase from 200 to 400 vph; and
- The ratio of the number of passes to the number of vehicles entering (expressed as a percentage) is about 50 percent when hourly 5-min rates of flow range from 400 to 600 vph.

TABLE 5 PASSING MANEUVER FREQUENCY RELATED TO VEHICLE TYPES

RESULTS	ROUTE NUMBER				
	70	70M	41	140	299
Autos Passing Autos					
- Expected Number	371	343	146	82	150
- Observed Number	356	346	109	74	154
- Significant Difference	No	No	No	No	No
Autos Passing Non-autos					
- Expected Number	41	33	20	6	26
- Observed Number	83	64	69	5	52
- Significant Difference	Yes+	Yes+	Yes+	No	Yes+
Non-autos Passing Autos					
- Expected Number	41	33	20	6	26
- Observed Number	16	3	6	0	0
- Significant Difference	Yes-	Yes-	No	No	Yes-
Non-autos Passing Non-autos					
- Expected Number	5	4	3	0	4
- Observed Number	3	0	5	15	0
- Significant Difference	No	No	No	Yes+	No
Chi-square Results					
- Calculated Value	59.7	60.4	141.6	∞	56.1
- Table Value	11.3	11.3	11.3	11.3	11.3
- Significant Difference	Yes	Yes	Yes	Yes	Yes

Passing Maneuver Frequencies Related to Vehicle Types

The reanalysis of the videotapes for passing maneuvers also provided the opportunity to study passing maneuver frequency by vehicle types. Because the proportion of automobiles and nonautomobiles was measured, it was possible to predict an expected fraction of passes by combinations of vehicle types assuming random behavior. For example, if passing maneuvers are independent of vehicle type and 90 percent of the traffic was automobiles, then one would expect that 81 percent of the passes would be of automobiles passing automobiles.

The actual number of passes by four vehicle-type combinations was observed for each of the described five data sets: automobiles passing automobiles, automobiles passing nonautomobiles, nonautomobiles passing automobiles, and nonautomobiles passing nonautomobiles. Chi-square tests were performed to test for significant differences with these vehicle-type distributions. The results are summarized in Table 5.

Automobiles passing automobiles had highest frequency of passes. No significant difference was noted between the expected number and the observed number. The next highest frequency of passes was for automobiles passing nonautomobiles. In almost all cases, the observed frequency of passes was significantly higher than the expected frequency. In the case of nonautomobiles passing automobiles, the observed number of passes was always less, frequently significantly less, than the expected number of passes. The last case was that of nonautomobiles passing nonautomobiles. The frequencies of such passes were so small that it was difficult to assess differences. Overall, each of the data sets revealed a significant difference between expected and observed distributions of vehicle-type passing. Automobiles passing nonautomobiles were more prevalent than expected, and nonautomobiles passing automobiles were less prevalent than expected.

SENSITIVITY ANALYSIS THROUGH SIMULATION

The research dealing with passing lanes on two-lane rural highways was directed to sensitivity analysis using the TRARR simulation model. The sensitivity analysis was designed to answer three questions:

- What effect does passing-lane length have on traffic performance within the passing lane?
- What effect do passing lanes and their lengths have on downstream traffic conditions?
- What effect do flow level and traffic composition have on traffic performance within the passing lane?

The TRARR model has been extensively used in Australia (*5*) and Canada (*6*), and was well suited to this research effort. This model is a stochastic microscopic simulation model with great versatility and is operational on IBM-compactible microcomputers.

The TRARR model was applied to existing conditions on three of the field study locations:

- Route 70—the short (0.5-mi) level terrain (0 to 1 percent) passing-lane site,
- Route 41—the short (0.5-mi) rolling terrain (5 percent) passing-lane site, and
- Route 299—the long (1.5-mi) mountainous terrain (5 to 8 percent) passing-lane site.

The predicted simulation model traffic performances were compared with the corresponding field measured traffic performances at the three sites. There were some relatively minor differences, but these were reduced by varying the vehicle performance characteristics and the standard deviations of vehicle speeds. Considerable effort was devoted to this calibration process before proceeding to the sensitivity analysis; this process is described in the project final report (*1*).

Effect of Passing-Lane Length on Traffic Performance

The model was applied to the three calibrated field data sets in which all input data were held constant except for passing-lane length. Passing-lane lengths of 0.25, 0.50, 0.75, 1.00, 1.50, and 2.00 mi were investigated. Three measures of effectiveness were used to assess the effect of passing-lane length on traffic performance within the passing lane. These measures were number of passes, reduction in percent time delay, and estimated annual travel time savings.

The results of the effect of passing-lane length on number of passes at the three sites are summarized in Figure 3. In the top diagram, the number of passes per hour is plotted as a function of passing-lane length. As expected, the number of passes increases with increased passing-lane length but at a decreasing rate. The resulting curve for Route 70 is the highest, followed by those for Routes 41 and 299. These differences are caused by site-specific characteristics, including existing flow level, vertical and horizontal alignment, and vehicle characteristics.

The results are normalized in the lower diagram of Figure 3 by dividing the number of passes by the passing-lane length. Passing-lane lengths less than 0.25 mi were not considered. Assuming that passing-lane costs are directly related to their lengths, short passing lanes from about 0.25 to 0.75 mi are most effective in terms of number of passes per mile. Due primarily to higher flow levels, the Route 70 curve is significantly higher than those for the other two sites.

The results of the effect of passing-lane length on reducing the percent time delay at the three sites are summarized in Figure 4. In the top diagram, the reductions in percent time delay are plotted as a function of passing-lane length. As expected, the reduction in percent time delay increases with longer passing-lane lengths but at a decreasing rate. The resulting curve is highest for Route 299, followed by Routes 70 and 41.

The results are normalized in the lower diagram of Figure 4 by dividing the reduction in percent time delay by passing-

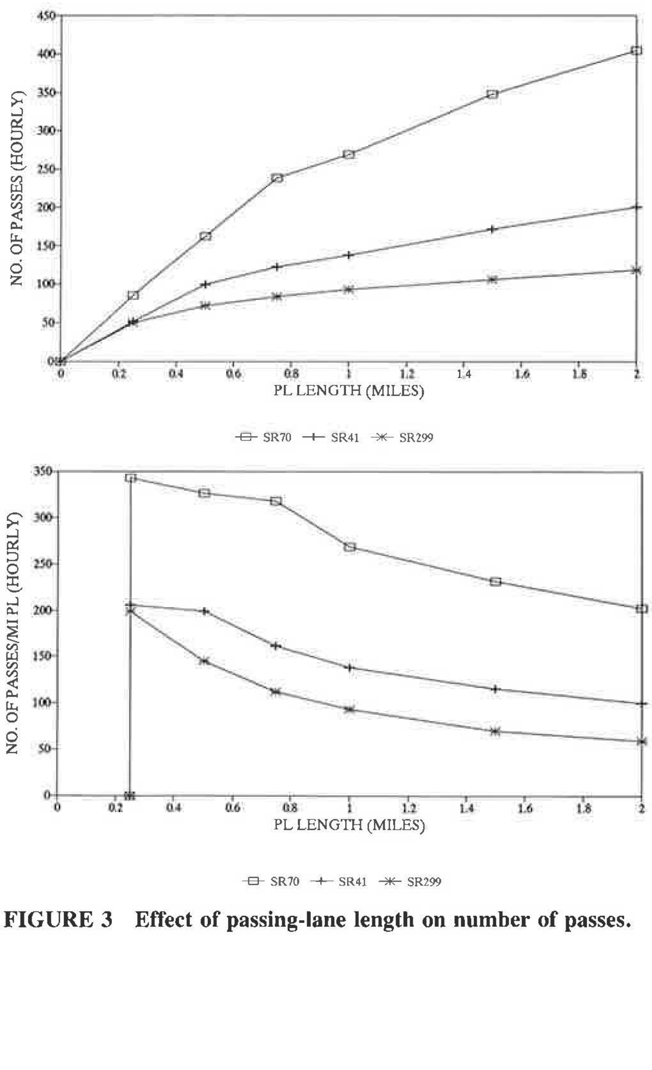

FIGURE 3 Effect of passing-lane length on number of passes.

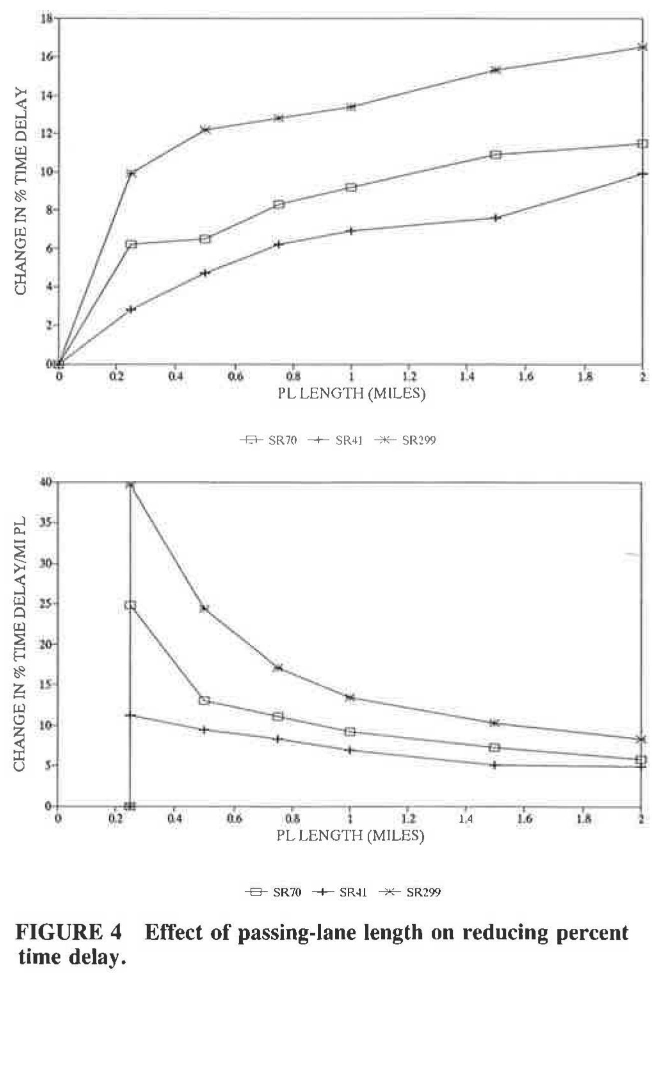

FIGURE 4 Effect of passing-lane length on reducing percent time delay.

lane length. Again, short passing lanes appear to be most effective in terms of reduction in percent time delay and are most effective under Route 299 conditions.

The results of the effect of passing-lane length on estimated annual travel time savings at the three sites are summarized in Figure 5. In the top diagram, estimated annual travel time savings are plotted as a function of passing-lane length. Again, as expected, the estimated savings increase with passing-lane length but at a decreasing rate. The resulting curves for Routes 70 and 41 are the highest.

The results are normalized in the lower diagram of Figure 5 by dividing the estimated savings by the passing-lane length. The results indicate that very short passing lanes are most effective for Routes 41 and 299, whereas slightly longer passing lanes are most effective for sites similar to Route 70. Savings of more than 3,000 vehicle hours per year per mile of passing lane are predicted for short passing lanes.

On the basis of these simulation results, the most effective passing-lane lengths for sites similar to the three study sites are 0.25 to 0.75 mi. Selecting the most effective site between the three study sites depends on the measure of effectiveness used. Route 70 is most effective in number of passes; Route 299 is most effective in reduction in percent time delay; and Route 41 is most effective in annual travel time savings.

Effect of Passing-Lane Length on Downstream Conditions

The second set of investigations with the simulation model dealt with the effect on passing-lane lengths of downstream traffic conditions. More specifically, the investigations attempted to answer the question: At what distance downstream of the end of the passing lane does percent time delay return to the percent time delay value as measured at the beginning of the passing lane? A passing lane will normally reduce the percent time delay over its length, but downstream of the passing lane the percent time delay gradually increases and at some point returns to its initial value. One application of such results is the selection of spacing between passing lanes. In these investigations all input data except passing-lane length were kept constant at each of the three sites. Passing-lane lengths of 0.25, 0.50, 0.75, 1.00, 1.50, and 2.00 mi were investigated at each of the three sites.

Sample results are presented in Figure 6 for 0.5-mi (top diagram) and 2.00-mi (lower diagram) passing-lane lengths at the Route 70 site. The vertical scale is percent vehicles in car-following (equivalent to percent time delay), and the horizontal scale is distance in miles from the start of the passing lane. The proportion of vehicles in car-following at the start of the passing lane in both cases was 54 percent. With the 0.5-mi passing lane, the percent of vehicles in car-following

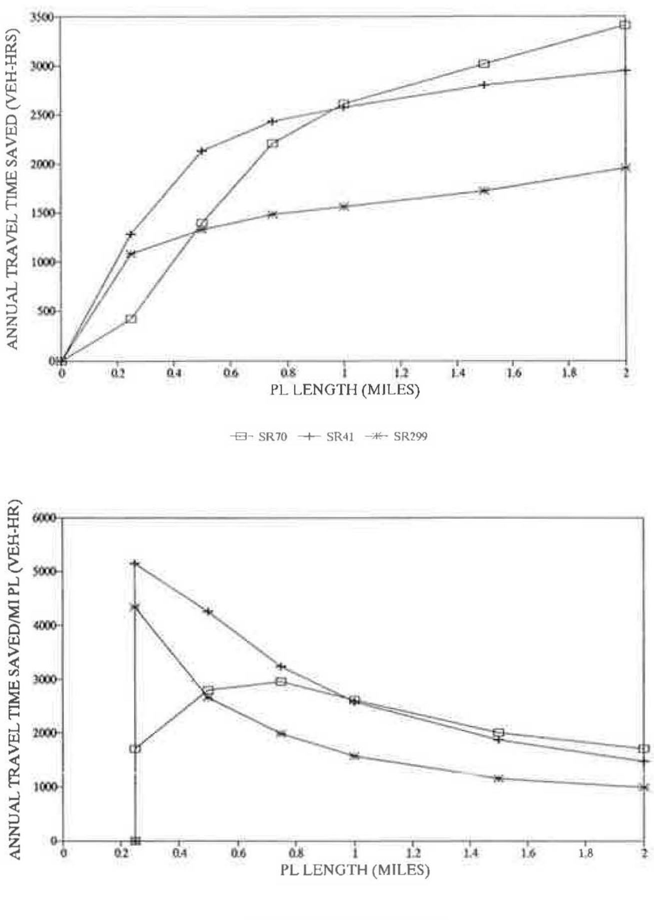

FIGURE 5 Effect of passing-lane length on annual travel time savings.

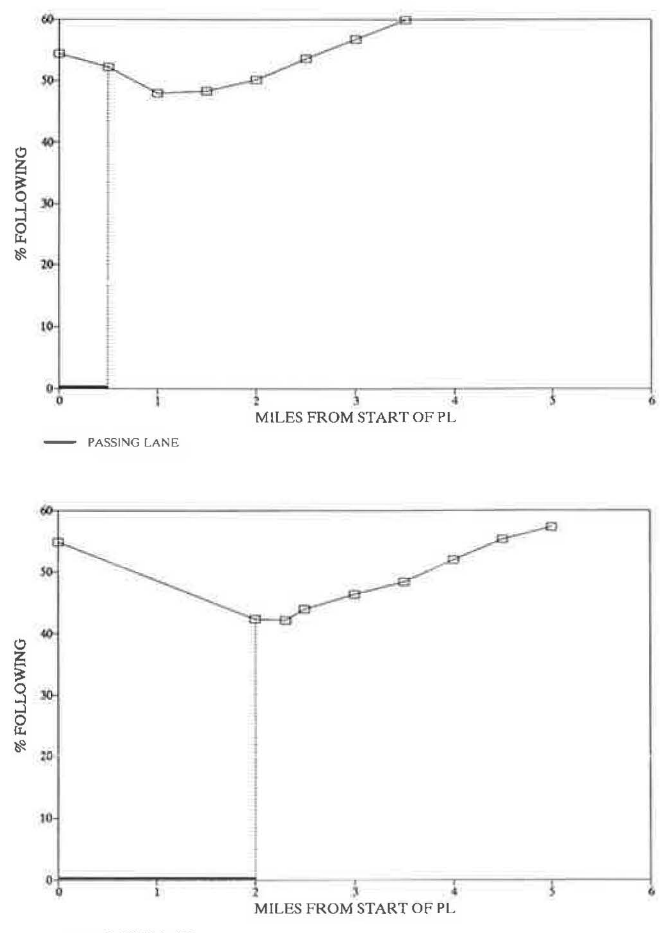

FIGURE 6 SR70: percent time delay downstream.

returns to 54 percent at a distance of 2.0 mi downstream of the end of the passing lane. With the 2.0-mi passing lane, the proportion of vehicles in car-following returns to 54 percent at a distance of 2.1 mi downstream at the end of the passing lane.

Composite results for all passing-lane lengths investigated for each of the three sites are depicted in Figure 7. In the upper diagram, the downstream effective length in miles is plotted as a function of passing-lane length. As expected, this effective distance increases with longer passing lanes but at a decreasing rate. Note that all three curves are quite flat with passing lanes longer than 0.75 mi.

These results are normalized in the lower diagram of Figure 7 by dividing the downstream effective length of the passing-lane length. Results for all sites indicate that short passing lanes are most productive in providing the highest downstream effective length per mile of passing lane.

The results pertaining to effective downstream distances support the conclusions on passing-lane lengths in that both support the desirability of 0.25- to 0.75-mi passing lanes. Passing lanes of such length provide effective downstream distances of 2 to 5 mi depending on downstream design and traffic conditions.

Effect of Flow Level and Vehicle Composition on Passing-Lane Performance

To determine the effect of flow level and vehicle composition, the model was applied to the three calibrated field data sets in which all input data except hourly flow level and percent nonautomobiles were held constant. The findings from the Route 41 site are a typical sample of the results.

Hourly flow levels varied from 50 to 300 vph in increments of 50 vph; percent nonautomobiles varied from 0 to 40 percent in increments of 10 percent. Three measures of traffic performance were obtained: number of passes per hour, change in percent time delay (exit percent minus entrance percent), and mean journey speed (mph).

The effect of hourly flow level and percent nonautomobiles on number of passes per hour using the Route 41 site data is presented in Figure 8. The curves showing 50, 100, and 150 passes per hour are denoted. As expected, the number of passes per hour increases with hourly flow level and percent nonautomobiles within the ranges studied. It is interesting that the ratio of number of passes in the passing lane to the number of vehicles entering the passing lane is about 50 percent at a nonautomobile percentage of 6 to 8 and increases to a ratio of 67 percent at a nonautomobile percentage of 40.

The effect of hourly flow level and percent nonautomobiles on change in percent time delay using the Route 41 site data is shown in Figure 9. The curves showing +2, 0, −2, −4, −6, −8, −10, and −12 changes in percent time delay are indicated. The detailed pattern is a little irregular but the overall pattern is as expected. The largest reductions in percent time delay occur under low flow levels with a high percentage of nonautomobiles. The smallest reductions (actually an increase) in percent time delay occur under high flow conditions with few nonautomobiles present.

The effect of hourly flow level and percent nonautomobiles on mean journey speeds using the Route 41 site data is presented in Figure 10. The curves showing speeds between 55

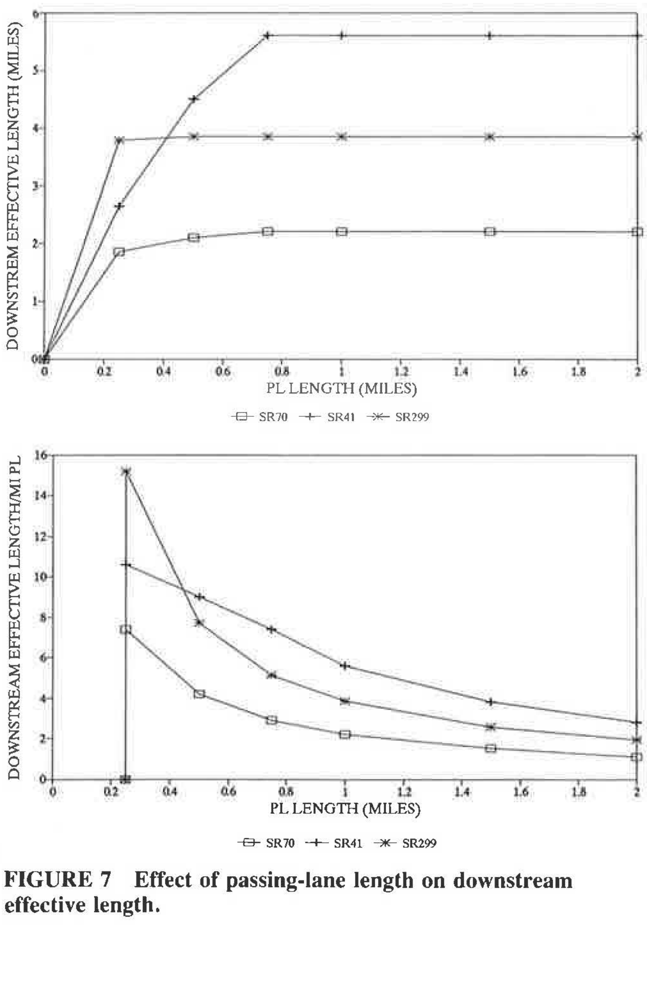

FIGURE 7 Effect of passing-lane length on downstream effective length.

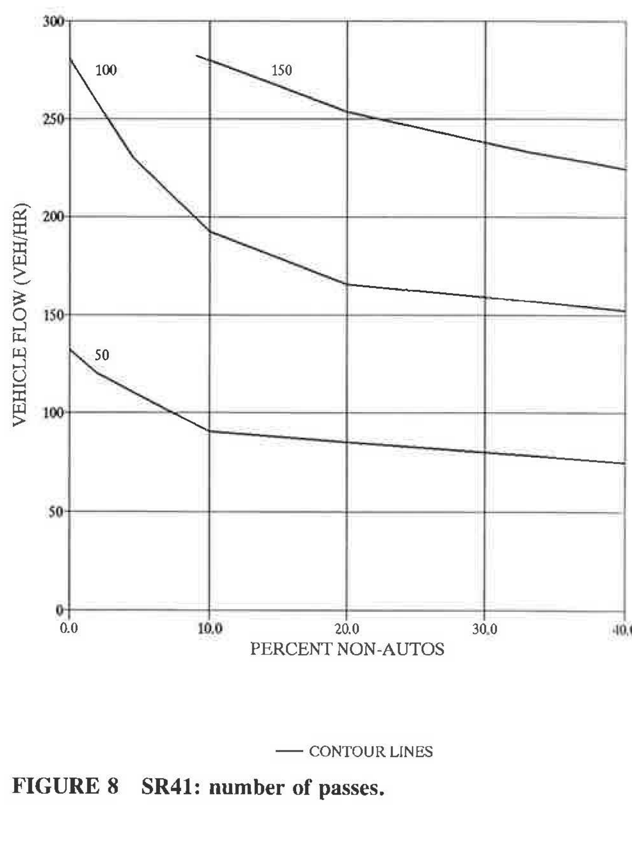

FIGURE 8 SR41: number of passes.

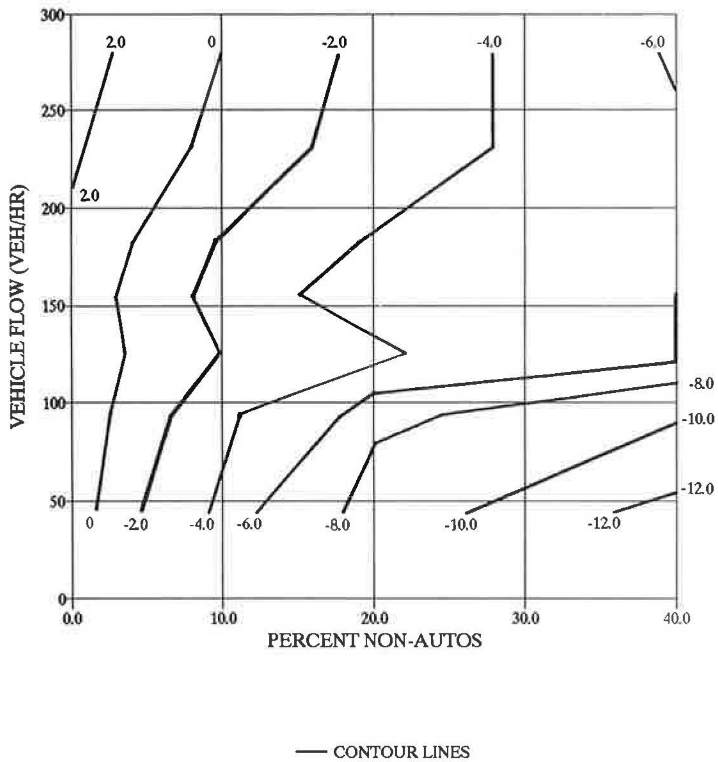

FIGURE 9 SR41: change in percent time delay.

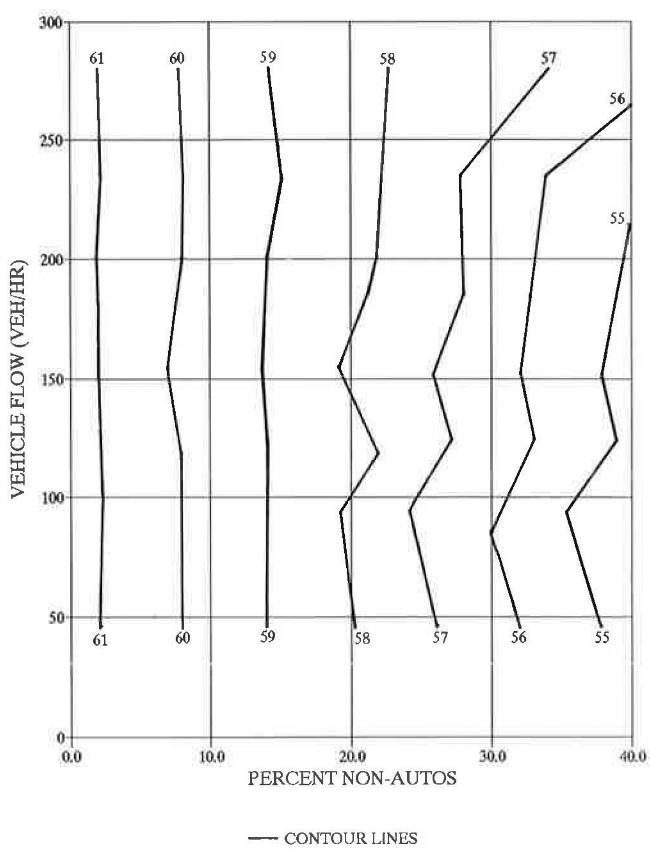

FIGURE 10 SR41: mean journey speed (mph).

and 61 mph in 1-mph increments are indicated. For the range in flow levels considered, the flow level had no effect on mean journey speeds. On the other hand, mean journey speeds decreased from 61 to 55 mph as the proportion of nonautomobiles increased from 0 to 40 percent.

In summary, hourly flow levels and percent nonautomobiles affect to various degrees the number of passes, changes in percent time delay, and mean journey speeds. While number of passes is primarily affected by flow level, changes in percent time delay and mean journey speeds are primarily due to percent nonautomobiles.

SUMMARY

In this study of traffic performance and design of passing lanes on two-lane, two-way rural highways, the four major research emphases were

- Field studies of traffic performance and design of five California passing lanes,
- Before-and-after field study of one of the passing-lane sites to assess two passing-lane entrance designs,
- Field observations of passing maneuvers for five site situations to determine the frequency of passing maneuvers as related to traffic flow levels and vehicle types, and
- Sensitivity analysis through simulation to determine the effect of passing-lane length on traffic performance, the effect of passing-lane length on downstream traffic conditions, and the effect of flow level and vehicle composition on passing-lane performance.

The field studies of traffic performance and design of five California passing lanes provided an operational assessment and raised questions about passing-lane entrance design, the consideration of using number of passes in the passing lane as a measure of performance, and the need for sensitivity analysis through simulation.

The before-and-after field study of two passing-lane entrance designs demonstrated that the modified design significantly increased the proportion of traffic that would enter the passing-lane section in the basic lane. There was no indication of traffic performance improvements, however, using existing measures of effectiveness.

Field observations of passing maneuvers clearly indicated that the number of passes per passing-lane length was a very good measure of effectiveness of passing lanes. Equations were developed for estimating the number of passes as a function of traffic flow level for each of the five data sets. The vehicle-type pattern of passes observed were not randomly distributed; automobiles passing nonautomobiles were much higher than expected, and nonautomobiles passing automobiles were much lower than expected.

The sensitivity analysis through simulation identified that passing lanes of 0.25 to 0.75 mi appeared to be the most effective; spacing of 2 to 5 mi between such passing lanes appeared appropriate depending on downstream roadway and traffic conditions. Estimates of the number of passes that would likely occur at three of the field sites under various traffic flow levels and vehicle composition mixes were determined.

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