Design Guide for Auxiliary Passing Lanes on Rural Two-Lane Highways

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The objective of this research was to determine the conditions under which the construction of an auxiliary passing lane on two-lane rural highways is economically justified. A conflict-opportunity model was developed which estimates the number of potential passing conflicts with an opposing vehicle that a given traffic volume will generate. By assigning a cost-per-conflict opportunity and adjusting for the length of passing zones available, the passing-accident costs for a given roadway segment were estimated. Based on prior research, a deterministic reduction of this cost was used to estimate the savings that would result from an auxiliary passing lane. The TWOWAF model was then used to simulate delay and travel speeds for trucks and passenger vehicles for typical highway sections both without and with an auxiliary passing lane. Benefit-cost analysis was applied to determine the average daily traffic (ADT) levels at which an auxiliary passing lane would be economically justified as a function of section length, percent passing zones available, cost per conflict, construction cost, and discount rate.

Rural, two-lane highways constitute over 80 percent of the national highway system mileage but carry only approximately 35 percent of the total annual vehicle-miles of travel (*1*). Yet this system is responsible for over 48 percent of all fatal motor vehicle accidents and 30 percent of all injury accidents each year (*2*). On this rural two-lane system, the head-on collision is the second most common type of rural fatal accident, responsible for approximately 5,100 fatalities annually (*3*). One of the most common and complex rural, two-lane operational maneuvers, and one which has the potential to cause head-on or severe accidents is the passing maneuver. But it is also the passing maneuver which has the capability to substantially reduce rural, two-lane travel time and delay. Thus, on the rural two-lane system there exists a need to improve safety performance by reducing severe accidents while maintaining or improving traffic operational performance.

Prior research has suggested that one alternative for improving rural roadway passing performance is to design for passing opportunities such that the following driver will generally not become intolerant to delay by having to seek too diligently for an acceptable passing gap in opposing traffic (*4*). If passing opportunities were provided either by the absence of opposing traffic or by the placement of passing lanes at appropriate locations, much of the accident cost of the passing maneuver might be eliminated. On many rural highways this minimized probability of accident and minimized delay occur frequently where the volumes of traffic are light, and thus the probability of meeting an opposing vehicle while performing the passing maneuver is small. However, where the volume of traffic increases and the percent passing decreases such that delay and the probability of an accident become high, the construction of auxiliary passing lanes or various types of four-lane highways may be justified to provide for additional safe passing opportunities.

Because of the expense associated with freeway construction, auxiliary passing lanes have begun to receive greater attention. Past research on the operational aspects of passing lanes by Franklin Research Institute (*5*) concluded that road widening, shoulder widening, and added lane construction would have marginal benefit-cost ratios less than 1.0. However, delay benefits were not included in the study because of insufficient data relating delay savings to improvements in operating speed. In another study, Harwood, St. John, and Warren (*6*) performed an operational evaluation of auxiliary passing lane (non-truck climbing) performance and concluded that passing lanes decrease the percentage of vehicles platooned, increase the rate of passing maneuvers, and have a small effect on mean travel speeds. A concurrent safety evaluation of passing lanes indicated that a passing lane can reduce the total accident rate by 38 percent with an approximate 29 percent reduction of fatal and injury accident rates.

Past research on the economic desirability of auxiliary lanes has concentrated on identifying those geometric and traffic conditions under which a truck climbing lane is warranted (*5, 7, 8*). Little consideration has been given to the need for passing lanes where truck climbing lanes are not warranted. The objective of the research reported herein was, therefore, to establish general guidelines for the construction of auxiliary passing lanes on two-lane rural highways based on an economic analysis of road-user benefits versus construction and maintenance costs (*9*). The scope of the research was confined to conditions found on those State Primary Highway System roads having pavement widths of 20 feet or greater. These roads represent approximately 78 percent of the entire State Primary Highway System (*10*).

PASSING CONFLICT MODEL

Models for accident occurrence are generally difficult to develop and calibrate due to the rare nature of an accident. However, in research by Stockton, Mounce, and Walton (*11*), a conflict analysis of the passing maneuver for low-volume, rural, two-lane roadways was performed using the Poisson distribution as the assumed empirical accident model. This analysis con-

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sidered the probability of simultaneous arrivals of two vehicles of different speeds in one direction and the probability of opposition to the resultant passing maneuver from the opposing vehicle. This methodology was used to develop an expected number of annual conflicts. Although developed for low-volume, rural roadways, the above procedure was judged to offer a reasonable basis for estimating the number of passing conflict opportunities on the higher volume State Primary Highway System. It was further assumed that any passing conflict that occurs with an opposing vehicle can be assigned a proportional share of the total passing-accident costs on two-lane roadways.

In adapting the above passing conflict opportunity model to this research, it was assumed that

1. A conflict opportunity is defined as that maneuver of vehicle A (following), B (lead), or C (opposing), such that the driver of the following vehicle will have less than the AASHTO time exposed to traffic in the left lane (t_2) plus the clearance time (t_3), which is assumed to be a minimum of 16 seconds when the pass is completed (*12*).
2. Average speed is 55 mph, which is the average of all three speeds of the lead vehicle (50 mph), following vehicle (60 mph) and opposing vehicle (assumed 55 mph).
3. Passing sight distance is at least 1,000 feet, which is the minimum operational (distance considered acceptable for passing operations at 60 mph speeds). Where this sight distance is not available, it is assumed the pass will not be completed. This minimum sight distance conforms to the requirements of the Manual on Uniform Traffic Control Devices for Streets and Highways (MUTCD) for the marking of no-passing zones at 60 mph (*13*).
4. The probabilities of passing and arrival of opposition assume that all vehicles arrive during a 1-hour analysis period.
5. A passing situation occurs when a pair of vehicles arrive following a Poisson distribution within an assumed constant headway of 2 seconds or less.
6. The average directional distribution is assumed to be 50/50.

The probability of a passing conflict opportunity occurring can be calculated as follows for a highway with an assumed traffic volume of 250 vehicles per hour (vph) and a 50/50 directional distribution. From the Poisson distribution

$$P(X) = e^{-m}mx/x! \qquad (1)$$

The probability that any two vehicles will be close enough for the following driver to desire to pass in any one hour is

$$P(h_t < 2 \text{ sec}) = 1 - P(0) - P(1) = 0.002302 \qquad (2)$$

and the number of such passing opportunities per hour, per direction is

$$[P(h_t < 2 \text{ sec})] \times 1800 = 4.15 \qquad (3)$$

In the passing maneuver, vehicle A will be exposed to traffic in the left lane for an assumed 16-second time interval. If an opposing vehicle appears within this 16-second interval, then by definition a conflict with the opposing vehicle is assumed to have occurred. The probability of arrival of the opposing vehicle in the 16-second interval is given by

$$P(1 \text{ or more}) = 1 - P(0) = 0.426 \qquad (4)$$

The number of such conflicts is given by the product of the number of passing opportunities per hour and the probability of the arrival of an opposing vehicle during the passing maneuver, or 1.77 passing-conflict opportunities per hour, per direction.

The above conflict situation occurs over an 18-second interval (including the two-second headway for vehicle A) during which time vehicle A is traveling at 60 mph and traverses a distance of 0.3 miles. Placing the conflict rate on a vehicle-mile basis

$$\begin{aligned}\text{Conflict opportunities/veh-mi/hr} &= 1.77/0.3/250 \\ &= 0.0236\end{aligned} \qquad (5)$$

Thus, over a 1-mile segment under the above traffic conditions and assumptions, there will develop approximately 5.91 (1.77/0.3) conflict opportunities with opposing vehicles during the hour the 250 vph volume level exists, or each vehicle will experience 2.36 conflict opportunities in every 100 miles of travel regardless of the direction of travel. Utilizing the above methodology, probable conflict opportunities per mile, per hour were developed over two-way volume levels ranging from 0 to 1,800 vph as shown in table 1. It was further assumed that these values would be reduced in direct proportion to the amount of available passing sight distance on the highway segment. Thus, where 50 percent passing sight distance is available, the conflict opportunities would be reduced from 5.91 to 2.95 conflicts per mile, per hour. This assumption is a conservative approach because where passing is severely restricted, passing conflicts may actually increase to compensate for the reduced opportunity to pass.

PASSING-ACCIDENT COSTS

The presence of an auxiliary passing lane is intended to reduce the number of catastrophic passing accidents that occur due to the presence of an opposing vehicle in the passing maneuver. Such accidents normally involve high-speed head-on, or run-off-the-road accident types. To identify the value of aggregate passing-accident costs, and, ultimately, the pro rata individual conflict costs, it was necessary to quantify the cost of passing-related accidents caused by the presence of an opposing vehicle. However, the lack of detailed data on passing accidents required that an approximate accident cost framework be developed using summary statistics from available data bases. Using data published by the Federal Highway Administration and the National Safety Council (*10, 14*), the distribution of accidents per year by severity on two-lane rural highways was estimated as

Fatal Accidents: 7,469

Injury Accidents: 148,591

PDO Accidents: 1,578,800

Total: 1,734,839

In a study conducted by the Franklin Institute Research Laboratories (*5*), it was concluded that approximately 10 percent of the accidents on the two-lane system are passing related. Therefore, the total number of passing-related accidents was estimated as 10 percent of the above value, or 173,484 per

TABLE 1 NUMBER OF ANNUAL PASSING CONFLICTS IN THE PRESENCE OF AN OPPOSING VEHICLE

HOURLY VOLUME	AVERAGE VOLUME (VPH)	HOURLY MILES* (MILLIONS)	PASSING CONFLICT RATE (#/MI/HR)	ANNUAL PASSING CONFLICTS (MILLIONS)
0 - 100	50	2041.1	.0605	123.5
100 - 200	150	333.7	1.437	479.5
200 - 300	250	130.2	5.91	765.8
300 - 400	350	16.7	14.37	239.9
400 - 500	450	19.3	27.27	526.3
500 - 600	550	5.4	44.60	240.8
600 - 700	650	2.1	66.29	139.2
700 - 800	750	3.2	92.03	294.5
800 - 900	850	1.1	122.0	133.7
900 - 1000	950	2.4	154.3	370.3
1000 - 1100	1050	0	190.1	0
1100 - 1200	1150	0.4	228.9	91.6
1200 - 1300	1250	0.5	270.1	135.0
1300 - 1400	1350	0	313.5	0
1400 - 1500	1450	0	358.9	0
1500 - 1600	1550	0.3	406.2	121.9
1600 - 1700	1650	0	455.1	0
1700 - 1800	1750	0.1	505.5	50.5
			TOTAL	3712.5

*Ref. 10

year. This aggregate number of passing-related accidents is consistent with NSC statistics, which indicate that 3.2 percent of all rural accidents (5,188,500), or 166,032 rural passing accidents, are caused by improper overtaking (*14*). Other research has estimated that 3.5 percent of all passing accidents involve a fatality, and 42 percent of all non-fatal accidents involve personal injury (*10*).

Not all of the above-mentioned accidents can be attributed to the presence of opposing vehicles because passing accidents on two-way rural roads may also occur at intersections (driveways), railroad crossings, narrow bridges, roadside developments, or other such sites. The results of other research indicate that 20 percent, 58 percent, and three percent of all passing-related accidents occurred at "special situation" locations in the states of North Carolina, Texas, and Utah respectively (*15*). These particular states were selected to permit a representation of geographical distributions to approximate the effects of flat, rolling, and mountainous terrains. The remaining non-special situation passing-related accidents, which constitute 80 percent, 42 percent, and 97 percent, respectively, of all rural, two-lane passing accidents, were therefore assumed to be high-speed passing maneuvers that could result in catastrophic accidents.

For this research, it was assumed that these remaining non-special situation passing accidents are passing accidents that occur in the presence of an opposing vehicle such that the

TABLE 2 ESTIMATES OF THE COST OF EACH CONFLICTING PASS DUE TO THE PRESENCE OF AN OPPOSING VEHICLE

	Low	Average	High
Estimated Total Passing Accident Costs per Year (Millions)	$1616.1	$2424.2	$3232.3
Estimated Total Conflicts Per Year (Millions)	3712	3712	3712
Estimated Cost per Conflict (two-way)	$ 0.44	$ 0.66	$ 0.88

presence of the opposition vehicle contributed to the occurrence of the accident. Because the Utah data were reportedly inaccurate, due to underreporting, only the Texas and North Carolina data were used to establish boundary conditions for opposing vehicle-related passing accidents. Values of 40 percent, 60 percent, and 80 percent were therefore used as estimates of low, average, and high opposing-vehicle passing-related accidents. The actual value will depend upon the general terrain, roadway characteristics, and other factors appropriate to a particular state or region within a state.

Using 1978 data, passing-accident costs were assumed to be $300,700 for a fatal accident, $15,800 for a personal-injury accident, and $750 for a property-damage accident (*16*). Combining these values with the estimated opposing vehicle-related, passing-accident frequency data, total nationwide passing-accident costs were estimated to range from $1.6 to $3.2 billion per year. These accident costs were divided by the number of annual passing conflicts in the presence of an opposing vehicle for volumes ranging from 0 to 1,800 vph, as listed in table 1. The resulting estimated proportional cost associated with each passing conflict opportunity is shown in table 2. A comparison of the estimated passing conflict cost over various average daily traffic (ADT) volumes is presented in figure 1. It may be noted that the 2,000 to 5,000 and the 5,000 to 10,000 ADT ranges appear to be generating costs far in excess of other ADT levels. This, in general, suggests that a substantial number of miles of rural two-way, two-lane mileage in the 2,000 to 10,000 ADT range should receive consideration for upgrading to freeway standards or being provided with auxiliary passing lanes to reduce conflict and accident costs.

PASSING LANE EFFECTIVENESS

A study by the California DOT reported on the accident reduction potential attributable to the construction of passing lanes on two-lane rural highways (*17*). This study examined 19 projects that reconstructed over 48 miles of rural roadway from their original two-lane cross-section to a three-lane cross-section composed of the original roadway plus a third lane for passing. It was found that auxiliary passing lanes can be expected to reduce fatal accidents by approximately 60 percent, personal injury accidents by approximately 20 percent, and property damage accidents by approximately 20 percent. Applying these effectiveness measures to the previously estimated nationwide passing-accident data, the estimated annual dollar savings that could be expected if auxiliary passing lanes

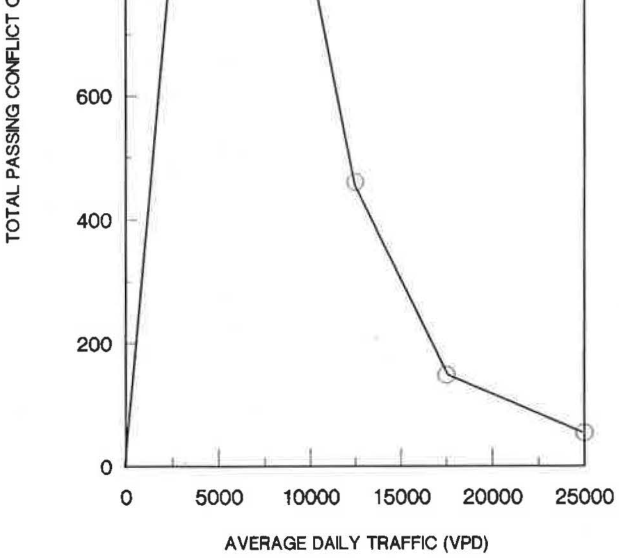

FIGURE 1 Comparison of passing conflict costs over various average daily traffic volumes.

TABLE 3 ESTIMATED PASSING ACCIDENT COST SAVINGS PRODUCED BY AUXILIARY PASSING LANES ANNUALLY

Accident Type	Cost Per Occurrence	Estimated Total Savings ($\$x10^6$) Low	Average	High	% of Total
Fatality	$300,700	438.1	657.3	876.2	71
Injury	$ 15,800	171.3	256.9	324.6	28
PDO	$ 750	5.9	8.7	11.7	1
Total		615.3	922.9	1230.5	100

were constructed on all two-lane state primary highways are shown in table 3. A comparison of the total cost savings to the total passing-related accident costs indicated that the construction of auxiliary passing lanes may reduce by approximately 38 percent the total cost of passing-related accidents. Thus, for purposes of this research, it was assumed that an auxiliary passing lane would be 38 percent effective in reducing opposing vehicle-related passing accident costs.

To examine the benefits of reduced vehicle operating cost and travel time savings, it was necessary to simulate traffic flow conditions both with and without the presence of an auxiliary passing lane. The TWOWAF model was used for this purpose (*10, 19*). An experimental design was developed to generate simulation data that could be used to estimate the travel-time and vehicle-operating-cost savings associated with auxiliary passing lanes. Parameters that were assumed to be randomized and held constant include

1. Alignment. A flat, tangent alignment was assumed for the simulation modeling. The influence of horizontal and vertical curves was introduced by varying the percent of roadway with no-passing zones.
2. Sight Distance. A minimum of 1,000 feet was defined as available except where limited by no-passing zones.
3. Desired Speeds. A speed of 55 mph was assumed for autos with a standard deviation of 5.3 mph. However, because average truck speeds in the 10-year period preceding the imposition of the 55 mph speed limit were 6 mph below passenger speeds, it was assumed that trucks operate at speeds 7.5 mph below passenger car speeds (*20*). An examination of this speed reduction for trucks indicated that this 7.5 mph assumption reduced the speed of all vehicles approximately 3 mph and caused an increase in delay to all vehicles of approximately 10 percent compared to all vehicles operating at identical speeds. These overall reductions were judged to be consistent with the general effect of trucks on rural two-lane roadways. The assumed standard deviation for trucks speeds was also 5.3 mph.
4. Directional Distribution. For the purpose of developing average speed and delay models, A 50/50 split was assumed as the most common directional distribution on two-lane rural roads.
5. Traffic Composition. A traffic stream composed by 10 percent trucks was assumed.

Independent variables used in the simulation modeling were ADT volume, percent of the highway with permitted passing, and length of highway section being considered for auxiliary passing-lane treatment. ADT was varied from 2,000 to 9,500 vehicles per day. The percent passing was varied from zero to 100 percent with no-passing zones introduced in 528-foot segments. Section length was defined in terms of a replicated standard passing lane module consisting of one passing lane in each direction within a two-mile module, and varied from two miles to ten miles in total length. The selection of these lengths corresponds to the California study, which recommended alternating the direction of the passing lane each mile (*17*). Based on this recommendation, the assumed passing lane plan view is shown in figure 2.

The full experimental design would have required 880 cells to be tested. To reduce the computational requirements, the statistical technique of response surface methodology was applied (*22*). The TWOWAF simulation model was then used to develop the speed and delay values for both passenger cars and trucks. For the without-passing-lane configuration, data were generated for each flow direction and then averaged. Because the passing lane configuration could not be explicitly simulated by the TWOWAF model, an auxiliary passing lane was approximated by removing traffic volumes from the opposite direction, thus permitting passing only at specified one-mile intervals in one direction.

Stepwise regression analysis was used to develop the speed and delay relationships from the TWOWAF simulation data. The resulting delay models are listed below, where X_1 = one way volume (100 to 580 vph range), X_2 = section length (10,560 to 52,800 ft range), and X_3 = percent passing (0 to 100 percent range).

1. Without auxiliary passing lane:

Average passenger car delay (sec/mi)

$$= -0.475 + 0.020X_1 + 0.000139X_2 - 0.020X_3 \qquad (6)$$

This model provided an R^2 of 96 percent with normal plots of residuals.

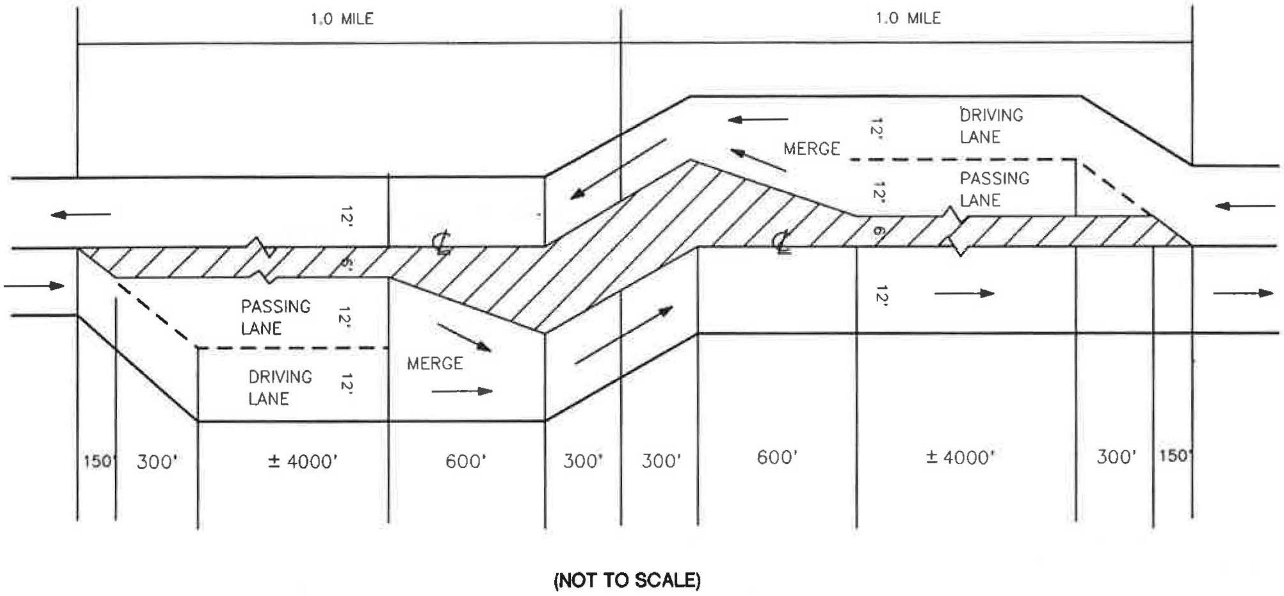

FIGURE 2 Typical passing lane horizontal alignment.

Average truck delay (sec/mi)

$$= -1.82 + 0.0095X_1 + 0.0001X_2 - 0.0078X_3 \qquad (7)$$

This model provided an R^2 of 89 percent with normal plots of residuals.

2. With auxiliary passing lane:

Average passenger car delay (sec/mi)

$$= 0.250 + 0.017X_1 \qquad (8)$$

This model provided an R^2 of 88 percent with normal plots of residuals.

Average truck delay (sec/mi)

$$= 0.0038 + 0.0083X_1 + 0.000029X_2 \qquad (9)$$

This model provided an R^2 of 63 percent with normal plots of residuals.

Examination of the above delay models indicates that the traffic volume, percent passing, and section lengths are all significant variables for a two-lane roadway. However, with an auxiliary passing lane in place, delay is primarily dependent upon the traffic volume. These delay relationships may be expected, since delay should be a function of all three independent variables when an auxiliary lane does not exist. However, with the addition of an auxiliary passing lane, the effect of percent passing becomes insignificant because passing is normalized at 50 percent.

Vehicle operating costs vary as a function of travel speed and longitudinal grade. Because longitudinal grade was constrained to 0 percent, the only parameter assumed to affect running cost was the speed of the various vehicles with and without the presence of an auxiliary passing lane. Regression analysis was again used to develop the following speed models from the TWOWAF simulation data. The independent variables are as defined above.

1. Without auxiliary passing lane:

Average passenger car speed (ft/sec)

$$= 79.8 - 0.0189X_1 - 0.00013X_2 + 0.018X_3 \qquad (10)$$

This model provided an R^2 of 96 percent with normal plots of residuals.

Average truck speed (ft/sec)

$$= 70.3 - 0.00798X_1 - 0.000088X_2 + 0.006X_3 \qquad (11)$$

This model provided an R^2 of 96 percent with normal plots of residuals.

2. With auxiliary passing lane:

Average passenger car speed (ft/sec)

$$= 79.1 - 0.0174X_1 \qquad (12)$$

This model provided an R^2 of 87 percent with normal plots of residuals.

Average truck speed (ft/sec) $= 68.3 - 0.0077X_1$ (13)

This model provided an R^2 of 66 percent with normal plots of residuals.

An examination of the speed models indicates that volume, percent passing, and section length are significant variables in the case of a two-lane roadway, while traffic volume is the only significant variable when an auxiliary passing lane is added. The models were used in conjunction with 1977 running-cost data (*22*) to estimate vehicle operating costs.

PASSING-LANE COSTS

To determine typical passing lane quantities and construction cost, it was assumed that most passing lanes would require some minor earthwork, 6 inches of aggregate base course, and 6 inches of asphalt surface course for the addition to the existing two lanes, and 1.5 inches of asphalt resurface over the entire length of the passing lane project. With this esti-

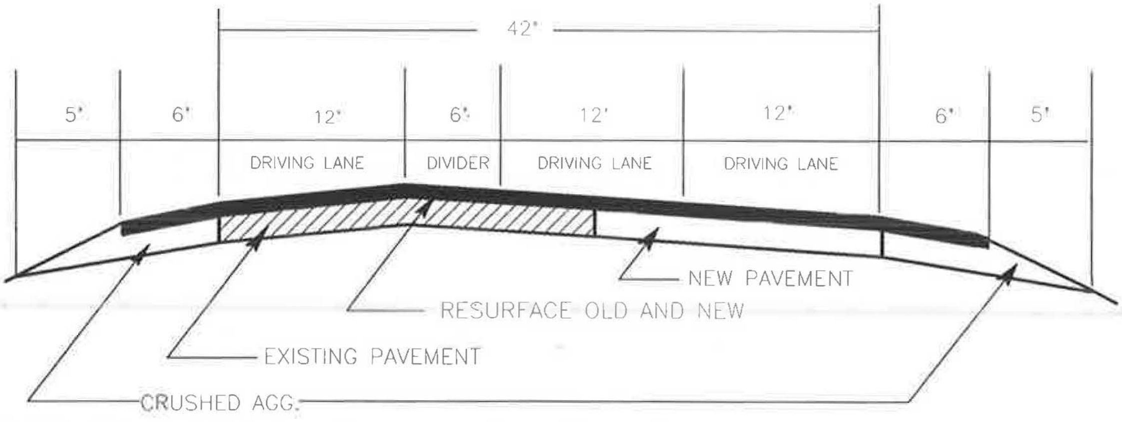

FIGURE 3 Typical APL cross section.

mate, figure 3 presents a typical cross-section of an auxiliary passing lane added to the outside of an existing two-lane roadway. It should be noted that the passing lane will vary from one side of the centerline to the other after each mile (thus the centerline location remains constant), and that, assuming a 42-foot surface width and 12-foot lanes, a six-foot median exists between opposing lanes. Using 1978 cost data, the initial cost of the typical auxiliary passing lane was estimated to range from \$250,000 to \$400,000 per mile. Maintenance cost savings attributable to the construction of an auxiliary passing lane plus overlay surface on the existing pavement was estimated at \$2,000 per mile, per year. The salvage value at the end of an assumed 20-year service life was estimated at \$35,000 per mile, which consists of the cost of right-of-way and one-half the cost of earthwork from the original estimate as suggested by AASHTO (*22*).

ECONOMIC ANALYSIS

The final task of the research was to incorporate the conflict, speed, delay, and cost relationship in an economic analysis model that would reveal the relative attractiveness of an auxiliary passing lane as traffic volumes vary over peak, off-peak, weekday, weekend, and monthly levels for highway sections of a given length and percent passing. By subtracting annual without-passing lane road-user costs from the with-passing lane user costs, an estimate of the total benefits of an auxiliary passing lane were determined. These benefits were then compared to the cost to construct and maintain an auxiliary passing lane after all costs and benefits were discounted to net present value. All cost data were adjusted to reflect 1978 conditions. The methodology used corresponds to that outlined in the 1977 AASHTO guidelines on economic analysis (*22*).

The results of the benefit-cost analyses were used to develop a break-even model that used two discount rates (four and eight percent), two construction costs (\$250,000 and \$400,000 per mile), and three conflict costs (\$0.22, \$0.33, and \$0.44 per conflict). Regression analysis was used to develop a break-even model which, for a given set of conditions, would indicate the minimum ADT at which an auxiliary passing lane would be economically justified. This would be that ADT associated with a benefit-cost ratio of 1.0. The resulting model is expressed as

$$\mathrm{ADT} = \exp[(17.0 - 0.369X_1 - 0.386 \ln X_2 + 0.138X_3 - 1.84X_4 + 0.00232X_5)/1.82] \tag{14}$$

where:

X_1 = section length
X_2 = length of roadway with permitted passing (%),
X_3 = discount rate (%),
X_4 = conflict cost (\$), and
X_5 = construction cost (\$1,000's).

An examination of the structure of the break-even model indicates that as the section length (number of replicated passing lanes constructed) increases, the ADT required to economically justify construction of the auxiliary passing lane section decreases, as it does when the percent passing and conflict cost are increased. However, when the discount rate or the cost of construction increases, the ADT at which the auxiliary passing lane is justified increases. Both of these observations conform to general expectations because more passing lanes (length), high percent passing available on the old road, and higher conflict costs should lower the ADT required to economically justify an auxiliary passing lane.

To simplify use of the break-even model, a nomograph was developed and is presented in figure 4. The nomograph is based on a 4 percent discount rate which has been recommended for safety projects (*16*) and includes values for passenger and truck delay costs (\$3.50 and \$10.00 per hour, respectively). To use the nomograph:

1. Estimate the per-mile construction cost of the auxiliary passing lane for the site as well as the cost of conflicts for the region or state. These estimates may be updated to current year dollar costs if it is assumed that any cost increases since 1978 are constant over all costs and all benefits. However, a better approach is to reduce current cost to 1978 cost levels.
2. Connect these estimated values to turn line 1.
3. Determine the extent to which passing is permitted on the existing road by comparing the directionally averaged length of no-passing zones to the total roadway length.
4. Connect turn line 1 and the percent passing to turn line 2.
5. Determine the length of roadway section that is to receive

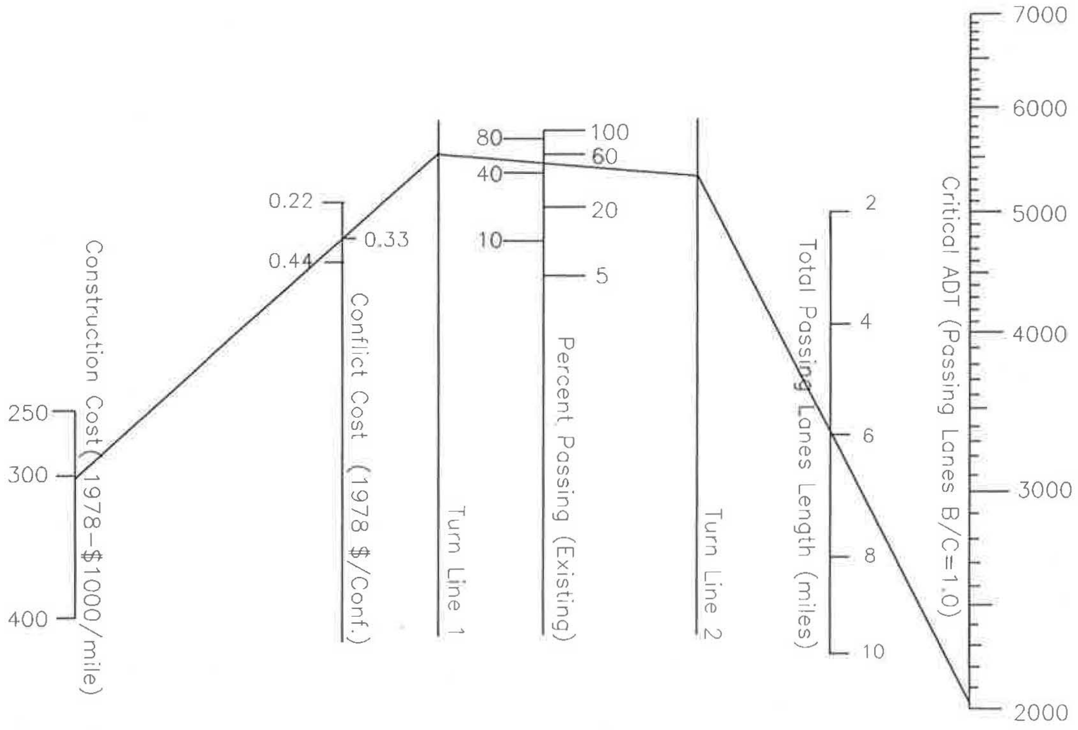

FIGURE 4 Economic analysis nomograph.

new passing lane construction, and connect the point on turn line 2 to the length to establish the ADT that must be exceeded to economically justify construction of the auxiliary passing lane. Conversely, the existing ADT at the site may be connected to the point on turn line 2 to determine the length of section for which the construction of auxiliary passing lanes is justified.

CONCLUSIONS

The auxiliary passing lane benefit-cost model and the nomograph for the critical ADT are based on a number of assumptions that constrain their general applicability.

The conflict-probability model estimates the number of passing conflicts that will occur on a two-lane roadway. The assumption of linear reduction to conflicts as the percent passing is reduced should be considered a limitation because, for some sites, a reduction in the percent passing may in fact stimulate the presence of conflict rather than reduce conflicts. However, since no research exists regarding an increase in accidents or conflicts as the percent passing is varied, the assumption of direct linearity appears reasonable. When figuring the cost per conflict, the relationship of intersection (special situation) passing accidents to all passing accidents was a determinant to the use of low, average, or high cost-per-conflict values, depending on the number of intersection-related passing accidents compared with all passing accidents. Care needs to be exercised in selecting an appropriate value for any case study application of the design warrant.

Similarly, with regard to the cost per conflict and the benefit to be derived from the construction of an auxiliary passing lane, the assumption of the accident reduction value of 38 percent of the original condition was based solely on California data. With further study of the safety benefits of other auxiliary passing lanes, this estimate of accident reduction potential may also vary, and may be increased to reflect the passing lane safety savings due to reduced passing accidents at special situation sites such as intersections and driveways.

The two-way traffic simulation model (TWOWAF) used to estimate speed and delay was capable of modeling a passing lane within the test section length only by eliminating traffic in the opposite direction. Thus, for a 6-mile segment, passing lanes were artificially introduced into alternating 1-mile lengths (1 mile in each direction) for the total 6-mile length. This was accomplished by restricting traffic flow in the opposing direction and permitting passing only at 1-mile intervals where passing is permitted. Future research should use a newer version of TWOWAF, which contains a passing-lane model capable of placing a specific size passing lane anywhere, and in either or both directions within the test section, and then developing several other general warrants where only one such lane, and not successive passing lanes, are used over varying length test sections.

Further limitations of the break-even model arise from the use of many assumed average values that were input to the TWOWAF traffic simulation model to generate travel speeds and delays for passenger and truck vehicles. Some of these parameters include vehicle composition, desired travel speeds and standard deviations of speed, available passing-sight distance and passing zone locations, as well as an assumed tangent roadway with a flat terrain, which inhibited truck speeds to 7.5 mph below passenger vehicle speeds. While it was necessary to normalize these and other roadway characteristics due to financial limitations placed on this research, a major revision of one or more of these assumed average conditions might cause the break-even model to overestimate or underestimate benefit-cost ratios and critical ADTs.

In summary, the model developed in this research was designed to assist engineers in evaluating the need for auxiliary passing lanes on two-lane highways. Where the critical ADT is determined to be substantially larger or substantially smaller than the ADT that exists at a site, many of the above limitations are expected to have only minor impact and may not affect the benefit-cost ratio or the critical ADT significantly. Where the critical ADT is reasonably close to the ADT that exists at the site in question, a detailed economic analysis should be undertaken using site-specific, TWOWAF-generated speed and delay data. A microcomputer program is available to provide detailed economic analysis of specific sites with specific input parameters.

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