Optimal Work Zone Lengths for Four-Lane Highways

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(Reviewed by the Urban Transportation Division)

Abstract: Highway pavement maintenance is very expensive not only in terms of costs to the responsible agencies but also in terms of disruptive delays to users. Construction and maintenance activities on four-lane highways (with two lanes in each direction) often require the closure of one of the two travel lanes. Longer work zones tend to increase the user delay costs. Maintenance work can be performed more efficiently, i.e., with fewer repeated setups, in longer zones. A relatively simple mathematical model is developed to optimize work zone lengths on four-lane highways where one lane in one direction at a time is closed. The objective is to minimize the total cost, including the agency cost, the accident cost, and the user delay cost. The optimized variable (e.g., work zone length) and the sensitivity results generated from a numerical example are presented in this study. With user-specified input parameters, this model can be used to optimize work zones on four-lane highways for a wide variety of circumstances.

INTRODUCTION

Highway pavement maintenance is very expensive. The delay costs to users may well exceed the maintenance expenditures by responsible highway agencies. Since both the agency and user costs are significantly influenced by work zone size, it is highly desirable to determine the optimal highway work zone size (i.e., zone length) so as to minimize costs to motorists as well as to highway agencies. On multilane highways, traffic flow is slowed down and the capacity is reduced if lanes are closed for maintenance activities. If incoming flows exceed the capacity of the open lanes, queues and associated delays are generated. Travel times may also increase due to reduced speeds through work zones. Such increases in travel times are also affected by the lengths of work zones.

Given a four-lane highway (two lanes per direction) with one closed lane in one direction, as shown in Fig. 1, the traffic in that direction uses the remaining lane. Since traffic volumes vary with time, the traffic flow approaching a work zone may exceed the zone's maximum discharge rate (i.e., capacity). In such situations, queuing delays are unavoidable unless the excess flow can be diverted (which also increases travel times in a different way). These queuing delays depend on the lengths of the work zones, the maintenance duration, and the magnitude of the approaching flow. During off-peak periods, the approaching flow may be less than the zone capacity. Therefore, the user delays are mainly caused by the reduced speed of vehicles through the zone.

In general, longer zones tend to increase the user delays, but the maintenance activities can be performed more efficiently (i.e., with fewer repeated setups) in longer zones. Since work zone lengths and maintenance duration significantly affect agency, user, and accident costs, it is important to find out what combinations of values for these variables are most effective under various circumstances.

This paper develops a simple and practical method for determining the work zone lengths that minimize a sum of agency, user, and accident costs, depending on the most important factors affecting such maintenance decisions for four-lane roads.

LITERATURE REVIEW

Highway maintenance issues concern transportation engineers, structural engineers, and construction management engineers, with different groups focusing on different aspects. Previous studies related to optimization of work zone length are few and limited in scope.

Krammes and Lopez (1994) provided recommendations on estimating the capacity of short-term lane closures based on 45 h of capacity counts at 33 different freeways with work zones in Texas between the years 1987 and 1991. Adjustments were suggested for the effects of the intensity of work zone activities, percentage of heavy vehicles in the traffic stream, and presence of entrance ramps near the beginning of a lane closure. Dudek and Richard (1982) presented more detailed information based on field data analysis for estimating road capacity during maintenance work. They considered lane closure strategies and obtained cumulative distributions of observed work zone capacities. In a later study (Dudek et al. 1986), they estimated capacities for work zones on four-lane highways.

Memmott and Dudek (1984) used a regression model to estimate the mean capacity for a work zone. The advantage of using the regression model was that most lane closure types were covered and the restricted capacity used for traffic management purposes could be reasonably estimated.

Since the travel delays of roadway users in a work zone are the primary determinant of user delay cost, studies related to speed and delay analysis for work zones were reviewed. In a study of traffic characteristics on Illinois freeways with lane closures, Rouphail and Tiwari (1985) evaluated the effects of the intensity and location of construction and maintenance activities on mean speeds through a work zone. The results showed that the mean speeds through a work zone decrease as the intensity of construction and maintenance activities in-

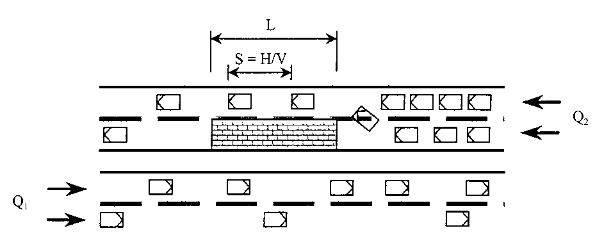

FIG. 1. Vehicle Movements in Work Zone

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crease. The mean speeds also decrease as the construction and maintenance activities move closer to the travel lanes. Pain et al. (1981) provided a detailed study of speeds in work zones. The mean speeds were found to vary depending on such factors as traffic volumes (e.g., in peak and off-peak hours), lane closure configurations (e.g., right lane closure, left lane closure, and a two-lane bypass), traffic control devices (e.g., cones, tubular cones, barricades, and vertical panels), and locations within work zones. Rouphail et al. (1988) derived various mean values and coefficients of variation to describe the speed change in work zones. They found that the average speed does not vary considerably at light traffic volumes and that the speed recovery time is longer at high traffic volumes. Their results also indicated that speed control has a very important role in reducing accident frequency.

Memmott and Dudek (1984) developed a computer model, called Queue and User Cost Evaluation of Work Zones (QUEWZ), and estimated the average speed in work zones to calculate user costs, including user delay costs and vehicle operating costs. The QUEWZ model determines the number of hours available for lane closures based on an assumed lane capacity and various traffic volumes. When traffic volumes were not large enough to cause congestion and queuing, the traffic delay was characterized entirely by the volumes and speeds. However, when congestion occurs, additional information (such as queue lengths) was needed to model the delay. Later, Richard and Dudek (1986) further confirmed the need for speed reduction in work zones and provided guidelines for implementing speed control to improve safety. Four speed control approaches, namely, flagging, law enforcement, changeable message signs, and effective lane width reduction, were discussed in that study.

A method for estimating vehicle delays and queue lengths on two-lane highways operating under one-way traffic control was developed by Cassidy and Han (1992). The average delays occurring over a given duration were obtained by using empirical data from a four-lane highway segment within a work zone. However, the work zone length was not optimized in that study.

McCoy et al. (1980) developed a method to optimize the work zone length by minimizing the road user and traffic control costs in construction and maintenance zones of rural four-lane divided highways. This method provided a framework for optimizing the lengths of work zones by minimizing the total cost, including construction costs, user delay costs, vehicle operating costs, and accident costs. The user delay costs were modeled based on average daily traffic (ADT) volumes, while the accident costs were computed by assuming that the accident rate per vehicle mile was constant in a work zone area. The optimal work zone length was derived based on 1979 data. Because the unit cost factors had changed considerably since 1981, McCoy and Peterson (1987) found the optimum work zone lengths to be about 60% longer than those used previously in the state of Nebraska.

Considering traffic safety in construction and maintenance work zones, Pigman and Agent (1990) conducted a statewide work zone accident analysis. The accident data were collected from the Kentucky Accident Reporting System (KARS) for the time period of 1983–1986. They found that the work zone accident rate varied from 36 to 1,603 accidents per 100 million vehicle miles (acc/100 mvm) on different highways.

McCoy and Peterson (1987) conducted a safety study for various lengths of work zones on four-lane divided highways. No relation was found between the lengths of work zones and accident rates or any of the speed distribution parameters, such as the standard deviation of vehicle speeds and the range of vehicle speeds. They also found the average accident rate was 30.8 acc/100 mvm on I-80 in the state of Nebraska between 1978 and 1984.

Various efforts to mitigate the impacts of work zones have been made by Janson et al. (1987). One such effort involving optimizing work zone traffic control design and practice, such as optimal control device design, optimal lane closure configuration, and optimal work zone length. Martinelli and Xu (1996) added the vehicle queue delay costs into McCoy's (1980) model. The work zone length was optimized by minimizing the total user cost, excluding the maintenance and accident costs. To estimate the roadway maintenance costs, Underwood (1994) analyzed the work duration and the maintenance cost per 10,000 m^2 for five different roadway maintenance activities (i.e., surface dressing, asphalt surface, porous asphalt, 10% patching, and milling out). The average maintenance costs were calculated based on prices quoted to highway authorities in the summer of 1993.

Most previous studies on work zones focused on the capacities of various work zones and the optimal work zone length on freeways. Only two studies (Zhou 1996; Schonfeld and Chien 1999) have been found for jointly optimizing traffic control and work zone length on two-lane highways, or for considering the effects of the maintenance cost incurred by highway agencies on optimal work zone length. Thus, Zhou (1996) developed a method for optimizing work zone lengths by minimizing the total cost including the user and the highway maintenance costs. Both the maintenance duration and construction cost functions were formulated and discussed in that study. Later, Schonfeld and Chien (1999) developed a mathematical model to optimize work zone lengths and traffic control on two-lane highways where one lane at a time was closed. By considering the aggregate effects of various work zone lengths and combined flow rates, their method provided a practical approach for reducing both traffic delays and maintenance costs. In that study, traffic control and work zone lengths are jointly optimized, while unbalanced traffic flows in both directions were considered. However, accidents were not considered in both studies.

METHODOLOGY AND ASSUMPTIONS

The basic method followed here is to formulate a total cost objective function and use it to optimize work zone lengths. The travel and queuing delays to users are formulated with deterministic queuing models.

The total cost function includes all cost components that significantly influence the optimal work zone length. The cost function is minimized by using the classical optimization approach, i.e., setting derivatives equal to zero and solving. Closed-form formulas are derived at several levels of complexity, to match the data availability and precision desired by users. The problem is formulated and solved very generally to encompass most conceivable circumstances and then the results are simplified to fit typical applications.

Several simplifying assumptions made in formulating this problem are listed below:

1. Traffic moves at a uniform speed through a work zone and at a different uniform speed elsewhere. Thus, accelerations, decelerations, and the shock wave effects are considered to be independent of the work zone length.
2. Vehicle arrival rates and discharge rates from queues (if any) may be approximated by uniform flows during a particular time period, since users can define arbitrarily short periods during which flows are roughly uniform.
3. The user delay cost may be represented by a constant average cost per vehicle hour. Thus, the delay cost for any vehicle is assumed to be proportional to the delay time.
4. The user travel cost may be represented by a constant average cost per vehicle hour. This reflects the dominant

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part of the occupants' time value in the travel cost per vehicle hour and the relatively lower effect of travel speeds on the cost per vehicle hour.

5. The traffic volumes in both directions are given. In practice, an equilibrium demand analysis that considers alternate routes and departure times may be needed to estimate traffic volume through work zones.
6. The total agency cost (C_M) for maintaining a zone of length L is a linear function of the form $C_M = z_1 + z_2L$, in which z_1 represents the fixed cost, independent of work zone length, for setting up the work for one zone, including setup for traffic control and for maintenance equipment. z_2 is the average additional maintenance cost per work zone lane kilometer.
7. The time required to complete the maintenance for a one-lane zone of length L is a linear function of the form $D = z_3 + z_4L$, in which z_3 represents the setup time and z_4 represents the additional time required per work zone kilometer.

The above assumptions yield a method that is simple enough and yet acceptable for many practical applications. However, future work should consider modifications to these assumptions. For instance, assumptions 3 and 4 may be easily extended to separate different classes of vehicles, such as trucks and buses, with different average costs per vehicle hour. Assumption 5 might be modified by computing the ''given'' volumes with a network equilibrium model. This seems unnecessary on rural four-lane highways, where few alternate paths are available and users seldom have prior information about work zones, but would be valuable for extending this modeling approach to dense and/or congested urban street networks.

MODEL FORMULATION

The objective function is the total cost including the user delay, the accident, and the agency costs. The user delay cost consists of the queue delay costs upstream of work zones and the moving delay costs through work zones. The queuing processes resulting from fixed demand on one open and one closed lane are illustrated in Fig. 2, which represents approaching traffic flow Q entering a work zone on a four-lane highway. The headway for the vehicles moving in the lane adjacent to the work zone is assumed to be H seconds. Therefore, the maximum discharge rate c_w of the work zone is 3,600/H vehicles per hour per lane (vphpl).

If the approaching volume Q exceeds the work zone capacity c_w, a queue forms, which then dissipates when Q falls below c_w. Otherwise, the queue delay is zero. The queue formation time D lasts from the beginning to the end of the

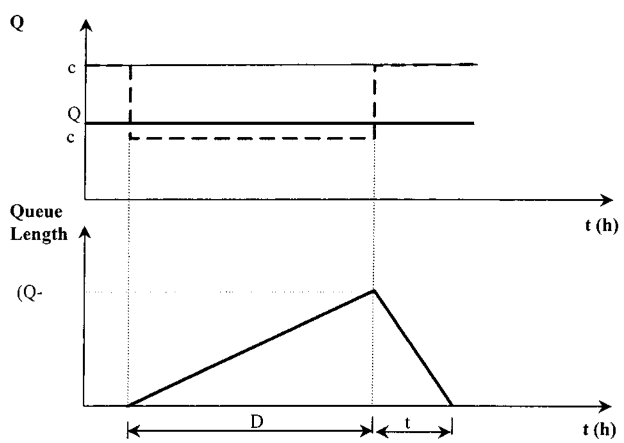

FIG. 2. Queue Delay

maintenance activity. D is also the total maintenance duration per zone with length L. The queue dissipation time is the maximum queue length divided by the queue dissipation rate s, where

$$s = \frac{n_o 3{,}600}{H} - Q \tag{1}$$

and where n_o = number of opened lane within the work zone. In a four-lane case, n_o is equal to 1. The queue dissipation time t_d is

$$t_d = \frac{(Q - c_w)D}{(c_o - Q)} \tag{2}$$

where c_o represents the roadway capacity in normal conditions (without work zones). The average maintenance duration d per kilometer is the total maintenance duration D divided by L, where D is the total maintenance duration for the work zone length L. From the stated assumptions, D can be formulated linearly as

$$D = z_3 + z_4L \tag{3}$$

in which z_3 represents the setup time; and z_4 represents the additional time required per work zone kilometer. Therefore, the average maintenance duration per kilometer

$$d = \frac{z_3}{L} + z_4 \tag{4}$$

Delay costs to road users are determined from the value of time lost while one is traveling through a work zone. The time lost includes vehicle delays in a queue (if any) and the difference between travel times on roadways at normal and maintained conditions. Thus, the user delay cost includes the queue delay and the moving delay costs. The average user delay cost is assumed to be v_d\$/veh-h. Therefore, the queue delay cost C_q per maintained kilometer is the queue delay t_q multiplied by the average delay cost v_d and divided by L, which is formulated as

$$C_q = \frac{t_q v_d}{L} \tag{5}$$

where t_q = queue delay incurred by the approaching traffic flow Q while work on one zone is completed. If Q is less than the maximum discharge rate of the work zone c_w, the queue delay t_q is neglected. However, if Q is greater than c_w, the queue delay t_q is

$$t_q = \frac{1}{2}(D + t_d)(Q - c_w)D \tag{6}$$

By substituting D and t_d obtained from (2) and (3) into (6), the queue delay per maintenance zone is

$$t_q = \frac{1}{2}\left(1 + \frac{Q - c_w}{c_o - Q}\right)(Q - c_w)(z_3 + z_4L)^2 \tag{7}$$

Therefore, if the approaching flow Q exceeds the zone capacity c_w, the average queue delay cost per maintained lane kilometer is

$$C_q = \frac{v_d}{2L}\left(1 + \frac{Q - c_w}{c_o - Q}\right)(Q - c_w)(z_3 + z_4L)^2 \tag{8}$$

Otherwise, if Q is less than c_w, the queue delay cost C_q is zero.

The moving delay cost per maintained kilometer C_v is the moving delay t_m multiplied by the average delay cost v_d and divided by L and formulated as

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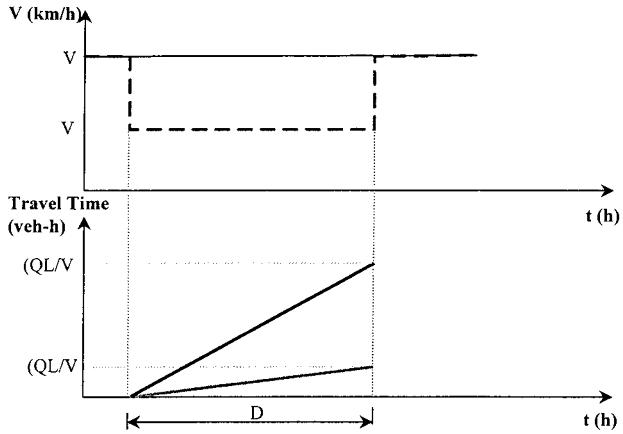

FIG. 3. Travel Delay

$$C_v = \frac{t_m v_d}{L} \tag{9}$$

where t_m = moving delay incurred by the approaching traffic flow Q. The moving delay t_m is a function of the difference between the travel times on a road with and without a work zone. According to the relation between the zone capacity and the volume of the approaching flow as shown in Fig. 3, t_m is formulated in two different ways. As Q is less than c_w, the moving delay per maintenance zone t_m is simply

$$t_m = \left(\frac{L}{V_w} - \frac{L}{V_a}\right) QD \tag{10}$$

where V_a = average approaching speed; and V_w represents the average work zone speed. However, if Q is greater than c_w, the variable Q in (10) is reduced by c_w, because the maximum flow allowed to pass through the work zone is c_w. In this case, the moving delay per maintenance zone t_m is

$$t_m = \left(\frac{L}{V_w} - \frac{L}{V_a}\right) c_w D \tag{11}$$

By substituting D, obtained from (2), into (10) and (11), the moving delay cost per maintained lane kilometer C_v for the cases when $Q \le c_w$ and $Q > c_w$, respectively, are derived as

$$C_v = \left(\frac{1}{V_w} - \frac{1}{V_a}\right) Q(z_3 + z_4 L)v_d \quad \text{when } Q \le c_w \tag{12}$$

$$C_v = \left(\frac{1}{V_w} - \frac{1}{V_a}\right) c_w(z_3 + z_4 L)v_d \quad \text{when } Q > c_w \tag{13}$$

The total user delay cost per maintained lane kilometer C_u is formulated as

$$C_u = C_q + C_v \tag{14}$$

By substituting C_q and C_v derived in (8) and (12) [or (13)] into (14), C_u is obtained.

The only traffic accidents considered in this study are those occurring in work zones and queue areas. The accident cost incurred by the traffic flow passing the work zone having length L can be determined from the number of accidents per 100 million vehicle hour n_a multiplied by the product of the increased delay ($t_q + t_m$) and the average cost per accident v_a and then divided by the work zone length L. The accident rates are available from references such as McCoy and Peterson (1987) and Pigman and Agent (1990). The average accident cost per maintained kilometer C_a is formulated as

$$C_a = \frac{(t_q + t_m)}{L} \frac{n_a v_a}{10^8} \tag{15}$$

By substituting (7) and (10) [or (11)] into (15), C_a is derived as

$$C_a = \left(\frac{1}{V_w} - \frac{1}{V_a}\right) Q(z_3 + z_4 L) \frac{n_a v_a}{10^8} \quad \text{when } Q \le c_w \tag{16}$$

$$C_a = \left[\frac{1}{2L}\left(1 + \frac{Q - c_w}{c_o - Q}\right)(Q - c_w)(z_3 + z_4 L)^2 + \left(\frac{1}{V_w} - \frac{1}{V_a}\right) c_w(z_3 + z_4 L)\right] \frac{n_a v_a}{10^8} \quad \text{when } Q > c_w \tag{17}$$

The agency cost per zone C_M is assumed to be

$$C_M = z_1 + z_2 L \tag{18}$$

where z_1 = fixed setup cost for the entire work zone; and z_2 = average maintenance (e.g., repaving) cost per additional lane kilometer within that zone. The average agency cost per lane kilometer C_m is the total agency cost C_M divided by the work zone length L and derived as

$$C_m = \frac{z_1}{L} + z_2 \tag{19}$$

Thus, the total cost function is the summation of the agency cost, the user delay cost, and the accident cost

$$C_t = C_m + C_u + C_a \tag{20}$$

By substituting (12), (16), and (19) into (20), the complete cost per kilometer of maintained road lane C_t, as $Q \le c_w$, is derived as follows:

$$C_t = \left(\frac{z_1}{L} + z_2\right) + \left(\frac{1}{V_w} - \frac{1}{V_a}\right) Q(z_3 + z_4 L)\left(v_d + \frac{n_a v_a}{10^8}\right) \tag{21}$$

However, if $Q > c_w$, the complete cost per maintenance kilometer can be obtained by substituting (13), (17), and (19) into (20). In this case

$$C_t = \left(\frac{z_1}{L} + z_2\right) + \left[\frac{1}{2L}\left(1 + \frac{Q - c_w}{c_o - Q}\right)(Q - c_w)(z_3 + z_4 L) + \left(\frac{1}{V_w} - \frac{1}{V_a}\right) c_w\right](z_3 + z_4 L)\left(v_d + \frac{n_a v_a}{10^8}\right) \tag{22}$$

The only difference between (21) and (22) is that the queue delay cost and the accident cost incurred are considered in (22).

OPTIMIZATION

The optimizable variable in the total cost function is the work zone length (L). The objective is to find the optimal L to minimize the total cost. The analytic solution for the optimal decision variable is obtained by setting the first-order condition of the total cost function with respect to the decision variable equal to zero and solving it. Thus, the optimal work zone lengths L are found by setting the partial derivatives of the total cost functions [e.g., (21) and (22)] with respect to L equal to zero in (23) and solving for L

$$\frac{\partial C_t}{\partial L} = 0 \tag{23}$$

In cases where a queue is formed upstream of a work zone, the resulting optimal work zone length L^* is

$$L^* = \sqrt{\frac{2z_1 + P_1 P_2 P_3 z_3^2}{P_1 P_2 P_3 z_4^2 + 2P_3 P_4 c_w z_4}} \tag{24}$$

In (24), parameters P_1 and P_3 are defined as the excess flow and the summation of delay and accident costs per vehicle hour, while P_2 and P_4 are the differences in discharge rates

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and in travel times on a roadway with and without a work zone, respectively. Thus, parameters P_1, P_2, P_3, and P_4 are

$$P_1 = Q - c_w \tag{25}$$

$$P_2 = 1 + \frac{Q - c_w}{c_o - Q} \tag{26}$$

$$P_3 = v_d + \frac{n_a v_a}{10^8} \tag{27}$$

$$P_4 = \frac{1}{V_w} - \frac{1}{V_a} \tag{28}$$

On the other hand, if work zone activities are performed during low traffic demand periods and no queues form, the optimal work zone length L^* is

$$L^* = \sqrt{\frac{z_1}{z_4 Q P_3 P_4}} \tag{29}$$

in which P_3 and P_4 are defined in (27) and (28).

The second derivatives of the total cost functions [e.g., (21) and (22)] with respect to L are positive, thus insuring a minimum rather a maximum. From the first-order and second-order conditions, we know that the objective function is convex, which implies that there is a unique optimal work zone length in each case (with queue delay or without queue delay). Therefore, the optimal work zone lengths derived in (24) and (29) minimize the costs in (22) and (21), respectively.

NUMERICAL EXAMPLE

In this numerical example, the optimization of the work zone length for a four-lane highway is analyzed. The capacity per direction is assumed to be 2,600 vehicles per hour (vph). Maintenance on the four-lane (two lanes per direction) road is performed by closing one of the lanes in the maintained direction for L kilometers and devoting the remaining lane to traffic. The average travel speed and the headway within that zone are assumed to be 40 km (25 mi) per h and 3 s, respectively. The maximum discharge rate is 1,200 vph (e.g., 3,600/3) for the zone. In order to optimize work zone lengths for both off-peak and peak conditions, the approaching traffic flows are assumed to be steady at 1,000 vph and 2,000 vph, respectively. The average approach speed is 64 km (e.g., 40 mi) per h under normal conditions. Other parameters used in this example and their baseline values are defined in Table 1. These values are intended to demonstrate the application of this model rather than to represent any specific site.

The objective of this example is to find the optimal work zone lengths when the approaching traffic volumes and the roadway geometric conditions (e.g., number of lanes opened and closed) are given. Eqs. (24) and (29) yield optimal work zone lengths of 1.4 km when the approaching flow rate Q is 1,000 vph, and 0.34 km when Q is 2,000 vph.

The maintenance durations per zone at both conditions [obtained from (3)] are 10.4 hours (Q = 1,000 vph) and 4.04 h (Q = 2,000 vph). When Q is 2,000 vph, a queue is formed because the approaching flow Q exceeds the maximum discharge rate. The queue dissipation time obtained from (2) is, therefore, 5.39 h. The user queuing t_q and moving t_m delays per maintained kilometer are 0 and 141.5 h when Q is 1,000 vph, while the queuing C_q and moving delay C_m cost yield 0 and 1,698.5 $/km. In a high traffic volume condition (Q = 2,000 vph), C_q and C_m are 537,650.9 $/km and 793.2 $/km, respectively.

Other information, such as the agency, user, accident, and total costs per maintained kilometer, are obtained from equations derived in this study and summarized in Table 2.

SENSITIVITY ANALYSIS

Sensitivity results for this model are presented to illustrate the relations among variables and identify the relative importance of causal factors. Fig. 4 shows that the optimal work zone length decreases when the approaching flow rate increases. In addition, the optimal work zone length increases as the maximum discharge rate increases from 800 vph to 1,400 vph. The optimal work zone length tends to approach zero when the ratio of the approaching flow rate and the maximum discharge rate (e.g., Q/c_w) increases. As suggested earlier, a fraction of the traffic flow might be diverted to other alternative routes. Ways to increase the maximum discharge

TABLE 1. Input for Numerical Example

Variable (1)	Description (2)	Values (3)
c_o	Maximum discharge rate without work zones	2,600 vph
c_w	Maximum discharge rate with work zones	1,200 vph
H	Average headway	3 s
n_a	Number of accidents per 100 million vehicle hour	(13.3) 40 acc/100 mvh
V_a	Average approaching speed	88 km/h
V_w	Average work zone speed	48 km/h
v_a	Average accident cost	142,000 $/acc
v_d	Average user cost	12 $/veh-h
z_1	Fixed setup cost	1,000 $/zone
z_2	Average agency cost per kilometer	80,000 $/km
z_3	Fixed setup time	2 h/zone
z_4	Average maintenance time per kilometer	6 h/km

TABLE 2. Results for Numerical Example

Variable	Unit	c_w = 1,200 vph	
		Q = 1,000	Q = 2,000
(1)	(2)	(3)	(4)
L^*	km	1.3966	0.3399
C_q	$/km	0	537,650.9
C_v	$/km	1,698.5	793.2
C_u	$/km	1,698.5	538,444.1
C_m	$/km	81,432	85,884.3
C_a	$/km	75.3	23,871
C_t	$/km	83,205.8	648,199.4
D	hours	10.4	4.04
t_d	hours	0	5.39
t_m	hours	141.5	66.1
t_q	hours	0	44,804.2

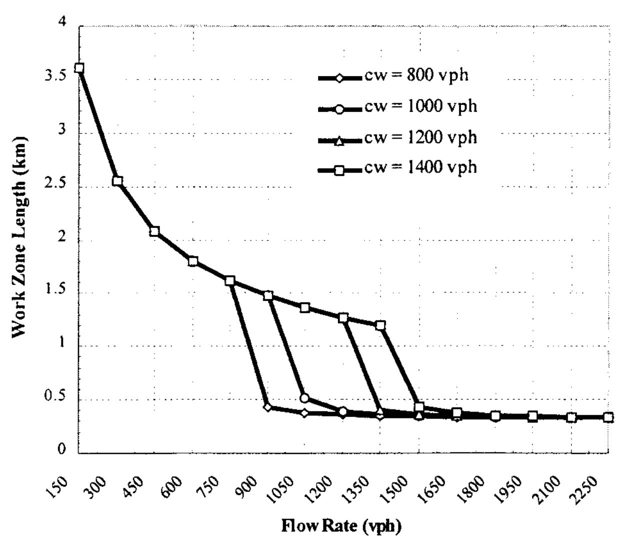

FIG. 4. Optimal Work Zone Length versus Approaching Traffic Flow for Various Discharge Rates

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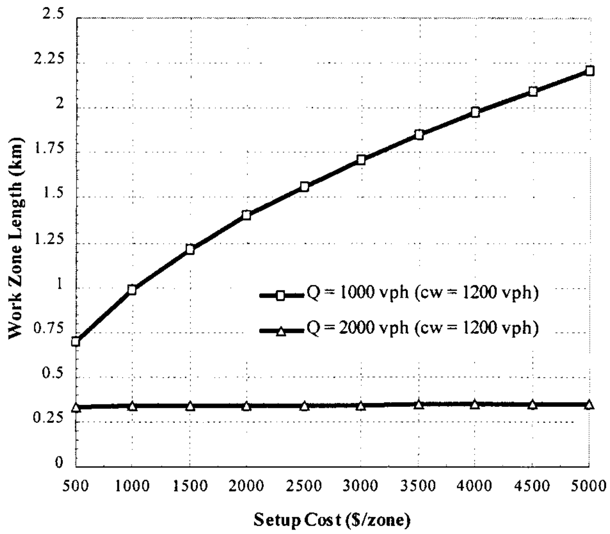

FIG. 5. Optimal Work Zone Length versus Setup Cost for Various Approaching Flows

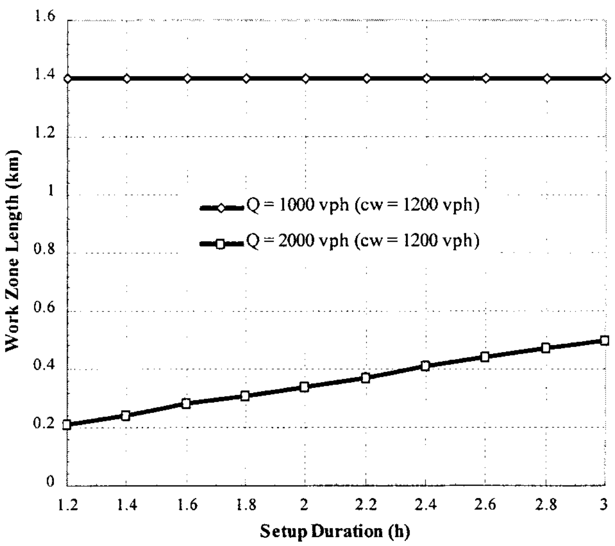

FIG. 6. Optimal Work Zone Length versus Setup Duration for Various Approaching Flows

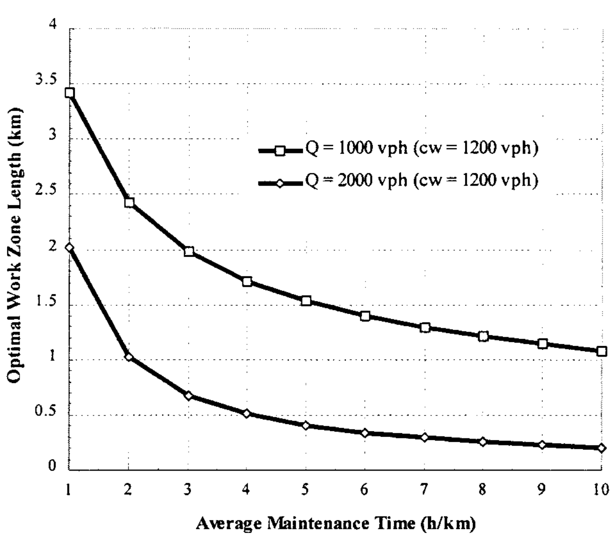

FIG. 7. Optimal Work Zone Length versus Average Maintenance Time for Various Approaching Flows

rate in a work zone, such as reducing the headway, increasing the travel speed with acceptable safety, or adding one more lane (e.g., using one side of roadway shoulders) within the work zone, should be strenuously sought in such cases. Otherwise, the total maintenance duration will increase significantly.

Fig. 5 represents the relation among optimal work zone lengths and the setup costs. The optimal work zone length is very sensitive to the work zone setup cost when the approaching flow rate is low. If Q is greater than c_w (as shown in Fig. 6) and the work zone setup duration increases, the optimal work zone length increases in order to reduce the number of setup. However, the setup duration does not affect the optimal work zone length when Q is less than c_w.

The optimal work zone length, shown in Fig. 7, decreases if the average allowable maintenance time per lane kilometer increases, in order to reduce the user delay cost. Moreover, the optimal work zone length increases as traffic demand decreases. The total cost is sensitive to the work zone length only if the approaching flow rate is high and the average maintenance time is short, as shown in Figs. 7 and 8.

In Fig. 8, where the approaching flow Q is less than the maximum discharge rate c_w (=1,200 vph), the user delay cost is much lower than the agency cost because the queuing delay is zero. However, if Q exceeds c_w, the user delay cost is always greater than the agency cost, because the queue delay cost is very high and increases rapidly as the work zone length and the resulting maintenance duration increase. This situation increases the total maintenance duration drastically, since with short optimal zones and the number of repeated work zone setups is large. For instance, the optimal work zone length of 0.34 km when Q is 2,000 vph is shorter than the 1.4 km optimal length when Q is 1,000 vph. Therefore, a fraction of traffic flow should, if possible, be diverted to other alternative routes when the approaching flow is much higher than the capacity of one open lane through a work zone. Then, a longer optimized work zone length may be expected, and the construction and agency costs can be decreased. The user cost increases if the work zone length increases. However, as the zone length increases, the agency cost per kilometer decreases due to fewer setups. Therefore, the optimal work zone length can be identified by the trade-off between the user and agency costs. Additionally, the accident cost contributes a small fraction of the total cost, and it does slightly affect the optimal work zone length.

Fig. 8 also confirms that queuing delays are zero as long as the approach volume Q stays below the work zone capacity

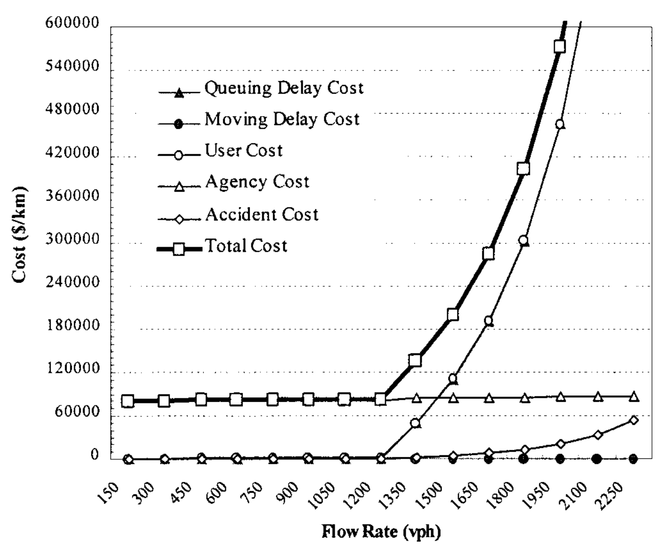

FIG. 8. Costs versus Approaching Flow Rate (c_w = 1,200 vph)

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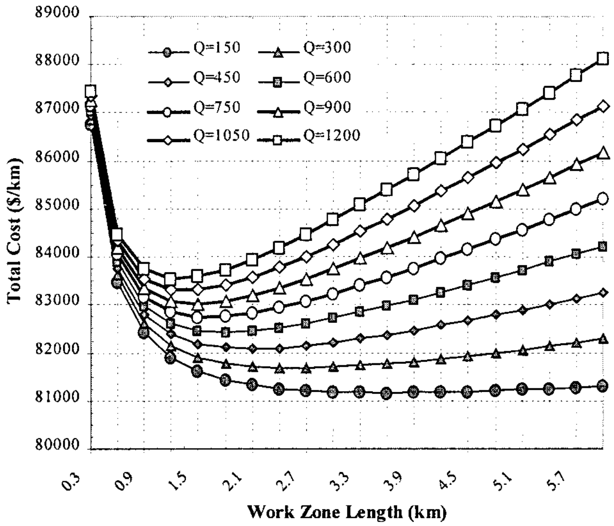

FIG. 9. Total Costs versus Work Zone Length for Various Approaching Flows ($Q < c_w$)

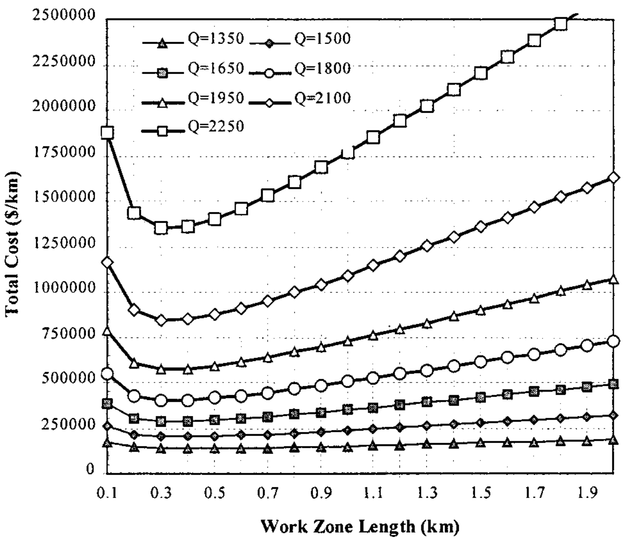

FIG. 10. Total Costs versus Work Zone Length for Various Approaching Flows ($Q > c_w$)

c_w. When Q exceeds c_w, the queue delay cost increases very rapidly, unlike the moving delay cost, which stays low. In addition, the relations between the main cost components (e.g., agency, user, and accident costs) and the approaching flow rate are demonstrated in the figure. It is clear that the user cost is the cost component most sensitive to the flow rate, especially after Q exceeds c_w. Since the agency and the accident costs are relatively insensitive compared with the user cost, the total cost curve is very similar to the user cost curve.

Figs. 9 and 10 show the relations among work zone lengths, approaching flow rates and total costs. Comparing the results shown on both figures, we clearly see that the total cost is very sensitive to Q, especially when $Q > c_w$. In these figures, we find that, at any given approaching flow rate, there exists a unique optimal work zone length at which the total cost is minimized.

The sensitivity analysis indicates that the total cost is stable (i.e., relatively flat) near the optimal work zone length when the approaching flow is less than the zone capacity. Therefore, as shown in Fig. 9, the work zone length can be changed without great penalties near its optimal values in order to accommodate local and geographical constraints on work zones (such as intersections) and still end up with an integer number of zones over an entire road maintenance project. These results also indicate that construction agencies (or the agencies performing traffic control in work zones) have considerable flexibility for increasing or decreasing the work zone length without changing the total cost significantly. However, in the high traffic demand periods, the total cost is relatively sensitive to the optimal work zone length, and construction agencies should determine the proper work zone length very carefully.

CONCLUSIONS

The developed model has been presented to calculate the additional user and accident costs generated by restricted capacity through a work zone as well as the agency cost. Opportunities to benefit substantially from applying this model exist in highway resurfacing (i.e., patching), rehabilitation (i.e., repaving), and reconstruction (i.e., road widening and realignment) related projects in rural settings. A revised model would be desirable for urban roads with many intersections and alternative paths.

The proposed modeling approach demonstrates how work zone lengths can be optimized based on the important factors (i.e., approaching traffic flows, work zone speeds, the maximum discharge rate, work zone setup costs, etc.) affecting such maintenance decisions for four-lane road segments without interchanges or intersections. In particular, by considering the aggregate effects of various work zone lengths and approaching flow rates, this method provides a practical approach for reducing both traffic delays and agency costs, while also considering the work zone safety impacts. With user-specified input parameters, this relatively simple mathematical model can be used to optimize work zone lengths on four-lane highways for a wide variety of situations.

The results from the sensitivity analysis show that, as traffic flow increases over time, shortening work zones offers a way to mitigate the user delays, albeit at increased agency cost. Results, such as Fig. 4, can be used to optimally vary the work zone lengths as demand changes over time. Other ways to increase the total flow through a work zone should be considered, such as increasing the average speed within the work zone, subject to safety considerations. Otherwise, we should either reschedule the work in zones according to traffic flow distributions over time or reduce work zone length during high traffic periods.

APPENDIX I. REFERENCES

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APPENDIX II. NOTATION

The following symbols are used in this paper:

C_a = average accident cost per kilometer per lane ($/km);
C_M = total agency cost ($/zone);
C_m = average agency cost per kilometer per lane ($/km);
C_o = maximum discharge rate without work zones (vph);
C_q = average queue delay cost per kilometer per lane ($/km);
C_t = average total cost per kilometer per lane ($/km);
C_u = total user delay cost per kilometer per lane ($/km);
C_v = average moving delay cost per kilometer per lane ($/km);
C_w = maximum discharge rate with work zones (vph);
D = total maintenance hours (h);
d = average maintenance time per kilometer per lane (h/km);
H = average headway (s);
L = work zone length (km);
L^* = optimal work zone length (km);
n_a = number of accidents per 100 million vehicle hour (acc/100 mvh);
n_o = number of opened lanes within work zones (lanes);
P_1 = parameter 1 in (24)–(28) (−);
P_2 = parameter 2 in (24)–(28) (−);
P_3 = parameter 3 in (24)–(28) (−);
P_4 = parameter 4 in (24)–(28) (−);
Q = flow rate approaching work zones (vph);
s = queue dissipation rate (vph);
t_d = queue dissipation time (h);
t_m = moving delays (veh-h);
t_q = queue delays (veh-h);
V_a = averaging approaching speed (km/h);
V_w = average work zone speed (km/h);
v_a = average accident cost ($/acc);
v_d = average user cost ($/veh-h);
z_1 = fixed setup cost ($/zone);
z_2 = average maintenance cost per kilometer ($/km);
z_3 = fixed setup time (h/zone); and
z_4 = average maintenance time per kilometer (h/km).

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