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OPTIMIZATION OF WORK ZONE SCHEDULE CONSIDERING TIME-VARYING TRAFFIC DIVERSION

Yimin Tang, Ph.D. (Corresponding Author)

Senior Traffic Engineer
AECOM USA Inc.
30 Knightsbridge Road, Building 5, Suite 520
Piscataway, NJ 08854
TEL: 732-564-3233; FAX: 732-369-0120
E-Mail: yimin.tang@gmail.com

Steven I-Jy Chien

Professor
Department of Civil and Environmental Engineering
New Jersey Institute of Technology
University Heights, Newark, NJ 07102
TEL: 973-596-6083; FAX: 973-596-6454
E-Mail: chien@adm.njit.edu

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ABSTRACT

Highway maintenance may cause excessive delay on transportation corridors and networks. Diverting traffic from congested highway work zones and accelerating maintenance progress can mitigate the adverse traffic impacts. In this study, the time-varying traffic diversion due to work zones is formulated analytically and incorporated with a work zone schedule optimization model. The developed model optimizes work zone schedules jointly considering the time-varying traffic diversion, variable maintenance cost and production rate of different maintenance crews, which minimizes the total cost including agency cost and user's cost. The numerical example compares various combinations of the mitigation plans in a generalized two-link network, consisting of a freeway and an alternate route. The results of sensitivity analysis indicate that implementing traffic diversion is desirable as the freeway volume exceeds the threshold found in this study. This study demonstrates a feasible approach to plan maintenance activities cost-effectively for a real-world highway resurfacing project. The developed model is also applicable to evaluate the effectiveness of traffic diversion plans for pre-determined work zone schedules.

KEYWORDS: Work Zone, Highway Maintenance, Scheduling, Traffic Diversion, Accelerated Construction, Genetic Algorithm, Optimization

I. INTRODUCTION

Highway maintenance activities (e.g., resurfacing, joint repairs and utility works, etc.) usually disrupt traffic operations and increase delays due to the capacity bottleneck of work zones. The 2009 Urban Mobility Report (*1*) indicated that the cost of traffic congestion to the U.S. drivers was $87.2 billion in 2007, resulting from 4.2 billion hours of delay and 2.8 billion gallons of wasted fuel. Delays caused by work zones on freeways were nearly 24% of total non-recurring delays and 10% of overall delay (*2*). Motorists are more sensitive to their travel time and fuel consumption due to the hike of fuel price.

Scheduling maintenance activities merely during nighttime and off-peak periods may ease the congestion; however, the increase in project cost and duration should be expected (*3*). Commonly used congestion mitigation strategies, including accelerated construction and traffic diversion, may be applied to reduce project duration and delay. However, accelerated and compressed construction schedule is expensive. Inappropriate traffic diversion plans will significantly degrade the level of service on the alternate routes. To address these concerns, a model is proposed to optimize work zone schedule, which yields the minimum total cost, subject to a given project duration. In addition, the joint effect of time-varying traffic diversion, variable production rates, and realistic maintenance time-cost relations are analyzed. Quantitative analyses are conducted to address the applicability and effectiveness of congestion mitigation plans for a real-world highway resurfacing project.

II. LITERATURE REVIEW

Previous studies (*4*, *5*, *6*) developed a number of models to optimize highway work zone schedule, which minimize the total agency and user costs, assuming a fixed production rate and unit maintenance cost. To consider practical constraints, Tang and Chien (*3*) adopted a discrete maintenance time-cost relation and optimized the work zone schedule subject to a given project duration, in which accelerated construction methods were evaluated without considering the potential benefit and effect of time-varying traffic diversion.

Motorists may change their travel behavior by using alternate routes to bypass a congested roadway with work zones. It was observed that the natural diversion behavior emerges on an urban freeway with frontage roads and frequent entrances and exits (7). Ullman and Dudek (*8*) introduced a constant corridor permeability factor and applied a macroscopic approach to predict the pattern of queue propagation due to work zone activities on an urban freeway. Further, Lee et al. (*9*) utilized different demand adjustment factors (DAF) for a mainline freeway, entrances and exits to estimate queue length and the associated delay caused by work zones. The key model parameters (i.e., corridor permeability factor and DAFs) were calibrated using the traffic volumes and queue lengths collected from freeways with work zones in Texas and Wisconsin. However, the site-specific values of these parameters are generally difficult to apply to freeways in other states. Moreover, the increased delay on alternate routes due to the diverted traffic was not considered.

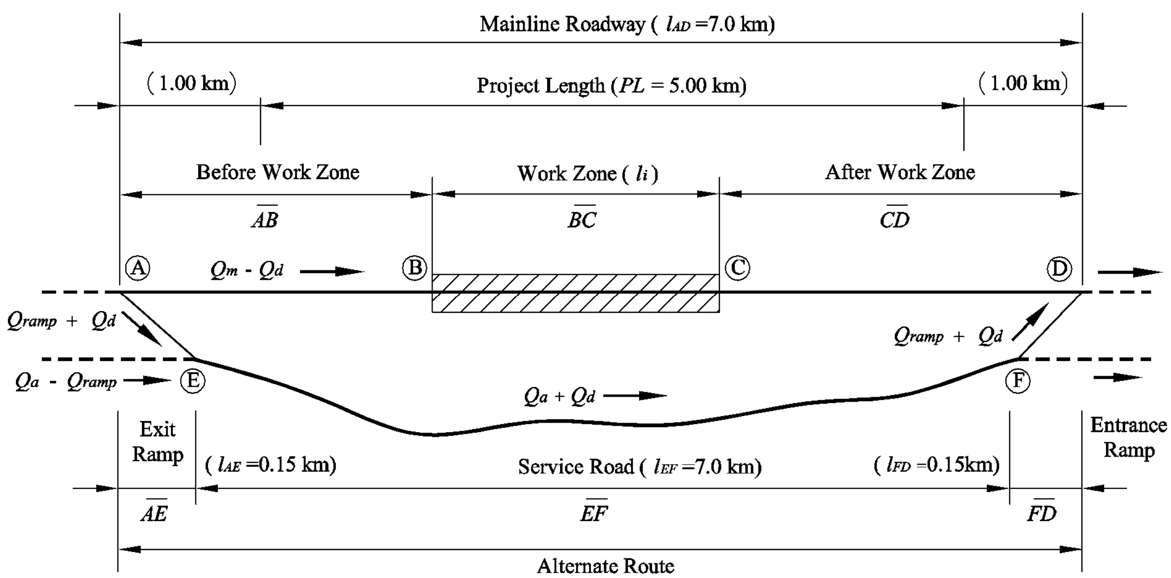
Chen (*5*, *6*) developed an analytical model to optimize work zone schedules, while a constant traffic diversion ratio was assumed for the entire duration of a maintenance project. Since traffic diversion may vary spatially and temporally depending on traffic conditions and work zone schedules, this assumption is relaxed by applying the time-varying traffic diversion formulated in this study.

Road user cost (RUC) is an important factor considered in planning road maintenance and construction. Construction Analysis for Pavement Rehabilitation Strategies (CA4PRS), a construction management software (*10*), has been applied to analyze cost and benefit for different pavement rehabilitation alternatives, considering constructability, RUC, resource constraints and lead-lag relations of construction activities. However with CA4PRS, optimizing construction time windows requires numerous trials and the resulting delays and RUC rely on external traffic analysis tools, such as microscopic simulation or demand-capacity analysis models which was not integrated with the optimization processes.

With the advent of ITS, such as Automated Work Zone Information System (AWIS) (*11*) and 511 Traveler Information System, traffic conditions in the vicinity of freeway work zones may be monitored and disseminated to motorists at designated locations in real-time. Motorists are capable to recognize a faster route to bypass a congested roadway segment to reach their destinations. In this study, the time-varying traffic diversion due to driver's responses to real-time travel information is formulated analytically and incorporated into a work zone optimization model (*3*). Additionally, a solution algorithm is developed to search the optimal work zone schedule and time-varying diverted flows which minimize the total cost.

III. METHODOLOGY

This study considers a typical traffic diversion scenario illustrated Figure 1, in which a highway maintenance project may be divided into several work zones sequentially along one direction of the mainline roadway. An alternate route is designated to carry the diverted traffic flow Q_d from the mainline. When congestion occurs on the mainline at interval j, a portion of the mainline traffic will start (or continue) to detour if the predicted time savings of using the alternate route exceeds a certain threshold $t_S{}^j$. Assumptions below are made to formulate the time-varying traffic diversion in the study network.



Note: Numbers within parentheses are baseline values used by the numerical example.

FIGURE 1 Configuration of a work zone in the study network.

1. The threshold of time saving denoted as $t_S{}^j$ is assumed as zero in this study, which represents the most sensitive diversion behavior to travel time. However, $t_S{}^j$ may be different during peak and off-peak periods, which can be calibrated by surveys of driver's perceptions within the project area.
2. The travel times on the exit and entrance ramps are constant because the length of ramps is minor. The capacity of the ramps is adequate to accommodate the combined existing ramp flow Q_{ramp} and the diverted flow Q_d.
3. The diverted traffic flow is uniformly distributed within a small interval *j* (*j* = 1 to *n*), where *n* is the number of intervals of the project duration.
4. The diverted flow $Q_d{}^j$ will equalize the travel times of both routes (i.e., $\overline{ABCD}$ and $\overline{AEFD}$ in Figure 1) at the end of interval *j*
5. The diverted traffic flow is limited by the capacity of the alternate route to avoid excessive congestion on the alternate route.

Based on given traffic volumes, roadway capacities, free-flow speeds and link travel distances, the travel times of the mainline with work zone and the alternative route can be formulated analytically as a mathematical function of $Q_d{}^j$. The development of the proposed model is discussed below.

1. The BPR Function

The BPR function in Equation 1, developed by the U.S. Bureau of Public Road, has been commonly used for estimating link travel times (*t*) based on the free-flow travel time (t^0) and the ratio of traffic volume (*x*) over capacity (*c*) of a link.

$$t = t^0 \times \left(1 + \alpha \cdot \left(\frac{x}{c} \right)^{\beta} \right) \qquad (1)$$

where the model parameters, α and β, are 0.15 and 4.0, respectively (*12*).

2. Travel Time of the Mainline

In Figure 1, link *AD* on the mainline is divided into three links by work zone *i*, where link *AB* represents the segment before the work zone, link *BC* is the actual work zone, and link *CD* is the segment after the work zone.

At interval *j*, the travel time on link *AB* before work zone *i*, denoted as $t_{AB}{}_i^j$, is the sum of the BPR function and the average queuing delay, denoted as $t_q{}_i^j$. Thus,

$$t_{AB}{}_i^j = t_{AB\,i}^0 \times \left(1 + \alpha \cdot \left(\frac{Q_m{}^j - Q_d{}^j}{c_0} \right)^{\beta} \right) + t_q{}_i^j \qquad \forall i, j \qquad (2)$$

where $t_{AB\,i}^0$, c_0 and Q_m^j represent the free-flow travel time, capacity and traffic flow of link *AB*, respectively. Note that $Q_d{}^j$ represents the diverted traffic flow at interval *j*, which is a decision variable to be optimized. When a vehicular queue occurs at the upstream of work zone *i*, the average queuing delay $t_{q\,i}^{\,j}$ can be derived as

$$t_{q\,i}^{\,j} = \frac{D_{Q\,i}^{\,j}}{(Q_m^{\,j} - Q_d^{\,j}) \cdot T} \qquad \forall j \tag{3}$$

where $D_{Q\,i}^{\,j}$ is the queuing delay in vehicle-hours caused by work zone *i* at interval *j*, which will be discussed later. *T* represents a user-specified duration for all intervals, i.e., 15 minutes per interval in this study.

The travel time for passing through work zone *i*, denoted as $t_{BC\,i}^{\,j}$, can be determined by the BPR function with work zone capacity c_w and the remaining flow $(Q_m^{\,j} - Q_d^{\,j})$ on the mainline. Note that the traffic flow entering work zone *i* will be metered by the work zone capacity c_w if $Q_m^{\,j} - Q_d^{\,j} \ge c_w$, and the delay due to the upstream spillback is considered in Equation 3. Thus,

$$t_{BC\,i}^{\,j} = t_{BC\,i}^{0} \times \left(1 + \alpha \cdot \left(\frac{Q_m^{\,j} - Q_d^{\,j}}{c_w} \right)^{\beta} \right) \qquad if \quad Q_m^{\,j} - Q_d^{\,j} < c_w \qquad \forall i, j \tag{4a}$$

$$t_{BC\,i}^{\,j} = t_{BC\,i}^{0} \times (1 + \alpha) \qquad if \quad Q_m^{\,j} - Q_d^{\,j} \ge c_w \ or \ t_{q\,i}^{\,j} > 0 \qquad \forall i, j \tag{4b}$$

where $t_{BC\,i}^{0}$ the free-flow travel time, is equal to the length of work zone *i*, denoted as l_i, divided by the work zone speed V_w.

$$t_{BC\,i}^{0} = \frac{l_i}{V_w} \qquad \forall i \tag{4c}$$

The travel time of link *CD* is denoted as $t_{CD\,i}^{\,j}$ and derived below,

$$t_{CD\,i}^{\,j} = t_{CD\,i}^{0} \times \left(1 + \alpha \cdot \left(\frac{Q_m^{\,j} - Q_d^{\,j}}{c_0} \right)^{\beta} \right) \qquad if \quad Q_m^{\,j} - Q_d^{\,j} < c_w \qquad \forall i, j \tag{5a}$$

$$t_{CD\,i}^{\,j} = t_{CD\,i}^{0} \times \left(1 + \alpha \cdot \left(\frac{c_w}{c_0} \right)^{\beta} \right) \qquad if \ \ Q_m^{\,j} - Q_d^{\,j} \ge c_w \ or \ t_{q\,i}^{\,j} > 0 \qquad \forall i, j \tag{5b}$$

where $t_{CD\,i}^{0}$ is the free-flow travel time on link *CD*, and c_w is the work zone capacity.

Finally, the total travel time on the mainline $\overline{ABCD}$ at interval *j*, denoted as $t_{m\,i}^{\,j}$, is the sum of travel times spent on the three links. Thus,

$$t_{m\,i}^{\,j} = t_{AB\,i}^{\,j} + t_{BC\,i}^{\,j} + t_{CD\,i}^{\,j} \qquad \forall\, i, j \tag{6}$$

Note that $t_{m\,i}^{\,j}$ is a mathematical function of $Q_d^{\,j}$.

3. Travel Time of the Alternate Route

The alternate route in Figure 1 includes exit ramp *AE*, link *EF* and the entrance ramp *FD*. The travel time of link *EF*, denoted as $t_{EF\,i}^{\,j}$, is derived from the BPR function as

$$t_{EF}{}_i^j = t_{EF}^0 \times \left(1 + \alpha \cdot \left(\frac{Q_a{}^j + Q_d{}^j}{c_a}\right)^\beta\right) \qquad \forall i, j \tag{7}$$

where t_{EF}^0, c_a and Q_a^j denote the free-flow travel time, capacity and existing flow of link *EF*, respectively.

Based on Assumption 2, the total travel time on ramp links *AE* and *FD*, denoted as t_{ramp}, is an constant,

$$t_{ramp} = \frac{l_{AE} + l_{FD}}{V_r} \tag{8}$$

where l_{AE} and l_{FD} are the lengths of links *AE* and *FD*, respectively, while V_r is the average speed of the ramps.

Finally, the travel time of the diverted traffic $Q_d{}^j$, denoted as $t_a{}_i^j$, is the sum of travel times of links *AE*, *EF* and *FD*. Thus,

$$t_a{}_i^j = t_{EF}{}_i^j + t_{ramp} \qquad \forall i, j \tag{9}$$

Note that $t_a{}_i^j$ is a mathematical function of $Q_d{}^j$.

4. Traffic Diversion

As discussed earlier, when congestion occurs on the mainline at interval *j* and the predicted time savings exceeds a certain threshold $t_S{}^j$ at the end of interval *j*, the traffic diversion from the mainline will be triggered (or continued), and the diverted traffic flow $Q_d{}^j$ will equalize the travel times of the mainline and the alternate route at the end of interval *j*. Thus,

$$t_m{}_i^j - t_a{}_i^j = 0 \qquad \forall i, j \tag{10}$$

Note that $Q_d{}^j$ is the only independent variable in Equation 10, which can be obtained by solving Equation 10 using a numerical method (e.g., the bisection method).

IV. WORK ZONE DELAYS

With the known diverted traffic flow $Q_d{}^j$, delays occurred on the mainline with a work zone and the alternate route are formulated next.

1. Queuing Delay on the Mainline

The queuing delay at interval *j* due to work zone *i*, denoted as $D_Q{}_i^j$, is

$$D_Q{}_i^j = \left(\frac{q_1{}_i^j + q_2{}_i^j}{2}\right) \cdot T \qquad \forall i, j \tag{11}$$

where $q_1{}_i^j$ and $q_2{}_i^j$ represent the numbers of queuing vehicles at the beginning and the end of interval j, respectively. Thus, $q_2{}_i^j$ can be formulated as

$$q_2{}_i^j = \begin{Bmatrix} q_1{}_i^j + (Q_m{}^j - Q_d{}^j - c_w)\,T & \text{if } \; q_2{}_i^j > 0) \\ 0 & \text{if } \; q_2{}_i^j \le 0 \end{Bmatrix} \qquad \forall i, j \tag{12}$$

Note that $D_{Q\,i}^{\;j}$ from Equation 11 is an input of Equation 3 for the average queuing delay $t_{q\,i}^{\;j}$.

2. Total Delay of the Mainline

The total delay occurred on the mainline at interval *j*, denoted as $D_{T\,i}^{\;j}$, can be derived by the additional travel time due to work zone *i*. Thus,

$$D_{T\,i}^{\;j} = (Q_m^{\;j} - Q_d^{\;j})(t_{m\,i}^{\;j} - t_{AD}^{j}) \cdot T \qquad \forall i, j \tag{13}$$

where $t_{m\,i}^{\;j}$ is the travel time of mainline $\overline{ABCD}$ (i.e., with work zone *i*) derived in Equation 6, while t_{AD}^{j} represents the original travel time of link *AD* without a work zone.

$$t_{AD}^{j} = t_{AD}^{0} \times \left(1 + \alpha \cdot \left(\frac{Q_m^{\;j}}{c_0} \right)^{\beta} \right) \qquad \forall j \tag{14}$$

where t_{AD}^{0} is the travel time at free flow speed through link *AD*.

3. Total Delay of the Alternate Route

The total delay occurred on the alternate route at interval *j*, denoted as $D_{A\,i}^{\;j}$, includes the delay experienced by the existing flow $Q_a^{\;j}$ on link *EF* and the diverted flow $Q_d^{\;j}$ through the alternate route $\overline{AEFD}$.

The delay of the existing flow $Q_a^{\;j}$, denoted as $D_{EF\,i}^{\;\;j}$, is derived as

$$D_{EF\,i}^{\;\;j} = Q_a^{\;j} \cdot (t_{EF\,i}^{\;\;j} - t_{EF}^{j}) \cdot T \qquad \forall i, j \tag{15}$$

where $t_{EF\,i}^{\;\;j}$ and t_{EF}^{j} are the travel times with and without $Q_d^{\;j}$ on link *EF*, respectively, while $t_{EF\,i}^{\;\;j}$ is obtained from Equation 7; and t_{EF}^{j} is estimated by the BPR function below.

$$t_{EF}^{j} = t_{EF}^{0} \times \left(1 + \alpha \cdot \left(\frac{Q_a^{\;j}}{c_a} \right)^{\beta} \right) \qquad \forall j \tag{16}$$

where t_{EF}^{0} is the free-flow travel time through link *EF*.

The delay incurred by the diverted traffic $Q_d^{\;j}$, denoted as $D_{d\,i}^{\;j}$, can be derived as,

$$D_{d\,i}^{\;j} = Q_d^{\;j} \cdot (t_{a\,i}^{\;j} - t_{AD}^{j}) \cdot T \qquad \forall i, j \tag{17}$$

where $t_{a\,i}^{\;j}$ is the travel time of $Q_d^{\;j}$ through the alternate route $\overline{AEFD}$; and t_{AD}^{j} represents the original travel time through mainline $\overline{ABCD}$ without work zone *i*. Note that $t_{a\,i}^{\;j}$ and t_{AD}^{j} are estimated by Equations 9 and 14, respectively. Finally, the total delay on the alternate route during interval *j* is derived as

$$D_{A\,i}^{\;j} = D_{EF\,i}^{\;\;j} + D_{d\,i}^{\;j} \qquad \forall i, j \tag{18}$$

V. THE OBJECTIVE FUNCTION

The objective total cost function in this study is enhanced from a cost model developed by Tang and Chien (*3*) and includes the road users' costs associated with the traffic diversion. The total cost (C_T) of a maintenance project consists of maintenance cost (C_M), cost of stopping maintenance work (C_I) and road users' cost (C_U). Thus,

$$\text{Minimize } C_T = C_M + C_I + \gamma \cdot C_U = \sum_{i=1}^{m} (C_{Mi}^{\ k} + C_{Ii}) + \phi \cdot \sum_{i=1}^{m} C_{Ui} \tag{19}$$

Subject to: User specified project length: $\sum_{i}^{m} p_i^k = PL \quad \forall i, k$

Minimum duration of a work zone or a work break: $D_i \geq D_{\min} \quad \forall i$

Maximum duration of the project: $\sum_{i}^{m} D_i \leq PD_{\max} \quad \forall i$

where m denotes the number of work zones (including work breaks) to be determined. The superscript k is the index of different maintenance crews. D_i and $D_{\min}$ represent the actual duration and the minimum duration of each work zone (or work breaks); $PD_{\max}$ is the maximum project duration, and PL is the given project length. The cost coefficient ϕ represents the weight of road users' cost in the project total cost. This study utilizes $\phi = 1.0$ according to the Road User Cost Manual (*13*) of New Jersey Department of Transportation (NJDOT).

1. Cost of Maintenance

The maintenance cost of work zone *i*, denoted as $C_{Mi}^{\ k}$, includes material, equipment and labor costs. Thus,

$$C_{Mi}^{\ k} = z_1 + z_{2i}^k \cdot p_i^k \quad \forall i, k \tag{20}$$

where z_1 is the fixed cost for setting and removing a work zone; and z_{2i}^k is the unit maintenance cost in \$/lane-km with respect to maintenance crew *k*.

In Equation 21, the length of construction to be completed in work zone *i*, denoted as p_i^k, is represented by the starting (S_i) and ending (E_i) intervals and the unit production time z_{4i}^k (hours/lane-km) of maintenance crew *k*.

$$p_i^k = \frac{E_i - S_i - z_3}{z_{4i}^k} \quad \forall i, k \tag{21}$$

where z_3 is the time required for setting and removing a work zone. Thus, $C_{Mi}^{\ k}$ is derived as a mathematical function of S_i and E_i as well as the index *k* of maintenance crews.

2. Cost of Stopping Maintenance Work

This cost incurred by the idling of equipment and maintenance crews during a work break is the product of the break duration D_i and the average idling cost v_d.. Thus,

$$C_{Ii} = v_d D_i = v_d (E_i - S_i) \quad \forall i \tag{22}$$

3. Road User Cost

The road user cost of work zone *i*, denoted as C_{Ui}, consists of the delay cost C_{Di}, vehicle operating cost C_{Vi}, and crash cost C_{Ai} associated with the work zone. Thus,

$$C_{Ui} = C_{Di} + C_{Vi} + C_{Ai} \quad \forall i \tag{23}$$

Cost of Delay

Delay cost denoted as $C_{D\,i}$ is the sum of work zone delays multiplied by the value of users' time (v). Work zone delays on the mainline and the alternate route are obtained from Equations 13 and 18, respectively. Thus,

$$C_{D\,i} = \sum_j (D_{T\,i}^{\;j} + D_{A\,i}^{\;j}) \cdot v \qquad \forall j \tag{24}$$

Vehicle Operating Cost

The vehicle operating cost (VOC), denoted as $C_{V\,i}$ on a vehicle-hourly basis, is caused by the queuing delay.

$$C_{V\,i} = \sum_j D_{Q\,i}^{\;j} \cdot v_o \qquad \forall j \tag{25}$$

where v_o is the unit vehicle idling cost additional to the VOC without a work zone.

Cost of Crashes

The crashes considered here are those occurring in and adjacent to a work zone on the mainline. The cost of crashes is based on the delays on the mainline, average crash rate r_a (i.e., crashes per 100 million veh-hour) and the average cost per crash v_a. Thus,

$$C_{A\,i} = \sum_j D_{T\,i}^{\;j}\, r_a v_a \qquad \forall j \tag{26}$$

Finally, the objective total cost function can be derived by substituting Equations 20, 22 and 23 into Equation 19

VI. SOLUTION ALGORITHM

The objective total cost function formulated in Equation 19 is a nonlinear, mix-integer and discontinuous function, in which the decision variables consist of work zone schedule (S_i, E_i, k_i, i = 1 to m), number of work zones (m) and time-varying diverted traffic flow ($Q_d^{\;j}$, j = 1 to n). The interdependent relations among the decision variables form a combinatorial optimization problem, which is difficult to be optimized analytically (*3*). The proposed solution algorithm in this study transforms the combinatorial problem into two sub-problems, which can be solved by the two interactive modules discussed below:

- Diversion Module: Given a set of initial work zone schedules, this module determines the time-varying traffic diversion. If the threshold of diversion is satisfied at interval j, the diverted traffic $Q_d^{\;j}$ can be obtained by solving Equation 10, i.e., the predicted travel times on the both routes are equal at the end of interval j (j = 1 to n).
- GA Module: Given the redistributed traffic flows obtained from the Diversion Module above, the Genetic Algorithm (GA) module developed by Tang and Chien (*3*) will generate improved work zone schedules and update the initial/previous work zone schedules in the Diversion Module for next iteration.

After iterations, the optimized work zone schedule and associated time-varying diverted flows which minimize the total cost can be obtained. Figure 2 illustrates the framework of the developed solution algorithm. The detailed development of GA can be referred to the previous paper (*3*). Other information about GA may be referred to a book authored by Michalewicz (*14*).

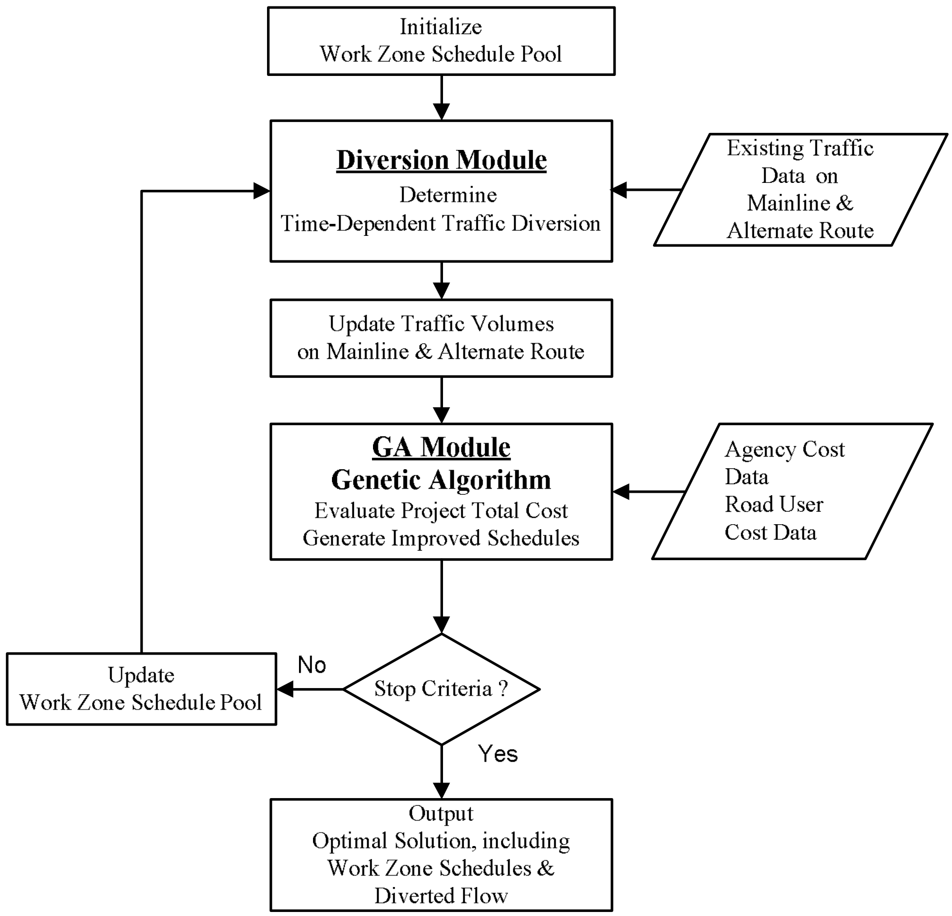


FIGURE 2 Framework of the solution algorithm

VI. NUMERICAL EXAMPLE

A 5-km long pavement resurfacing project was conducted on a principle arterial (i.e., mainline) with 2 travel lanes per direction in Middlesex County, New Jersey. As illustrated in Figure 1, the project was situated between exit ramp *AE* and entrance ramp *FD* on the 7-km long mainline. The resurfacing work was performed by closing one travel lane at a time. During the construction, the mainline traffic may be diverted to the 7-km long alternate route *EF* through exit ramp *AE*, and returns onto the mainline through entrance ramp *FD*. The alternate route *EF* is a minor arterial having one travel lane in each direction.

1. Parameters of Traffic and Maintenance Work

The baseline values of unit maintenance cost z_2^k and production time z_4^k (i.e., maintenance crew 2 in Table 1) of resurfacing 2-inch asphalt pavement referred to the *Means Heavy Construction Cost Data* (*15*). In Table 1, the alternative maintenance crews 1, 3 and 4, which were derived by adjusting the baseline labor/equipment costs and daily production, were assumed to demonstrate the developed model and may be substituted by project-specified construction cost data. In this example, the maintenance crew 1 represents the lowest productive crew at the least unit cost, while the maintenance crew 4 is the most productive but expensive one.

TABLE 1 Unit Maintenance Cost and Production Time for 2-inch Pavement Resurfacing

Index of Maintenance Crews	**Name of Maintenance Crews**	**Daily Output (8-hr)** sq. yard	**Material Cost** $/ sq. yd	**Labor & Equipment** $/ sq. yard	**Total Cost** $ / sq. yd	**Unit maintenance cost** z_2^k $/ln-km (3.6 m lane)	**Unit production time** z_4^k Hr/ln-km
1	M-1	5,200	4.18	0.80	5.68	24,860	6.75
2 (Baseline)	B-25B	6,345	4.18	0.83	5.71	24,983	5.50
3	M-3	7,400	4.18	0.85	5.85	25,243	4.75
4	M-4	9,000	4.18	1.07	5.98	26,211	3.89

The existing hourly traffic distributions in the project area were obtained from the Road User Cost Manual (*13*) of NJDOT. The Annual Average Daily Traffic (AADT) on the mainline and the alternate route are denoted as $AADT_m$ and $AADT_a$, respectively. The hourly volumes corresponding to various $AADT_m$ and $AADT_a$ are provided in Table 2. The baseline values of other model parameters are summarized in Table 3.

2. Parameters of the Developed Genetic Algorithm

The parameters of the GA were calibrated in a previous study (*16*) and are provided in Table 3. The stop-criterion of the GA was set at 100 generations for each run. The optimal solution was based on 30 program runs (i.e., 3 random population pools times 10 runs per population pool), which took approximately 1~2 minutes (without traffic diversion) and 8~10 minutes (with traffic diversion) on a 2.4 GHz Intel® Core™ 2 Duo Processor.

3. Optimized Solutions

Two scenarios are compared in this example to demonstrate how traffic diversion may affect the optimized work zone schedule, the least project total cost and project duration. Scenario "A" did not include the alternate route defined in Figure 1, while Scenario "B" considered time-varying traffic diversion during the construction. In the both scenarios, the baseline maintenance crew 2 was employed, and $AADT_m$ = 45,000 vehicles /day (vpd) and the maximum project duration $PD_{\max}$ = 64 hours were used. $AADT_d$ = 25,000 vpd on the alternate route was adopted in Scenario "B".

TABLE 2 AADT and Hourly Traffic Volumes on the Mainline and the Alternate Route

Hour	Directional Split	Mainline								Alternate Route	
		% of AADT	AADT on Mainline ($AADT_m$)							% of AADT	$AADT_a$ =25,000
			30,000	35,000	40,000	45,000	50,000	55,000	60,000		
0-1	0.48	1.2	173	202	230	259	288	317	346	0.7	84
1-2	0.48	0.8	115	134	154	173	192	211	230	0.6	72
2-3	0.45	0.6	81	95	108	122	135	149	162	0.4	45
3-4	0.53	0.6	95	111	127	143	159	175	191	0.4	53
4-5	0.53	0.9	143	167	191	215	239	262	286	0.6	80
5-6	0.53	1.8	286	334	382	429	477	525	572	1.6	212
6-7	0.57	4.2	718	838	958	1,077	1,197	1,317	1,436	4.4	627
7-8	0.54	7.0	1,134	1,323	1,512	1,701	1,890	2,079	2,268	6.0	810
8-9	0.56	7.6	1,277	1,490	1,702	1,915	2,128	2,341	2,554	5.3	742
9-10	0.56	5.7	958	1,117	1,277	1,436	1,596	1,756	1,915	5.1	714
10-11	0.51	4.8	734	857	979	1,102	1,224	1,346	1,469	5.2	663
11-12	0.51	5.1	780	910	1,040	1,170	1,301	1,431	1,561	5.7	727
12-13	0.50	5.7	855	998	1,140	1,283	1,425	1,568	1,710	6.3	788
13-14	0.52	5.4	842	983	1,123	1,264	1,404	1,544	1,685	6.5	845
14-15	0.51	5.7	872	1,017	1,163	1,308	1,454	1,599	1,744	6.4	816
15-16	0.53	6.5	1,034	1,206	1,378	1,550	1,723	1,895	2,067	6.2	822
16-17	0.49	7.2	1,058	1,235	1,411	1,588	1,764	1,940	2,117	6.2	760
17-18	0.47	7.7	1,086	1,267	1,448	1,629	1,810	1,990	2,171	6.3	740
18-19	0.47	6.2	874	1,020	1,166	1,311	1,457	1,603	1,748	6.5	764
19-20	0.47	4.7	663	773	884	994	1,105	1,215	1,325	6.0	705
20-21	0.46	3.5	483	564	644	725	805	886	966	4.6	529
21-22	0.48	3.1	446	521	595	670	744	818	893	3.8	456
22-23	0.48	2.3	331	386	442	497	552	607	662	2.9	348
23-24	0.48	1.7	245	286	326	367	408	449	490	2.3	276

TABLE 3 Baseline Values of Model Parameters

Parameters	Descriptions	Baseline Values
c_0	Capacity of the mainline	4,500 vph
c_w	Capacity of the mainline with a work zone	1,200 vph
c_a	Capacity of the alternate route	1,700 vph
V_m	Design speed of the mainline	80 km/hour
V_w	Regulated speed limit in work zones	50 km/hour
V_a	Design speed of the alternated route	55 km/hour
V_r	Average speed of ramps *AE* and *FD*	40 km/hour
α, β	Coefficients of BPR function for mainline and alternated route	α=0.15, β=4.0
p_i	Length of construction work within work zone i	To be determined
l_T	Total length of tapers and buffers	0.360 km
l_i	Length of work zone i, $l_i = p_i + l_T$	To be determined
v	Value of users' time	15 $/veh-hour
r_a	Average crash rate in number of crashes per 100 million veh-hour	40 crashes/100 mvh
v_a	Average cost per crash	40,000 $ /crash
v_d	Average idling cost per hour	800 $/hour
v_O	Additional vehicle operating cost due to queuing delay	0.91 $/veh-hour
z_1	Fixed setup cost	1,000 $/zone
z_3	Fixed total time of setting and removing a work zone	2.0 hours/zone
z_2^k	Unit maintenance cost per lane-km using maintenance crew k	$/lane-km (see Table 1)
z_4^k	Unit production time per lane-kilometer using maintenance crew k	hr/lane-km (see Table 1)
k	Index of maintenance crews	2
PL	Project length	5.000 km
PD_{max}	Maximum project duration	64 hours
n	Total number of intervals within the maximum project duration	256
T	Duration of an interval	15 minutes
D_{min}	Minimum duration of work zone / work break	3 hours / 2 hours
P	Population size used in the GA	1,000
r	Selection ratio used in the GA	0.45
P_{XO}	GA Crossover ratio used in the GA	0.65
P_{MU}	Mutation ratio used in the GA	0.025

Table 4 summarizes the optimized schedule of Scenario "A", in which the best project starting time was 0:00, and the resulting project duration was 53.5 hours. Five work zones were scheduled during three overnight off-peak periods (i.e., work zones i =1, 5, 9) and two mid-day off-peak periods (i.e., i =3, 7) because the traffic volumes in other time periods exceeded the work zone capacity of 1,200 vph. Four work breaks during peak hours (i.e., i =2, 4, 6, 8) were scheduled to avoid excessive travel delay and the associated user costs. The minimized project total cost is $150,258 per lane.

TABLE 4 Scenario "A": Optimized Schedule without Traffic Diversion, Using the Maintenance Crew 2

Work Zone *i*	Work Zone Start & End Times	Duration (hours)	Construction Length p_i (km)	Maintenance Cost ($)	User Cost ($)	Idling Cost ($)	Total Cost ($/lane)
1	00:00–07:00	7.00	0.909	23,712	357	0	24,069
2	07:00–09:45	2.75	Work Break	0	0	2,200	2,200
3	09:45–13:30	3.75	0.318	8,949	2,188	0	11,137
4	13:30–18:45	5.25	Work Break	0	32	4,200	4,232
5	18:45–07:00	12.25	1.864	47,559	1,610	0	49,169
6	07:00–09:45	2.75	Work Break	0	0	2,200	2,200
7	09:45–13:30	3.75	0.318	8,949	2,188	0	11,137
8	13:30–18:45	5.25	Work Break	0	32	4,200	4,232
9	18:45–05:30	10.75	1.591	40,746	1,136	0	41,882
Total (per lane)		53.50	5.000	129,915	7,543	12,800	**150,258**

Itemized User Costs		
Total Queuing Delay Cost ($)	3,665	Note:
Total Moving Delay Cost ($)	3,628	Total Delay=Queuing Delay + Moving
Vehicle Operating Cost and Crash Cost ($)	250	Delay

TABLE 5 Scenario "B": Optimized Schedule Considering Traffic Diversion, Using the Maintenance Crew 2

Work Zone *i*	Work Zone Start & End Times	Duration (hours)	Construction Length p_i (km)	Maintenance Cost ($)	User Cost ($)	Idling Cost ($)	Total Cost ($/lane)
1	19:00–07:00	12.00	1.818	46,424	1,419	0	47,842
2	07:00–10:00	3.00	Work break	0	0	2,400	2,400
3	10:00–05:30	19.50	3.182	80,491	10,831	0	91,322
Total (per lane)		34.50	5.000	126,915	12,250	2,400	**141,565**

Itemized User Costs		
Total Queuing Delay Cost on Mainline ($)	2,805	
Total Moving Delay Cost on Mainline ($)	7,354	
Total Delay Cost on Alternate Route ($)	1,875	Note: Mainline Total Delay=Queuing Delay
Vehicle Operating Cost and Crash Cost ($)	216	+ Moving Delay

Compared with Scenario "A", the optimized schedule for Scenario "B" in Table 5 indicates that the number of work zones was reduced from five to two, meanwhile work breaks were reduced from four to one. Accordingly, the least project total cost and project duration were decreased by $ 8,692 (i.e., 5.8%) and 19 hours (i.e., 36%) per lane, respectively, which suggested traffic diversion was a more cost-effective strategy. Note that the resultant cost reduction was not significant for $AADT_m$ = 45,000 vpd in this example, but as $AADT_m$ increases, considerable reduction in total cost will be achieved by applying traffic diversion, which is discussed in the section of sensitivity analyses.

The time-varying diverted flow corresponding to the optimized schedule in Scenario “B” is depicted in Figure 3, in which the first work zone was scheduled during the overnight hours and traffic diversion was not necessary because of a low volume over capacity ratio on the mainline. For the morning peak period, scheduling a work break instead of traffic diversion turned to be more economical due to high volumes on the both routes. However, diverting traffic from 12:15 PM to 7:00 PM would be desirable because it provided a continuous time window to complete the reminder of the project within one work zone, which reduced repetitive work zone setup cost and time considerably compared with Scenario “A”. A total of 1,509 vehicles were diverted to the alternate route, which accounted for 16% of the mainline traffic arrived between 12:15 PM and 7:00 PM.

It is worth noting that the diverted flow fluctuated over time due to the variation of travel times on both routes. The traffic diversion triggered in a preceding interval, which had improved the travel condition on the mainline, was generally followed by a lower diversion rate unless a sharp increase of the mainline traffic at the subsequent interval (e.g., at 3:00 PM in Figure 3). Consequently, the remaining mainline traffic flow oscillated around the work zone capacity as depicted in Figure 3. This pattern suggests that the optimal diversion strategy based on the equalized travel time of both routes is to level the mainline traffic with the work zone capacity.

4. Sensitivity Analysis

To investigate the combined effects of traffic diversion and accelerated construction methods on the project total cost, the aforementioned Scenarios “A” and “B” were optimized while employing the maintenance crews 1, 3 and 4 provided in Table 1. The minimized total costs, cost components and project durations associated with each maintenance crew are summarized in Table 6.

The maintenance crew 3 asterisked in Table 6 is deemed as the most cost-effective crew in terms of the lowest total cost in both scenarios. In Scenario “A” (no diversion), employing the best maintenance crew 3 can save 13,529 $/lane (i.e., -9.4%) compared with the highest project total cost associated with the maintenance crew 1; however, the difference in the total cost was narrowed to 4,805$/lane (-3.4%) in Scenario “B” (traffic diversion). This comparison suggests that choosing an effective accelerated construction method and maintenance crew would be critical if no alternate route is available.

Compared with Scenario “A”, it is worth noting that applying traffic diversion (Scenario “B”) reduced mainline queuing delay cost, but it did not always reduce the total road user cost because of the increased moving delay cost on both routes, except using the most cost-effective maintenance crew 3. However, Scenario “B” still outperformed Scenario “A” in terms of lower minimized total cost and shorter project duration because of the reduced work zone setup and idling costs, which was indicated by the reduced numbers of work zones and work breaks in the third column of Table 6.

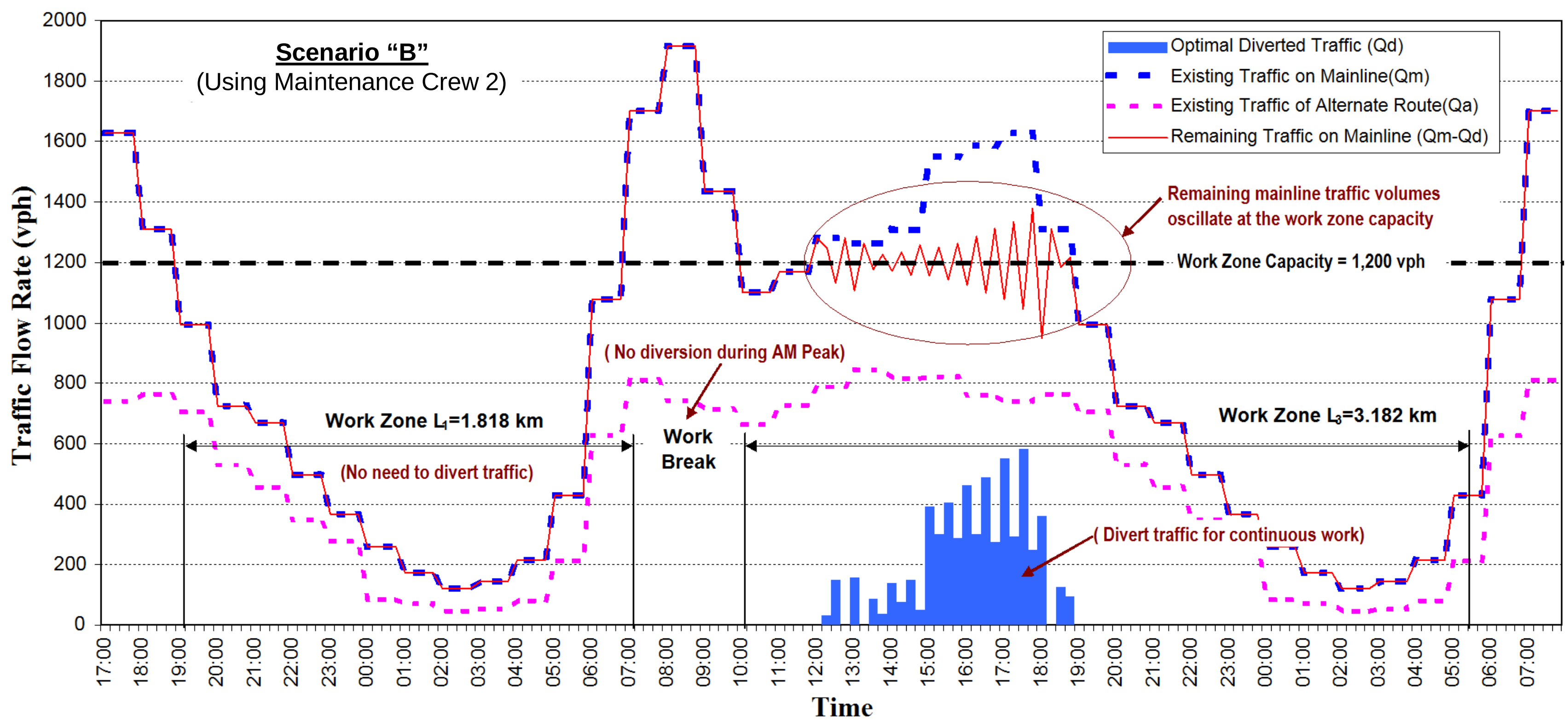


FIGURE 3 Optimal diverted traffic flows over time under Scenario "B", using Maintenance Crew 2.

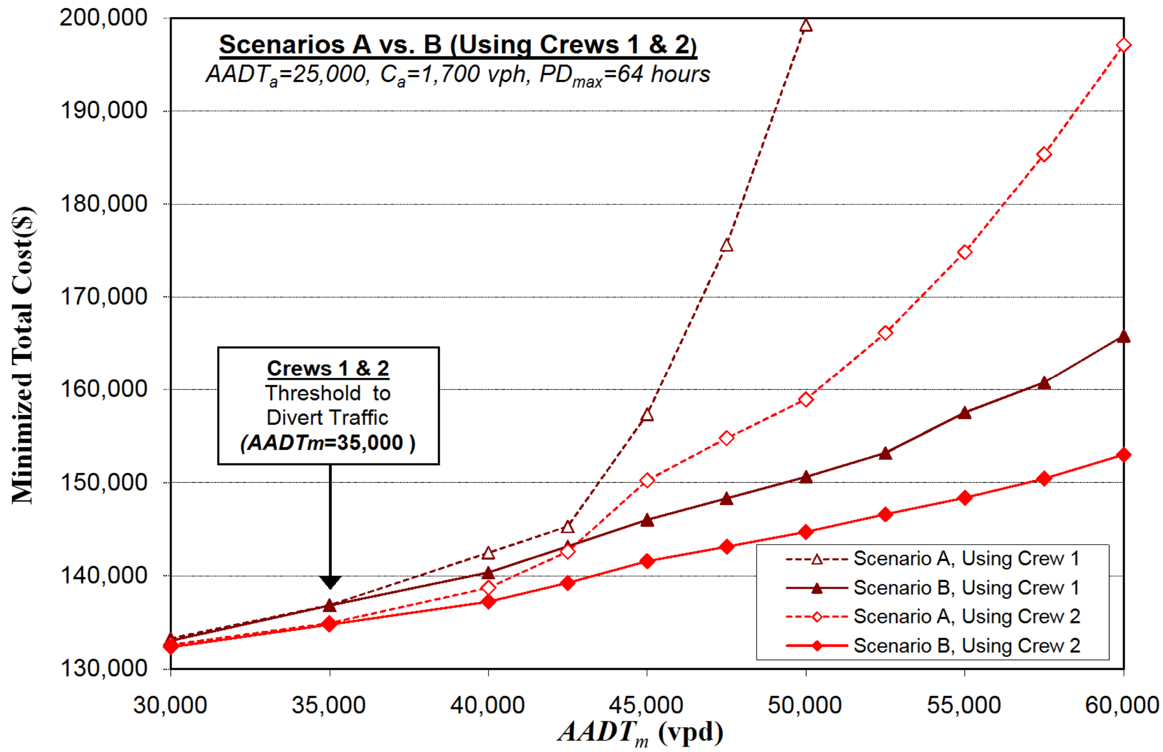
TABLE 6 Scenarios “A” and “B”: Summary of Cost Components for Various Maintenance Crews ($AADT_m$ = 45,000 and $AADT_a$ = 25,000)

Scenarios	Index of Maintenance Crews	Numbers of work zones / work breaks	Maint-enance Cost ($)	Idling Cost ($)	Road User Cost				Minimal Total Cost ($/lane)	Project Duration (Hours)
					Queuing Delay Cost ($)	**Moving Delay Cost ($)**	**VOC& Crash Cost ($)**	**Sub Total ($)**		
“A” Without Traffic Diversion	1	5 / 4	129,300	9,200	13,190	4,807	868	18,865	157,365	55.25
	2	5 / 4	129,915	12,800	3,665	3,628	250	7,543	150,258	53.50
	3*	3 / 2	129,215	5,400	4,489	4,426	306	9,221	**143,836***	**36.50**
	4	3 / 2	134,055	6,800	1,085	3,405	83	4,573	145,428	34.00
“B” With Traffic Diversion	1	2 / 0	126,300	0	6,118	13,215	445	19,778	146,078	37.75
	2	2 / 1	126,915	2,400	2,805	9,229	216	12,250	141,565	34.50
	3*	3 / 2	129,215	4,600	2,665	4,603	190	7,458	**141,273***	**35.50**
	4	3 / 2	134,055	5,600	1,809	3,654	131	5,594	145,249	32.50

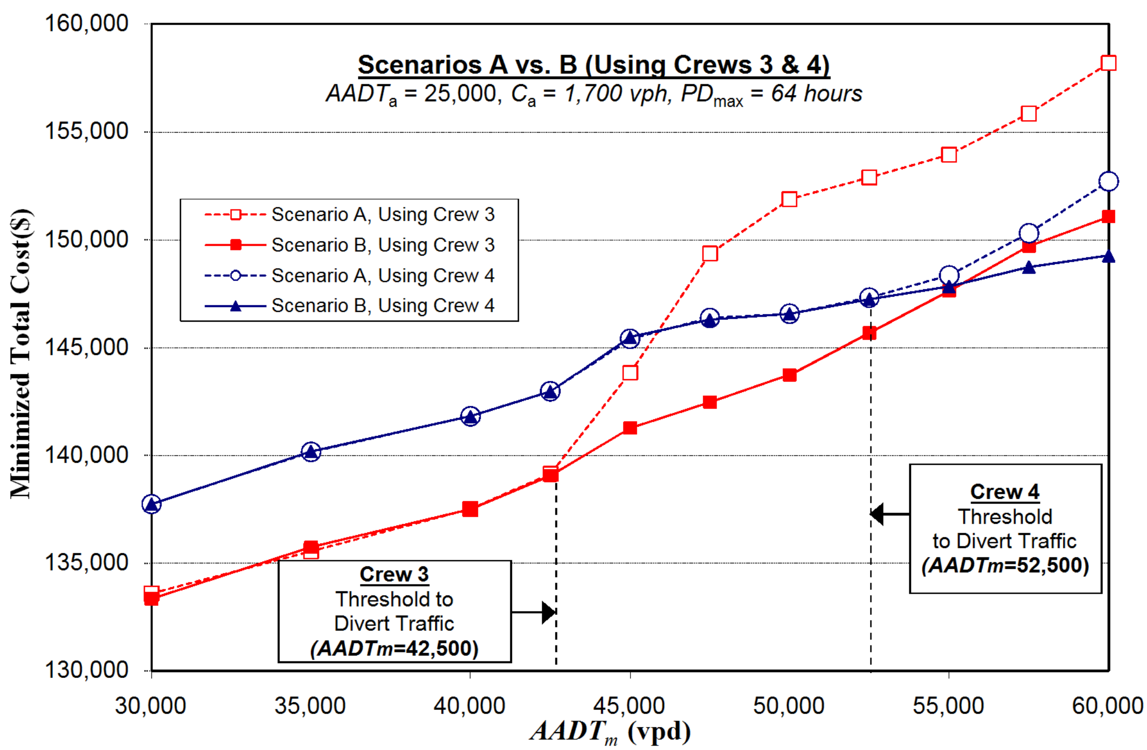
To evaluate the benefit of traffic diversion (i.e. Scenario “B”), sensitivity analyses were conducted as the mainline $AADT_m$ increased from 30,000 vpd to 60,000 vpd while the alternate route $AADT_a$ remained at 25,000 vpd. The minimized total costs associated with each maintenance crew in Scenarios “A” and “B” are depicted in Figures 4(a) and 4(b).

When the maintenance crews 1 and 2 were employed, Figure 4(a) indicates that Scenario “B” outperformed Scenario “A” in terms of lower total cost when $AADT_m$ > 35,000 vpd. Thus, diverting traffic would be an economical strategy if the $AADT_m$ exceeded the threshold value of 35,000 vpd. Note that traffic diversion can significantly reduce the total delay and cost as $AADT_m$ grows over 42,500 vpd. Figure 4(b) shows that higher thresholds of $AADT_m$ to divert traffic were needed when employing the more productive crews 3 (i.e., $AADT_m$ > 42,500 vpd) and crew 4 (i.e., $AADT_m$ > 52,500 vpd); however, the reductions of total cost achieved by Scenario “B” are not as significant as the reduction associated with the maintenance crews 1 and 2.

The above findings suggest that diverting traffic would be beneficial if less productive maintenance crews were employed for work zones on heavily traveled highways. However, a more productive maintenance crew would be cost-effective if traffic was not able to divert to alternate route(s) due to roadway geometrics and congestion constraints, etc. For instance, using the accelerated maintenance crew 4 without traffic diversion (Scenario “A”) may achieve a comparable total cost as the less productive maintenance crew 3 with an alternate route (Scenario “B”) when $AADT_m$ exceeds 50,000 in Figure 4(b).



(a) Using Maintenance Crews 1 and 2



(b) Using Maintenance Crews 3 and 4

FIGURE 4 Scenarios "A" and "B": minimized total costs versus $AADT_m$

VII. CONCLUSIONS AND FUTURE EXTENSIONS

The developed model determines a cost-effective work zone schedule to minimize the total cost, considering time-varying traffic diversion and productivity of maintenance crews as well as practical constraints. This model may be utilized for planning maintenance operations with limited input data, such as historical traffic volumes, road user cost, unit maintenance costs, and production rates of different maintenance crews. Furthermore, with given work zone schedules (e.g., determined by other methods or past practices), this model can be applied to decide the optimal traffic diversion strategy if the option of alternate route(s) is available.

For real-world implementation, the practical threshold values of time saving, which triggers the action of traffic diversion, should be calibrated through public surveys on the agency's website. The duration of time interval (i.e., 15 minutes) in this study may be extended (e.g. to an hour) for long project duration. In construction stages, the work zone schedule and maintenance crews optimized in this study may be adopted by other software (e.g., CA4PRS) for further construction scheduling analysis, while the optimal traffic diversion rate may be considered as a target rate that can be achieved by real time travel information displayed on VMS, AWIS and other ITS applications, such as the 511 Traveler Information System.

Future studies will focus on investigating the impact of multiple entrance/exit ramps and alternate routes affecting the decision of traffic diversion and work zone schedules. In addition, the traffic signals along the alternate route may be considered for more realistic estimation of travel time. Additionally, the evaluation and comparison of optimal diversion strategy and work zone schedule under the concepts of System-Optimal (SO) and User-Equilibrium (UE) traffic assignment will be explored.

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