Work Zone Optimization for Two-Lane Highway Resurfacing Projects with an Alternate Route

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Pavements on two-lane two-way highways are usually resurfaced by closing one lane at a time. Vehicles then travel in the remaining lane along the work zone, alternating directions within each control cycle. In an earlier work, Chen and Schonfeld developed a work zone optimization model for two-lane highways with time-dependent inflows and no detours, based on simulated annealing. In this paper, several alternatives are evaluated, defined by the number of closed lanes and fractions of traffic diverted to alternate routes. The algorithm referred to as SAUASD (simulated annealing for uniform alternatives with a single detour) is developed to find the best single alternative within a resurfacing project. The algorithm referred to as SAMASD (simulated annealing for mixed alternatives with a single detour) is developed to search through possible mixed alternatives and their diverted fractions, to minimize total cost, further including agency cost (resurfacing cost and idling cost) and user cost (user delay cost and accident cost). Thus, traffic management plans are developed with uniform or mixed alternatives within a two-lane highway resurfacing project.

Pavement resurfacing on two-lane two-way highways often requires closing one lane for a work zone. Vehicles then travel in the remaining lane along the work zone, alternating directions within each control cycle. Such a two-lane work zone can be analyzed as a one-way traffic control system in which queuing and delay processes are analogous to those at a two-phase signalized intersection. Schonfeld and Chien (*1*) and Chien et al. (*2*) optimized work zone lengths for two-lane highways; however, neither time-dependent inflows nor detours were considered in those studies. Chen and Schonfeld (*3*) developed a work zone optimization model applying simulated annealing (*4, 5*) for two-lane highways with time-dependent inflows and no detour. That previous study (*3*), in which traffic flows in both directions are alternated on one lane, without any detour, is considered Alternative 1 in this paper.

Alternative 2 pertains to the best available alternate route that bypasses the work zone area as a detour, and the original traffic flow on the road being resurfaced is distributed between that road and the detour. Thus, in Alternative 2, traffic on the road being resurfaced can use the remaining lane for alternating two-way flows, as well as the alternate route. In Alternative 3, all traffic in one direction is diverted to the alternate route, while the remaining lane is used only for traffic in the other direction. Thus, the diverted traffic percentage from one direction of the main road is 0% in Alternative 1, 100% in Alternative 3, and somewhere between those extremes in Alternative 2. In Alternative 4, all traffic in both directions is diverted to the alternate route, and both lanes are closed for resurfacing. Figure 1*a* through 1*d* illustrates Alternatives 1, 2, 3, and 4, respectively. The preferred alternative(s) is determined after all four alternatives are evaluated. Methods and solutions are developed to address the following questions about work zone traffic management plans:

1. What are the best starting times for the project and each zone?
2. How long should each zone be?
3. When should there be pauses in resurfacing activities?
4. When should traffic flows reverse direction on single lanes along work zones?
5. What fraction of the traffic should be diverted to the specified alternate route?
6. What alternatives are best for various sections along a road?

The previous study for Alternative 1 (*3*) has developed methods to resolve Questions 1 through 4 as just mentioned. This paper focuses on resurfacing projects with an alternate route, presenting models for optimizing work plans, including zone lengths, work durations, starting times, pausing times (if any), control cycle times, alternative selection, and diverted fractions. Thus, all the foregoing questions are solved jointly in this work. This is done by minimizing total cost, including agency cost (resurfacing cost and idling cost) and user cost (user delay cost and accident cost), while dealing with traffic demand variations over time.

METHODOLOGY AND ASSUMPTIONS

The basic approach followed is to formulate comprehensive total cost objective functions for each alternative and use them to optimize various controllable aspects of work zones. Ending and idling times for each zone can be obtained from the relation between zone length and duration, explained in Assumption 2. The algorithm referred to as SAUASD (simulated annealing for uniform alternatives with a single detour) is developed as based on the previous study (*3*) to find the best single alternative to apply throughout a resurfacing project. To further minimize total costs, different alternatives may be preferable for various traffic levels on the main road and detour or for different detour lengths. An improved search method, referred to as SAMASD (simulated annealing for mixed alternatives with a single detour), is developed that allows different alternatives to be selected and optimized for successive zones within a project. Such mixed alternatives may yield lower minimized total cost than uniform

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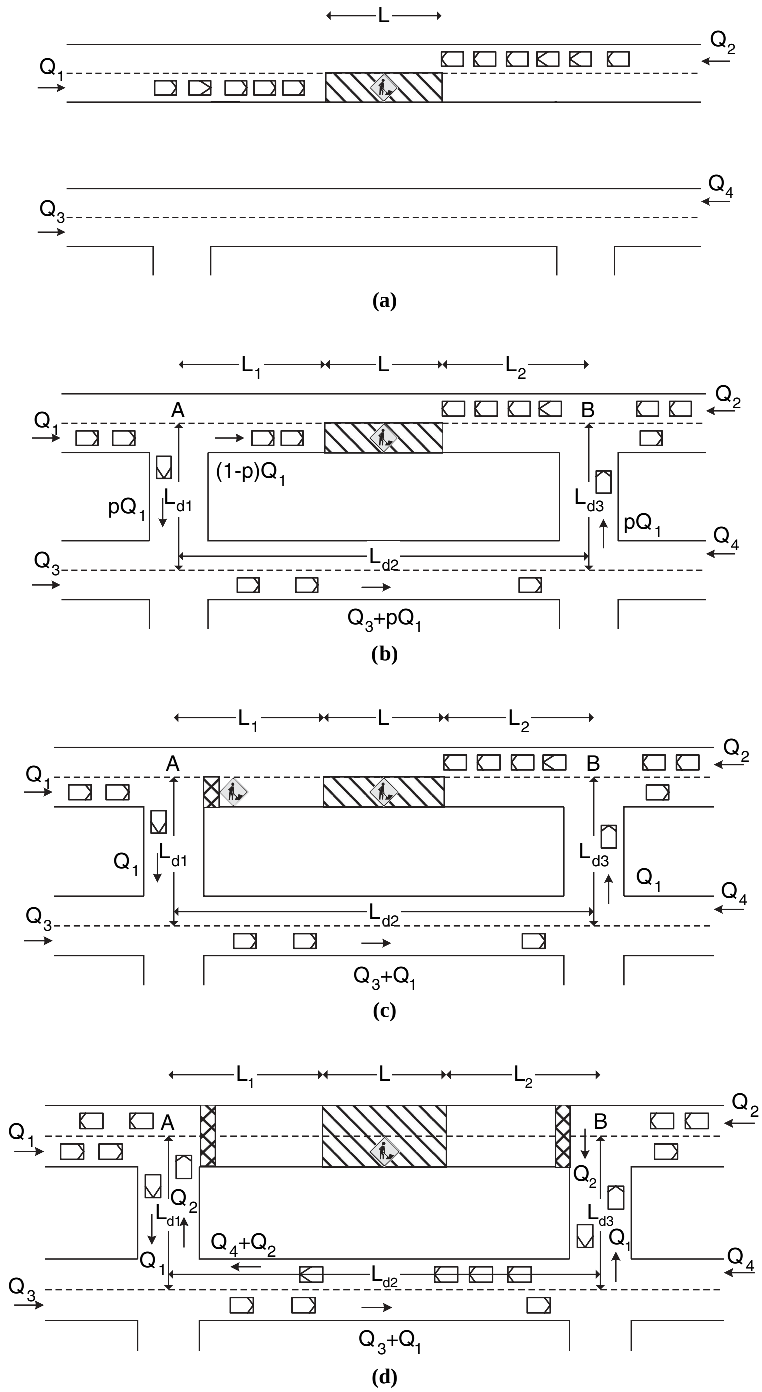


FIGURE 1 Geometries and flows of analyzed work zone alternatives for two-lane, two-way highways: (*a*) Alternative 1, without detour; (*b*) Alternative 2, with detour—pQ_1 on detour $(1-p)Q_1$ along work zone; (*c*) Alternative 3, detour for only one direction; and (*d*) Alternative 4, two directions detoured.

alternatives. Thus, traffic management plans with uniform alternatives or mixed alternatives are developed for a two-lane highway resurfacing project.

Several simplifying assumptions made in formulating this problem are listed as follows:

1. The cost of resurfacing zone i with length L_i is a linear function of the form $C_{mi} = z_1 + z_2 L_i$, in which z_1 is the fixed cost for setting up a work zone, and z_2 is the average additional resurfacing cost per work zone kilometer.
2. The time required to resurface a zone i with length L_i is a linear function of the form $D_i = z_3 + z_4 L_i$, in which z_3 is the setup time for a work zone, and z_4 is the additional time required per work zone kilometer.
3. Only one lane is resurfaced in Alternative 4, although both lanes are closed for work.
4. The average resurfacing time per kilometer, z_4, for Alternative 4 with both lanes closed may be significantly lower than for other alternatives.

MODEL FORMULATION

Alternative 1

Chen and Schonfeld (*3*) developed a work zone cost function that includes agency cost and user cost for a two-lane highway resurfacing project. Consider the varying traffic flows in Directions 1 and 2 over 1 day, as shown in Figure 1*a* through 1*d*. A resurfacing project for a two-lane two-way road with total length L_T in one direction would be resurfaced by scheduling m work zones over the entire resurfacing period. Assume that zone i ($i = 1, 2, \ldots, m$) is resurfaced over n duration units (different zones would likely have different n values) and D_{ij} ($j = 1, 2, \ldots, n$) is a duration unit in which inflows stay constant. According to Assumption 1, the resurfacing cost for zone i for Alternative 1, C^1_{mi}, is as follows:

$$C^1_{mi} = z_1 + z_2 L_i \tag{1}$$

The queuing delay cost for zone i, C^1_{qi}, derived from deterministic queuing analysis for control cycles that alternate traffic directions along work zones, is this:

$$C^1_{qi} = \sum_j^n \frac{\left[Q_1^{ij}\left(\frac{3{,}600}{H} - Q_1^{ij}\right) + Q_2^{ij}\left(\frac{3{,}600}{H} - Q_2^{ij}\right)\right]v}{V\left(\frac{3{,}600}{H} - Q_1^{ij} - Q_2^{ij}\right)} D_{ij} L_i \tag{2}$$

where

Q_1^{ij} and Q_2^{ij} = varying traffic flows in Directions 1 and 2 during period j for zone i,
V = average work zone speed,
H = average headway through the work zone area, and
v = value of user time.

The discharge phases for traffic flows Q_1^{ij} in Direction 1 and Q_2^{ij} in Direction 2, t_1^{ij} and t_2^{ij}, are as follows:

$$t_1^{ij} = \frac{r_i\left(\frac{3{,}600}{H} + Q_1^{ij} - Q_2^{ij}\right)}{\left(\frac{3{,}600}{H} - Q_1^{ij} - Q_2^{ij}\right)} \tag{3}$$

$$t_2^{ij} = \frac{r_i\left(\frac{3{,}600}{H} + Q_2^{ij} - Q_1^{ij}\right)}{\left(\frac{3{,}600}{H} - Q_1^{ij} - Q_2^{ij}\right)} \tag{4}$$

$$\text{where } r_i = \frac{L_i}{V} \tag{5}$$

More detailed derivations are provided in Chen and Schonfeld (*3*).

Equations 3 and 4 indicate that the one-way traffic control is a time-dependent control policy in which the phase durations for Directions 1 and 2 depend on the time-dependent flows Q_1^{ij} and Q_2^{ij}.

The moving delay cost of the traffic flows Q_1 and Q_2 in work zone i, C^1_{vi}, is this:

$$C^1_{vi} = \sum_j^n (Q_1^{ij} + Q_2^{ij}) D_{ij}\left(\frac{L_i}{V} - \frac{L_i}{V_0}\right)v \tag{6}$$

where V_0 is the approaching speed without a work zone.

The idling cost, which is idling time multiplied by the average cost of idling time for crews and equipment, is considered for work zones with time-dependent traffic demands. Idling time is a pause between two successive work zones, denoted as $\Delta t_i = (t_{s,i} - t_{e,i-1})$. The idling cost per zone, C^1_{Ii}, is this:

$$C^1_{Ii} = v_d \Delta t_i \tag{7}$$

where

v_d = average cost of idling time,
$t_{s,i}$ = starting time for zone i, and
$t_{e,i-1}$ = ending time for zone $i - 1$.

Note that Δt_i is 0 for $i = 1$.

The accident cost to traffic passing by the work zone can be determined from the number of accidents per 100 million vehicle hours n_a multiplied by the product of the increasing delay ($C^1_{qi}/v + C^1_{vi}/v$) and the average cost per accident v_a (*6*), where C^1_{qi}/v is the queuing delay and C^1_{vi}/v is the moving delay for work zone i. The accident cost per work zone C_{ai} is formulated in this way:

$$C^1_{ai} = \frac{\left(C^1_{qi} + C^1_{vi}\right)}{v}\frac{n_a v_a}{10^8} \tag{8}$$

The total cost for work zone i, C^1_{ti}, is $C^1_{mi} + C^1_{qi} + C^1_{vi} + C^1_{Ii} + C^1_{ai}$. The total cost for resurfacing road length L_T per lane by scheduling m work zones, C^1_T, is expressed as this (*3*):

$$\begin{aligned} C^1_T &= \sum_i^m C^1_{ti} \\ &= \sum_i^m (z_1 + z_2 L_i) + \sum_i^m \sum_j^n \left\{ \frac{\left[\begin{array}{l} Q_1^{ij}\left(\frac{3{,}600}{H} - Q_1^{ij}\right) \\ + Q_2^{ij}\left(\frac{3{,}600}{H} - Q_2^{ij}\right) \end{array}\right]v}{V\left(\frac{3{,}600}{H} - Q_1^{ij} - Q_2^{ij}\right)} D_{ij} L_i \right\} \\ &\quad + \sum_i^m \sum_j^n \left[\left(Q_1^{ij} + Q_2^{ij}\right)\left(\frac{1}{V} \quad \frac{1}{V_0}\right) v D_{ij} L_i\right] \\ &\quad + \sum_i^m v_d \Delta t_i + \sum_i^m \frac{\left(C_{qi} + C_{vi}\right)}{v}\frac{n_a v_a}{10^8} \end{aligned} \tag{9}$$

Possible queuing delays due to detour capacity and intersections along the detour are derived here for time-dependent inflows. Figure 2 shows the queuing delay and queue dissipation on a detour. For Alternative 1, no diverted flow affects the original flow Q_3^{ij} in Direction 3. With time-dependent traffic inflows, if Q_3^{ij} exceeds the detour capacity c_{d3}, a queue develops. The queuing delay is represented by the area **D** in Figure 2.

Then considered is what happens if pQ_1^{ij} is diverted to the detour and the flow in Direction 3 is $pQ_1^{ij} + Q_3^{ij}$ for work zone i. Figure 2 shows that the detour queue resulting from work zone $i - 1$ is not dissipated completely, and the queue length is q_{i-1} as work starts in zone i. The maximum queue length reached in work zone i is this:

$$q_{i,\max} = q_{i-1} + \left(pQ_1^{i1} + Q_3^{i1} - c_{d3}\right)D_{i1} + \left(pQ_1^{i2} + Q_3^{i2} - c_{d3}\right)D_{i2} + \cdots + \left(pQ_1^{i,j-1} + Q_3^{i,j-i} - c_{d3}\right)D_{i,j-1} \tag{10}$$

which equals the area **A** plus q_{i-1}. The area **A** plus q_{i-1} equals area **B**, which represents the number of dissipated vehicles. Note that work in zone i is completed at $t_{e,i}$ but there remains a dissipation time, $t_{rd,i}$. Figure 2 indicates that queue is dissipated completely before the next zone is started so that work zone i is completed at $t_{e,i}$, the queue is dissipated completely at $t_{e,i} + t_{rd,i}$, and zone $i + 1$ starts at $t_{e,i} + \Delta t_{i+1}$. Then the detour queuing delay for zone i is the area **C**. The queuing delay cost for zone i is this:

$$C_{qd,i} = (\text{area of } \mathbf{C})\,v \tag{11}$$

The queuing delay represented by the area **D**, which results from Q_3^{ij} only in Direction 3, is not included in the queuing delay due to the diverted flow pQ_1^{ij} in Direction 3 represented by the area **C**.

Here, the user delay cost for work zone i of the diverted flow pQ_1^{ij} along the detour due to intersection signal or stop delay, denoted as $C_{\text{int},i}$, is equal to the flow pQ_1^{ij} multiplied by the following: (a) resurfacing duration per zone, D_i, (b) number of intersections along detour, N_{int}, (c) average waiting time per intersection, t_{int}, and (d) value of time, v. Thus, the equation is as follows:

$$C_{\text{int},i} = \sum_j^n pQ_1^{ij} D_i N_{\text{int}} \frac{t_{\text{int}}}{3{,}600} v \tag{12}$$

Alternative 2

Figure 1b shows that the fraction p of the flow pQ_1^{ij} in Direction 1 is diverted to the alternate route. The user queuing delay cost for control cycles that alternate traffic directions past work zone i, $C^2_{q(1-p)2,i}$, can be expressed as follows:

$$C^2_{q(1-p)2,i} = \sum_j^n \frac{\left\{(1-p)Q_1^{ij}\left[\frac{3{,}600}{H} - (1-p)Q_1^{ij} + Q_2^{ij}\left(\frac{3{,}600}{H} - Q_2^{ij}\right)\right]\right\}v}{V\left(\frac{3{,}600}{H} - (I-p)Q_1^{ij} - Q_2^{ij}\right)} D_{ij} L_i \tag{13}$$

The possible queuing delay cost of the diverted flow pQ_1^{ij} and Q_3^{tj} in Direction 3 for zone i, denoted as $C^2_{qd,i}$, is this:

$$C^2_{qd,i} = (\text{area of } \mathbf{C})\,v \tag{14}$$

where the area **C** is shown in Figure 2. The user delay cost of the diverted flow pQ_1^{ij} from Direction 1 along detour due to intersection signal or stop delay, denoted as $C^2_{\text{int},i}$, is this:

$$C^2_{\text{int},i} = \sum_j^n pQ_1^{ij} D_i N_{\text{int}} \frac{t_{\text{int}}}{3{,}600} v \tag{15}$$

The combined queuing delay cost for the resurfaced Road AB and the detour of Alternative 2, C^2_{qi}, is this:

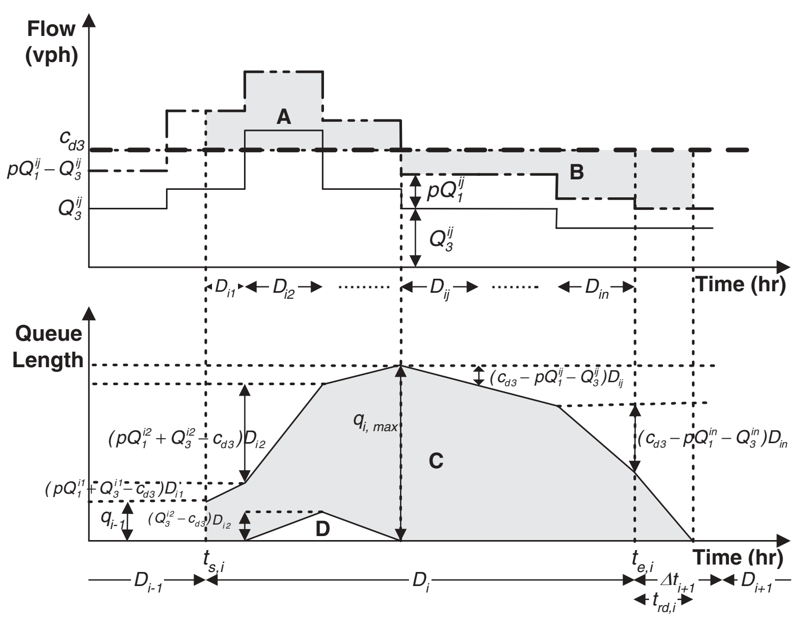


FIGURE 2 Queuing delay and dissipation of queue length along detour for Flow Q_3.

$$C_{qi}^2 = C_{q(1-p)2,i}^2 + C_{qd,i}^2 + C_{\text{int},i}^2 \tag{16}$$

The moving delay cost of the remaining traffic flow in Direction 1, $(1-p)Q_1^{ij}$, and Q_2^{ij}, for zone i, denoted as $C_{v(1-p)2,i}^2$, is formulated in this way:

$$C_{v(1-p)2,i}^2 = \sum_j^n \left[(1-p)Q_1^{ij} + Q_2^{ij}\right] D_{ij} \left(\frac{L_i}{V} - \frac{L_i}{V_0}\right) v \tag{17}$$

The moving delay cost of the diverted flow pQ_1^{ij} from Direction 1, denoted as $C_{vp,i}^2$, is this:

$$C_{vp,i}^2 = \sum_j^n pQ_1^{ij} D_i \left(\frac{L_{d1} + L_{d3}}{V_0} + \frac{L_{d2}}{V_d^{*3}} - \frac{L_t}{V_0}\right) v \tag{18}$$

where

V_d^{*3} = detour speed affected by diverted traffic in Direction 3;
L_t = project road length; and
L_{d1}, L_{d2}, and L_{d3} = lengths of first, second, and third detour segments, respectively.

The moving delay cost $C_{v3,i}^2$ to the original flow on the detour, Q_3^{ij}, as affected by the pQ_1^{ij}, is this:

$$C_{v3,i}^2 = \sum_j^n Q_3^{ij} D_i \left(\frac{L_{d2}}{V_d^{*3}} - \frac{L_{d2}}{V_{d0}}\right) v \tag{19}$$

where V_{d0} is the original detour speed unaffected by diverted traffic. The combined moving delay cost for the resurfaced Road AB and the detour C_{vi}^2 is this:

$$C_{vi}^2 = C_{v(1-p)2,i}^2 + C_{vp,i}^2 + C_{v3,i}^2 \tag{20}$$

The idling cost for zone i, C_{Ii}^2, is $v_d \Delta t_i$. Its accident cost, C_{ai}^2, is $\dfrac{(C_{qi}^2 + C_{vi}^2)}{v} \dfrac{n_a v_a}{10^8}$.

The resurfacing cost for zone i, C_{mi}^2, is $z_1 + z_2 L_i$. Then the total cost for work zone i, C_{ti}^2, is $C_{mi}^2 + C_{qi}^2 + C_{vi}^2 + C_{Ii}^2 + C_{ai}^2$. The total cost for resurfacing road length L_T per lane, C_T^2, is this:

$$\begin{aligned} C_T^2 &= \sum_i^m C_{ti}^2 \\ &= \sum_i^m (z_1 + z_2 L_i) + \sum_i^m C_{qi}^2 + \sum_i^m C_{vi}^2 + \sum_i^m v_d \Delta t_i \\ &\quad + \sum_i^m \frac{(C_{qi}^2 + C_{vi}^2)}{v} \frac{n_a v_a}{10^8} \end{aligned} \tag{21}$$

Alternative 3

Figure 1*c* shows that the entire flow Q_1^{ij} in Alternative 1 is diverted to the alternate route. The possible queuing delay cost of the diverted flow Q_1^{ij} and Q_3^{ij} in Direction 3 for zone i, denoted as $C_{qd,i}^3$, is this:

$$C_{qd,i}^3 = (\text{area of } \mathbf{C}) v \tag{22}$$

where the area **C** is shown in Figure 2 and the p-value is 1 (full diversion). The user delay cost of the diverted flow Q_1^{ij} from Direction 1 along the detour due to intersection signal or stop delay, denoted as $C_{\text{int},i}^3$, is this:

$$C_{\text{int},i}^3 = \sum_j^n Q_1^{ij} D_i N_{\text{int}} \frac{t_{\text{int}}}{3{,}600} v \tag{23}$$

The combined queuing delay cost for the resurfaced Road AB and the detour C_{qi}^3 is this:

$$C_{qi}^3 = C_{qd,i}^3 + C_{\text{int},i}^3 \tag{24}$$

The user moving delay cost in Direction 1 for zone i, denoted as $C_{v1,i}^3$, has the same formulation as in Equation 18 but with Q_1^{ij} substituted for pQ_1^{ij}.

$$C_{v1,i}^3 = \sum_j^n Q_1^{ij} D_i \left(\frac{L_{d1} + L_{d3}}{V_0} + \frac{L_{d2}}{V_d^{*3}} - \frac{L'_t}{V_0}\right) v \tag{25}$$

The moving delay cost of Q_2^{ij} along work zone for zone i, denoted as $C_{v2,i}^3$, is this:

$$C_{v2,i}^3 = \sum_j^n Q_2^{ij} D_{ij} \left(\frac{L'_i}{V} - \frac{L_i}{V_0}\right) v \tag{26}$$

The moving delay cost $C_{v3,i}^3$ of the original flow on the detour, Q_3^{ij}, as affected by the Q_2^{ij}, has the same formulation as in Equation 19, $C_{v3,i}^3 = C_{v3,i}^2$.

The combined moving delay cost for the resurfaced Road AB and the detour C_{vi}^3 is this:

$$C_{vi}^3 = C_{v1,i}^3 + C_{v2,i}^3 + C_{v3,i}^3 \tag{27}$$

The idling cost for zone i, C_{Ii}^3, is $v_d \Delta t_i$. The accident cost for zone i, C_{ai}^3, is $\dfrac{C_{qi}^3 + C_{vi}^3}{v} \dfrac{n_a v_a}{10^8}$.

The resurfacing cost for zone i, C_{mi}^3, is $z_1 + z_2 L_i$. Then the total cost for zone i, C_{ti}^3, is $C_{mi}^3 + C_{qi}^3 + C_{vi}^3 + C_{Ii}^3 + C_{ai}^3$. The total cost for resurfacing road length L_T per lane, C_T^3, is this:

$$\begin{aligned} C_T^3 &= \sum_i^m C_{ti}^3 \\ &= \sum_i^m (z_1 + z_2 L) + \sum_i^m C_{qi}^3 + \sum_i^m C_{vi}^3 + \sum_i^m v_d \Delta t_i \\ &\quad + \sum_i^m \frac{(C_{qi}^3 + C_{vi}^3)}{v} \frac{n_a v_a}{10^8} \end{aligned} \tag{28}$$

Alternative 4

As shown in Figure 1*d*, in Alternative 4 the entire flows Q_1^{ij} and Q_2^{ij} are diverted to the alternate route and both lanes between Roads A and B are entirely closed. The queuing delay cost of the diverted flow Q_1^{ij} plus Q_3^{ij} in Direction 3 and the diverted flow Q_2^{ij} plus Q_4^{ij} in Direction 4, denoted as $C_{qd,i}^4$, is this:

$$C_{qd,i}^4 = (\text{area of } \mathbf{C} + \text{area of } \mathbf{C}') v \tag{29}$$

where the area **C** is shown in Figure 2 and the p-value is 1 (full diversion). The area **C′** is the queuing delay of the diverted flow Q_2^{ij} plus Q_4^{ij} in Direction 4. The calculation of the area **C′** is similar to that for area **C** but with Q_2^{ij} substituted for Q_1^{ij}, with Q_4^{ij} substituted for Q_3^{ij}, and with c_{d4} substituted for c_{d3}, where c_{d2} is the detour capacity in Direction 4.

The user delay cost of the diverted flow Q_1^{ij} from Direction 1 and the diverted flow Q_2^{ij} from Direction 2 along the detour due to intersection signal or stop delay, denoted as $C^4_{\text{int},i}$, is this:

$$C^4_{\text{int},i} = \sum_j^n \left(Q_1^{ij} + Q_2^{ij}\right) D_i N_{\text{int}} \frac{t_{\text{int}}}{3{,}600} v \tag{30}$$

The combined queuing delay cost for the resurfaced Road AB and the detour C^4_{qi} is this:

$$C^4_{qi} = C^4_{qd,i} + C^4_{\text{int},i} \tag{31}$$

The user moving delay cost in Direction 1 for zone i, denoted as $C^4_{v1,i}$, has the same formulation as in Equation 25, $C^4_{v1,i} = C^3_{v1,i}$.

The user moving delay cost of the flow Q_2^{ij} for zone i, denoted as C^4_{v2}, has the same formulation as in Equation 25 but with Q_2^{ij} substituted for Q_1^{ij} and with V_d^{*4} substituted for V_d^{*3}.

$$C^4_{v2,i} = \sum_j^n Q_2^{ij} D_i \left(\frac{L_{d1} + L_{d3}}{V_0} + \frac{L_{d2}}{V_d^{*4}} - \frac{L_t}{V_0}\right) v \tag{32}$$

The moving delay cost $C^4_{v3,i}$ to the original flow on the detour in Direction 3, Q_3^{ij}, as affected by the Q_1^{ij}, has the same formulation as in Equation 19, $C^4_{v3,i} = C^2_{v3,i}$.

Similarly, the moving delay cost $C^4_{v4,i}$ of the original flow on the detour in Direction 4, Q_4^{ij}, as affected by the Q_2^{ij}, has the same formulation as in Equation 19 but with Q_4^{ij} substituted for Q_3^{ij} and V_d^{*4} substituted for V_d^{*3}.

$$C^4_{v4,i} = \sum_j^n Q_4^{ij} D_i \left(\frac{L_{d2} + L_{d3}}{V_d^{*4}} - \frac{L_{d2}}{V_{d0}}\right) v \tag{33}$$

The combined moving delay cost for the resurfaced Road AB and the detour C^4_{vi} is this:

$$C^4_{vt} = C^4_{v1,i} + C^4_{v2,i} + C^4_{v3,i} + C^4_{v4,i} \tag{34}$$

The idling cost for zone i, C^4_{Ii}, is $v_d \Delta t_i$. The accident cost for zone i, C^4_{ai}, is $\dfrac{C^4_{qi} + C^4_{vi}}{v} \dfrac{n_a v_a}{10^8}$.

The resurfacing cost for zone i, C^4_{mi}, is $z_1 + z_2 L_i$. Then the total cost for zone i, C^4_{ti}, is this: $C^4_{mi} + C^4_{qi} + C^4_{vi} + C^4_{Ii} + C^4_{ai}$. The total cost for resurfacing road length L_T per lane, C^4_T, is this:

$$\begin{aligned} C^4_T &= \sum_i^m C^4_{ti} \\ &= \sum_i^m (z_1 + z_2 L_i) + \sum_i^m C^4_{qi} + \sum_i^m C^4_{vi} + \sum_i^m v_d \Delta t_i \\ &\quad + \sum_i^m \frac{\left(C^4_{qi} + C^4_{vi}\right)}{v} \frac{n_a v_a}{10^8} \end{aligned} \tag{35}$$

OPTIMIZATION

The previous study by Chen and Schonfeld (*3*) shows that their simulated annealing algorithm can reliably find solutions that are very close to the global optimum. In this paper, the SAUASD algorithm is developed based on that previous study (*3*) to find the best uniform alternative (i.e., without different alternatives in successive zones) for an entire resurfacing project. To further minimize total costs, different alternatives may be preferable for various traffic levels on the main road and detour. An improved search algorithm, SAMASD, is developed that allows different alternatives to be optimized for successive zones within a project.

The optimized variables of the total cost function include the work zones lengths L_i and required starting times $t_{s,i}$. The zone ending times $t_{e,i}$, the duration of resurfacing pauses between two work zones Δt_i, and the time-dependent cycle lengths for discharging directional traffic over different time periods can be uniquely determined from the optimized variables L_i and $t_{s,i}$. If mixed alternatives are allowed, two optimized variables, the selected alternative for zone i, A_i, and diverted fraction for zone i, p_i, are added.

Simulated annealing is a stochastic computational technique derived from statistical mechanics for finding near globally optimum solutions to large optimization problems. It was developed by Metropolis et al. (*7*) to simulate the annealing process of crystals on a computer. Kirkpatrick et al. (*5*) adapted this methodology to an algorithm exploiting the analogy between annealing solids and solving combinatorial optimization problems. The simulated annealing search process attempts to avoid becoming trapped at a local optimum by using a stochastic computational technique to find globally or near globally optimal solutions to combinatorial problems.

The simulated annealing algorithms, including SAUASD and SAMASD, as shown in Figure 3, adapted here for work zone optimization are as follows:

Step 0. Generate an initial solution. Calculate average flow volume between two peak traffic periods, $\bar{Q}$. Given a project starting time, the initial work zone length L_i and duration D_i can be obtained by using the traffic volume $\bar{Q}$ for each stage and optimizing for steady traffic flows by using Chen's model (*8*). Here a stage is the period between two highest peak traffic flow volumes. The number of zones in each stage depends on how many D_i can be contained within the stage duration. The solution $S = (L_1, L_2, \ldots, L_i, \ldots, L_m, t_{s,1}, t_{s,2}, \ldots, t_{s,i}, \ldots, t_{s,m})$ is the initial solution for work zone lengths and starting times. Set $j = 0$ and $k = 0$, $j = 0$ to $J_{\max}$ and $k = 0$ to $K_{\max}$. Set the values of T_0 and T_f. If SAMASD is applied, set initial $A_{\text{opt},i} = 1$ and $p_{\text{opt},i} = 0$. $A_{\text{opt},i}$ and $p_{\text{opt},i}$ are the values of A_i and p_i for final solutions. $A_i = 1, 2, 3, 4$ and $p_i = 0, 0.1, 0.2, \ldots, 1$.

Step 1. Generate a neighboring solution. Randomly generate four numbers: n_1, n_2, n_3, and n_4. The numbers n_1 and n_2 are two zones chosen randomly from all work zones in the previous solution. The number n_1 or n_2 is equal to 1+ int(m*r), where int is a function that takes only the integer part of a real number; r is a uniform random number between 0 and 1. The number n_3 is a binary random number, in which 0 indicates that zone length decreases by one unit in zone n_1 and increases by one unit in zone n_2 while 1 indicates length increases by one unit in zone n_1 and decreases by one unit in zone n_2. The number n_4 is a binary random number, in which 0 or 1 indicates that an "increase event" or "decrease event" occurs at the end or at the beginning of zones, respectively. When zone n_1 is randomly chosen, $i = n_1$, and that zone length increases or decreases by one unit, from L_i to L'_i, while zone n_2 decreases or increases by one unit, from L_j to L'_j, to keep the total project length unchanged. Other zone lengths stay unchanged. The details for increase, including "Increase in end"

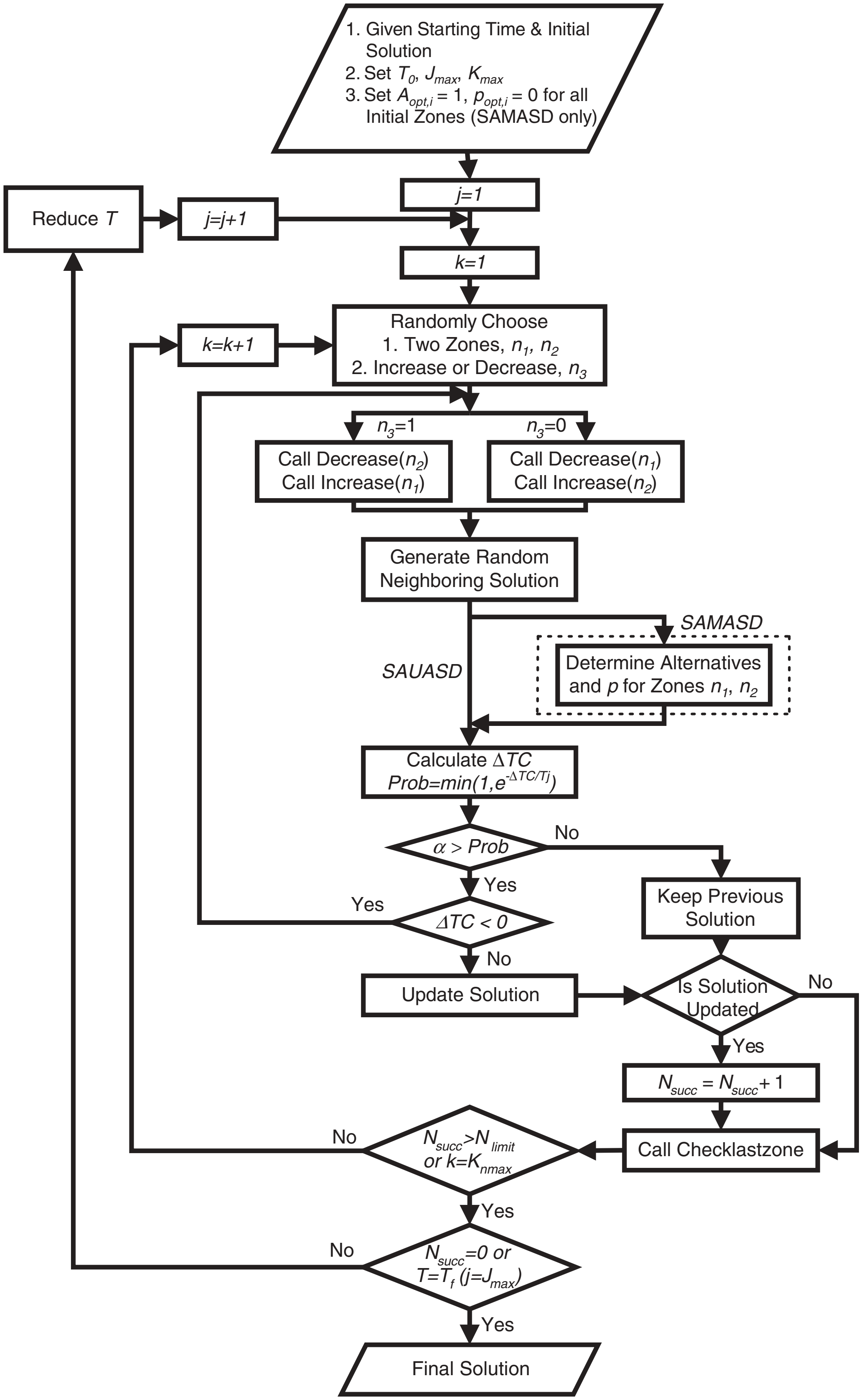


FIGURE 3 SAUASD and SAMASD algorithms.

and "Increase in begin"; and for decrease, including "Decrease in end" and "Decrease in begin"; and "Call Checklastzone" are covered in Chen (*8*). The neighboring solution $S' = (L_1, L_2, \ldots, L_i', \ldots, L_j', \ldots, t_{s,1}, t_{s,2}, \ldots, \ldots, t_{s,j}', \ldots, t_{s,m})$ is generated after one decrease event and one increase event. If the SAUASD is applied, then skip Step 1.1 and go to Step 1.2. If the SAMASD is applied, then continue with Steps 1.1 and 1.2 that follow.

Step 1.1. Determine alternatives and p for zone n_1 and n_2. Test all possible A_i and p_i combinations and calculate the total cost. If total cost for the current combination is lower than for the previous combination, update A_i and p_i; otherwise, keep the previous solution. This procedure terminates when all A_i and p_i combinations are tested. Figure 4 shows how SAMASD determines alternatives and diverted fractions.

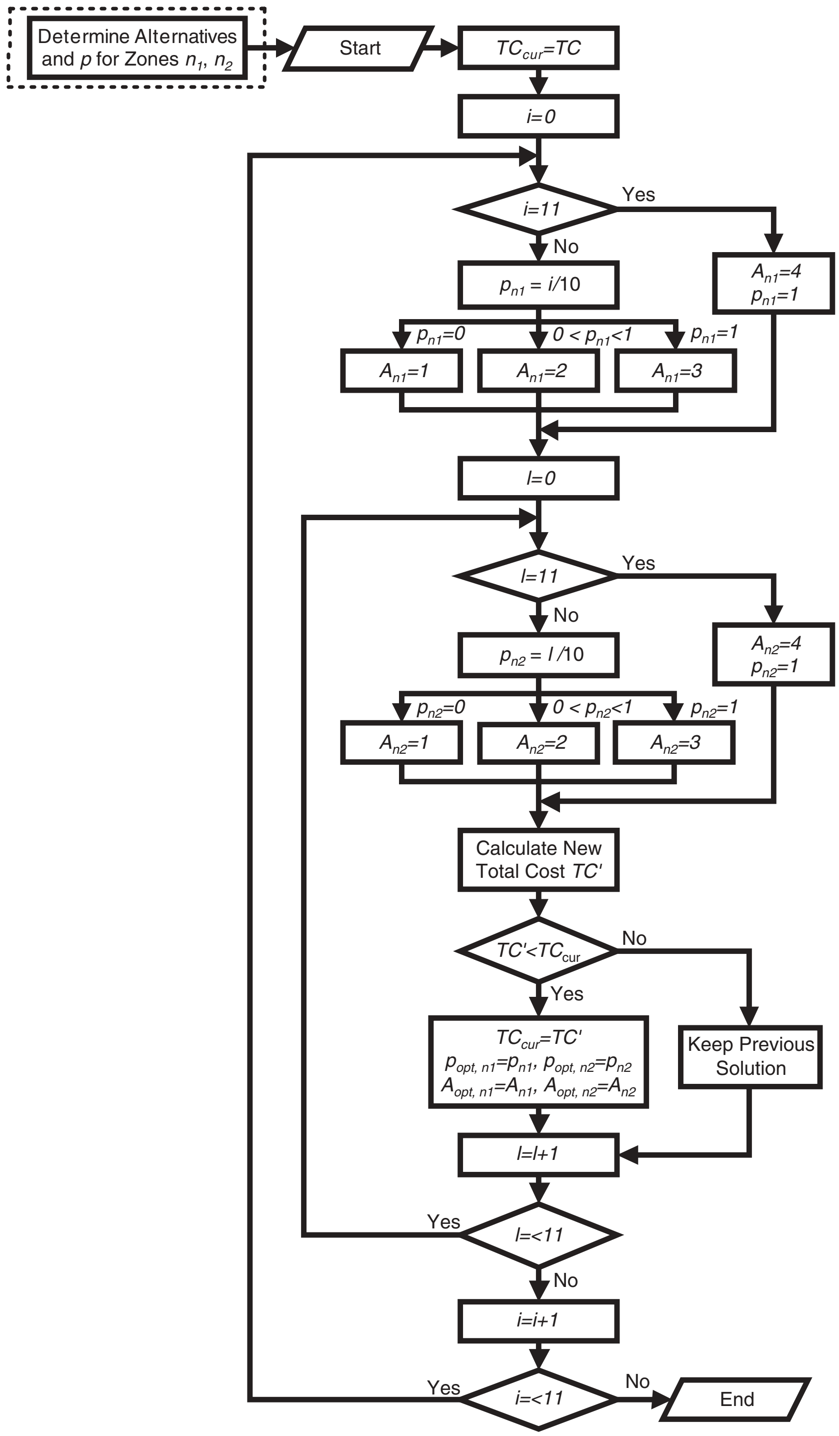


FIGURE 4 Determining alternatives and diverted fractions in SAMASD (TC_{cur} is the current total cost in *j*th iteration while temperature is reduced from T_0 to T_f).

Step 1.2. Compute the objective function value and the difference between the new and previous total costs: $\Delta TC = TC(S') - TC(S)$. If $\Delta TC < 0$, go to Step 3. Otherwise, go to Step 2.

Step 2. ($\Delta TC > 0$). Select a random variable $\alpha \in U(0, 1)$. If $\alpha < \text{Prob}(\Delta TC) \equiv \exp(-\Delta TC/T_j)$, then go to Step 3. If $\alpha \geq \text{Prob}(\Delta TC) \equiv \exp(-\Delta TC/T_j)$, then reject this new solution and go to Step 4.

Step 3. [$\Delta TC < 0$ or $\alpha < \text{Prob}(\Delta TC)$]. Accept the new solution S' and new total cost TC(S'). Store the new solution and total cost.

Step 4. If $T_j > T_f$ and $k < K_{\max}$, then $k = k + 1$ and go to Step 1. If $T_j > T_f$ and $k = K_{\max}$, then reduce T_j, $j = j + 1$, $k = 1$, and go to Step 1. Otherwise, stop. In Figure 3, N_{succ} is the cumulative number of optimization iterations at temperature T_j and N_{limit} is the maximum number of optimization iterations at temperature T_j.

RESULTS

The effects of various parameters on the preferable alternatives and work zone scheduling for two-lane highways are examined in this section. Optimized solutions for a 7.5-lane-km resurfacing project are developed and explained using a numerical example, whose baseline numerical values are shown in Table 1. It should be noted that the baseline values for costs and work durations shown in Table 1 are based on data or estimates provided by the Maryland State Highway Administration. Table 2 shows the hourly traffic distributions on the main road and detour. The annual average daily traffic (AADT) volume on the main road and on the detour are 15,000 and 10,000 vehicles, respectively.

TABLE 1 Notation and Baseline Inputs for Numerical Example

Variables	Description	Input Values
c_{d3}	Maximum discharge rate along detour L_{d2}	1,300 vph
H	Average headway through work zone area	3 s
$AADT_m$	Annual average daily traffic on main road	15,000
$AADT_d$	Annual average daily traffic on detour	10,000
L_i	Zone length for zone i	—
L_T	Project road length	7.5 lane km
L_{d1}	Length of first detour segment	0.5 km
L_{d2}	Length of second detour segment	7.5 km
L_{d3}	Length of third detour segment	0.5 km
N_{int}	Number of intersections along detour	3
n_a	Number of accidents per 100 million vehicle hours	40 acc/100 mvh (*9*)
Q_1^{ij}	Traffic flows in Direction 1 during period j for zone i	—
Q_1^{ij}	Traffic flows in Direction 2 during period j for zone i	—
t_{int}	Average waiting time per intersection	30 s
t_1^{ij}	Discharge phase for traffic in Direction 1 during period j for zone i	—
t_2^{ij}	Discharge phase for traffic in Direction 2 during period j for zone i	—
$t_{e,i}$	Ending time for zone i	—
$t_{s,i}$	Starting time for zone i	—
Δt_i	Idling time for zone i	—
V	Average work zone speed	50 km/hr
v	Value of user time	\$12/veh hr
v_a	Average accident cost	\$142,000/accident (*6*)
v_d	Average cost of idling time	\$800/hr
z_1	Fixed setup cost	\$1,000/zone
z_2	Average resurfacing cost per lane kilometer	\$80,000/lane km
z_3	Fixed setup time	2 hr/zone
z_4	Average resurfacing time per lane kilometer	6 hr/lane km

Uniform Alternatives

Figure 5 shows the minimized total costs and project starting times for Alternatives 1 ($p = 0$), 2 ($p = .3, .6, .9$), 3 ($p = 1$) and 4. These results are obtained with SAUASD. First, it is assumed that all alternatives have the same z_4 baseline value, 6 h/km, as shown in Figure 5*a*. The best project starting times are 12:00, 11:00, and 9:00, respectively, for Alternatives 1, 3, and 4; and 20:00 for Alternative 2 ($p = .3, .6, .9$). Figure 5*a* indicates that Alternative 4 is preferable for most project starting times. However, based on the baseline values in Table 1, the total cost of Alternative 3 is minimized by starting the work at 11:00, as shown in Table 3. Its minimized total cost is \$614,416 per project, with three work zones whose optimized lengths of 2.64, 2.23, and 2.63 km add up to 7.5 km, and whose idling time is 0. Table 4 shows the optimized result for Alternative 4, starting at 11:00. Note that the agency cost, including resurfacing cost and idling cost, for Alternative 4 (\$601,000) is lower than for Alternative 3 (\$603,000). However, the user cost, including queuing delay and moving delay, and accident costs, for Alternative 4 (\$14,459) is higher than for Alternative 3 (\$11,417). This occurs because Alternative 4 has only one zone in the project (for both lanes are closed), resulting in lower resurfacing cost (for setup) and higher user cost (full diversion in both directions).

To consider the speed-up effect of closing both lanes in Alternative 4, a lower average resurfacing time per kilometer is applied for Alternative 4—that is, z_4 is 5 h/km, versus 6 h/km for other alternatives. Alternative 4 has lowest total cost for all project starting times, as shown in Figure 5*b*, and its cost is minimized by starting the work at 17:00, as shown in Table 5. This occurs because a lower average resurfacing time per kilometer reduces the total project duration and moving delay cost, compared to Table 5. One can find that Alternatives 3 and 4 in Tables 3 and 5 have almost the same user cost, but Alternative 4 has a lower agency cost due to its single zone. Such tradeoffs between agency costs and user costs, or determination of cost and duration parameters for different alternatives, should be carefully considered in project scheduling.

Sensitivity Analysis

Figure 6*a* shows that Alternatives 1, 2, and 3 are on the lowest cost envelope. The first of three thresholds with respect to AADT occurs at 22,000 vehicles per day, beyond which Alternative 2 ($p = .6$) becomes preferable to Alternative 3 ($p = 1.0$). Beyond 24,000 vehicles per day, Alternative 2 ($p = .3$) becomes preferable to Alternative 2 ($p = .6$). Beyond 32,000 vehicles per day, Alternative 1 ($p = 0$) becomes preferable to Alternative 2 ($p = .3$). A sharp increase in cost occurs for all alternatives except for Alternative 1, because the

TABLE 2 AADT and Hourly Traffic Distribution on a Two-Lane, Two-Way Highway

Hour	Main Road Volume (both directions)	Q_1 (vph)	Q_2 (vph)	Detour Volume (both directions)	Q_3 (vph)	Q_4 (vph)
0	349	167	182	233	112	121
1	350	168	182	233	112	121
2	349	157	192	233	105	128
3	350	185	165	233	123	110
4	349	185	164	233	123	110
5	350	186	164	233	123	110
6	552	315	237	368	210	158
7	900	504	396	600	336	264
8	1,152	645	507	768	430	338
9	1,002	541	461	668	361	307
10	800	408	392	533	272	261
11	649	331	318	433	221	212
12	600	300	300	400	200	200
13	552	287	265	368	191	177
14	650	332	318	433	221	212
15	852	452	400	568	301	267
16	1,100	539	561	733	359	374
17	844	397	447	563	265	298
18	750	353	397	500	235	265
19	702	330	372	468	220	248
20	600	276	324	400	184	216
21	500	240	260	333	160	173
22	349	167	182	233	112	121
23	349	167	182	233	112	121
AADT	15,000	7,632	7,368	10,000	5,088	4,912

detour queuing delays increase drastically when the diverted flow plus original detour flow exceed the detour capacity. The differences in total costs among various alternatives also become quite significant when detour AADT exceeds about 20,000. Because Alternative 1 has no detour, its minimized total cost is insensitive to detour AADT. Note that the first sharp increase occurs in Alternative 4 due to full diversion in both directions. This threshold analysis indicates that higher detour traffic increases the time that diverted motorists need to return to the original main road. If motorists must spend much more time on the detour, little or no diversion is desirable.

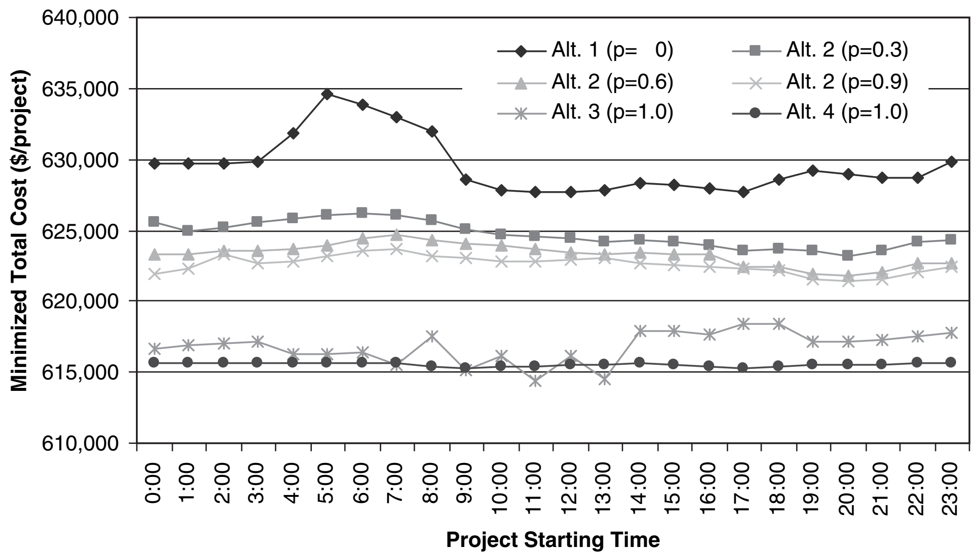
Mixed Alternatives

In Figure 6*a*, the minimized total costs for different detour AADTs can be obtained through threshold analysis. Here Figure 6*a* is modified by adding a curve that represents the total costs for mixed alternatives minimized with the SAMASD algorithm. The modified result, in Figure 6*b*, shows that in most situations with increased detour AADT, mixed alternatives can yield lower minimized total costs than with the envelope on which Alternatives 1, 2, and 3 are included in Figure 6*a*. With a detour AADT at 5,000 to 15,000 vehicles per day, mixed alternatives are not significantly better than Alternative 3, and they provide no further improvement.

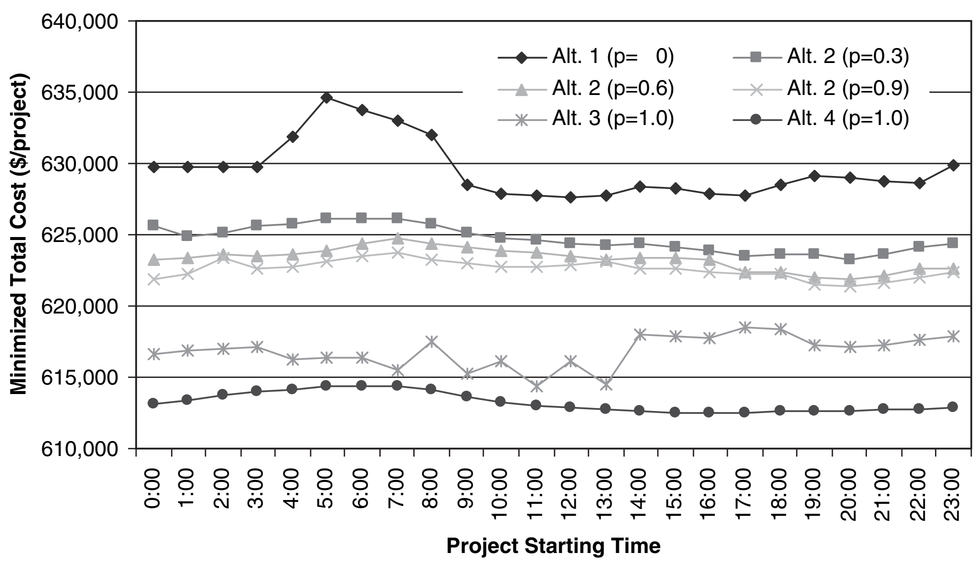
When the detour AADT increases to 20,000 vehicles per day, Alternative 3 has a minimized total cost of $622,036 per project; however, a lower minimized total cost, at $619,770 per project, is found by considering mixed alternatives. Tables 6 and 7 show the optimized results for Alternative 3 and the mixed alternatives with an 11:00 start. Table 7 indicates that no diversion (Alternative 1) is applied in the first and last zones; full diversion (Alternative 3) is applied in other zones when mixed alternatives are considered.

Tables 8 and 9 indicate the optimized results for mixed alternatives when the detour AADT reaches 30,000 and 35,000 vehicles per day, respectively. The minimized total costs with mixed alternatives are also lower than those with the envelope of Alternatives 2 ($p = 0.3$) and 1. The differences in total costs are $2,636, and $3,449, respectively. Table 8 shows that partial or no diversion is applied during daytime—that is, in Zones 1, 3, and 5 in Tables 8 and 9. Full diversion is applied during nighttime—that is, in Zones 2, 4, and 6. Note that diverted fraction during daytime decreases as detour AADT increases, because a little additional diverted traffic sharply increases queuing delay costs as the diverted flow plus original detour flow approach detour capacity.

From Figure 6*b* and Tables 6 through 9, it is found that when detour AADT is low, for example, below 15,000 vehicles per day, the total cost is minimized with uniform alternatives throughout the project. As detour AADT increases, mixed alternatives with no diversion, partial diversion, or full diversion in different zones can yield lower minimized total cost than do uniform alternatives. Thus, appropriate traffic management plans should be developed based on the different traffic inflows of main roads and detours.



(a)



(b)

FIGURE 5 Minimum total cost versus project starting time: (*a*) z_4 = 6 h/km for all alternatives and (*b*) z_4 = 5 h/km for Alternative 4 and 6 h/km for other alternatives.

TABLE 3 Optimized Result for Numerical Example: Project Starting Time = 11:00, z_4 = 6 h/km, Alternative 3

Zone No.	Optimized Length (km)	Duration (hr)	Starting Time (0~23.99)	Ending Time (0~23.99)	Idling Time (hr)	Total Cost ($/zone)
1	2.64	17.84	11.00	4.84	0.00	215,842
2	2.23	15.38	4.84	20.22	0.00	183,511
3	2.63	17.78	20.22	14.00	0.00	215,063
Total	7.50	51.00			0.00	614,416
Resurfacing cost						603,000
Queuing delay cost						0
Moving delay cost						11,363
Idling cost						0
Accident cost						54
Total cost						614,416
Total cost/project km ($/lane km)						81,922

TABLE 4 Optimized Result for Numerical Example: Project Starting Time = 11:00, z_4 = 6 h/km, Alternative 4

Zone No.	Optimized Length (km)	Duration (hr)	Starting Time (0~23.99)	Ending Time (0~23.99)	Idling Time (hr)	Total Cost ($/zone)
1	7.50	47.00	11.00	10.00	0.00	615,459
Total	7.50	47.00			0.00	615,459
Resurfacing cost						601,000
Queuing delay cost						0
Moving delay cost						14,391
Idling cost						0
Accident cost						68
Total cost						615,459
Total cost/project km ($/lane km)						82,061

TABLE 5 Optimized Result for Numerical Example: Project Starting Time = 17:00, z_4 = 5 h/km, Alternative 4

Zone No.	Optimized Length (km)	Duration (hr)	Starting Time (0~23.99)	Ending Time (0~23.99)	Idling Time (hr)	Total Cost ($/zone)
1	7.50	39.50	17.00	8.50	0.00	612,447
Total	7.50	39.50			0.00	612,447
Resurfacing cost						601,000
Queuing delay cost						0
Moving delay cost						11,393
Idling cost						0
Accident cost						54
Total cost						612,447
Total cost/project km ($/lane km)						81,660

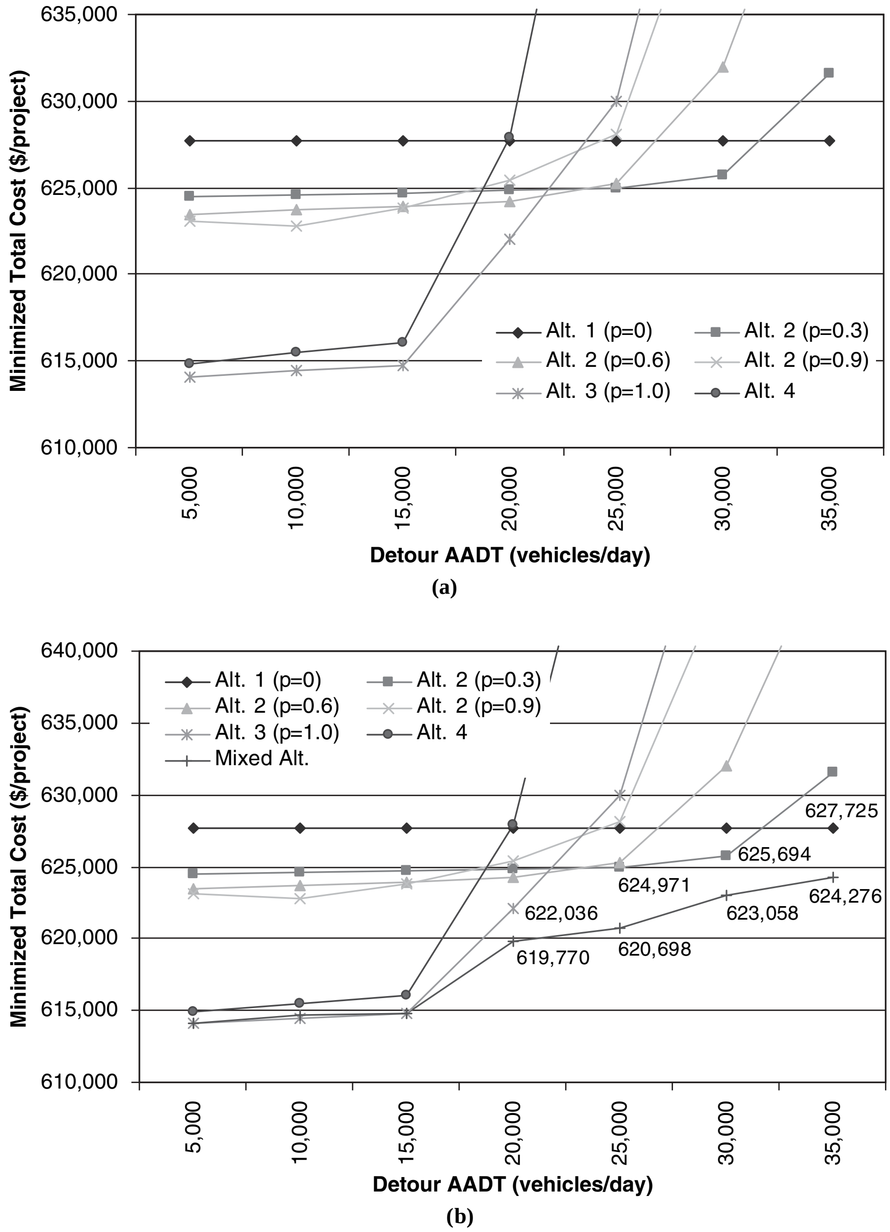


FIGURE 6 Minimized total cost versus detour AADT: (*a*) uniform alternatives and (*b*) mixed alternatives.

TABLE 6 Optimized Result for Numerical Example: Detour AADT = 20,000 Vehicles, Project Starting Time = 11:00, Alternative 3

Zone No.	Optimized Length (km)	Duration (hr)	Starting Time (0~23.99)	Ending Time (0~23.99)	Idling Time (hr)	Total Cost ($/zone)
1	0.69	6.17	11.00	17.17	0.00	57,953
2	0.76	6.59	17.17	23.75	0.00	63,241
3	1.03	8.21	23.75	7.96	0.00	84,890
4	0.80	6.83	8.95	15.78	0.99	67,750
5	0.77	6.65	15.78	22.42	0.00	64,376
6	1.25	9.53	22.42	7.95	0.00	102,656
7	0.67	6.05	8.98	15.03	1.03	57,116
8	0.56	5.39	15.03	20.41	0.00	47,471
9	0.93	7.61	20.41	4.02	0.00	76,583
Total	7.50	63.00			2.02	622,036
Resurfacing cost						609,000
Queuing delay cost						22
Moving delay cost						11,345
Idling cost						1,615
Accident cost						54
Total cost						622,036
Total cost/project km ($/lane km)						82,938

TABLE 7 Optimized Result for Numerical Example: Detour AADT = 20,000 Vehicles, Project Starting Time = 11:00, Mixed Alternatives

Zone No.	Optimized Length (km)	Duration (hr)	Starting Time (0~23.99)	Ending Time (0~23.99)	Idling Time (hr)	Preferred Zone Alternative	Preferred Diverted Fraction	Total Cost ($/zone)
1	0.26	3.56	11.00	14.56	0.00	1	0.00	22,056
2	0.89	7.34	14.56	21.90	0.00	3	1.00	73,900
3	1.35	10.10	21.90	8.00	0.00	3	1.00	110,392
4	1.37	10.22	8.95	19.17	0.95	3	1.00	114,072
5	1.80	12.80	19.17	7.97	0.00	3	1.00	146,996
6	1.44	10.64	8.99	19.63	1.02	3	1.00	119,815
7	0.39	4.34	19.63	23.97	0.00	1	0.00	32,538
Total	7.50	59.00			1.97			619,770
Resurfacing cost								607,000
Queuing delay cost								491
Moving delay cost								10,649
Idling cost								1,578
Accident cost								53
Total cost								619,770
Total cost/project km ($/lane km)								82,636

TABLE 8 Optimized Result for Numerical Example: Detour AADT = 30,000 Vehicles, Project Starting Time = 11:00, Mixed Alternatives

Zone No.	Optimized Length (km)	Duration (hr)	Starting Time (0~23.99)	Ending Time (0~23.99)	Idling Time (hr)	Preferred Zone Alternative	Preferred Diverted Fraction	Total Cost ($/zone)
1	0.67	6.01	11.00	17.01	0.00	2	0.40	56,164
2	1.99	13.93	17.01	6.95	0.00	3	1.00	162,496
3	0.86	7.15	9.03	16.18	2.08	2	0.40	73,585
4	2.00	13.99	16.98	6.97	0.80	3	1.00	163,964
5	0.86	7.14	9.02	16.16	2.05	2	0.40	73,391
6	1.13	8.77	16.97	1.75	0.81	3	1.00	93,459
Total	7.50	57.00			5.75			623,058
Resurfacing cost								606,000
Queuing delay cost								3,584
Moving delay cost								8,817
Idling cost								4,598
Accident cost								59
Total cost								623,058
Total cost/project km ($/lane km)								83,074

TABLE 9 Optimized Result for Numerical Example: Detour AADT = 35,000 Vehicles, Project Starting Time = 11:00, Mixed Alternatives

Zone No.	Optimized Length (km)	Duration (hr)	Starting Time (0~23.99)	Ending Time (0~23.99)	Idling Time (hr)	Preferred Zone Alternative	Preferred Diverted Fraction	Total Cost ($/zone)
1	0.51	5.03	11.00	16.03	0.00	1	0.00	42,308
2	2.00	13.97	17.00	6.97	0.97	3	1.00	164,034
3	0.71	6.23	9.73	15.97	2.76	2	0.10	61,259
4	1.99	13.95	17.02	6.97	1.05	3	1.00	163,725
5	0.71	6.23	9.73	15.96	2.76	2	0.10	61,261
6	1.60	11.58	17.05	4.63	1.10	3	1.00	131,688
Total	7.50	57.00			8.63			624,276
Resurfacing cost								606,000
Queuing delay cost								3,630
Moving delay cost								7,685
Idling cost								6,908
Accident cost								54
Total cost								624,276
Total cost/project km ($/lane km)								83,237

CONCLUSIONS

A work zone planning model for a two-lane highway resurfacing projects with an alternate route is developed to determine the best project starting time, optimal zone lengths, zone starting times, ending times, any pauses between zones, control cycle times, best alternatives, and diverted fractions for time-dependent traffic, by minimizing total costs, including agency cost and user costs. When uniform alternatives are specified, full diversion in one direction (Alternative 3) is preferable in the numerical example. If one considers a speed-up in average resurfacing time per kilometer when closing both lanes, full diversion in both directions (Alternative 4) is preferable. For mixed alternatives, partial diversion or no diversion is appropriate during daytime; full diversion is usually preferable at night due to faster return to the main road than in daytime.

Future extensions of the present work might consider multiple detour paths and optimized traffic assignment through alternate paths around work zones as well as trade-offs between the cost and time of resurfacing particular road sections.

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