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Evaluating the Effectiveness of Traffic Diversion and Managed Lanes on Highway Work Zones

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16. Abstract

Temporary work zones (TWZs) have become the second largest contributor to the non-recurring delay of U.S. highways, causing nearly 24 % of all non-recurring delay and 10 % of overall delay. Efficient traffic management in vicinity of a TWZ may greatly reduce the total cost attributed to this delay, including user and agency costs. Therefore, it is desirable to develop an accurate model to assist in evaluating the impact of traffic diversion and managed lanes (i.e. the use of road shoulders) and alternatives for mitigating congestion. The objective of this study is to develop a mathematical model that can be used to quantify impacts of planned traffic diversion and managed lanes for TWZs on multi-lane highways, considering prevailing road capacity, and time-varying traffic volumes. The findings of this study would be useful in developing decision support guidance on alternative strategy selection to mitigate traffic congestion caused by a work zone.

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LIST OF ABBREVIATIONS

Abbreviation	**Description**
ALDOT	Alabama Department of Transportation
ATIS	Advanced Traveler Information System
AWIS	Automated Work Zone Information System
CA4PRS	Construction Analysis for Pavement Rehabilitation Strategies
Caltrans	California Department of Transportation
CDOT	Colorado Department of Transportation
CPF	Corridor Permeability Factor
DAF	Demand Adjustment Factor
DOT	Department of Transportation
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
GA	Genetic Algorithm
HCS	Highway Capacity Software
INDOT	Indiana Department of Transportation
ITS	Intelligent Transportation Systems
MDOT	Michigan Department of Transportation
MDSHA	Maryland State Highway Administration
NCHRP	National Cooperative Highway Research Program
NJDOT	New Jersey Department of Transportation
ODOT	Ohio Department of Transportation
QUEWZ	Queue and User Cost Evaluation of Work Zones
RUC	Road User Cost
TVM	Traffic Volume Multiplier
TWZ	Temporary Work Zones
TxDOT	Texas Department of Transportation
VMT	vehicle mile traveled
WisDOT	Wisconsin Department of Transportation
WZ	Work Zone

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INTRODUCTION

Highway repair and maintenance projects (e.g. deck replacement, resurfacing, joint repairs, utility works, etc.) occupy the road and disrupt traffic operations, which increase delays because of reduced capacity. According to an urban mobility report conducted by Schrank et al. (2010), 2009 traffic congestion data suggests that urban Americans travelled an additional 4.8 billion hours and consumed extra 3.9 billion gallons of fuel, which is equivalent to 115 billion U.S. dollars. In New Jersey (NJDOT, 2008), the annual congestion cost is 8.6 billion U.S. dollars (i.e., $1,465 per licensed driver), including 129 million gallons of wasted fuel while sitting in traffic (Spasovic et al., 2008).

The vehicle miles travelled has far exceeded the addition of new lane miles to the Highway System. Therefore, extending the useful life of the existing system of roads by optimizing the capacity utilization is becoming more imperative. Temporary work zones (TWZs) have become the second largest contributor to the non-recurring delay of U.S. highways, which caused nearly 24 % of all non-recurring delay and 10% of overall delay.

In addition to congestion impact, construction and maintenance operations on highways also increase safety concerns to motorists, pedestrians, and workers. Efficient management of traffic within a TWZ and its vicinity has the potential of increasing safety and mobility benefits thereby reducing the total cost, including user and agency. The development of a robust and accurate model is important to evaluate the impacts of traffic diversion and managed lanes (i.e. the use of road shoulders) for mitigating congestion. The Measures of Effectiveness (MOEs) and Key Performance Indices (KPIs) from these models can be used for the benefit cost analysis for the alternatives and mitigation strategies, in terms of changes in vehicle delays, speed, number of crashes, vis-à-vis cost for traffic diversion setup or lane management.

Traditionally demand/capacity methods have been applied to estimate travel delays. However, the traffic speed and time estimation was based on oversimplified equations (i.e. the BPR function). Therefore, the congestion impact caused by temporal and spatial traffic variation associated with road geometry and limited capacity due to work zone activities was difficult to measure with an accepted level of accuracy. The traffic data technologies utilizing probe-vehicle concepts have improved dramatically in the past few years, in terms of geographic coverage, sample size, precision in detecting vehicle location, and data processing algorithms. These improvements resulted in greater accuracy and reliability of estimated vehicle speed derived from the probe-vehicle traffic data. This presents an opportunity to address the shortcomings of the traditional queuing models by introducing observed speed data into the user cost calculation in the context of Highway Mobility studies.

Scheduling maintenance activities within nighttime and off-peak periods may ease the impact of congestion within peak periods, yet the maintenance cost and duration might increase (Chien et al, 2002). Commonly used congestion mitigation strategies, including accelerated construction associated with appropriated traffic diversion plans, may reduce project duration and delay but are relatively expensive. Note that inappropriate plans for traffic diversion may significantly degrade the level-of-service and safety of the alternate routes. The objective of this study is to develop a mathematical model in an effort to quantify effects of the planned traffic diversion and managed lanes for TWZs on multi-lane highways, considering prevailing road capacity, and time-varying traffic volumes. The float car data is applied to develop empirical speed-flow models for travel time estimation. Conducting a sensitivity analysis, exploring the relationships among the decision variables and model parameters is an important part of the study. The findings will help in developing a guideline on selecting strategies for work zone traffic management for mitigating traffic congestion and safety concerns.

LITERATURE REVIEW

The research team conducted a comprehensive review of available literature relevant to this study. The summary of the exhaustive review of topics on work zone impact analysis and optimization of work zone length and schedule is presented in this section.

Work Zone Impact Analysis

Several state DOTs have developed lane closure policies that provide guidance in determining permitted lane closure time, namely time of day, week, or season a lane closure is allowed on a facility and at a specific location or segment (see Table 1). In conjunction with policies, software planning tools are also developed to assess the impacts of work zone lane closures on the motorist. The results are then used to assist in scheduling TWZs.

The NJDOT's Road User Cost Manual (NJDOT, 2001) describes an analytical approach of calculating vehicle operating and delay costs due to construction, maintenance, or rehabilitation activities. The total cost is a function of the characteristics of a work zone (e.g. work zone duration, length, etc.), the traffic volume, and the unit operating and user delay costs. The Maryland State Highway Administration (MDSHA) has developed a Lane Closure Analysis Program based upon the guidance written in the Work Zone Lane Closure Analysis Guidelines which provides state traffic engineers with a method to analyze work zone impacts (i.e., queues and delays) resulting from capacity reduction caused by freeway work zones (MDSHA, 2006).

California DOT (Caltrans) has developed a lane closure approval process as there is a lane closure request for construction and/or maintenance activities (FHWA, 2010). A web-based system is applied to review the details of a lane closure request and ensure that the closure is consistent with transportation management plans. As indicated in a study (Maze and Wiegand, 2007), the Ohio DOT (ODOT) developed a lane closure policy which provides more detailed information for specific corridors, including methods to determine the lane closure restrictions and suggestions for congestion mitigation strategies. The Wisconsin DOT (WisDOT) developed lane closure and delay guidelines in the 2007 update of its Facilities Development Manual (Maze and Wiegand, 2007), which offers a tool to assess the effects (i.e., queue and delay) of lane closures. The Colorado DOT (CDOT) developed lane closure policies which provide engineers and contractors guidelines for scheduling lane closures and detailed flowcharts to calculate delays.

Table 1 A Summary of Lane Closure Policies and Management Systems

State DOT/Agency	*Lane Closure Policies and Management Systems*
CDOT	Published lane closure maps and spreadsheets Roadway Information System database, Automatic traffic recorders, and CDOT spot traffic counts are used to determine the lane closure policy for a given segment of road
Caltrans	Developed a lane closure approval process for use when requesting a lane closure A web-based lane closure system is applied to review the details of a lane closure request, check for potential conflicts, approve or mitigate requests, and monitor closure progress
Indiana DOT (INDOT)	A statewide lane closure map and close-up lane closure maps to identify the restrictions in place on each roadway
MDSHA	Published Work Zone Lane Closure Analysis Guidelines Defined a process for conducting traffic analyses to determine the impacts of work zone lane closures
ODOT	Provided statewide lane closure policy with detailed information for specific corridors, including queue analysis methodologies and mitigation strategy suggestions
WisDOT	Provided lane closure and delay guidelines in its *Facilities Development Manual*, including queue and delay estimation tools A web-based system to determine lane closure policy for a given roadway

(Source: MDSHA, 2006; Maze and Wiegand, 2007; FHWA, 2010)

A NCHRP report (Bourne et al., 2010) indicated that many state transportation agencies considered road user cost (RUC) in the maintenance project decisions, which found that several agencies have developed simple spreadsheet tools to estimate RUC, whereas others reported using software such as QUEWZ-98 (Queue and User Cost Evaluation of Work Zones) and QuickZone for simple freeway sections, and more sophisticated simulation software (e.g., Synchro or TSIS-CORSIM) for other roadway types or more complicated sections. For instance, NJDOT developed a RUC manual to guide the estimation and application of RUCs. Similarly, WisDOT developed an impact mitigation investigating process based on the ratio of RUC savings to costs (Bourne et al., 2010). **Table 2** provides a list of various methods used by different State DOTs to estimate RUC, a full list could be found in a study by Mallela and Sadasivam (2011).

The work zone RUC, by definition, is the additional cost borne by the motorists and local communities due to a work zone activity and is an important factor considered while planning road maintenance and construction (Paracha and Mallela, 2011). For instance, Construction Analysis for Pavement Rehabilitation Strategies (CA4PRS), a construction management software (Lee and Ibbs, 2005), 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, where the delay and RUC calculation must rely on external traffic analysis tools, such as traffic simulation model or demand-capacity analysis models that are not integrated into the optimization processes.

Mallela and Sadasivam (2011) discussed key components of work zone RUC, input needs, and available tools. In their study, RUC primarily refers to the monetized components of work zone impacts, such as the user delay costs, vehicle operating costs, crash costs and the cost of emissions. The expected increase in emissions (ton/mile) by emission type was estimated as a function of vehicle type, reduced work zone speed, and increased congestion due to queuing and detours. Once the emission rates by vehicle types are estimated, the emission cost was calculated as a function of vehicle mile traveled (VMT) and unit cost ($/ton).

Table 2 Methods of Estimating RUC in Different Agencies

State DOT/Agency	*RUC Estimation Method*	*Category*
Alabama DOT (ALDOT)	A Microsoft Excel-based “Lane Rental Model”, with work zone capacity values based on 1994 Highway Capacity Manual (Batson et al., 2009)	Spreadsheet -based Tools
Caltrans	A decision support system integrated with work zone traffic simulation to estimate road user cost arising from construction	CA4PRS
CDOT	A standalone program estimates lane capacity in work zone location for road user cost and allows only crossovers and single lane closure analysis	Spreadsheet -based Tools
Florida DOT (FDOT)	A spreadsheet which could perform demand-capacity analysis and include formulae for calculating crash costs and a general impact factor to adjust the overall RUC results	Spreadsheet -based Tools
MDSHA	MD_QuickZone, a modified work zone traffic analysis software program to assist traffic impact analysis of highway work zones (MDSHA, 2006)	QuickZone
Michigan DOT (MDOT)	A Construction Congestion Cost which measures the impact of congestion during a construction project (Carr et al, 1997)	Spreadsheet -based Tools
NJDOT	A road user cost manual designed for estimating road user cost due to work zone activity, including ten potential cost components, which are classified into two categories based on traffic states (i.e., base case and queue situation) (NJDOT, 2001)	Spreadsheet -based Tools
Texas DOT (TxDOT)	A microcomputer analysis tool designed to evaluate freeway work zones through simulating traffic flows with and without work zone lane closures, which estimate capacity through work zone, average speed, delay and queuing delay to estimate road user cost, including travel time, vehicle operating costs, and excess emissions	QUEWZ-98
WisDOT	A general lane closure impact analysis is applied to provide a rough analysis of the impacts of lane closures, primarily for maintenance projects and	Spreadsheet -based Tools

small construction projects (WisDOT, 2011)

With a macroscopic approach, Ullman and Dudek (2003) introduced a corridor permeability factor (CPF) to predict queue propagation due to a work zone activity on urban freeways. In addition to CPF, Lee et al. (2008) utilized different demand adjustment factors (DAF) associated with freeway mainline, entrances and exits to estimate queue length and delay caused by a work zone. The key model parameters (i.e., CPF and DAF) were calibrated using the traffic volumes and queue lengths collected on freeways in Texas and Wisconsin. However, the increased delay on alternate routes due to diverted traffic was not considered.

Schnell et al. (2001) evaluated traffic flow analysis tools including Highway Capacity Software (HCS), Synchro, CORSIM, NETSIM, QUEWZ-92, and the ODOT applied spreadsheet to estimate the capacity and queue length at four work zones on multilane freeways in Ohio. The results from those tools were compared with the field data. The simulation models was considered not applicable for the oversaturated conditions of the work zone sites, since even after calibration, these models consistently underestimated the queue length. QUEWZ-92 was more accurate tool than others in estimating the work zone capacity. When this capacity estimate was used in the ODOT spreadsheet, a fairly realistic estimate of queue length was projected as compared to the queue lengths estimated by other tools.

Chitturi and Benekohal (2004) compared the performance of QUEWZ-92, FRESIM, and QuickZone with field data of 11 freeway work zones in Illinois. Some of these work zones did not experience any queues. The results showed that none of these models offered an accurate representation of real field conditions. QUEWZ-92 overestimated the capacity and underestimated the queue lengths, mainly because of an outdated speed-flow relationship employed. FRESIM consistently overestimated the speeds under queuing conditions, while the queue length estimations fluctuated. QuickZone consistently underestimated the queue length and delay compared to the field data.

Khanta (2008) evaluated several traffic simulation models (e.g. QUEWZ, Quick Zone, CORSIM and VISSIM) for traffic impact associated with work zones in the New England area. The results suggest that QuickZone is capable of analyzing 24-hr traffic volumes to estimate the expected queues for rural and urban freeways. Similar to QuickZone, QUEWZ could estimate queue lengths under alternative work strategies on freeways. However, QUEWZ is not effective in estimating delay considering network geometry.

Most of previous studies estimate RUC through capacity and deterministic queue length estimation. The errors in capacity estimation will propagate and result in inaccuracy of RUC estimation. With the availability of floating car data (i.e., speed data), the speed-flow relationship under normal and work zone conditions could be accurately captured. Therefore, the average delay within both work zone area and its upstream segment can be directly estimated in relation to different work zone configurations.

This study reviews a work zone project in New Jersey to demonstrate the proposed model applicability. The speed and traffic volume data under normal and work zone conditions are collected, for developing accurate comparative models reflecting the speed reduction for the work zone area and its upstream segments. Considering traffic diversion, the speed-flow relationship for alternative routes is also developed based on historical data collected from various sources, which will be described in details in the sections that follow. Note that the RUC components considered in this study include user delay cost, vehicle operating cost, and accident cost.

Optimization of Work Zone Length and Schedule

Previous studies focused on various aspects of work zones, including capacities (Dudek and Richard, 1982; Krammes and Lopez, 1994), speeds through work zones (Rouphail and Tiwari, 1985; Memmott and Dudek, 1984), user delays (Cassidy and Han, 1992), and safety (Ullman et al, 2008; Bai and Li, 2011). Few studies looked at the optimization of work zones considering the joint impact of road user’s delay, incident, and work zone setup costs. Schonfeld and Chien (1999) developed a mathematical model to optimize work zone length and associated traffic control for two-lane, two-way highways with one lane closures minimizing cumulative agency and user delay costs. To optimize the length of a work zone section on a four-lane, two-way highways considering one-lane closure, another model (Chien and Schonfeld, 2001) was developed that minimized the total cost, including agency, accident, and user delay costs. Jiang and Adeli (2003) applied artificial neural network (ANN) and simulated annealing (SA) approaches to search for the optimal work zones and the associated starting times, considering darkness and numbers of closed lanes. The studies discussed above assumed that the approaching traffic flow to the work zone was steady. Therefore, the impact of potentially diverted traffic was not considered in the optimization processes.

Several studies (Chien et al., 2002; Chen et al., 2005 and 2006) optimized work zone schedule, with the objective function of minimizing total cost, assuming a fixed crew production rate and constant unit maintenance cost. Considering practical situations, Tang and Chien (2008) adopted a discrete maintenance time-cost relation and optimized work zone schedule subject to a pre-specified project duration, in which various accelerated construction methods were evaluated. Wong et al. (2010) developed a spatial queuing model to optimize coordinated signal settings across two closely spaced work zones to prevent a gridlock, which applied the cell transmission model and aimed at minimizing the total number of vehicles on the critical section between two adjacent work zones. Later, Meng and Weng (2011) optimized short-term work zones on four-lane, two-way freeways with time window and uniform work zone length constraints to yield the minimum total cost. A deterministic queuing model was employed to estimate user delay, which incorporated variable traffic speed to estimate total user delay caused by the work zone project.

Considering excessive delay due to work zone lane closure, the motorists may change travel behavior, such as using alternate routes to bypass congested roadway segments (Ullman, 1996; Lee and Kim, 2006; Chu et al., 2005). However, the studies on quantifying and optimizing diversion rate are limited because of unavailable real-world data. Zhang et al. (2008) proposed a regression-based model to estimate time-dependent demand diversion in response to work zone delay and various traffic management strategies, providing traffic performance measures under different scenarios. Song and Yin (2008) applied a binary logit model to compute detour rate, where travel time, work zone location and weather conditions were found to be major influencing factors of user diversion decision. Most of the previous work considered the diversion rate as a fixed value over time, while Tang and Chien (2010) improved the work zone optimization model by utilizing user-equilibrium assignments to find the optimal diversion rate, and Yang and Schonfeld (2011) further considered diversion behavior in response to different detour control strategies. At the advent of Intelligent Transportation Systems (ITS), such as Automated Work Zone Information System (AWIS) (Lee and Kim, 2006) and 511 Traveler Information System, traffic conditions in the vicinity of freeway work zones may be monitored and disseminated in real-time.

This study considers different traffic management strategies, for short term or non-recurrent work zones. Since traffic equilibrium may not be achieved in a short time, an open-loop binary logit model developed by Song and Yin (2008) and enhanced by Yang and Schonfeld (2011) is applied.

METHODOLOGY

The study work zone optimization problem discussed here considers a typical traffic diversion scenario illustrated **Figure 1.** The total segment length of a maintenance project on a freeway mainline is divided into three traffic zones: the work area, the upstream and downstream segments of the work zone. An alternate route is designated for traffic diversion to relieve the congestion on the mainline.

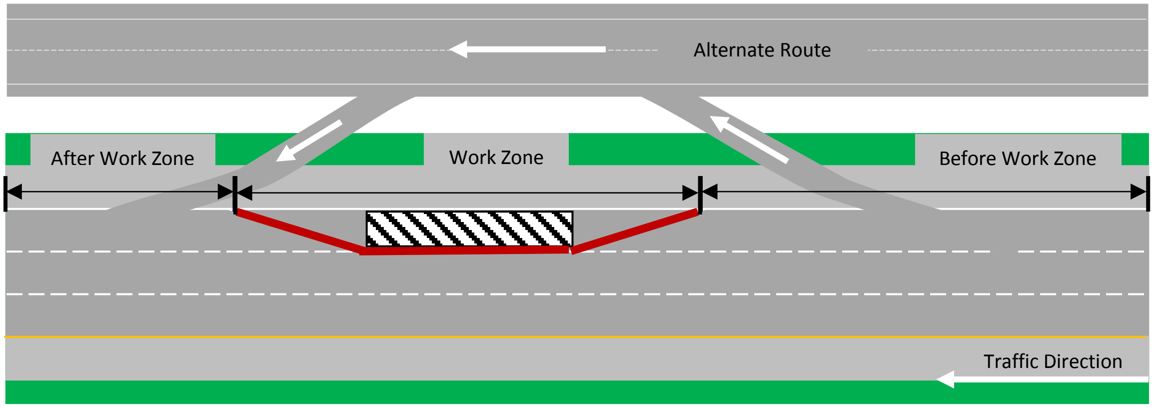

Figure 1 Configuration of a Freeway Work Zone with an Alternate Route

Assumptions

Several assumptions are made to formulate the proposed model:

1. To avoid excessive congestion on the alternative route, the maximum diverted traffic flow from the mainline is set equal to the capacity minus the existing flow of the alternate route.
2. The ramp capacity is adequate to accommodate the sum of the original ramp flow and the diverted flow at any time interval.
3. There are a limited number of maintenance crews with different costs and production rates, which could work in different work zones.
4. The maintenance project is conducted on urban freeways under normal weather condition.

5. The traffic volume is considered as equivalent passenger car volume.
6. The user delay cost is proportional to the delay time.

Model Formulation

Total Cost

The objective function is total cost, denoted as C_T, of a maintenance project, consisting of three components: Maintenance Cost (C_M), Idling Cost (C_I), and User Cost (C_U). Thus,

$$C_T = C_M + C_I + C_U \tag{1}$$

Since a maintenance project could be long in length, it could be finished by several smaller work zones performed in different time periods. Therefore, the total cost could also be presented as follows:

$$C_T = \sum_{i=1}^{n} (C_{M_i} + C_{I_i} + C_{U_i}) \tag{2}$$

where i is the index of work zones, and n is the total number of work zones.

The constraints considered in this study include the total project length, the minimum duration of maintenance activity, and maximum duration of the project. The project length constraint is

$$\sum_{i=1}^{n} l_i = L \tag{3}$$

where l_i is the length of work zone i, L represents the project length. This constraint ensures that the sum of work zone length should equal to the total project length. The minimum duration of maintenance activity constraint is

$$D_i \geq D_m, \forall i \tag{4}$$

where D_i is the work duration for work zone i, and D_m is the minimum duration for each maintenance activity (i.e., working or idling). Eq. 4 defines that the duration for each working or idling activity should be larger than a minimum pre-defined duration. The maximum duration of the project constraint is

$$\sum_{i=1}^{n} D_i \leq D_M \tag{5}$$

where D_M represents the maximum project duration, which defines that the project should be completed within a pre-defined duration.

Maintenance Cost

Maintenance cost for work zone i includes a fixed cost for setting and removing a work zone, and maintenance variable cost associated with the length of the work zone (i.e., material, equipment, and labor usage, etc.). The total maintenance cost is the sum of the maintenance cost for each work zone i. Thus,

$$C_M = \sum_{i=1}^{n} C_{M_i} \tag{6}$$

where C_{Mi} is the maintenance cost of zone i. C_M could be defined as:

$$C_M = \sum_{i=1}^{n} (z_1 + z_2^k \cdot l_i) \tag{7}$$

where z_1 is the fixed cost for setting/removing a work zone, and z_2^k is the unit maintenance cost for the maintenance crew k. As discussed earlier, the crews with different production rates are associated with different costs.

The duration needed to perform maintenance activity in work zone i, denoted as D_i, is the elapse time from the starting time (S_i) to ending time (E_i). Thus,

$$D_i = E_i - S_i = z_3 + z_4^k \cdot l_i, \forall i \in \{ i : l_i > 0 \} \tag{8}$$

where z_3 is the time required for setting and removing a work zone, and z_4^k is the unit maintenance time per mile for the maintenance crew k. By substituting l_i derived from Eq. 8 into Eq. 7, C_M can be derived as:

$$C_M = \sum_{i=1}^{n} \left(z_1 + z_2^k \cdot \frac{E_i - S_i - z_3}{z_4^k} \right), \forall i \in \{ i : l_i > 0 \} \tag{9}$$

Idling Cost

A work break is considered as a dummy work zone with a variable duration and the length of the dummy work zone is zero. The idling cost of a work break is the product of D_i and the average idling cost denoted as v_d, which is incurred by the idling of equipment and the crews during a work break. Thus,

$$C_I = \sum_{i=1}^{n} C_{I_i} = \sum_{i=1}^{n} v_d (E_i - S_i), \forall i \in \{ i : l_i = 0 \} \tag{10}$$

User Cost

User cost, denoted as ***C***C_U, is the sum of user delay cost, vehicle operating cost, and accident cost associated with work zone ***i***, denoted as C_{Di}, C_{Vi}, and C_{Ai}, respectively. Thus,

$$C_U = \sum_{i=1}^{n} (C_{D_i} + C_{V_i} + C_{A_i}), \forall i \tag{11}$$

User Delay Cost

User delay cost is defined as a product of user's value of time and the total delay time, the difference of travel times between normal and work zone conditions. Thus,

$$C_D = \sum_{i=1}^{n} C_{D_i} = v \sum_{i=1}^{n} \sum_{t=S_i}^{E_i} (T_{it} - \overline{T_{it}}) \cdot V_{it}, \forall i \tag{12}$$

where C_D is the total user delay cost, v represents user's value of time, T_{it} is the vehicle travel time in work zone ***i*** during time period ***t***, $\overline{T_{it}}$ is vehicle travel time under normal condition for the same work zone segment during the same time period, and V_{it} is the traffic volume in work zone ***i*** during time period ***t***.

Vehicle Operating Cost

Vehicle operating cost, denoted as C_V , is caused by delay associated with zone ***i***, which is the product of delay as calculated in the user delay cost, and the unit vehicle operating cost, denoted as v_o. Thus,

$$C_V = \sum_{i=1}^{n} C_{V_i} = \sum_{i=1}^{n} \sum_{t=S_i}^{E_i} (T_{it} - \overline{T_{it}}) \cdot v_o \cdot V_{it} \tag{13}$$

Accident Cost

The number of accidents considered in this study is based on the number of vehicle hours traveling through a work zone, so that the accidents cost can be defined as the product of accident rate denoted as r_a (i.e. number of accidents per 100 million vehicle hours of travel), total delay caused by work zone, and the average cost per accident denoted as v_a. Thus,

$$C_A = \sum_{i=1}^{n} C_{A_i} = v_a \sum_{i=1}^{n} \sum_{t=S_i}^{E_i} (T_{it} - \overline{T}_{it}) \cdot V_{it} \cdot r_a \qquad (14)$$

Traffic Diversion

Traffic patterns under temporary lane closures or long term lane closures on high-volume urban freeways can be fairly different. For a short term or temporary lane closure, some road users may use an alternate route, if there is any, because of congestion resulting from work zones. However, equilibrium may not be achieved during such a short time period. Therefore, an ‘open-loop’ estimation of diversion rate is applied. If the duration of project is long enough and with a proper detour control strategy, road users can quickly learn from their travel experience in the work zone area, and the equilibrium may be ultimately achieved. Therefore, a ‘closed-loop’ estimation of diversion rate (i.e., user equilibrium based traffic diversion model) can be applied.

Short-Term Work Zones

A binary logit model developed by Song and Yin (2008) and enhanced by Yang and Schonfeld (2011) is applied here to approximate the traffic diversion rate for short-term work zones on urban freeways under normal weather conditions. In the study conducted by Song and Yin (2008), the authors designed a stated-preference survey to collect diversion data under hypothetical scenarios. Regression analyses identified major factors which significantly affect travelers’ route choices, including the travel times along the mainline and alternate routes, work zone locations, and the weather condition (i.e., bad weather, urban work zone, or less travel time on the alternate route leads to higher diversion rate). It is shown in previous studies that the road users may naturally search for detours in response to queuing and delays caused by work zones (Ullman, 1996; Chu et al., 2005; Lee and Kim, 2006), and this diversion rate (i.e., natural diversion rate) may vary with congestion level, location of exit ramps, time of day, etc. Therefore, in the study conducted by Yang and Schonfeld (2011), a natural diversion rate p is introduced to estimate the diversion rate for short-term work zone projects.

$$\begin{cases} p_{it} = p & \text{if } T_{it} \le T_t^d \\ p_{it} = 1 - (1-p)\dfrac{1}{1+e^{0.1416(T_{it}-T_t^d)+\rho}} & \text{if } T_{it} > T_t^d \end{cases} \quad \forall i \in \{i : l_i > 0\}, t \qquad (15)$$

where p_{it} is an adjusted diversion rate in work zone i during time period t, p is the natural diversion rate. T_t^d is travel time needed for traveling on the alternate route during time period t, if multiple alternate routes are available, T_t^d should be the average travel time of all alternatives. ρ is a parameter representing the combination of work zone locations and weather conditions (**Table 3**), which is 0.1054 for urban work zones under normal weather condition.

Long Term Work Zones

On the other hand, if the duration of maintenance project is long enough, travelers may learn from their travel experience, and adjust their route choice, so that the user equilibrium (UE) could be achieved in the end (Yang and Schonfeld, 2011). Under such situation, the optimal diversion rate could be obtained by solving the traffic assignment problem:

$$
\begin{aligned}
&\boldsymbol{Min.} \quad Z = \int_0^{V_{it}^r} T_{it}^r(V_{it}^r)\,dV_{it}^r + \int_0^{V_{it}^{rd}} T_{it}^d(V_{it}^{rd} + V_{it}^d)\,dV_{it}^d \\
&\boldsymbol{S.T.} \\
&\qquad V_{it}^r + V_{it}^{rd} = V_{it} \\
&\qquad V_{it}^r \geq 0 \\
&\qquad V_{it}^{rd} \geq 0 \\
&\qquad V_{it}^{rd} \leq Q^d - V_{it}^d
\end{aligned}
\tag{16}
$$

where V_{it}^r is the remaining traffic flow on the mainline route during work zone i at time period t, V_{it}^{rd} is the diverted traffic flow from the original route to the alternate route, V_{it}^d is the existing traffic flow on the alternate route, Q^d is the capacity of the alternate route. T_{it}^r is the travel time for the remaining traffic flow on the mainline route, T_{it}^{rd} is the travel time on the alternate route after diversion, which are dependent on the traffic volume on the respective routes.

Table 3 Value of Parameter ρ (Song and Yin, 2008)

		Work Zone Location	
		Rural	Urban
Weather	Normal	-0.6166	0.1054

Condition	Bad	-0.2207	0.5013

Summary

In summary, the objective function discussed in this study is to minimize the total cost, which includes maintenance cost, idling cost, and user cost, considering the influence of time varying demand and the presence of traffic diversion strategy. The decision variables contain the number of work zones, the associated durations and maintenance crews. Thus, the full model can be represented by Eq. 17 below.

$$\textbf{\textit{Min.}}$$

$$C_T = \sum_{i\in\{i:l_i>0\}} \left(z_1 + z_2^k \cdot \frac{E_i - S_i - z_3}{z_4^k}\right) + \sum_{i\in\{i:l_i=0\}} v_d (E_i - S_i)$$

$$+ v\sum_{i=1}^{n}\sum_{t=S_i}^{E_i}(T_{it} - \overline{T_{it}})\cdot V_{it} + v_o\sum_{i=1}^{n}\sum_{t=S_i}^{E_i}(T_{it} - \overline{T_{it}})\cdot V_{it} + v_a\sum_{i=1}^{n}\sum_{t=S_i}^{E_i}(T_{it} - \overline{T_{it}})\cdot V_{it}\cdot r_a$$

$$\textbf{\textit{S.T.}} \qquad (17)$$

$$\sum_{i=1}^{n} l_i = L$$

$$D_i \geq D_{\mathrm{m}}, \forall i$$

$$\sum_{i=1}^{n} D_i \leq D_M$$

SOLUTION ALGORITHM

The objective total cost is a function of number of work zones and their corresponding starting and ending times, which makes it a multidimensional combinatorial optimization problem. Therefore, a genetic algorithm (GA) is developed and applied to solve it. GA discussed in various studies (Tang and Chien, 2008, 2009; Chien et al., 2001) has demonstrated itself an efficient way in solving combinatorial optimization problems. GA usually consists of five major components, including

- a genetic representation of potential solutions;
- a criterion for evaluating the performance of a solution;
- a selection mechanism for promoting the evolution of good solutions;
- a reproduction function to produce new solutions; and
- a constraint handling method to fix invalid solutions.

GA in the Global Optimization Toolbox in Matlab is applied in this study to find the optimal solution for a study maintenance project. The detailed development of GA can be referred to a previous paper by **Tang and Chien (2009)**.

Genetic Representation and Data Structure

The work zone schedule is represented by the starting time of the first work zone, denoted as S_1 , and the duration of every work zone associated with its maintenance crew. Thus, besides an integer variable S_1 , the work zone schedule could be coded as follows:

$$(D,K)=\{(D_1,k_1),(D_2,k_2)\ldots(D_i,k_i),\ldots(D_n,k_n)\} \tag{18}$$

Where D_i represent the duration between the starting time S_i and ending time E_i , and k_i is the production index associated with work zone i. Then, each (D_i,k_i) pair can be treated as a “node” element. This data structure is enhanced from the study conducted by **Tang and Chien (2007)**, and uses D_i instead of S_i and E_i as decision variables to remove duplicated representation and reduce the number of decision variables from $(3t_i+1)$ to $(2t_i+2)$, yielding improved calculation efficiency.

Criterion of Evaluation

The performance of solutions in each generation is evaluated based on the objective value of the total cost function. For the cost minimization problem discussed here, the solution that achieves the least total cost is deemed as the best solution.

Elitist Selection

The elitist selection method is utilized to guarantee that the best solution in current generation can always evolve to the next generation. The Global Optimization Toolbox in MATLAB will handle this part with its own function codes. The selection ratio is a parameter set by user to decide if the solution is good enough to evolve to next generation.

Crossover and Mutation

The Matlab GA function codes the coordinate sequence of solution as a gene. The cross-over operators combine the coordinates from two parenting genes; while mutations randomly occur at each coordinate. In this study, the elapse time D_i and production index k_i are the decision variables to form the optimization targets. GA is a stochastic algorithm. The probabilities of performing crossover and mutation are defined as crossover ratio and mutation ratio which can be set in Matlab by user. Detailed information about Crossover and Mutation principle may be referred to **Tang and Chien (2007).**

CASE STUDY

In order to demonstrate that the proposed methodology can function effectively in handling work zone optimization problem, a case study, based on a hypothetical maintenance project on a segment of Interstate Highway I-80 in New Jersey, is selected. As illustrated in **Figure 2**, a 3-mile long work zone segment was identified between milepost 46.5 and milepost 51.5, a 5-mile stretch on the mainline. It was considered that the maintenance work will be performed by closing the right most travel lane for resurfacing the segment. During the construction, the mainline traffic may be diverted to the 5-mile long alternative route US Highway 46 (US-46) through exit ramp A and return onto the mainline through entrance ramp B. The alternative route US-46 is an urban principal arterial having two travel lanes in each direction. Each of the ramps is approximately 0.5 miles long with a posted speed limit of 25 mph.

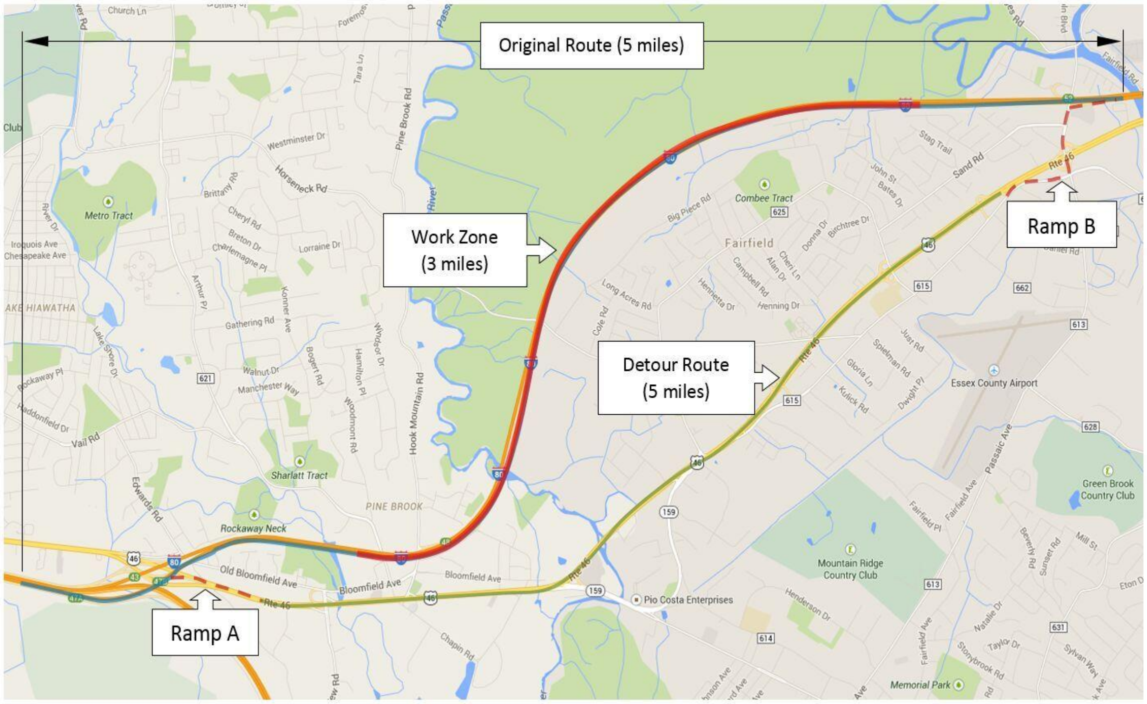

Figure 2 The Network Associated with the Study Work Zone

The traffic flow under normal condition and with work zone operation throughout a day for the mainline, derived from NJDOT Interactive Traffic Count Reports developed by NJDOT, is shown in **Figure 3** clearly indicating reduced traffic volume during work zone operation. **Figure 4** represents the traffic volume in the alternative route (i.e., US-46) throughout a day under normal operating conditions, showing the maximum flow of 4,300 vehicles per hour occurring at 7 a.m.

Table 4 lists the input parameters for the model and their values. It is assumed that the maximum project duration is 64 hours. The time and cost required for setting up and removing a work zone are 2 hours and $1,000, respectively. Under work zone operation, the natural diversion rate is assumed to be 0. The average idling cost for the agency is 800 $/hr. The user value of time is 15 $/veh-hr for single-occupancy passenger cars, and the unit vehicle operating cost is 0.91 $/veh-hr. The unit production rate and unit maintenance cost for different maintenance crews are also represented. The baseline values of unit maintenance cost z_2^k and production rate z_4^k for constructing 2-inch asphalt pavement are referred to the Means Heavy Construction Cost Data 2006 (Goulias et al., 2001).

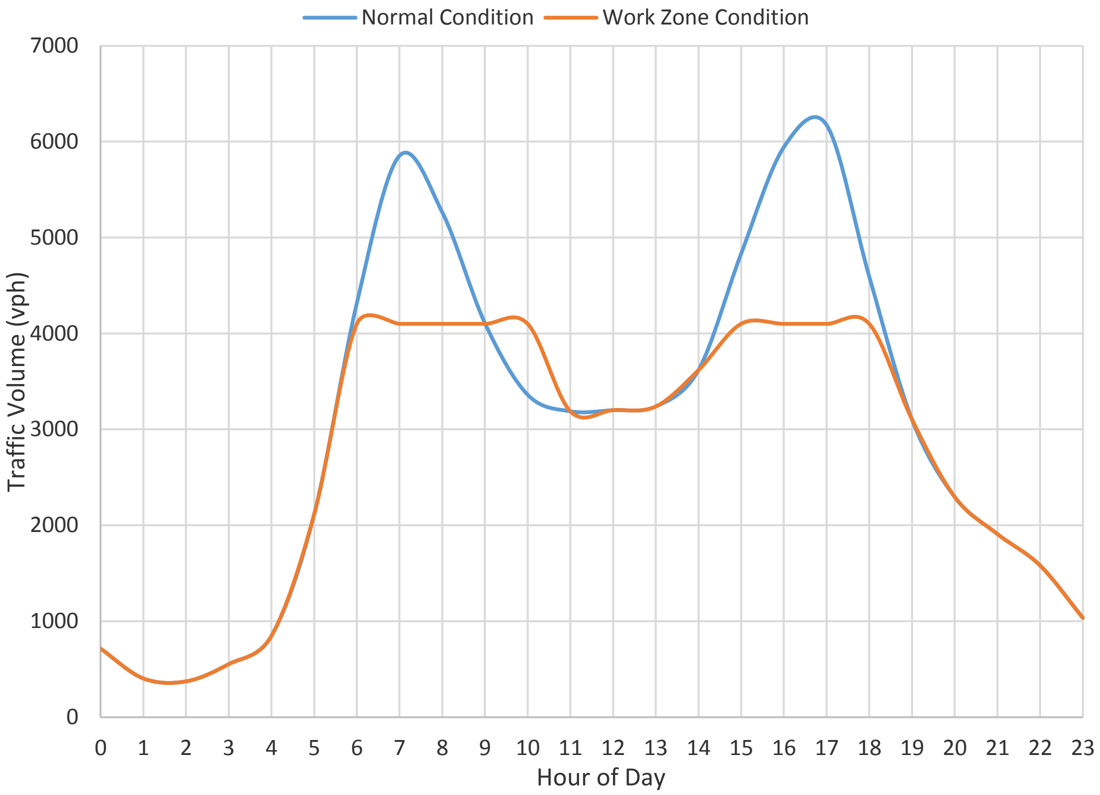

Figure 3 Traffic Volume under Normal and Work Zone Conditions

Table 4 Model Inputs

VARIABLES	DEFINITIONS	VALUES	UNITS
D_M	maximum project duration	64	hrs
L	the project length	3	miles
p	Natural diversion rate	0	
r_a	the number of accidents per 100 million vehicle hour	40	
v	user value of time	15	$/veh-hr
v_d	the average idling cost	800	$/hr
v_o	unit vehicle operating cost	0.91	$/ veh-hr
v_a	the average cost per accident	78000	$
z_1	the cost for setting and removing a work zone	1000	$
z_3	the time required for setting and removing a work zone	2	hrs
z_2^1	unit maintenance cost for maintenance crew ***1***	24,860	$/mile
z_2^2	unit maintenance cost for maintenance crew ***2***	24,983	$/mile
z_2^3	unit maintenance cost for maintenance crew ***3***	25,243	$/mile
z_2^4	unit maintenance cost for maintenance crew ***4***	26,211	$/mile
z_4^1	unit production rate for maintenance crew ***1***	6.75	hrs/mile
z_4^2	unit production rate for maintenance crew ***2***	5.5	hrs/mile
z_4^3	unit production rate for maintenance crew ***3***	4.75	hrs/mile
z_4^4	unit production rate for maintenance crew ***4***	3.89	hrs/mile

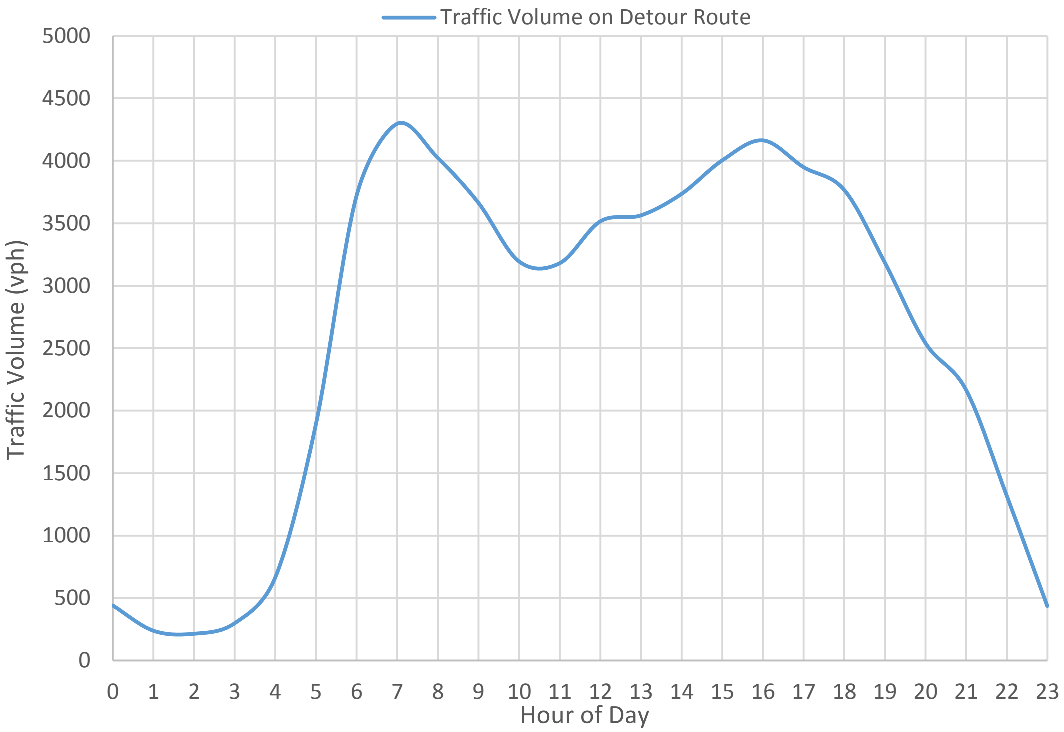

Figure 4 Traffic Volume on the Alternate Route under Normal Condition

Derivation of Volume-Speed Relationship

One of the major efforts before solving the optimization model is to derive the volume-speed relationship under different situations so that the travel times could be generated for traffic diversion.

Figure 5 shows the relationship between traffic speed and flow under ideal condition. As the flow increases from zero to maximum (road capacity) under uncongested condition, the speed will decrease from free-flow speed to the jam speed. When the flow continues to increase, the speed will drop to zero because there are too many vehicles and not enough capacity resulting in unprocessed queues. It is possible to have two different speeds for a given flow.

Using the traffic volume provided by NJDOT traffic counts database[1] and traffic speed provided by INRIX[2], the speed-flow relations of the mainline and detour routes will be identified, respectively. Both the traffic volume (hourly) and speed

---

[1] Source: http://www.state.nj.us/transportation/refdata/roadway/traffic_counts

[2] Source: http://www.inrix.com

data (aggregated to one-hour interval) of the study routes were collected between October 1, 2013 and October 3, 2013. It is noted that the speed data provided by INRIX contains three categories (i.e., historical, blend of historical and real time, and purely real time data). This study uses only the purely real time speed data as reported by INRIX to develop the speed-volume relations. As shown in **Figure 6**, the normal mainline speed can be expressed as a function of traffic volume (black and green dashed lines). Thus,

$$S_n = f(V_n) = \begin{cases} 66.94 & V_n < 2000vph \\ -0.0000007V_n^{\ 2} + 0.0028V_n + 64.14 & 2000 \le V_n < 7000vph \end{cases} \qquad (19)$$

Where S_n and V_n represent the normal speed (mph) and traffic volume of the mainline (vph), respectively.

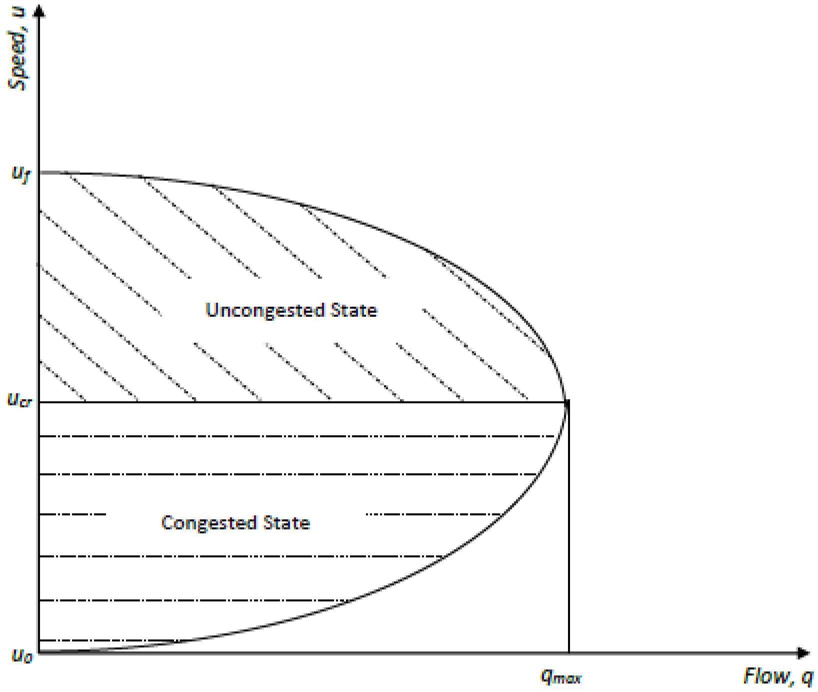

Figure 5 Generalized Relationships among Speed and Flow Rate

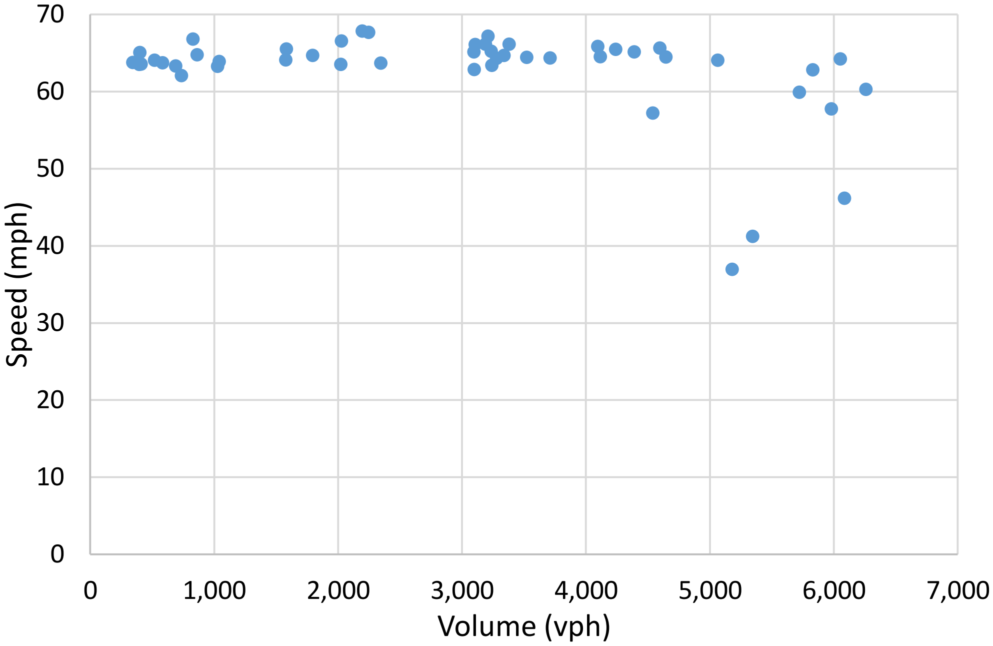

Figure 6 Speed vs. Volume on the Mainline without Work Zone

Figures 7 through 9 provide a scatter plot of traffic speed within the work zone, traffic speed upstream of the work zone, and the speed of the alternate route and can be determined by Eqs. 19 - 21, respectively. Note that the parameters associated with the equations will need to be calibrated if the location of the work zone changes.

$$S_w = f(V_w) = \begin{cases} 55 & V_w < 2000vph \\ -0.0000007V_w^{\ 2} + 0.0028V_w + 52 & 2000 \le V_w < 7000vph \end{cases} \tag{20}$$

$$S_{uw} = f(V_n) = \begin{cases} -0.003V_n + 65.45 & V_n < 1500vph \\ -0.000001V_n^{\ 2} + 0.003V_n + 58.2 & 1500 \le V_n < C_w \\ 87.31 \times (V_n - C_w)^{-0.262} & V_n \ge C_w \end{cases} \tag{21}$$

$$S_d = f(V_d) = \begin{cases} 0.0032V_d + 52.98 & V_d < 2000vph \\ -0.0000001V_d^{\ 2} + 0.004V_d + 54.72 & 2000 \le V_d < 4500vph \end{cases} \tag{22}$$

where S_w is the traffic speed (mph) and V_w is the traffic volume of the study work zone (vph); S_{uw} is the average speed in the upstream of the work zone (mph); C_w is work zone capacity (vph); S_d represents the average traffic speed (mph) and V_d is the traffic volume of the alternate route (vph).

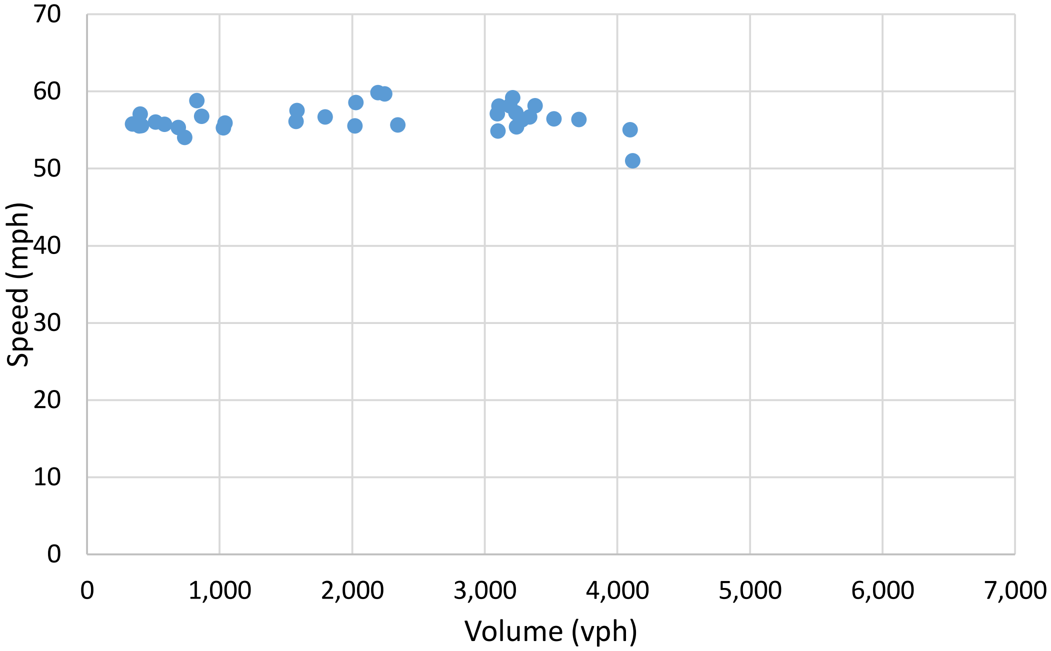

Figure 7 Speed vs. Volume on the Mainline with Work Zone

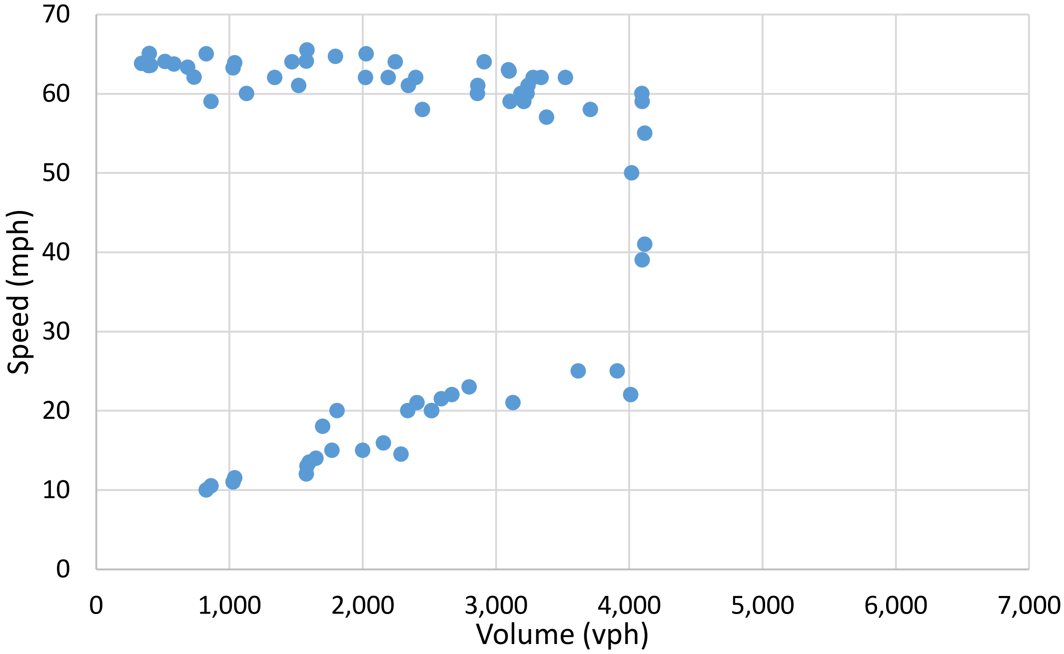

Figure 8 Speed vs. Volume in the Upstream of the Work Zone

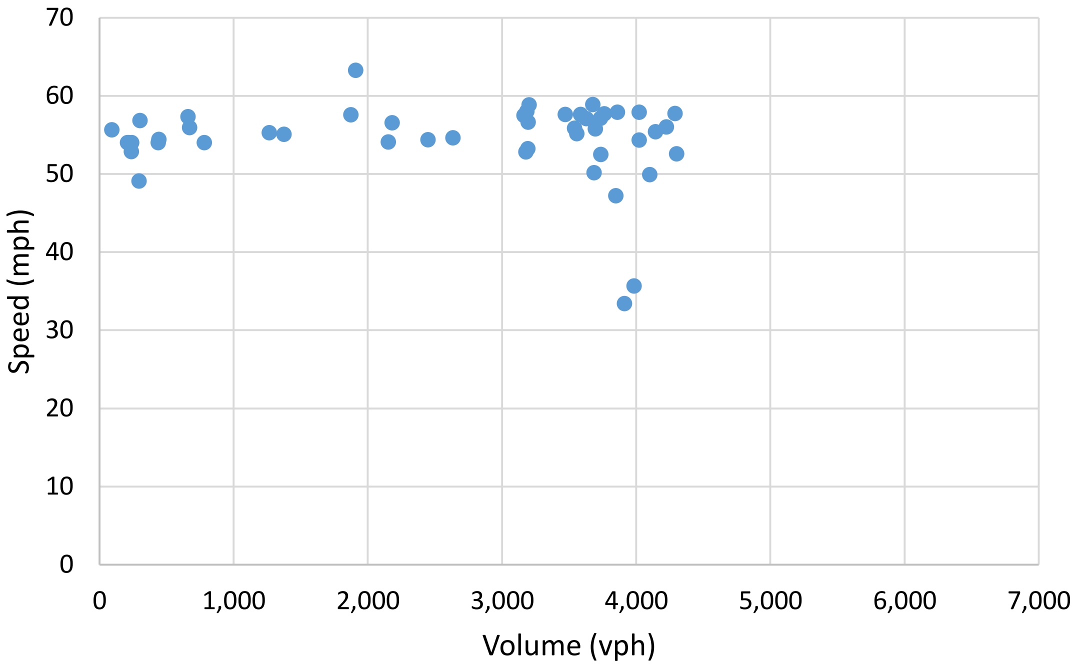

Figure 9 Speed vs. Volume of the Alternate Route

OPTIMIZATION RESULTS

Due to the inherent characteristics of GA, each run may only provide a near-optimal solution. Therefore, to ensure the quality of the final solution, 30 runs of GA with the same model were conducted, which generated a total of 30 ‘minimum total cost’. The least ‘minimum total cost’ out of all 30 solutions was selected as the optimal solution for the case study. The total cost for the 3-mile project is estimated at $90,857 for a total 20.25 hours including 2-hour idling (with non-UE diversion rate). The detailed optimal results are shown in **Table 5**. It is suggested that the first work duration should be 13.25 hours starting at 7:00PM and ending at 8:15AM. Following a 2-hour break, the second work duration should be 5 hours starting from 10:15AM and ending at 3:15PM.

SENSITIVITY ANALYSIS

A sensitivity analysis is conducted to explore the relationship between the optimal solutions and model parameters, which also provide guidelines on scheduling work zone activities. Therefore, different scenarios in terms of traffic volume and the associated management strategy were created.

Traffic Volume

To evaluate the benefit of traffic diversion, a sensitivity analysis was conducted as the traffic volume multiplier (TVM) for the mainline route changed from 0.2 to 2.0 with 1.0 corresponding to the original set for the case study, while the volume of alternate route remained the same. **Table 6** presents the optimal maintenance crews and schedules, and **Figures 10 and 11** illustrate the trends of cost components of the minimized total cost with various traffic levels.

For different traffic levels, the optimized number of sub work zones would be two with a break between them (**Table 6**). As shown in **Table 6**, the starting time for the project is postponed when the traffic volume increases. Furthermore, it is noted that under light traffic conditions, the working time for the project includes peak hours since the influence from work zones could be neglected with light traffic. Therefore, the project could start earlier with less productive maintenance crew, in order to lower down the total cost even though it may take longer time to complete. However, when traffic level increases, it is suggested that the work zones should avoid peak hours as much as possible to reduce the impact on the mainline traffic even though diversion strategies are available.

Table 5 Optimal Results

Traffic Diversion Model	*Work ID*	*Starting Time*	*Ending Time*	*Duration*	*Maintenance Crew*	*Work Zone Length*	*Maintenance Cost*	*User Delay Cost*	*Vehicle Operating Cost*	*Accident Cost*	*Idling Cost*	*User Cost*	*Total Cost*
Non-UE based Diversion	1	19:00	8:15	13.25	3	2.37	60,786	6,029	259	1	0	6,289	67,075
	2	8:15	10:15	2	0	0	0	0	0	0	1,600	0	1,600
	3	10:15	15:15	5	3	0.63	16,943	5,014	225	1	0	5,239	22,182
	TOTAL			20.25		3	77,729	11,043	484	2	1,600	11,528	90,857

As illustrated in **Figures 10 and 11**, with the increase in traffic volume along the mainline, the minimized total cost increases substantially. The major contribution of increase in total cost comes from the mainline user delay cost. Therefore, to compensate the mainline delay, the entire project duration shrinks and requires working with more productive maintenance crews (**Table 6**). For instance, at the lightest traffic level, the maintenance crew 1 is applied for both sub work zones; while at the highest traffic level, maintenance crews 4 and 3 are applied in order to complete the project in a shorter period of time.

Table 6 Traffic Volume vs. Optimal WZ Schedule and Minimized Total Costs

TVM	*WZ ID*	*Starting Time*	*Ending Time*	*Duration*	*Maintenance crew*	*WZ Length*	*Total Cost*
0.2	1	1:45	15:00	13.25	1	1.67	80,784
	2	15:00	17:00	2	0	0	
	3	17:00	4:00	11	1	1.33	
0.4	1	9:45	17:15	7.5	3	1.16	83,335
	2	17:15	19:15	2	0	0	
	3	19:15	6:00	10.75	3	1.84	
0.6	1	11:00	18:00	7	3	1.05	85,471
	2	18:00	20:00	2	0	0	
	3	20:00	7:15	11.25	3	1.95	
0.8	1	10:15	16:00	5.75	3	0.79	88,020
	2	16:00	18:00	2	0	0	
	3	18:00	6:30	12.5	3	2.21	
1.0	1	19:00	8:15	13.25	3	2.37	90,857
	2	8:15	10:15	2	0	0	
	3	10:15	15:15	5	3	0.63	
1.2	1	18:30	6:45	12.25	4	2.63	101,123
	2	6:45	11:45	5	0	0	
	3	11:45	15:30	3.75	3	0.37	

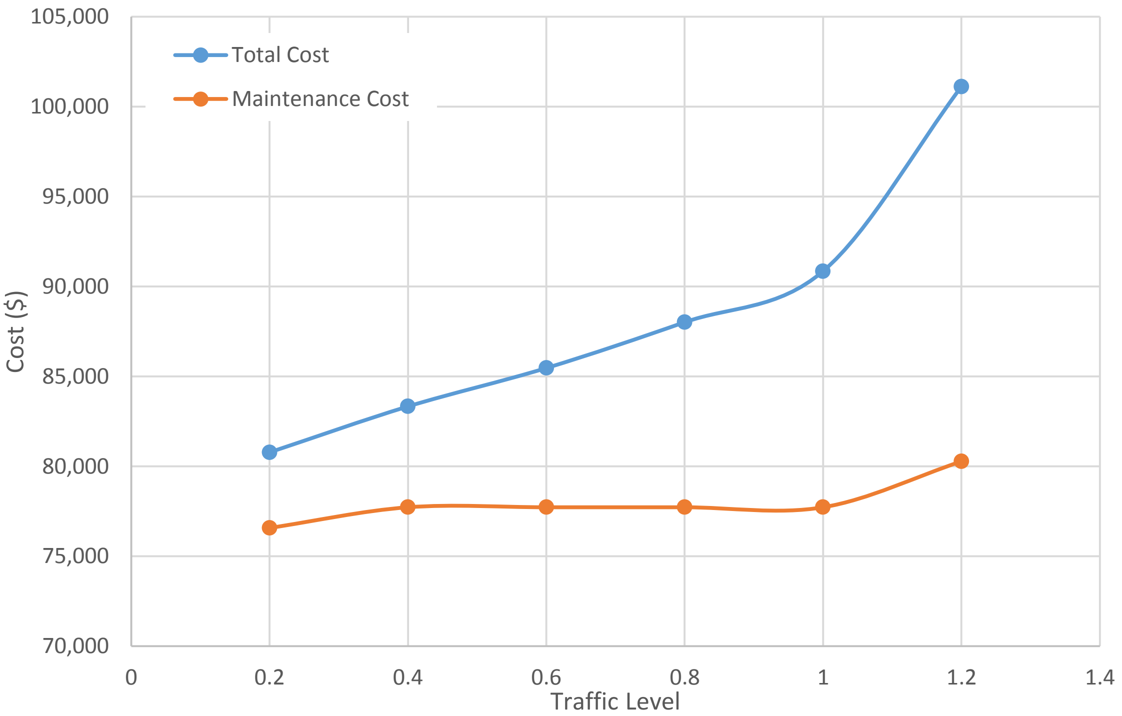

Figure 10 TVM vs. Total Cost

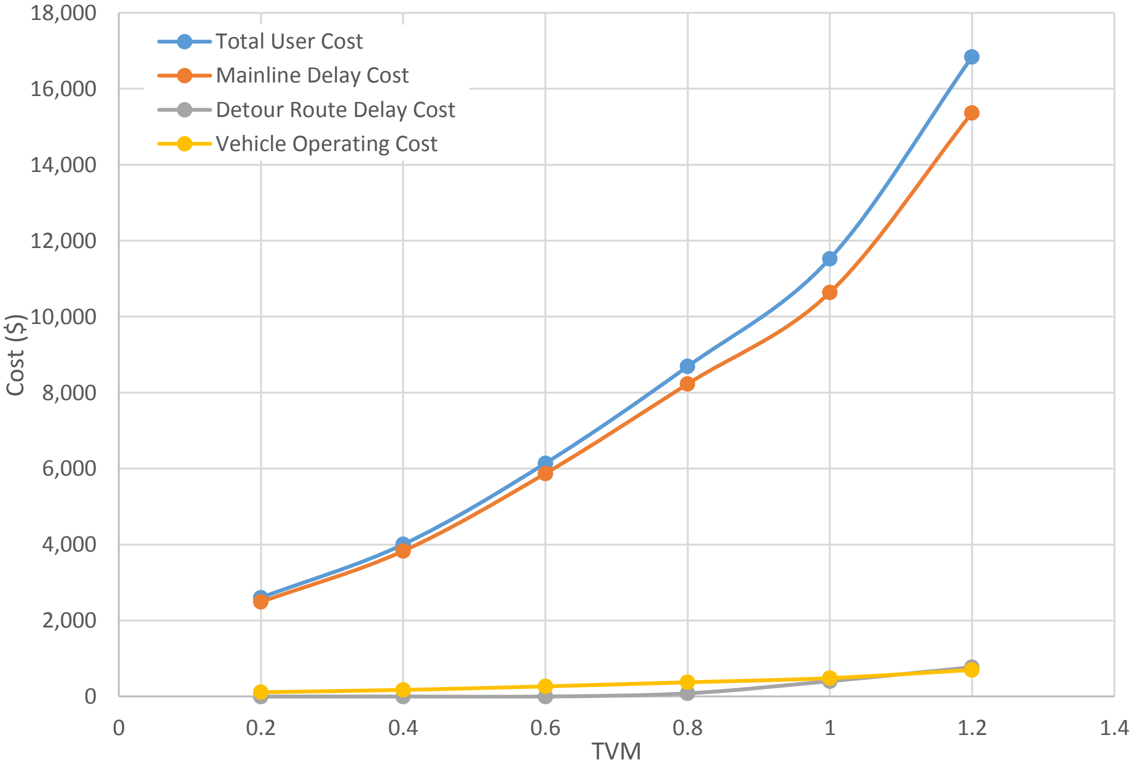

Figure 11 TVM vs. User Costs

Traffic Management Strategy

Various traffic management strategies may have influence on the user as well as the agency cost, which leads to varying optimal work zone schedules. Therefore, in the sensitivity analysis, four scenarios are considered comparing different work zone traffic management strategies. Due to lack of data in shoulder use case within work zones, it is assumed in this study that different percentages of delay time (i.e., 0~15% with 5% interval) are associated with shoulder use to compare with the other scenarios.

Scenario 1: work zone without any traffic management strategy
Scenario 2: Work zone with traffic diversion (Non-UE based)
Scenario 3: Work zone with traffic diversion (UE based)
Scenario 4: Work Zone with shoulder use only
    4-A: without delay
    4-B: 5% delay time
    4-C: 10% delay time
    4-D: 15% delay time

Since the unit maintenance cost and the product rate with shoulder use would be different from that without shoulder use, the values of z_2^k , z_3 , and z_4^k are adjusted to fit selected traffic management strategy. Therefore in Scenario 4, the shoulder will open for reducing user delay cost as shown in **Figure 12**, although the maintenance cost increases due to the installation cost of shoulder use. Therefore, the work zone has four 11 foot lanes of traffic, including the shoulder. Since the mainline route is an interstate freeway, the shoulder width and bituminous depth are adequate and only signing and striping are needed. The additional maintenance cost per lane mile (z_2^k) will increase \$5,000[3] for implementing shoulder use, additional work zone setup time (z_3) required for shoulder use is 0.5 hr/zone, and additional maintenance time per lane mile (z_4^k) for shoulder installation is 0.5 h/ln-mi. All the other baseline parameters remain the same as those under Scenario 2 (base condition).

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[3] Source: Kuhn, B. (2009). "Personal Interview with MnDOT Staff." Minnesota Department of Transportation Metro District.

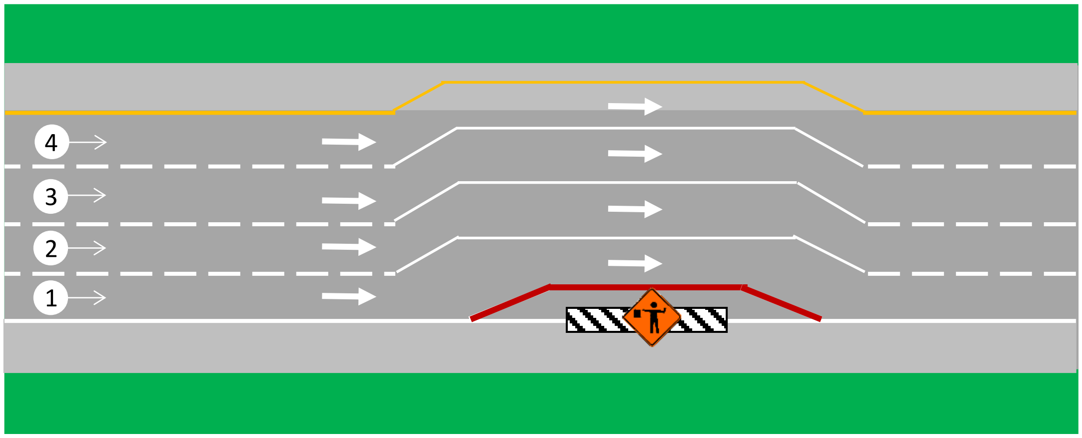

Figure 12 Work Zone on I-80 with Shoulder Use

The minimized total cost yielded by the optimal maintenance crews under different scenarios is shown in **Table 7**. Because of additional time required for work zone setups and removals, as well as reduced production rate due to shoulder use, the entire project duration with shoulder use is always higher than the durations of the other two scenarios, leading to increased maintenance cost. Therefore, under Scenario 3A assuming no user delay, the minimized total cost is still higher than the minimized costs of the other scenarios, which suggests that shoulder use is not a better option. On the other hand, if the shoulder use causes more delay, higher productive maintenance crew should be assigned to the work zones and the project is suggested to be completed within a shorter time period.

Table 7 Optimal Maintenance Crews and Minimized Total Cost under Different Scenarios

Scenario		*Duration*	*WZ Length S1*	*WZ Length S2*	*Maintenance Crew S1*	*Maintenance Crew S2*	*Maintenance Cost*	*User Delay Cost*	*Vehicle Operating Cost*	*Accident Cost*	*Idling Cost*	*Total User Cost*	*Total Cost*
1		19.5	2.31	0.68	4	3	79,914	9,676	440	2	2,600	10,117	92,631
2		20.25	2.37	0.63	3	3	77,729	11,042	484	2	1,600	11,528	90,857
3		21	1.00	2.00	2	3	77,469	4,153	252	1	1,600	4,406	83,475
4	A	25	1.63	1.38	2	2	91,949	0	0	0	1,600	0	93,549
	B	25	1.58	1.42	2	2	91,949	4,626	210	1	1,600	4,837	98,386
	C	22.75	1.14	1.86	3	3	92,729	8,403	382	1	1,600	8,787	103,116
	D	22.75	1.86	1.14	3	3	92,729	12,685	577	2	1,600	13,264	107,593

Traffic Volume and Management Strategy

Considering the shoulder use and traffic diversion under different traffic level, this section provides the optimal work zone schedules which yielded minimized total costs correspondingly. The results could be used to develop a guideline for selecting proper traffic management strategies for different traffic volumes, with respect to constant alternate route volume.

Table 8 represents the minimized total costs under different scenarios. As is evident for the case study it is not recommended to open shoulder for additional travel lane under light traffic conditions because of high cost of preparing shoulder lane. However, if the shoulder is well prepared, the travel time savings could compensate the additional cost for preparing shoulder lane. On the contrary, if the travel volume is too high in the mainline route, the congestion mitigation effect through traffic diversion would be marginal. Under such circumstance (e.g., TVM 1.2 in **Table 8**), shoulder use can be considered for reduce average delay.

Table 8 Minimized Total Cost vs. Traffic Volume and Management Strategies

TVM	*Scenario 2*	*Scenario 3*	*Scenario 4*			
			A	B	C	D
0.2	80,784	78,464	93,549	94,466	95,376	96,291
0.4	83,335	79,981	93,549	95,386	97,224	99,020
0.6	85,471	81,705	93,549	96,323	99,171	101,840
0.8	88,020	83,134	93,549	97,300	101,011	104,578
1.0	90,857	83,475	93,549	98,386	103,116	107,593
1.2	101,123	89,329	93,549	99,635	105,385	110,848

CONCLUSIONS

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.

The methodology developed here has demonstrated a feasible way to optimize a combinatorial, multi-dimensional work-zone scheduling problem considering traffic diversion. By considering a realistic, discrete time-cost relation and time-varied traffic demand, this study provides a practical approach to schedule minimum total cost operations for highway maintenance work. The volume and speed relationships have been developed specifically for the case study to estimate and predict the user delay cost, instead of traditional moving and queuing delay model based on the deterministic queuing theory. The sensitivity analysis explored the relationship among the objective total cost with traffic volume and traffic management strategies. The results will be helpful for transportation agencies to determine appropriate project duration and schedules.

For real-world implementation, the parameters of the volume-speed relationships applied in this study need to be calibrated based on data collected in the field. Depending on the duration of a project, the length per time interval (i.e., 15 minutes in this study) may be reduced or extended for practical concerns. 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 disseminated by ITS equipment (i.e. Variable Message Signs) and 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 and User-Equilibrium traffic assignment will be explored, while the presence of the Advanced Traveler Information System (ATIS) that may lead to system equilibrium instead of user equilibrium shall be investigated.

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APPENDIX

Variables	**Definitions**
C_A	Accident cost
C_{A_i}	Accident cost for work zone ***i***
C_D	Total user delay cost
C_{D_i}	User delay cost for work zone ***i***
C_M	Maintenance Cost
C_{M_i}	Maintenance cost for each work zone ***i***
C_I	Idling Cost
C_{I_i}	Idling cost of a work break ***i***
C_T	Total cost
C_U	User Cost
C_V	Vehicle operating cost
C_{V_i}	Vehicle operating cost for work zone ***i***
D_i	Work duration for work zone ***i***
D_m	Minimum duration for each maintenance activity
E_i	Ending time for work zone ***i***
L	Project length
D_M	Maximum project duration
S_i	Starting time for work zone ***i***
T_{it}	Vehicle travel time in work zone ***i*** during time period ***t***
$\overline{T_{it}}$	Vehicle travel time under normal condition in work zone ***i*** during time period ***t***
T_t^d	Travel time on the alternate route during time period ***t***
V_{it}	Traffic volume in work zone ***i*** during time period ***t***
i	Index of work zone
l_i	Length of work zone ***i***
n	Total number of work zones
r_a	Accident rate (number of accidents per 100 million vehicle hours)
p	Natural diversion rate
p_{it}	Adjusted diversion rate in work zone ***i*** during time period ***t***
v	User value of time
v_a	Average cost per accident
v_d	Average idling cost
v_o	Unit vehicle operating cost
z_1	Fixed cost for setting and removing a work zone

$\boldsymbol{z}_2^k$	Unit maintenance cost for the maintenance crew $\boldsymbol{k}$
$\boldsymbol{z}_3$	Time required for setting and removing a work zone
$\boldsymbol{z}_4^k$	Unit maintenance time per mile for the maintenance crew $\boldsymbol{k}$
ρ	Traffic diversion parameter