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RESEARCH REPORT

INTEGRATED MANAGEMENT OF MAINTENANCE AND TRAFFIC

UNIVERSITY OF MARYLAND

SP107B45
FINAL REPORT

July 2002

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16. Abstract

This project developed a customized version of FHWA's QuickZone program to help the SHA in planning maintenance activities and managing traffic around highway work zones as efficiently and safely as possible. This study focused on estimating the traffic disruption and safety costs of particular work zone configurations and on using those results to determine how road segments should be divided into work zones on rural two-lane roads and rural four-lane divided roads. A second phase of this project is expected to begin in the Fall of 2002. Phase two will make improvements to the analysis method and software. The current models will be extended to analyze six and eight lane rural roads as well as freeways with four, six, and eight lanes.

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Integrated Management of Maintenance and Traffic

Phase I: Final Report

Prepared for the

Maryland State Highway Administration

by Peter Chen, Eungcheol Kim and Paul Schonfeld

Department of Civil and Environmental Engineering

University of Maryland, College Park

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Chapter 1 Introduction

1.1 Motivation

Highway maintenance, especially pavement resurfacing work that requires lane closures, is one of the main responsibilities of the Maryland State Highway Administration. Given the very substantial cost of doing that maintenance and the very substantial traffic disruption and safety hazards associated with highway maintenance work, it is desirable to plan and manage the work in ways that minimize the combined cost of maintenance, traffic disruptions and accidents. The overall costs of road maintenance and traffic disruption may be very significantly reduced through properly integrated decisions about the conduct and schedule of maintenance activities and the development of appropriate traffic management plans. Among the questions to be considered in a comprehensive analysis are the following:

1. How frequently should various maintenance activities be conducted?
2. At what times (day, night, weekend) should the work be done and how long should closures last?
3. How should roads and road networks be divided into work zones?
4. How long and wide should work zones be?
5. How should traffic be safely managed through or around work zones and how do work zone considerations and control alternatives affect safety?
6. How does the availability of alternate routes and their characteristics (e.g., length, design speed, excess capacity, traffic patterns) influence the decisions above?
7. How can the frequency and duration of maintenance work be reduced and at what cost? In other words, what maintenance cost and time tradeoffs result from different

combinations of materials, equipment types, labor skills, work procedures and resource allocations?

8. How does the effectiveness of various maintenance and traffic management solutions depend on the characteristics of particular road sections and the surrounding network?

To properly deal with the above questions in an integrated way, this study develops a decision support system to help the SHA in planning maintenance activities and managing traffic around highway work zones as efficiently and safely as possible. We have concluded that such a decision support system, which is not available from any source, would be highly beneficial to the SHA. However various components of such systems have been developed or are currently being developed by FHWA (especially in the SWAT and QuickZone projects), by the University of Maryland, and by other organizations. This work is coordinated and integrated with other related studies to avoid duplication and effort and enhances the value of the deliverable product.

1.2 Objectives

The objectives of Phase I of this project were to develop an evaluation and decision support system for highway maintenance planning and management. This system should be able to identify feasible alternatives, evaluate in detail their costs and other effectiveness measures, and optimize the work zone characteristics to minimize the combined costs of resurfacing to the SHA and of travel time to the users.

1.3 Scope

The objectives of this project are quite challenging. We expect to fulfill these objectives over a three-year period. In the first of three phases, lasting eight months, we proposed to focus on estimating the traffic disruption and safety costs of particular work zone configurations and on using those results to determine how road segments should be divided into work zones. Given our time and resource constraints, we limited the Phase 1 analysis to rural two-lane roads and rural four-lane divided roads.

1.4 Methodology

The basic approach in Phase 1 has been to develop analytic models for various situations in which some lanes or road sections would be closed for pavement resurfacing. For each alternative a total cost function is formulated to take into account the cost and duration of the resurfacing work, the additional user costs (including especially the value of time) and the additional accident costs. The controllable system characteristics (such as work zone length, number of lanes closed and the fraction of traffic diverted to alternate routes) can then be optimized in order to minimize the total cost function. Afterwards, the minimized costs for various alternatives are compared to determine for what traffic flow levels, detour lengths or other conditions (if any) a particular alternative is preferable.

1.5 Organization of the Report

This final report includes the findings of our literature review, descriptions of the models developed and case studies analyzed, discussions and recommendations for further

development in the next phases, appendices including the selected published papers for work zone optimization and a user's manual for the developed software, which was designed to be compatible with QuickZone version 1.0.

Chapter 2 Literature Review

The literature review consists of three sections. The first section identifies and summarizes the main issues for the analysis of work zones. Section 2.2 focuses on the work zone cost items that are important and sensitive to work zone configurations. Research trends for work zones are then discussed. Finally, previously developed software for work zone analysis is briefly reviewed. The findings from the literature review are used in developing the new models.

2.1 Work Zone Issues

Work zone studies involve various aspects of work zone configurations. Issues for work zones include (1) capacity (discharge rate) estimation of work zones, (2) delay estimation (3) maximum queue length estimation, (4) work zone travel speed estimation, (5) safety model development and (6) optimization of work zone lengths. The factors for these issues are total traffic volumes (especially, truck volumes), availability of alternate roads, road types, work zone configurations, work intensity, weather conditions and work time.

These issues are directly related to the development of cost functions for analyzing work zones. Most of these issues have been the subject of considerable research. Capacity estimation and work zone travel speed estimation are issues that many early work zone studies have focused on. Delay estimation and queue length estimation methods have been developed and used to analyze traffic disruptions and to determine the maximum feasible work intensity. Recently, work zone studies have sought to develop

safety models that can predict the frequencies of accidents according to work zone configurations.

Optimizing work zone lengths is an important issue that has been neglected. Such lengths have been usually designed to minimize costs to highway agencies rather than to users.

Meanwhile, highway agencies have developed associated regulations to improve workers' safety and to enhance public awareness of scheduled maintenance work.

Highway maintenance issues concern transportation engineers, structural engineers and construction management engineers, with different groups focusing on different aspects.

2.2 Work Zone Cost Items

Work zone cost items largely fall into two categories: (1) agency costs and (2) user costs. Agency costs are the expenses they spend to finish the work zone activities based on the work types. Those normally include labor costs, equipment costs, material costs and traffic maintenance costs.

Meanwhile, user costs can be classified into (1) user delay costs and (2) safety (accident) costs. Since delay and accidents by work zone activities are very important to optimize work zone lengths and schedules, researchers have tried several methods to properly estimate the user (delay and safety) by developing several models. (McCoy and Peterson, 1987; Schonfeld and Chien, 1999 and 2001; Venugopal and Tarko, 2000)

Recently, user costs have received more attention in work zone analysis because they tend to dominate other costs and because community concerns and reactions to work zone activities affect many aspects of work zone decisions.

2.3 Research Trends

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

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

Since the travel delays of roadway users in a work zone are the primary determinant of user delay cost, studies related to speed and delay analysis for work zones were reviewed. In a study of traffic characteristics on Illinois freeways with lane closures, Rouphail and Tiwari (1985) evaluated the effects of intensity and location of

construction and maintenance activities on mean speeds through a work zone. The results showed that the mean speeds through a work zone decrease as the intensity of construction and maintenance activities increase. The mean speeds also decrease as the construction and maintenance activities move closer to the travel lanes.

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

Memmott and Dudek (1984) developed a computer model, called Queue and User Cost Evaluation of Work Zone (QUEWZ), to estimate the average speed in work zones to calculate user costs, including user delays costs and vehicle operating costs. The effects of different lane-closure strategies and the number of hours available for lane closures are determined based on an assumed lane capacity and various traffic volumes. However, that model does not consider any alternate path and the effect of diverting traffic to it.

Cassidy and Han (1994) used the empirical data to estimate vehicle delays and queue lengths on two-lane highways operating under one-way traffic control. However, the work zone length was not optimized in that study.

McCoy et al. (1980) developed a method to optimize the work zone length by minimizing the road user and traffic control costs in construction and maintenance zones of rural four-lane divided highways. This method provided a framework for optimizing the lengths of work zones by minimizing the total costs, including construction costs. The user delay costs were modeled based on average daily traffic (ADT) volumes, while the accident costs were computed by assuming that the accident rate per vehicle mile was constant in a work zone area. The optimal work zone length was derived based on 1979 data. Because the unit cost factors had changed considerably since 1981, McCoy and Peterson (1987) found the optimum work zone lengths to be about 64% longer that those used previously in the State of Nebraska. They (1987) also conducted a safety study for various lengths of work zones on four-lane divided highways. No relation was found between the lengths of work zones and accident rates or any of the speed distribution parameters, such as the standard deviation of vehicle speeds and the range of vehicle speeds. They also found the average accident rate was 30.8 accidents per 100 million vehicle miles (acc/100 mvm) on I-80 in Nebraska between 1978 and 1984.

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

Various efforts to mitigate the impacts of work zones have been made by Janson et al (1987). One such effort optimized work zone traffic control design and practice considering such aspects as optimal design of control devices, optimal lane closure

configuration and optimal work zone length. Martinelli and Xu (1996) added the vehicle queue delay costs into McCoy's (1980) model. The work zone length was optimized by minimizing the total user cost, excluding the maintenance and accident costs. To estimate the roadway maintenance costs, Underwood (1994) analyzed the work duration and the maintenance cost per 10,000 m^2 for five different roadway maintenance activities (i.e., surface dressing, asphalt surface, porous asphalt, 10% patching, and milling out). The average maintenance costs were calculated based on prices quoted to highway authorities in the summer of 1993.

Schonfeld and Chien (2001) developed a mathematical model to optimize the work zone lengths on four-lane highways using a single-lane closure approach. The objective of the study was to minimize the total cost including agency cost, accident cost and user delay cost based on two steady demands. They did not consider alternate paths and assumed uniform traffic flow. Viera-Colon (1999) extended that research to four-lane highways and considered the effect of different traffic conditions and an alternate path.

Schonfeld and Chien (1999) also developed a mathematical model to optimize the work zone lengths plus associated traffic control for two-lane, two-way highways where one lane at a time is closed. That study found the optimal work zone length and cycle time for traffic control and minimized the total cost, including agency cost and user delay cost, but no alternative route was considered.

Carr (2000) developed the construction congestion cost (CO^3) system to estimate the impact of traffic maintenance contract provisions on congestion, road user cost, and construction cost. CO^3 is implemented in a Microsoft Excel spread sheet and consists of three sheets: (1) route sheet computing equivalent average vehicle routes for complex

diversion routes, (2) input sheet providing for documentation of vehicle and route inputs and computing user cost for individual trips through the work zone, diversions, and cancellations, and (3) traffic sheet computing daily traffic impacts and user costs for each construction method. Although CO^3 provides practical information with which engineers select construction methods, it does not optimize work zone configurations.

This study extends Schonfeld and Chien's work (1999 and 2001) for two-lane, two-way rural highways by considering an alternate path and four-lane rural divided highways.

2.4 Software and Information Sources for Work Zones

1. QuickZone

This software is developed by the Turner-Fairbank Highway Research Center of the USDOT (http://www.tfhrc.gov/its/quickzon.htm, January, 14th, 2002).

The 1998 FHWA report "Meeting the Customer's Needs for Mobility and Safety During Construction and Maintenance Operations" recommends the development of an analytical tool to estimate and quantify work zone delays. This scope of work lays out a plan for the development of an easy-to-master analytic tool (currently under the working title "QuickZone") for quick and flexible estimation of work zone delay in all four phases of the project development process (policy, planning, design and operations). The QuickZone concept is to provide an easy-to-use, easy-to-learn tool that utilizes software tools that are familiar to the target user base. The primary functions of QuickZone are:

- Quantification of corridor delay resulting from capacity decreases in work zones.

- Identification of delay impacts of alternative project phasing plans.
- Supporting tradeoff analyses between construction costs and delay costs.
- Examination of impacts of construction staging, by:

  - location along mainline

  - time-of-day (peak vs. off-peak)

  - season (summer vs. winter)
- Assessment of travel demand measures and other delay mitigation strategies.
- Allowing the establishment of work completion incentives.

A QuickZone Tailor-Made for Maryland

: from http://www.tfhrc.gov/focus/mar01/quick.htm, January, 14th, 2002.

QuickZone, which is the first product to come out of FHWA's new strategic Work Zone Analysis Tools (SWAT) program, can be used to compare the traffic impacts for work zone mitigation strategies and estimate the costs associated with these impacts. The costs can be estimated for both an average day of work and for the whole life cycle of construction.

QuickZone's open source code has allowed the University of Maryland, under contract with SHA, to customize the program to better meet the State's needs. The university, for example, has added its own capacity estimation model to the program. In Maryland's version of the program, users can also define the criteria that will be used for analysis, such as setting a maximum allowable queue of vehicles or length of delay. The Maryland version uses a 24-hour traffic count, instead of the average daily traffic count found in the standard program.

2. HDM-4

: from http://hdm4.piarc.org/main/home-e.htm, January, 14th, 2002.

This software is developed under the PIARC (World Road Association) ISOHDM (International Study of Highway Development and Management Tools) Project. ISOHDM, an international project to develop new road investment analysis tools, has continued since 1993. This project has been sponsored by the World Bank, the UK Department for International Development, the Asian Development Bank, the Swedish National Road Administration, and other sponsoring organizations, including PIARC member governments. PIARC has assumed the role of leading the management and coordination of international HDM-4 implementation activities within the ISOHDM Project since 1998.

Compared with its predecessor (HDM-III), the scope of the new HDM-4 has been broadened considerably beyond traditional project appraisals, to provide a powerful system for the analysis of road management and investment alternatives. The new HDM-4 is intended to cater to the wide ranging needs of road agencies, international funding institutions, consultants and research organizations through separate application tools developed to perform the following management functions:

- Strategic planning
- Roadwork programming
- Project preparation
- Research and policy studies

The HDM-4 technology is designed to be modular to allow its integration with present and future road management systems. The technology has been developed at three levels:

- The knowledge and algorithms embodied in the modelling of technical and economic performance of road infrastructure;
- The program modules which deliver the models in explicit terms;
- The HDM-4 software, including the modeling modules, which provides the investment analysis and works programming functions.

The system architecture consists of

- A database – manages the input data and analysis results;
- Data Managers – software which provides the user interface, and controls data flows;
- Models – software modules which reflect the modeling algorithms;
- Analysis Tools – software which controls the system applications.

These modules can interface with, or in some cases be integrated into, existing road agency information systems.

3. Workzone Safety Information Clearinghouse

: from http://wzsafety.tamu.edu, January, 14th, 2002.

In February 1998, the American Road and Transportation Builders Association joined forces with the Federal Highway Administration to improve safety in highway work zones by creating the National Work Zone Safety Information Clearinghouse. A work zone is defined as "a segment of the roadway marked to indicate that construction,

maintenance, or utility work is being performed." The purpose of the Clearinghouse is to provide information and referrals to government agencies, public and private organizations, and the general public concerning the safe and effective operation of traffic work zones. The Clearinghouse began operations in February 1998 under FHWA funding, and is currently a cooperative partnership between the American Road & Transportation Builders Association and the Texas Transportation Institute. It is maintained and supported through contributions by private and public organizations.

Chapter 3 Optimization of Work Zones

3.1 Approach

(1) Two-Lane Two-Way Highway Work Zone

Pavement maintenance on two-lane, two-way highways often requires closing one lane for a work zone. In such circumstances, vehicles travel in the remaining lane along the work zone, alternating direction within each control cycle. Such a two-lane work zone can be considered 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 (1999) analyzed the effect of longer work zones and longer cycle times in increasing the user delay and decreasing the total maintenance time and costs due to fewer setups for fewer zones.

Here we consider the best available alternate route that bypasses the work zone area, so that the original flow on the road is divided between the flow passing along the work zone and the flow through the detour. Thus, in the second alternative considered, the remaining lane is still used for alternating two-way traffic, but some traffic from the maintained road also can use the alternate route. In the third alternative all traffic in one direction is diverted to the alternate route, while the remaining lane is only used for traffic in the other direction. Thus, the diverted traffic percentage from one direction of the main road is 0% in Alternative 2.1, 100% in Alternative 2.3 and somewhere between those extremes in Alternative 2.2. In Alternative 2.4, all traffic in both directions is diverted to the alternate route and both lanes are closed for work. The preferred alternative can be determined after evaluating all four alternatives.

(2) Four-Lane Two-Way Highway Work Zone

Pavement maintenance on four-lane, two-way highways often requires closing one or two lanes for a work zone. This does not require one-way control as in a two-lane highway work zone because at least one lane is usually still available in the direction of closure. Chien and Schonfeld (2001) developed a work zone cost function, which includes the user delay, the accident, and the agency costs, for four-lane two-way highways without considering any detour.

Here we consider the best available alternate route that bypasses the work zone area, so that the original flow on the road is divided between the flow passing along the work zone and the flow through the detour. Thus, in the second alternative considered, the remaining lane in direction 1 is still used for traffic in direction 1, but traffic from the maintained road also can use the alternate route. In the third alternative all traffic in one direction is diverted to the alternate route, while the remaining lane is only used for traffic in the other direction. Thus, the diverted traffic percentage from one direction of the main road is 0% in Alternative 4.1, 100% in Alternative 4.3 and somewhere between those extremes in Alternative 4.2. In Alternative 4.4, both lanes in one direction are closed for a work zone and the entire traffic in one direction crosses over to one lane in the opposite direction without considering here any alternate route. The preferred alternative can be again determined here after evaluating all four alternatives.

This study proposes a methodology to minimize the total cost, including agency cost and user delay cost, and to optimize the work zone length for each alternative, while considering the best available alternate route that bypasses the work zone. Finally,

guidelines for determining the best alternative for different conditions of traffic flow, road characteristics (i.e. detour length, the distance of main road between the beginning and end of detour) and maintenance characteristics (i.e. maintenance setup cost, average maintenance time per kilometer) are developed by deriving the minimum cost thresholds between pairs of alternatives with respect to key variables.

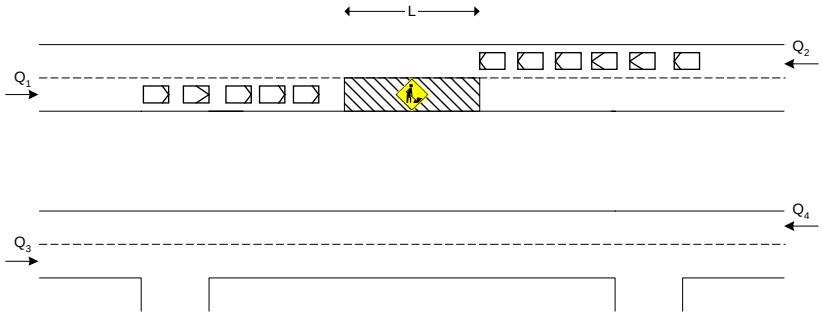
3.2 Methodology and Assumptions

The basic method followed here is to formulate a total cost objective function and use it to optimize work zone lengths at work zones for four alternatives. The queuing delays to users are formulated with deterministic queuing models. Then thresholds among alternatives are derived with respect to key variables, to determine the best alternative for different conditions of traffic flow, road characteristics and maintenance characteristics.

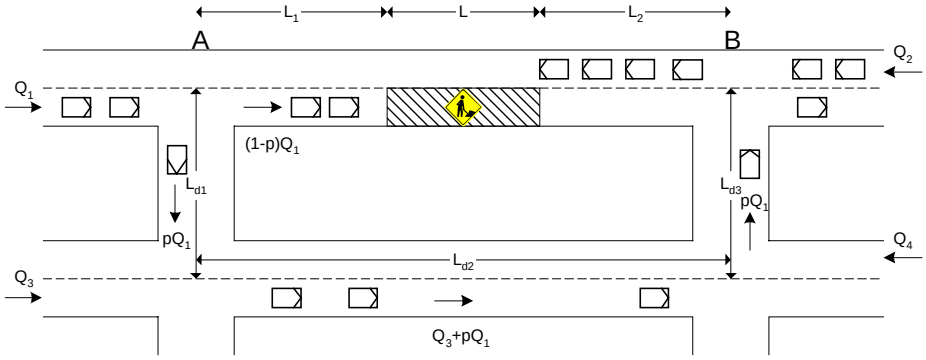
The following four alternatives are considered for two-lane two-way highways in this study:

1. Alternating flow on one lane, without any detour
2. Alternating flow on one lane, with a detour
3. One-directional flow on one lane along work zone; other direction on detour
4. Both directions detoured and both lanes closed for work

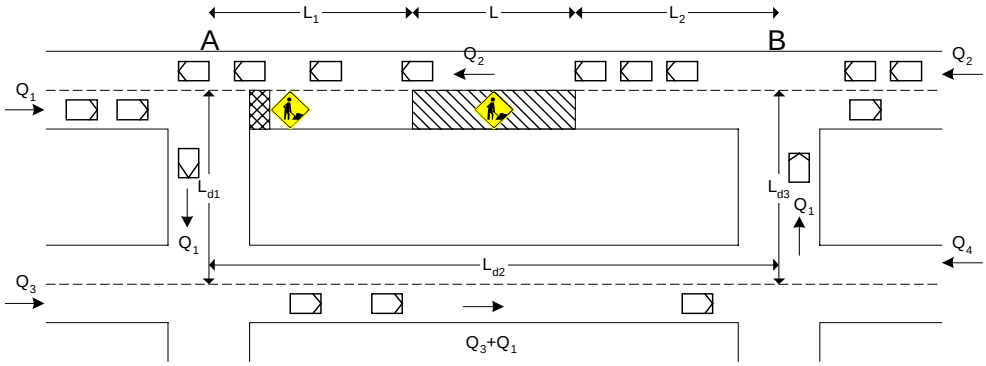
The geometries of these four cases are shown in Figure 1.



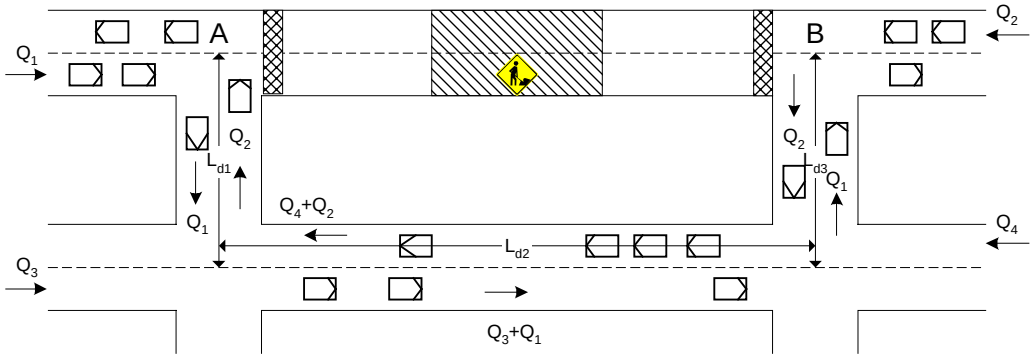
(a) Alternative 2.1: without Detour



(b) Alternative 2.2: with Detour; pQ_1 on Detour, $(1-p)Q_1$ along Work Zone



(c) Alternative 2.3: Detour for Only One Direction



(d) Alternative 2.4: Two Directions Detoured

Figure 1 Geometry of Analyzed Work Zone for Two-Lane Two-Way Highway

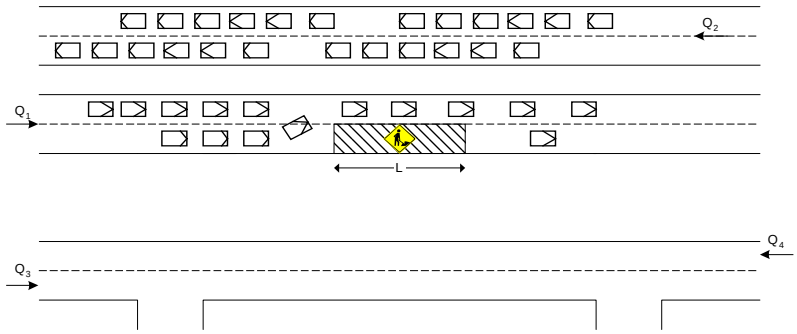
The following four alternatives are considered for four-lane two-way highways in this study:

1. No detour. One of the two lanes closed for Q_1 traffic
2. A fraction of Q_1 traffic is diverted through detour
3. All of Q_1 is diverted through detour, allowing work zone on both lanes in direction 1
4. All of Q_1 crosses over into one lane in the opposite direction, allowing work on both lanes in direction 1

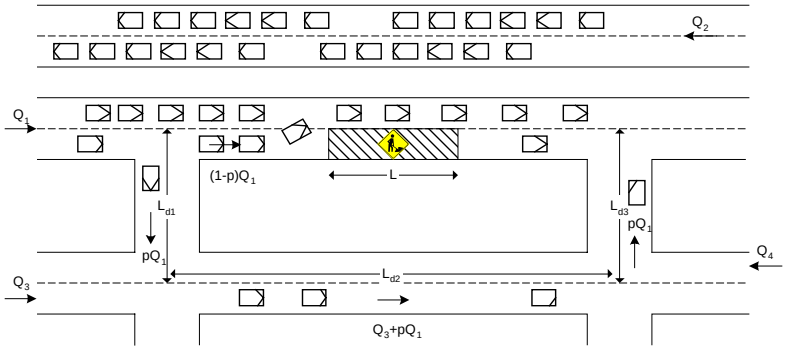
The geometries of these four cases are shown in Figure 2.

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

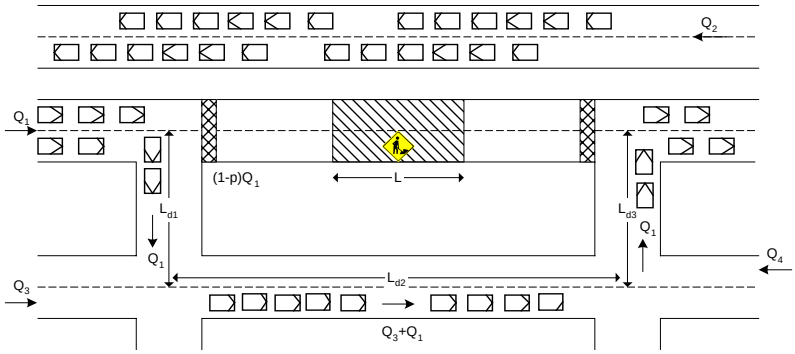
1. Traffic moves at a uniform speed through a work zone and at a different uniform speed elsewhere.
2. Queues in both directions will be cleared within each cycle for two-lane two-way highways. Thus, the one-lane work zone capacity exceeds the combined flows of both directions.
3. The original detour flows on the relatively short L_{d1} and L_{d3} are negligible but original flow Q_3 on L_{d2} is considered.
4. Possible signal or stop sign delays on the detour in Alternatives 2.2, 2.3, 2.4 and 4.2, 4.3 can be neglected.



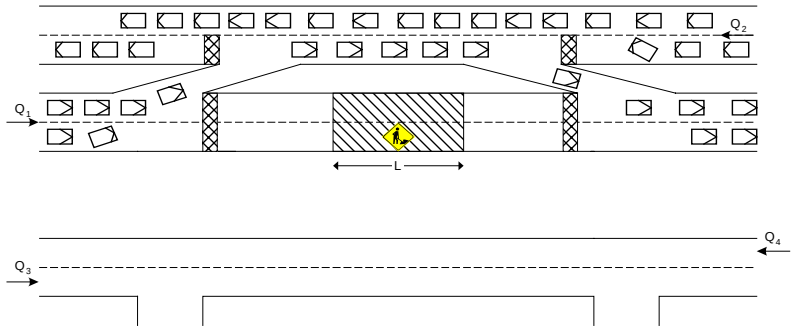
(a)Alternative 4.1: No Detour, One of the Two Lanes closed for Q_1 Traffic



(b) Alternative 4.2: A Fraction of Q_1 Traffic through Detour



(c) Alternative 4.3: All Q_1 through Detour, Allowing Work Zone on Both Lanes in Direction 1



(d) Alternative 4.4: Crossover of All Q_1 into One Lane in Opposite Direction, Allowing Work Zone on Both Lanes in Direction 1

Figure 2 Geometry of Analyzed Work Zone for Four-Lane Two-Way Highway

3.3 Model Formulation

1. Two-Lane Two-Way Highway Work Zone

Alternative 2.1: Flow on one lane without detour

Schonfeld and Chien (1999) developed a work zone cost function which includes user delay cost and maintenance cost:

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

where C_T = total cost per lane-kilometer; C_M = maintenance cost per lane-kilometer; C_U = user delay cost per lane-kilometer.

The user delay cost C_U per maintained lane-kilometer is the total delay per cycle Y in both directions multiplied by the number of cycles N per maintained lane-kilometer and the users' value of time v (in \$/veh-hr):

$$C_U = YNv \tag{2}$$

where Y = summation of the delays (e.g., Y_1 and Y_2) incurred by the traffic flows from directions 1 and 2 per cycle. Y_1 and Y_2 can be derived by using deterministic queuing analysis. The value of time v has been estimated and used in numerous previous studies. According to the report of Federal Highway Administration (1998), the following values of time were recommended by vehicle class: passenger vehicles = \$11.58/veh-hr; single-unit trucks = \$18.54/veh-hr; combination trucks = \$22.31/veh-hr. These values are derived from the value of time in 1970 multiplied by escalation factor, the proportion of CPI (consumer Price Indexes) in 1996 and CPI in 1970. More precise values of time can be obtained by the using current CPI, national wage rate, vehicle classification, and trip type and purpose, etc., weighting different values of time of all types of users or vehicles. However, vehicle classification and trip type or purpose varies in different areas. To

simplify this Phase 1 optimization model and increase the ease of use, an assumption that all users have the same value of time is applied in this study.

Schonfeld and Chien formulated the zone delay cost without any alternate route around the work zone and obtained the following relation:

$$C_U^1 = \frac{(z_3 + z_4 L)[Q_1(\frac{3600}{H} - Q_1) + Q_2(\frac{3600}{H} - Q_2)]v}{V(\frac{3600}{H} - Q_1 - Q_2)} \tag{3}$$

where C_U^1 = user delay cost per lane-kilometer for Alternative 1; z_3 = setup time; z_4 = average maintenance time per lane-kilometer; L = work zone length; Q_1 = hourly flow rate in direction 1; Q_2 = hourly flow rate in direction 2; H = average headway; V = average work zone speed; v = value of user time; and z_3+z_4L represents the maintenance duration per zone.

The maintenance cost per zone is assumed to be z_1+z_2L, where z_1 = fixed setup cost; and z_2 = average maintenance cost per additional lane-kilometer. The average maintenance cost per lane-kilometer, C_M, is the total maintenance cost per zone divided by the zone length L

$$C_M = (z_1 + z_2 L)/L = \frac{z_1}{L} + z_2 \tag{4}$$

Then the total cost for Alternative 2.1, C_T^1 , is $C_M + C_U^1$. Its optimal work zone length of Alternative 1, L^{*1}, obtained by setting the partial derivative of the total cost function C_T^1 with respect to L equal to zero and solving for L, is:

$$L^{*21} = \sqrt{\frac{z_1 V(\frac{3600}{H} - Q_1 - Q_2)}{z_4[Q_1(\frac{3600}{H} - Q_1) + Q_2(\frac{3600}{H} - Q_2)]v}} \tag{5}$$

The second derivative of C_T^1 with respect to L is positive in this case and the following ones, indicating that function is convex and has a unique global minimum for L.

Alternative 2.2: Flow on one lane as well as detour

It is assumed in Alternative 2.2 (Figure 1b) that the fraction p of the flow Q_1 in direction 1 is diverted to the alternate route. Then the user delay cost of the remaining flow in direction 1, $(1-p)Q_1$, and Q_2, denoted as C_{1-p} , has the same formulation as Eq.(3) but with $(1-p)Q_1$ substituted for Q_1.

$$C_{1-p} = \frac{(z_3 + z_4 L)[(1-p)Q_1(\frac{3600}{H} - (1-p)Q_1) + Q_2(\frac{3600}{H} - Q_2)]v}{V(\frac{3600}{H} - (1-p)Q_1 - Q_2)} \qquad (6)$$

The user delay cost of the diverted flow pQ_1 from direction 1, denoted as C_p, is equal to the flow pQ_1 multiplied by: (1) the average maintenance duration per kilometer, $\frac{z_3}{L} + z_4$, which is the maintenance duration per zone, z_3+z_4L, divided by work zone L, (2) the time difference between the time vehicles through the detour, $\frac{L_{d1} + L_{d3}}{V_0} + \frac{L_{d2}}{V_d^{*2}}$, and the time vehicles through the original road AB without work zone, $\frac{L_t}{V_0}$, and (3) the value of time, v. Thus:

$$C_p = pQ_1(\frac{z_3}{L} + z_4)[\frac{L_{d1} + L_{d3}}{V_0} + \frac{L_{d2}}{V_d^{*2}} - \frac{L_t}{V_0}]v \qquad (7)$$

where L_{d1}, L_{d2}, L_{d3} are the lengths of the first, second and third segments of the detour shown in Figure 1. V_0 represents the speed on the original road without any work zone

and V_d^{*2} is the detour speed affected by pQ_1 in direction 3 in Alternative 2.2. Both speeds are computed with Eq. (20), derived below.

In addition to delay costs of flows remaining on the maintained road, the delay cost to the original flow on the detour, Q_3, as affected by the pQ_1, is also considered. Denoted as C_{U3}, it equals the flow Q_3 multiplied by: (1) the average maintenance duration per kilometer, $\frac{z_3}{L} + z_4$, (2) the travel time difference over L_{d2} with the diverted flow pQ_1, $\frac{L_{d2}}{V_d^{*2}}$, and without it, $\frac{L_{d2}}{V_{d0}}$, and (3) the value of time, v. Thus:

$$C_{U3} = Q_3(\frac{z_3}{L} + z_4)(\frac{L_{d2}}{V_d^{*2}} - \frac{L_{d2}}{V_{d0}})v \tag{8}$$

where V_{d0} represents the original speed on L_{d2} unaffected by pQ_1.

The combined user delay cost for the original road AB and the detour can be derived as:

$$C_U^2 = C_{1-p} + C_p + C_{U3} \tag{9}$$

where

$C_U^2 =$ user delay cost per kilometer per lane for Alternative 2.2

$C_{U12} =$ user delay cost of the remaining flow $(1-p)Q_1$ in direction 1 and the flow Q_2 in direction 2

$C_{U1}^P =$ user delay cost of diverted flow pQ_1

C_{U3} = additional delay cost to the original flow Q_3 due to diverted flow pQ_1

Then the total cost for Alternative 2.2, C_T^2, is $C_M + C_U^2$. Its optimal work zone length L^{*2} is obtained by setting the partial derivative of C_T^2 with respect to L equal to zero and then solving for L. This yields:

$$L^{*22} = \sqrt{\frac{V(\frac{3600}{H} - (1-P)Q_1 - Q_2)[\frac{z_1}{v} + pQ_1 z_3(\frac{L_{d1} + L_{d3} - L_t}{V_0} + \frac{L_{d2}}{V_d^{*2}}) + Q_3 z_3(\frac{L_{d2}}{V_d^{*2}} - \frac{L_{d2}}{V_{d0}})]}{z_4[(1-p)Q_1(\frac{3600}{H} - (1-p)Q_1) + Q_2(\frac{3600}{H} - Q_2)]}} \quad (10)$$

Alternative 2.3: One direction along work zone and the other detoured

Here it is assumed that the entire flow Q_1 in Alternative 2.1 is diverted to the alternate route. Then the user delay cost in direction 1, denoted as C_{U1}, has the same formulation as Eq. (6) but with Q_1 substituted for pQ_1.

$$C_{U1} = Q_1(\frac{z_3}{L} + z_4)[\frac{L_{d1} + L_{d3}}{V_0} + \frac{L_{d2}}{V_d^{*3}} - \frac{L_t}{V_0}]v \quad (11)$$

where V_d^{*3} is the detour speed affected by Q_1 in direction 3 in Alternative 2.3.

The user delay cost of the flow Q_2, denoted as C_{U2}, is the cost increment due to the work zone. It is equal to the flow Q_2 multiplied by: (1) the average maintenance duration per kilometer, $\frac{z_3}{L} + z_4$, (2) the time difference over section AB (in Figure 2c) with the work zone, $\frac{L_1 + L_2}{V_0} + \frac{L}{V}$, and without the work zone, $\frac{L_t}{V_0}$, and (3) the value of time, v. Thus:

$$\begin{aligned} C_{U2} &= Q_2(\frac{z_3}{L} + z_4)(\frac{L_1 + L_2}{V_0} + \frac{L}{V} - \frac{L_t}{V_0})v \\ &= Q_2(\frac{z_3}{L} + z_4)(\frac{L}{V} - \frac{L}{V_0})v \end{aligned} \quad (12)$$

The delay cost C_{U3} of the original flow Q_3 in direction 3, as affected by the Q_1, is also considered. It has the same formulation as equation (7) but with V_d^{*3} substituted for V_d^{*2}.

$$C_{U3} = Q_3(\frac{z_3}{L} + z_4)(\frac{L_{d2}}{V_d^{*3}} - \frac{L_{d2}}{V_{d0}})v \tag{13}$$

The total user delay cost including original road and detour can be determined as follows:

$$C_U^3 = C_{U1} + C_{U2} + C_{U3} \tag{14}$$

where

C_U^3 = user delay cost per kilometer per lane for Alternative 2.3

C_{U1} = user delay cost of the totally diverted flow Q_1

C_{U2} = user delay cost of the flow Q_2 in direction 2 due to lower speed through the work zone

C_{U3} = user delay cost of the original detour flow Q_3 due to additional flow Q_1

Then the total cost for Alternative 2.3, C_T^3 , is $C_M + C_U^3$. Its optimal work zone length L^{*23} is then found to be:

$$L^{*23} = \sqrt{\frac{\frac{z_1}{v} + Q_1 z_3(\frac{L_{d1} + L_{d3} - L_t}{V_0} + \frac{L_{d2}}{V_d^{*3}}) + Q_3 z_3(\frac{L_{d2}}{V_d^{*3}} - \frac{L_{d2}}{V_{d0}})}{Q_2 z_4(\frac{1}{V} - \frac{1}{V_0})}} \tag{15}$$

Because the second derivatives $\partial C_T^1/\partial L^2$, $\partial C_T^2/\partial L^2$, $\partial C_T^3/\partial L^2$ of the three objective functions C_T^1 , C_T^2 and C_T^3 are positive, those functions are convex and L^{*21}, L^{*22} and L^{*23} are global optima.

Alternative 2.4: Both directions detoured and both lanes closed for work

Here it is assumed that the entire flows Q_1 and Q_2 are diverted to the alternate route and both lanes between A and B are entirely closed for maintenance. Then the user delay cost in direction 1, denoted as C_{U1}, has the same formulation as equation (7) but with Q_1 substituted for pQ_1.

$$C_{U1} = Q_1(\frac{z_3}{L} + z_4)[\frac{L_{d1} + L_{d3}}{V_0} + \frac{L_{d2}}{V_d^{*3}} - \frac{L_t}{V_0}]v \tag{16}$$

where V_d^{*3} is the detour speed in direction 3 affected by Q_1 in Alternative 2.4.

The user delay cost of the flow Q_2, denoted as C_{U2}, has the same formulation as equation (7) but with Q_2 substituted for pQ_1.

$$C_{U2} = Q_2(\frac{z_3}{L} + z_4)[\frac{L_{d1} + L_{d3}}{V_0} + \frac{L_{d2}}{V_d^{*4}} - \frac{L_t}{V_0}]v \tag{17}$$

where V_d^{*4} is the detour speed in direction 4 affected by Q_1 in Alternative 2.4.

The delay cost C_{U3} of the original flow Q_3 in direction 3, as affected by the Q_1, is also considered. It has the same formulation as equation (8) but with V_d^{*3} substituted for V_d^{*2}.

$$C_{U3} = Q_3(\frac{z_3}{L} + z_4)(\frac{L_{d2}}{V_d^{*3}} - \frac{L_{d2}}{V_{d0}})v \tag{18}$$

Similarly, the delay cost C_{U4} of the original flow Q_4 in direction 4, as affected by the Q_2, is considered as well. It has the same formulation as equation (8) but with V_d^{*4} substituted for V_d^{*2}.

$$C_{U4} = Q_4(\frac{z_3}{L} + z_4)(\frac{L_{d2}}{V_d^{*4}} - \frac{L_{d2}}{V_{d0}})v \tag{19}$$

It is assumed here that Q_3 and Q_4 are equal so that the original detour speeds for direction 3 and 4 are equal, V_{do}, which will be derived by using Eq.(78).

The total user delay cost including original road and detour can be determined as follows:

$$C_U^4 = C_{U1} + C_{U2} + C_{U3} + C_{U4} \tag{20}$$

where

C_U^4 = user delay cost per kilometer per lane for Alternative 2.4

C_{U1} = user delay cost of the totally diverted flow Q_1

C_{U2} = user delay cost of the flow Q_2 in direction 2 due to lower speed through the work zone

C_{U3} = user delay cost of the original detour flow Q_3 due to additional flow Q_1

C_{U4} = user delay cost of the original detour flow Q_4 due to additional flow Q_2

Then the total cost for Alternative 2.4, C_T^4 , is:

$$C_T^4 = \frac{1}{2}\alpha(\frac{z_1}{L} + z_2) + C_U^4 \tag{21}$$

Eq.(21) includes the parameter α which is reduction factor that is defined as the maintenance cost for two lanes divided by the maintenance cost for one lane. The ½ parameter is because two lanes are closed for maintenance and $\alpha(\frac{z_1}{L} + z_2)$ is the maintenance cost for two lanes. The first and second partial derivatives of C_T^4 are then found to be:

$$\frac{\partial C_T^4}{\partial L} = -[\frac{\alpha z_1}{2L^2} + \frac{Q_1 z_3}{L^2}(\frac{L_{d1} + L_{d3}}{V_0} + \frac{L_{d2}}{V_d^{*3}} - \frac{L_t}{V_0})v + \frac{Q_2 z_3}{L^2}(\frac{L_{d1} + L_{d3}}{V_0} + \frac{L_{d2}}{V_d^{*4}} - \frac{L_t}{V_0})v + \frac{Q_3 z_3}{L^2}(\frac{L_{d2}}{V_d^{*3}} - \frac{L_{d2}}{V_{d0}})v + \frac{Q_4 z_3}{L^2}(\frac{L_{d2}}{V_d^{*4}} - \frac{L_{d2}}{V_{d0}})v] < 0 \tag{22}$$

$$\frac{\partial^2 C_T^4}{\partial L^2} = \frac{\alpha z_1}{L^3} + 2\frac{Q_1 z_3}{L^3}\left(\frac{L_{d1} + L_{d3}}{V_0} + \frac{L_{d2}}{V_d^{*3}} - \frac{L_t}{V_0}\right)v + 2\frac{Q_2 z_3}{L^3}\left(\frac{L_{d1} + L_{d3}}{V_0} + \frac{L_{d2}}{V_d^{*4}} - \frac{L_t}{V_0}\right)v + 2\frac{Q_3 z_3}{L^3}\left(\frac{L_{d2}}{V_d^{*3}} - \frac{L_{d2}}{V_{d0}}\right)v + 2\frac{Q_4 z_3}{L^3}\left(\frac{L_{d2}}{V_d^{*4}} - \frac{L_{d2}}{V_{d0}}\right)v > 0 \quad (23)$$

The first partial derivative of C_T^4 is less than zero and the second partial derivative is greater than zero. Therefore the function C_T^4 is convex and the slope of the curve is decreasing, and its unique global minimum is reached at L_t.

2. Four-Lane Two-Way Work Zone

Alternative 4.1: No Detour. One of the Two Lanes closed for Q_1 Traffic

Chien and Schonfeld (2001) developed a work zone cost function, which includes the user delay, the accident, and the agency costs, for four-lane two-way highway without considering a detour (Figure 2a). The user delay cost consists of the queue delay costs upstream of work zones and the moving delay costs through work zones. The following variables are defined:

Q_1 = approaching traffic flow in the direction 1 of work zone maintained (veh/hr)

c_w = work zone capacity (veh/hr)

D = maintenance duration per zone

If Q_1 exceeds the work zone capacity c_w, a queue forms, which then dissipates when the closed lane is open again. The queue dissipation time t_d is

$$t_d = \frac{(Q_1 - c_w)D}{(c_0 - Q_1)} \quad (24)$$

where c_0 represents the road capacity in normal (two lanes) conditions in direction 1 without work zone.

The queue delay cost C_q per maintained kilometer is queue delay t_q multiplied by the average delay cost v_d and divided by L.

$$C_q = \frac{t_q v_d}{L} \tag{25}$$

where t_q = queue delay incurred by the approaching traffic flow Q_1 while work on one zone is completed. If Q_1 is less than the maximum discharge rate of work zone, c_w, the queue delay t_q is neglected. If Q_1 is greater than c_w, the queue delay t_q is:

$$\begin{aligned} t_q &= \frac{1}{2}(D + t_d)[(Q_1 - c_w)D)] \\ &= \frac{1}{2}(1 + \frac{Q_1 - c_w}{c_0 - Q_1})(Q - c_w)(z_3 + z_4 L)^2 \end{aligned} \tag{26}$$

Then

$$\begin{aligned} C_q &= 0 && when\ \ Q_1 \le c_w \\ C_q &= \frac{v_d}{2L}(1 + \frac{Q_1 - c_w}{c_0 - Q_1})(Q_1 - c_w)(z_3 + z_4 L)^2 && when\ \ Q_1 > c_w \end{aligned} \tag{27}$$

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

$$C_v = \frac{t_m v_d}{L} \tag{28}$$

where t_m = moving delay incurred by the approaching traffic flow Q_1. The t_m is a function of the difference between the travel time on a road with and without a work zone.

$$\begin{aligned} t_m &= (\frac{L}{V_w} - \frac{L}{V_a})Q_1 D && when\ \ Q_1 \le c_w \\ t_m &= (\frac{L}{V_w} - \frac{L}{V_a})c_w D && when\ Q_1 > c_w \end{aligned} \tag{29}$$

where V_a = average approaching speed; V_w = average work zone speed. If Q_1 is greater than c_w, the variable Q_1 is reduced by c_w, because the maximum flow allowed to pass through the work zone is c_w.

Then

$$C_v = (\frac{1}{V_w} - \frac{1}{V_a})Q_1(z_3 + z_4 L)v_d \qquad when\ Q_1 \le c_w$$
$$C_v = (\frac{1}{V_w} - \frac{1}{V_a})c_w(z_3 + z_4 L)v_d \qquad when\ Q_1 > c_w \tag{30}$$

Total user delay per maintained lane kilometer C_u is:

$$C_u = C_q + C_v \tag{31}$$

The accident cost incurred by the traffic flow passing through the work zone can be assumed to be proportional to the total delay and can be determined from the number of accidents per 100 million vehicle hour n_a multiplied by the product of the increasing delay (t_q+t_m) and the average cost per accident v_a and then divided by work zone length L. Average accident cost per maintained kilometer C_a is formulated as

$$C_a = \frac{(t_q + t_m)}{L}\frac{n_a v_a}{10^8} \tag{32}$$

Then

$$C_a = (\frac{1}{V_w} - \frac{1}{V_a})Q_1(z_3 + z_4 L)\frac{n_a v_a}{10^8} \qquad when\ Q_1 \le c_w$$
$$C_a = [\frac{1}{2L}(1 + \frac{Q_1 - c_w}{c_0 - Q_1})(Q_1 - c_w)(z_3 + z_4 L)^2 + (\frac{1}{V_w} - \frac{1}{V_a})c_w(z_3 + z_4 L)]\frac{n_a v_a}{10^8} \qquad when\ Q_1 > c_w \tag{33}$$

Total cost is

$$C_T = C_M + C_u + C_a \tag{34}$$

Then

$$C_T = (\frac{z_1}{L} + z_2) + (\frac{1}{V_w} - \frac{1}{V_a})Q_1(z_3 + z_4 L)(v_d + \frac{n_a v_a}{10^8}) \qquad when\ \ Q_1 \le c_w$$

$$C_T = (\frac{z_1}{L} + z_2) + [\frac{1}{2L}(1 + \frac{Q_1 - c_w}{c_0 - Q_1})(Q_1 - c_w)(z_3 + z_4 L)^2 \tag{35}$$

$$+ (\frac{1}{V_w} - \frac{1}{V_a})c_w(z_3 + z_4 L)](v_d + \frac{n_a v_a}{10^8}) \qquad when\ \ Q_1 > c_w$$

Its optimal work zone length L^{*41} is then found to be:

$$L^{*41} = \sqrt{\frac{z_1}{z_4 Q_1 P_3 P_4}} \qquad when\, Q_1 \le c_w$$

$$L^{*41} = \sqrt{\frac{2z_1 + P_1 P_2 P_3 z_3^2}{P_1 P_2 P_3 z_4^2 + 2P_3 P_4 c_w z_4}} \qquad when\, Q_1 > c_w \tag{36}$$

where

$$P_1 = Q_1 - c_w \tag{37}$$

$$P_2 = 1 + \frac{Q_1 - c_w}{c_0 - Q_1} \tag{38}$$

$$P_3 = v_d + \frac{n_a v_a}{10^8} \tag{39}$$

$$P_4 = \frac{1}{V_w} - \frac{1}{V_a} \tag{40}$$

Alternative 4.2: A Fraction of Q_1 Traffic through Detour

It is assumed in Alternative 4.2 (Figure 2b) that the fraction *p* of the flow Q_1 in direction 1 is diverted to the alternate route. In this section pQ_1 and $(1-p)Q_1$ are considered separately. The user delay costs include queue delay and moving delay cost.

Total user delay cost per maintained lane kilometer for $(1-p)Q_1$, C_u^{1-p}, is:

$$C_u^{1-p} = C_q^{1-p} + C_v^{1-p} \tag{41}$$

The user queue delay cost of the remaining flow in direction 1, *(1-p)Q₁*, denoted as C_q^{1-p} , is the queue delay t_q^{1-p} for *(1-p)Q₁* multiplied by the average delay cost v_d and divided by *L*. t_q^{1-p} has the same formulation as equation (26) but with *(1-p)Q₁* substituted for Q_1:

$$\begin{aligned} t_q^{1-p} &= 0 && when\ (1-p)Q_1 \le c_w \\ t_q^{1-p} &= \frac{1}{2}\left(1+\frac{(1-p)Q_1-c_w}{c_0-(1-p)Q_1}\right)((1-p)Q-c_w)(z_3+z_4L)^2 && when\ (1-p)Q_1 > c_w \end{aligned} \tag{42}$$

C_q^{1-p} has the same formulation as equation (27) but with *(1-p)Q₁* substituted for Q_1:

$$\begin{aligned} C_q^{1-p} &= 0 && when\ (1-p)Q_1 \le c_w \\ C_q^{1-p} &= \frac{v_d}{2L}\left(1+\frac{(1-p)Q_1-c_w}{c_0-(1-p)Q_1}\right)((1-p)Q_1-c_w)(z_3+z_4L)^2 && when\ (1-p)Q_1 > c_w \end{aligned} \tag{43}$$

The moving delay cost per maintained kilometer C_v^{1-p} for *(1-p)Q₁* is the moving delay t_m^{1-p} for *(1-p)Q₁* multiplied by the average delay cost v_d and divided by *L*. t_m^{1-p} has the same formulation as equation (29) but with *(1-p)Q₁* substituted for Q_1:

$$\begin{aligned} t_m^{1-p} &= \left(\frac{L}{V_w}-\frac{L}{V_a}\right)(1-p)Q_1D && when\ (1-p)Q_1 \le c_w \\ t_m^{1-p} &= \left(\frac{L}{V_w}-\frac{L}{V_a}\right)c_wD && when\ (1-p)Q_1 > c_w \end{aligned} \tag{44}$$

Then, C_v^{1-p} has the same formulation as equation (30) but with *(1-p)Q₁* substituted for Q_1:

$$\begin{aligned} C_v^{1-p} &= \left(\frac{1}{V_w}-\frac{1}{V_a}\right)(1-p)Q_1(z_3+z_4L)v_d && when\ (1-p)Q_1 \le c_w \\ C_v^{1-p} &= \left(\frac{1}{V_w}-\frac{1}{V_a}\right)c_w(z_3+z_4L)v_d && when\ (1-p)Q_1 > c_w \end{aligned} \tag{45}$$

The user delay cost per maintained lane kilometer for the detoured flow in direction 1, pQ_1, denoted as C_u^p, is equal to:

$$C_u^p = C_q^p + C_v^p \tag{46}$$

where C_q^p represents the queue delay for pQ_1 and C_v^p represents the moving delay for pQ_1. We assume the detour capacity c_d is always greater than pQ_1, so the queue delay of pQ_1 is equal to zero.

The user moving delay cost of the diverted flow pQ_1 from direction 1, C_v^p, is equal to the flow pQ_1 multiplied by: (1) the average maintenance duration per kilometer, $\frac{z_3}{L} + z_4$, which is the maintenance duration per zone, z_3+z_4L, divided by work zone L, (2) the time difference between the time vehicles through the detour, $\frac{L_{d1} + L_{d3}}{V_a} + \frac{L_{d2}}{V_d^{*2}}$, and the time vehicles through the original road AB without work zone, $\frac{L_t}{V_a}$, and (3) the value of time, v_d. Thus:

$$C_v^p = pQ_1(\frac{z_3}{L} + z_4)[\frac{L_{d1} + L_{d3}}{V_a} + \frac{L_{d2}}{V_d^{*2}} - \frac{L_t}{V_a}]v_d \tag{47}$$

Therefore, the user delay cost for pQ_1 is equal to:

$$C_u^p = C_q^p + C_v^p = C_v^p = pQ_1(\frac{z_3}{L} + z_4)[\frac{L_{d1} + L_{d3}}{V_a} + \frac{L_{d2}}{V_d^{*2}} - \frac{L_t}{V_a}]v_d \tag{48}$$

where V_d^{*2} is the detour speed affected by pQ_1 in direction 3 in Alternative 4.2

In addition to user delay cost, the accident cost is also considered. The average accident cost per maintained kilometer for $(1-p)Q_1$, C_a^{1-p}, is

$$C_a^{1-p} = \frac{(t_q^{1-p} + t_m^{1-p})}{L}\frac{n_a v_a}{10^8} \tag{49}$$

Then,

$$C_a^{1-p} = (\frac{1}{V_w} - \frac{1}{V_a})(1-p)Q_1(z_3 + z_4 L)\frac{n_a v_a}{10^8} \qquad when\ (1\text{-}p)Q_1 \le c_w$$

$$C_a^{1-p} = [\frac{1}{2L}(1 + \frac{(1-p)Q_1 - c_w}{c_0 - (1-p)Q_1})((1-p)Q_1 - c_w)(z_3 + z_4 L)^2 \qquad (50)$$

$$+(\frac{1}{V_w} - \frac{1}{V_a})c_w(z_3 + z_4 L)]\frac{n_a v_a}{10^8} \qquad when\ (1\text{-}p)Q_1 > c_w$$

The average accident cost per maintained kilometer for pQ_1, C_a^p, is

$$C_a^p = \frac{(t_q^p + t_m^p)}{L}\frac{n_a v_a}{10^8} \qquad (51)$$

where

$$t_m^p = \frac{C_v^p L}{v_d} = (\frac{L_{d1} + L_{d3}}{V_a} + \frac{L_{d2}}{V_d^{*2}} - \frac{L_t}{V_a})pQ_1(z_3 + z_4 L) \qquad when\ pQ_1 \le c_d \qquad (52)$$

and t_q^p =0. Then

$$C_a^p = (\frac{L_{d1} + L_{d3}}{V_a} + \frac{L_{d2}}{V_d^{*2}} - \frac{L_t}{V_a})pQ_1(\frac{z_3}{L} + z_4)\frac{n_a v_a}{10^8} \qquad when\ pQ_1 \le c_d \qquad (53)$$

Another delay cost C_{U3} of the original flow Q_3 in direction 3, as affected by the detoured flow Q_1, is also considered. It has the same formulation as equation (8).

$$C_{U3} = Q_3(\frac{z_3}{L} + z_4)(\frac{L_{d2}}{V_d^{*2}} - \frac{L_{d2}}{V_{d0}})v_d \qquad (8)$$

where V_d^{*2} is the detour speed affected by pQ_1 in direction 3 in Alternative 4.2.

The total cost is:

$$C_T = C_M + C_u + C_a = C_M + (C_u^{1\text{-}p} + C_u^p) + (C_a^{1-p} + C_a^p) \qquad (54)$$

Then

$$
\begin{aligned}
C_T = & (\frac{z_1}{L} + z_2) \\
& + (\frac{1}{V_w} - \frac{1}{V_a})(1-p)Q_1(z_3 + z_4 L)v_d + pQ_1(\frac{z_3}{L} + z_4)[\frac{L_{d1} + L_{d3}}{V_a} + \frac{L_{d2}}{V_d^{*2}} - \frac{L_t}{V_a}]v_d \\
& + (\frac{1}{V_w} - \frac{1}{V_a})(1-p)Q_1(z_3 + z_4 L)\frac{n_a v_a}{10^8} \\
& + (\frac{L_{d1} + L_{d3}}{V_a} + \frac{L_{d2}}{V_d^{*2}} - \frac{L_t}{V_a})pQ_1(\frac{z_3}{L} + z_4)\frac{n_a v_a}{10^8} \\
& + Q_3(\frac{z_3}{L} + z_4)(\frac{L_{d2}}{V_d^{*2}} - \frac{L_{d2}}{V_{d0}})v_d \qquad \text{when } (1-p)Q_1 \le c_w \\
C_T = & (\frac{z_1}{L} + z_2) + \frac{v_d}{2L}(1 + \frac{(1-p)Q_1 - c_w}{c_0 - (1-p)Q_1})((1-p)Q_1 - c_w)(z_3 + z_4 L)^2 \\
& + (\frac{1}{V_w} - \frac{1}{V_a})c_w(z_3 + z_4 L)v_d + pQ_1(\frac{z_3}{L} + z_4)[\frac{L_{d1} + L_{d3}}{V_a} + \frac{L_{d2}}{V_d^{*2}} - \frac{L_t}{V_a}]v_d \\
& + [\frac{1}{2L}(1 + \frac{(1-p)Q_1 - c_w}{c_0 - (1-p)Q_1})((1-p)Q_1 - c_w)(z_3 + z_4 L)^2 + (\frac{1}{V_w} - \frac{1}{V_a})c_w(z_3 + z_4 L)]\frac{n_a v_a}{10^8} \\
& + (\frac{L_{d1} + L_{d3}}{V_a} + \frac{L_{d2}}{V_d^{*2}} - \frac{L_t}{V_a})pQ_1(\frac{z_3}{L} + z_4)\frac{n_a v_a}{10^8} \qquad (55) \\
& + Q_3(\frac{z_3}{L} + z_4)(\frac{L_{d2}}{V_d^{*2}} - \frac{L_{d2}}{V_{d0}})v_d \qquad \text{when } (1-p)Q_1 > c_w
\end{aligned}
$$

The optimal work zone length is:

$$
L^{*42} = \sqrt{\frac{z_1 + pQ_1 z_3(\frac{L_{d1} + L_{d3}}{V_a} + \frac{L_{d2}}{V^{*2}} - \frac{L_t}{V_a})(v_d + \frac{n_a v_a}{10^8}) + Q_3 z_3(\frac{L_{d2}}{V_d^{*2}} - \frac{L_{d2}}{V_{d0}})v_d}{(\frac{1}{V_w} - \frac{1}{V_a})(1-p)Q_1 z_4(v_d + \frac{n_a v_a}{10^8})}} \qquad (56)
$$

$$\text{when } (1-p)Q_1 \le c_w$$

$$
L^{*42} = \sqrt{\frac{z_1 + [(1 + \frac{(1-p)Q_1 - c_w}{c_0 - (1-p)Q_1})((1-p)Q_1 - c_w)\frac{z_3^2}{2} + pQ_1 z_3(\frac{L_{d1} + L_{d3}}{V_a} + \frac{L_{d2}}{V^{*2}} - \frac{L_t}{V_a})](v_d + \frac{n_a v_a}{10^8}) + Q_3 z_3(\frac{L_{d2}}{V_d^{*2}} - \frac{L_{d2}}{V_{d0}})v_d}{(\frac{1}{V_w} - \frac{1}{V_a})c_w z_4(v_d + \frac{n_a v_a}{10^8}) + (1 + \frac{(1-p)Q_1 - c_w}{c_0 - (1-p)Q_1})((1-p)Q_1 - c_w)\frac{z_4^2}{2}(v_d + \frac{n_a v_a}{10^8})}}
$$

$$\text{when } (1-p)Q_1 > c_w$$

Alternative 4.3: All Q_1 Traffic through Detour, Allowing Work Zone on Both Lanes in Direction 1

Here it is assumed that the entire flow Q_1 in Alternative 4.2 is diverted to the alternate route. Then the total cost in direction 1 has the same formulation as equation (55) but with Q_1 substituted for pQ_1 and p is replaced by 1 and no matter how Q_1 is

greater than c_w or not because Q_1 would not pass through work zone in this case. The total cost for Alternative 3 is:

$$\begin{aligned} C_T = & (\frac{z_1}{L} + z_2) \\ & + Q_1(\frac{z_3}{L} + z_4)[\frac{L_{d1} + L_{d3}}{V_a} + \frac{L_{d2}}{V_d^{*2}} - \frac{L_t}{V_a}]v_d \\ & + Q_1(\frac{L_{d1} + L_{d3}}{V_a} + \frac{L_{d2}}{V_d^{*2}} - \frac{L_t}{V_a})(\frac{z_3}{L} + z_4)\frac{n_a v_a}{10^8} \\ & + Q_3(\frac{z_3}{L} + z_4)(\frac{L_{d2}}{V_d^{*3}} - \frac{L_{d2}}{V_{d0}})v_d \end{aligned} \tag{57}$$

where V_d^{*3} is the detour speed affected by Q_1 in direction 3 in Alternative 4.3.

The first and second partial derivatives of C_T are then found to be:

$$\begin{aligned} \frac{\partial C_T}{\partial L} = & -[\frac{z_1}{L^2} + \frac{Q_1 z_3}{L^2}(\frac{L_{d1} + L_{d3}}{V_a} + \frac{L_{d2}}{V_d^{*2}} - \frac{L_t}{V_a})v_d + \frac{Q_1 z_3}{L^2}(\frac{L_{d1} + L_{d3}}{V_a} + \frac{L_{d2}}{V_d^{*2}} - \frac{L_t}{V_a})\frac{n_a v_a}{10^8} \\ & + \frac{Q_3 z_3}{L^2}(\frac{L_{d2}}{V_d^{*3}} - \frac{L_{d2}}{V_{d0}})v_d\,] < 0 \end{aligned} \tag{58}$$

$$\begin{aligned} \frac{\partial^2 C_T}{\partial L^2} = & \frac{2z_1}{L^3} + 2\frac{Q_1 z_3}{L^3}(\frac{L_{d1} + L_{d3}}{V_a} + \frac{L_{d2}}{V_d^{*2}} - \frac{L_t}{V_a})v_d + 2\frac{Q_1 z_3}{L^3}(\frac{L_{d1} + L_{d3}}{V_0} + \frac{L_{d2}}{V_d^{*4}} - \frac{L_t}{V_0})\frac{n_a v_a}{10^8} \\ & + 2\frac{Q_3 z_3}{L^3}(\frac{L_{d2}}{V_d^{*3}} - \frac{L_{d2}}{V_{d0}})v_d > 0 \end{aligned} \tag{59}$$

The first partial derivative of C_T is less than zero and the second partial derivative is greater than zero. Therefore the function C_T is convex and the slope of the curve is decreasing, and its unique global minimum is reached at L_t.

Alternative 4.4: Crossover of All Q_1 Traffic into One Lane in Opposite Direction, Allowing Work Zone on Both Lanes in Direction 1

Here it is assumed that the entire flow Q_1 in Alternative 4.1 is crossover to one lane in opposite direction, direction 2 in this case. Both lanes in direction 1 are closed for

work zone. The flow Q_2 in direction 2 only uses the remaining lane. In this alternative, assume (1) the vehicles in Q_1 go through alternate lane in direction 2 by the speed as going through work zone, V_w, as well as the vehicles of Q_2 go through the remaining lane by the same speed, V_w, (2) the capacity of each lane in direction 2 between the start and end of work zone for Q_1 and Q_2 is equal to work zone capacity, c_w, (3) the distance between the start and end of work zone in direction 1 is equal to the distance of crossover route through alternate lane in direction 2.

In Alternative 4.4, the queue delay and moving delay may occur in Q_1 and Q_2. Below are all possible combinations for user delays.

$$\begin{aligned} C_{q1} &= 0 && \text{when } Q_1 \le c_w \\ C_{q1} &= \frac{v_d}{2L}(1+\frac{Q_1-c_w}{c_0-Q_1})(Q_1-c_w)(z_3+z_4L)^2 && \text{when } Q_1 > c_w \end{aligned} \tag{60}$$

$$\begin{aligned} C_{q2} &= 0 && \text{when } Q_2 \le c_w \\ C_{q2} &= \frac{v_d}{2L}(1+\frac{Q_2-c_w}{c_0-Q_2})(Q_2-c_w)(z_3+z_4L)^2 && \text{when } Q_2 > c_w \end{aligned} \tag{61}$$

$$\begin{aligned} C_{v1} &= (\frac{1}{V_w}-\frac{1}{V_a})Q_1(z_3+z_4L)v_d && \text{when } Q_1 \le c_w \\ C_{v1} &= (\frac{1}{V_w}-\frac{1}{V_a})c_w(z_3+z_4L)v_d && \text{when } Q_1 > c_w \end{aligned} \tag{62}$$

$$\begin{aligned} C_{v2} &= (\frac{1}{V_w}-\frac{1}{V_a})Q_2(z_3+z_4L)v_d && \text{when } Q_2 \le c_w \\ C_{v2} &= (\frac{1}{V_w}-\frac{1}{V_a})c_w(z_3+z_4L)v_d && \text{when } Q_2 > c_w \end{aligned} \tag{63}$$

$$\begin{aligned} C_{a1} &= (\frac{1}{V_w}-\frac{1}{V_a})Q_1(z_3+z_4L)\frac{n_a v_a}{10^8} && \text{when } Q_1 \le c_w \\ C_{a1} &= [\frac{1}{2L}(1+\frac{Q_1-c_w}{c_0-Q_1})(Q_1-c_w)(z_3+z_4L)^2 \\ &\quad +(\frac{1}{V_w}-\frac{1}{V_a})c_w(z_3+z_4L)]\frac{n_a v_a}{10^8} && \text{when } Q_1 > c_w \end{aligned} \tag{64}$$

$$C_{a2} = (\frac{1}{V_w} - \frac{1}{V_a}) Q_2 (z_3 + z_4 L) \frac{n_a v_a}{10^8} \qquad when\ Q_2 \le c_w$$

$$C_{a2} = [\frac{1}{2L}(1 + \frac{Q_2 - c_w}{c_0 - Q_2})(Q_2 - c_w)(z_3 + z_4 L)^2 + (\frac{1}{V_w} - \frac{1}{V_a}) c_w (z_3 + z_4 L)] \frac{n_a v_a}{10^8} \qquad when\ Q_2 > c_w \tag{65}$$

The total cost is:

$$\begin{aligned} C_T &= C_M + C_u + C_a \\ &= C_M + (C_{q1} + C_{v1}) + (C_{q2} + C_{v2}) + (C_{a1} + C_{a2}) \end{aligned} \tag{66}$$

Q_1 has two conditions: greater than c_w or less than or equal to c_w and Q_2 also has the two same conditions; therefore, there are four combinations for total cost formulation:

(1) $Q_1 \le c_w \quad Q_2 \le c_w$

$$\begin{aligned} C_T = &(\frac{z_1}{L} + z_2) + [0 + (\frac{1}{V_w} - \frac{1}{V_a}) Q_1 (z_3 + z_4 L) v_d] \\ &+ [0 + (\frac{1}{V_w} - \frac{1}{V_a}) Q_2 (z_3 + z_4 L) v_d] + (\frac{1}{V_w} - \frac{1}{V_a}) Q_1 (z_3 + z_4 L) \frac{n_a v_a}{10^8} \\ &+ (\frac{1}{V_w} - \frac{1}{V_a}) Q_2 (z_3 + z_4 L) \frac{n_a v_a}{10^8} \end{aligned} \tag{67}$$

$$L^{*44} = \sqrt{\frac{z_1}{z_4 (Q_1 + Q_2)(v_d + \frac{n_a v_a}{10^8})(\frac{1}{V_w} - \frac{1}{V_a})}} \tag{68}$$

(2) $Q_1 > c_w \quad Q_2 \le c_w$

$$\begin{aligned} C_T = &(\frac{z_1}{L} + z_2) + [\frac{v_d}{2L}(1 + \frac{Q_1 - c_w}{c_0 - Q_1})(Q_1 - c_w)(z_3 + z_4 L)^2 + (\frac{1}{V_w} - \frac{1}{V_a}) c_w (z_3 + z_4 L) v_d] \\ &+ [0 + (\frac{1}{V_w} - \frac{1}{V_a}) Q_2 (z_3 + z_4 L) v_d] \\ &+ [\frac{1}{2L}(1 + \frac{Q_1 - c_w}{c_0 - Q_1})(Q_1 - c_w)(z_3 + z_4 L)^2 + (\frac{1}{V_w} - \frac{1}{V_a}) c_w (z_3 + z_4 L)] \frac{n_a v_a}{10^8} \\ &+ (\frac{1}{V_w} - \frac{1}{V_a}) Q_2 (z_3 + z_4 L) \frac{n_a v_a}{10^8} \end{aligned} \tag{69}$$

$$L^{*44} = \sqrt{\frac{z_1 + \frac{z_3^2}{2}(1+\frac{Q_1 - c_w}{c_0 - Q_1})(Q_1 - c_w)(v_d + \frac{n_a v_a}{10^8})}{z_4(c_w + Q_2)(v_d + \frac{n_a v_a}{10^8})(\frac{1}{V_w} - \frac{1}{V_a}) + \frac{z_4^2}{2}(1+\frac{Q_1 - c_w}{c_0 - Q_1})(Q_1 - c_w)(v_d + \frac{n_a v_a}{10^8})}} \quad (70)$$

$(3)\, Q_1 \le c_w \quad Q_2 > c_w$

$$\begin{aligned} C_T = & (\frac{z_1}{L} + z_2) \\ & + [0 + (\frac{1}{V_w} - \frac{1}{V_a})Q_1(z_3 + z_4 L)v_d] \\ & + [\frac{v_d}{2L}(1+\frac{Q_2 - c_w}{c_0 - Q_2})(Q_2 - c_w)(z_3 + z_4 L)^2 + (\frac{1}{V_w} - \frac{1}{V_a})c_w(z_3 + z_4 L)v_d] \\ & + (\frac{1}{V_w} - \frac{1}{V_a})Q_1(z_3 + z_4 L)\frac{n_a v_a}{10^8} \\ & + [\frac{1}{2L}(1+\frac{Q_2 - c_w}{c_0 - Q_2})(Q_2 - c_w)(z_3 + z_4 L)^2 + (\frac{1}{V_w} - \frac{1}{V_a})c_w(z_3 + z_4 L)]\frac{n_a v_a}{10^8} \end{aligned} \quad (71)$$

$$L^{*44} = \sqrt{\frac{z_1 + \frac{z_3^2}{2}(1+\frac{Q_2 - c_w}{c_0 - Q_2})(Q_2 - c_w)(v_d + \frac{n_a v_a}{10^8})}{z_4(c_w + Q_1)(v_d + \frac{n_a v_a}{10^8})(\frac{1}{V_w} - \frac{1}{V_a}) + \frac{z_4^2}{2}(1+\frac{Q_2 - c_w}{c_0 - Q_2})(Q_2 - c_w)(v_d + \frac{n_a v_a}{10^8})}} \quad (72)$$

$(4) Q_1 > c_w \quad Q_2 > c_w$

$$\begin{aligned} C_T = & (\frac{z_1}{L} + z_2) + [\frac{v_d}{2L}(1+\frac{Q_1 - c_w}{c_0 - Q_1})(Q_1 - c_w)(z_3 + z_4 L)^2 + (\frac{1}{V_w} - \frac{1}{V_a})c_w(z_3 + z_4 L)v_d] \\ & + [\frac{v_d}{2L}(1+\frac{Q_2 - c_w}{c_0 - Q_2})(Q_2 - c_w)(z_3 + z_4 L)^2 + (\frac{1}{V_w} - \frac{1}{V_a})c_w(z_3 + z_4 L)v_d] \\ & + [\frac{1}{2L}(1+\frac{Q_1 - c_w}{c_0 - Q_1})(Q_1 - c_w)(z_3 + z_4 L)^2 + (\frac{1}{V_w} - \frac{1}{V_a})c_w(z_3 + z_4 L)]\frac{n_a v_a}{10^8} \\ & + [\frac{1}{2L}(1+\frac{Q_2 - c_w}{c_0 - Q_2})(Q_2 - c_w)(z_3 + z_4 L)^2 + (\frac{1}{V_w} - \frac{1}{V_a})c_w(z_3 + z_4 L)]\frac{n_a v_a}{10^8} \end{aligned} \quad (73)$$

$$L^{*44} = \sqrt{\frac{z_1 + \frac{z_3^2}{2}(v_d + \frac{n_a v_a}{10^8})[(1+\frac{Q_1 - c_w}{c_0 - Q_1})(Q_1 - c_w) + (1+\frac{Q_2 - c_w}{c_0 - Q_2})(Q_2 - c_w)]}{2z_4 c_w(v_d + \frac{n_a v_a}{10^8})(\frac{1}{V_w} - \frac{1}{V_a}) + \frac{z_4^2}{2}(v_d + \frac{n_a v_a}{10^8})[(1+\frac{Q_1 - c_w}{c_0 - Q_1})(Q_1 - c_w) + (1+\frac{Q_2 - c_w}{c_0 - Q_2})(Q_2 - c_w)]}} \quad (74)$$

3. Determination of Work Zone and Detour Speeds

In traffic flow theory, the relation among flow *Q*, density *K*, and speed *V* is:

$$Q = KV \tag{75}$$

The detour speeds depend on the diverted flows. The speed function can be formulated by applying Greenshield's model (Gerlough and Huber, 1975):

$$V = V_f - \frac{V_f}{K_j} K \tag{76}$$

where V_f is free flow speed, K_j is jam density.

Substituting (76) into (75), we obtain

$$Q = K_j V - \frac{K_j}{V_f} V^2 \tag{77}$$

Solving Eq. (77) for the speed V, we obtain:

$$V = \frac{K_j V_f + \sqrt{(K_j V_f)^2 - 4K_j V_f Q}}{2K_j} \tag{78}$$

Then, V_0, V_{d0}, V_d^{*2} and V_d^{*3} in Alternatives 2.2 and 2.3 or 4.2 and 4.3 can be determined from Eq. (78). The other solution of Eq.(77), $V = \frac{K_j V_f - \sqrt{(K_j V_f)^2 - 4K_j V_f Q}}{2K_j}$, which is congestion speed (Gerlough and Huber, 1975), is not applied because V_0, V_{d0}, V_d^{*2} and V_d^{*3} are applied based on the assumption that the original road without work zone and detour has enough capacity so that the speeds on the original road (V_0) and detour (V_{d0}, V_d^{*2} and V_d^{*3}) are free-flowing speeds.

Chapter 4 Threshold and Sensitivity Analysis

4.1 Threshold Analysis

This chapter discusses the selection of the best alternatives under different situations. Guidelines for selecting the best alternative for different traffic flows, roads and maintenance characteristics are developed by deriving thresholds among those alternatives.

1. Thresholds among Alternatives

C_T^{*1}, C_T^{*2}, C_T^{*3} and C_T^{*4} are the minimized total costs of Alternatives 2.1, 2.2, 2.3 and 2.4, (or Alternatives 4.1, 4.2, 4.3 and 4.4) computed with their respective optimal work zone lengths L^{*1}, L^{*2} L^{*3} and L^{*4}. The threshold between any two alternatives can be obtained by setting their two cost functions equal. For example, Figure 3 shows the relation between total cost and detour length. It indicates that Alternative 2.3 is preferable up to a detour length of T_{32}^{DL}, beyond which Alternative 2.2 is preferable up to T_{21}^{DL}.

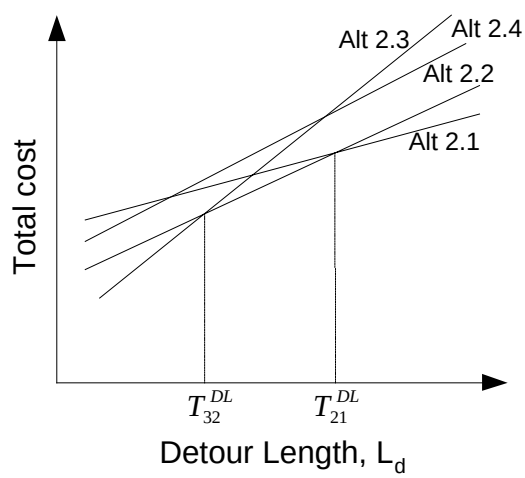


Figure 3 Total Cost vs. Detour Length

Thresholds with respect to the distance AB, setup cost z_1, average maintenance time z_4, and other input parameters, can be obtained similarly to the detour length thresholds. For some variables or alternatives, if the thresholds are not positive or not located within applicable ranges, then no threshold exists.

2. Derivation of Threshold

For example, the threshold with respect to detour length between Alternatives 2.2 and 2.3 is derived as follows:

Let $C_T^{*2} = C_T^{*3}$

Thus

$$\begin{aligned}
C_T^{*2} &= (\frac{z_1}{L^{*2}} + z_2) + \frac{(z_3 + z_4 L^{*2})[(1-p)Q_1(\frac{3600}{H} - (1-p)Q_1) + Q_2(\frac{3600}{H} - Q_2)]v}{V(\frac{3600}{H} - (1-p)Q_1 - Q_2)} \\
&\quad + pQ_1(\frac{z_3}{L^{*2}} + z_4)[\frac{L_{d1} + L_{d3}}{V_0} + \frac{L_{d2}}{V_d^{*2}} - \frac{L_t}{V_0}]v \\
&\quad + Q_3(\frac{z_3}{L^{*2}} + z_4)(\frac{L_{d2}}{V_d^{*2}} - \frac{L_{d2}}{V_{d0}})v \\
&= (\frac{z_1}{L^{*3}} + z_2) + Q_1(\frac{z_3}{L^{*3}} + z_4)[\frac{L_{d1} + L_{d3}}{V_0} + \frac{L_{d2}}{V_d^{*3}} - \frac{L_t}{V_0}]v + Q_2(\frac{z_3}{L^{*3}} + z_4)(\frac{L^{*3}}{V} - \frac{L^{*3}}{V_0})v \\
&\quad + Q_3(\frac{z_3}{L^{*3}} + z_4)(\frac{L_{d2}}{V_d^{*3}} - \frac{L_{d2}}{V_{d0}})v \\
&= C_T^{*3}
\end{aligned} \tag{79}$$

Then, the threshold with respect to detour length between Alternatives 2.2 and 2.3, T_{32}^{DL}, or L_d in Eq.(79), is:

$$T_{32}^{DL} =$$

$$L_d = \frac{1}{Q_1 z_3(\frac{p}{V_d^{*2}L^{*2}} - \frac{1}{V_D^{*3}L^{*3}}) + Q_1 z_4(\frac{p}{V_d^{*2}} - \frac{1}{V_d^{*3}}) + Q_3[\frac{z_3}{L^{*2}}(\frac{1}{V_d^{*2}} - \frac{1}{V_{d0}}) - \frac{z_3}{L^{*3}}(\frac{1}{V_d^{*3}} - \frac{1}{V_{d0}}) + z_4(\frac{1}{V_d^{*2}} - \frac{1}{V_d^{*3}})]} \{$$

$$\frac{1}{v}(\frac{z_1}{L^{*3}} - \frac{z_1}{L^{*2}}) + Q_1(\frac{z_3}{L^{*3}} + z_4)(\frac{L_{d1} + L_{d3} - L_t}{V_0} - \frac{L_{d1} + L_{d3}}{V_d^{*3}}) - pQ_1(\frac{z_3}{L^{*2}} + z_4)(\frac{L_{d1} + L_{d3} - L_t}{V_0} - \frac{L_{d1} + L_{d3}}{V_d^{*2}})$$

$$+ Q_2(\frac{z_3}{L^{*3}} + z_4)(\frac{L^{*3}}{V} - \frac{L^{*3}}{V_0}) - \frac{(z_3 + z_4 L^{*2})[(1-p)Q_1(\frac{3600}{H} - (1-p)Q_1) + Q_2(\frac{3600}{H} - Q_2)]}{V(\frac{3600}{H} - (1-p)Q_1 - Q_2)} +$$

$$Q_3(L_{d1} + L_{d3})[\frac{z_3}{L^{*2}}(\frac{1}{V_d^{*2}} - \frac{1}{V_{d0}}) - \frac{z_3}{L^{*3}}(\frac{1}{V_d^{*3}} - \frac{1}{V_{d0}}) + z_4(\frac{1}{V_d^{*2}} - \frac{1}{V_d^{*3}})]\} \quad (80)$$

where

$$L^{*2} = \sqrt{\frac{V(\frac{3600}{H} - (1-P)Q_1 - Q_2)[\frac{z_1}{v} + pQ_1 z_3(\frac{L_{d1} + L_{d3} - L_t}{V_0} + \frac{L_{d2}}{V_d^{*2}}) + Q_3 z_3(\frac{L_{d2}}{V_d^{*2}} - \frac{L_{d2}}{V_{d0}})]}{z_4[(1-p)Q_1(\frac{3600}{H} - (1-p)Q_1) + Q_2(\frac{3600}{H} - Q_2)]}} \quad (81)$$

$$L^{*3} = \sqrt{\frac{\frac{z_1}{v} + Q_1 z_3(\frac{L_{d1} + L_{d3} - L_t}{V_0} + \frac{L_{d2}}{V_d^{*3}}) + Q_3 z_3(\frac{L_{d2}}{V_d^{*3}} - \frac{L_{d2}}{V_{d0}})}{Q_2 z_4(\frac{1}{V} - \frac{1}{V_0})}} \quad (82)$$

and $L_{d2} = L_d - (L_{d1} + L_{d3})$ (83)

Variable L_d, which should be equal to T_{32}^{DL}, appears on both sides of Eq.(83). This equation can easily be solved numerically.

4.2 Sensitivity Analysis

(1) Two-Lane Two-Way Highway Work Zone

The effects of various parameters on two-lane two-way highway work zone length and the preferable alternatives are examined in this section. The baseline numerical values for each variable in this section are defined in Table 1.

Table 1 Inputs for Numerical Example and Sensitivity Analysis for Two-Lane Two-Way Highway Work Zones

Variable	Description	Values
H	Average headway through work zone area	3 s
K_j	Jam density along AB and detour	200 veh/lane·km
L_{d1}	Length of first detour segment	0.5 km
L_{d2}	Length of second detour segment	5 km
L_{d3}	Length of third detour segment	0.5 km
L_t	Distance from A to B	5 km
Q_3	Hourly flow rate in direction 3	500 veh/hr
V	Average work zone speed	50 km/hr
V_f	Free flow speed along AB and detour	80 km/hr
V	Value of user time	12 $/veh·hr
z_1	Fixed setup cost	1,000 $/zone
z_2	Average maintenance cost per lane·kilometer	80,000 $/lane·km
z_3	Fixed setup time	2 hr/zone
z_4	Average maintenance time per lane·kilometer	6 hr/lane·km

The optimized solutions for work zone length and total cost are shown in Table 2 for various traffic flow combinations. For Alternatives 2.1 and 2.2, when Q_1 or Q_2 increases, the optimal zone length decreases. However, for Alternative 2.3, the optimal zone length increases slightly with Q_1 and decreases with Q_2, because increasing zone length decreases the delay cost of Q_1 in Eq.(11). The optimal zone length ranges from 1.78 to 0.52 km for Alternative 2.1, 2.54 to 0.34 km for Alternative 2, and 4.41 to 1.75 km for Alternative 2.3. Table 2 shows that the optimal zone length increases with the diverted fraction from Q_1 to the detour. At the baseline values, Alternative 2.3 dominates

all others in Table 2, as its optimized total cost is the lowest for any flow combination Q_1 and Q_2.

Table 2 Optimal Work Zone Lengths for Two-Lane Two-Way Highway Work Zones and Total Costs for Different Flow Rates

$\Sigma(Q_1+Q_2)$	Q_1	Q_2	Alt. 2.1		Alt.2.2 (p=0.3)		Alt.2.2 (p=0.6)		Alt.2.2 (p=0.9)		Alt.2.3	
			Optimal length	Min. total cost	Optimal length	Min. total cost	Optimal length	Min. total cost	Optimal length	Min. total cost	Optimal length	Min. total cost
200	100	100	1.78	81231	1.96	81159	2.20	81076	2.54	80981	4.41	80612
400	200	200	1.18	81937	1.32	81811	1.52	81675	1.81	81518	3.20	80959
600	200	400	0.90	82650	1.00	82457	1.13	82271	1.30	82083	2.26	81274
800	200	600	0.70	83512	0.80	83154	0.92	82845	1.06	82561	1.85	81524
1000	200	800	0.52	85118	0.63	84195	0.75	83539	0.91	83020	1.60	81741
1200	200	1000	-	-	0.35	88710	0.55	85120	0.77	83589	1.43	81936
600	400	200	0.90	82650	1.07	82401	1.32	82157	1.76	81876	3.36	81234
800	400	400	0.66	83804	1.29	83259	1.00	82844	1.29	82467	2.38	81556
1000	400	600	0.45	86057	0.61	84476	0.80	83611	1.05	82989	1.94	81811
1200	400	800	-	-	0.39	87835	0.61	84838	0.89	83533	1.68	82032
1400	400	1000	-	-	-	-	0.29	92290	0.72	84381	1.50	82230
800	600	200	0.70	83512	0.90	83005	1.18	82633	1.73	82242	3.53	81520
1000	600	400	0.45	86057	0.66	84258	0.90	83446	1.27	82862	2.50	81848
1200	600	600	-	-	0.44	86884	0.70	84504	1.04	83433	2.04	82108
1400	600	800	-	-	-	-	0.48	86841	0.86	84074	1.77	82332
1600	600	1000	-	-	-	-	-	-	0.67	85286	1.58	82534
1000	800	200	0.52	85118	0.77	83692	1.08	83113	1.70	82618	3.72	81818
1200	800	400	-	-	0.52	85828	0.81	84103	1.26	83270	2.63	82152
1400	800	600	-	-	0.21	99491	0.60	85633	1.03	83895	2.15	82416
1600	800	800	-	-	-	-	0.33	91359	0.84	84647	1.86	82644
1800	800	1000	-	-	-	-	-	-	0.61	86350	1.66	82849
1200	1000	200	-	-	0.65	84616	1.00	83607	1.68	83006	3.91	82131
1400	1000	400	-	-	0.34	90067	0.73	84850	1.25	83693	2.76	82470
1600	1000	600	-	-	-	-	0.50	87258	1.01	84375	2.26	82738
1800	1000	800	-	-	-	-	-	-	0.82	85257	1.95	82969
2000	1000	1000	-	-	-	-	-	-	0.56	87653	1.75	83176

To examine sensitivities to other factors, we fix the traffic flow rates Q_1 and Q_2 at 400 vehicles per hour (vph) each. Figure 4 shows increases in user cost as the zone length increases in Alternatives 2.1 and 2.2. However, the user cost of Alternative 2.3 is always much lower than in the others because alternating one-way traffic flows and their associated queues are avoided.

Table 3 compares the delay costs for different directional flows that add up to 1400 vph. For Alternative 2.2 (p=0.6), although the combined flow is the same, the combinations with larger Q_2 have shorter optimal zone lengths and higher total costs. This occurs because the delay cost on the main road, C_{1-p} , which is the main part of the total delay costs, increases as Q_2 increases.

In Figure 5, as the zone length increases, the maintenance costs per kilometer decreases due to fewer setups but stays the same for all alternatives. Combined with the user cost in Figure 4, the zone lengths that minimize total costs are determined by trade-offs between the user and maintenance cost. The optimal zone lengths for Alternatives 2.1, 2.2, and 2.3 are 0.66 km, 1.29 km, and 2.38 km, respectively. Faster increases in the user cost of Alternative 2.1 shorten its optimal zone length.

Figures 6, 7 and 8 show the relations between the optimal zone length and other key factors. Figure 6 shows that the optimal zone length increases when the setup cost z_1 increases, because longer zones imply fewer setups and decreased total cost. In this case, the optimal zone length of Alternative 2.3 is quite sensitive to setup cost.

Table 3 Comparison of the Delay Costs for Different Directional Flows in Alternative 2.2 (p=o.6)

$\Sigma(Q_1+Q_2)$	$Q1$	$Q2$	Optimal Length	C_T	C_M	C_U			
						Σ	C_{1-p}	C_p	C_{U3}
1400	400	1000	0.29	**92290**	**83469**	**8821**	**8199**	**536**	**86**
				100%	90.44%	9.56%	8.88%	0.58%	0.09%
							Flow $(1-p)Q_1+Q_2$ = 1160	Flow pQ_1=240	Flow Q_3=500
1400	1000	400	0.73	**84850**	**81366**	**3484**	**2455**	**875**	**153**
				100%	95.89%	4.11%	2.89%	1.03%	0.18%
							Flow $(1-p)Q_1+Q_2$ = 800	Flow pQ_1=600	Flow Q_3=500

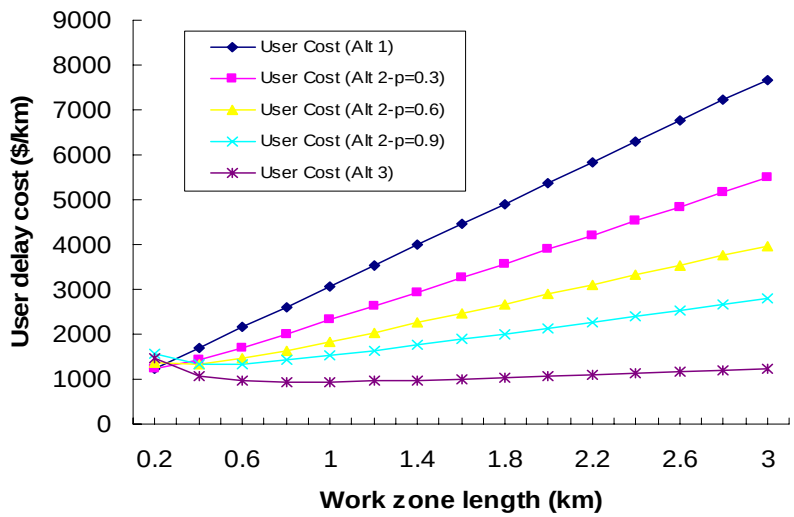


Figure 4 User Costs versus Various Zone Lengths (Q_1=400vph, Q_2=400vph)

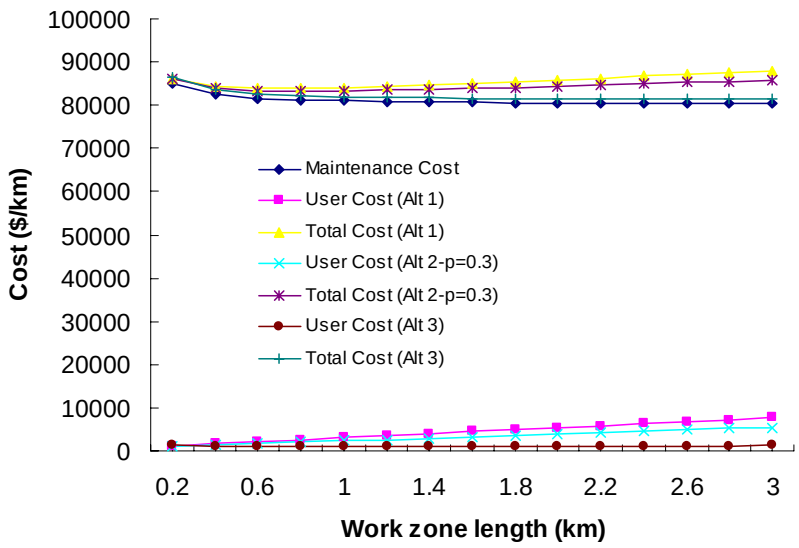


Figure 5 User, Maintenance, and Total Costs versus Various Work Zone Lengths (Q_1=400vph, Q_2=400vph)

Figure 7 shows that the optimal zone length decreases when the average maintenance time z_4 increases, in order to avoid excessive increases in user delay. In particular, Figure 7 shows that Alternative 2.3 is quite sensitive to average maintenance time. Figure 7 shows that the optimal zone length for Alternative 2.1 is not influenced at all by setup duration z_3 and other alternatives are only slightly affected by setup duration. Setup duration has similar effects to setup cost. Thus, longer work zones imply fewer

setup cycles and decreased total cost. On the other hand, increasing setup duration increases user delay; hence, the zone length should decrease. The total effects of increasing setup duration on zone length become quite small, as shown in Figure 8. Table 4 compares the effects of changes of setup cost and setup duration on optimal zone length and minimal total cost. When setup cost increases by 50%, the higher setup cost increases the optimal zone length from 0.15 to 0.46 km. However, a 50% increase in setup duration increases the optimal zone length by at most 0.08 km. Table 4 shows that the zone length is more sensitive to setup cost than to setup duration.

Figure 9 shows that at lower *p* values the optimal work zone length is more sensitive to headway. Alternative 2.1, which has lowest p value (zero), is the most sensitive to headway. Because increasing headway decreases the maximum discharge rate in a work zone and thus increases user delay, it decreases the optimal zone length of Alternatives 2.1 and 2.2 with one-way traffic control. In Alternative 2.3, without any traffic control, the headway through the zone has no effect on the optimal zone length. In Figure 10, as zone speed increases, the optimal zone length increases very slightly for Alternatives 2.1 and 2.2 but increases very quickly for Alternative 2.3. This occurs because higher speed reduces delay cost, thus allowing longer zones. Moreover, without any traffic control or queues in Alternative 2.3, the optimal zone length is quite sensitive to speed through the zone.

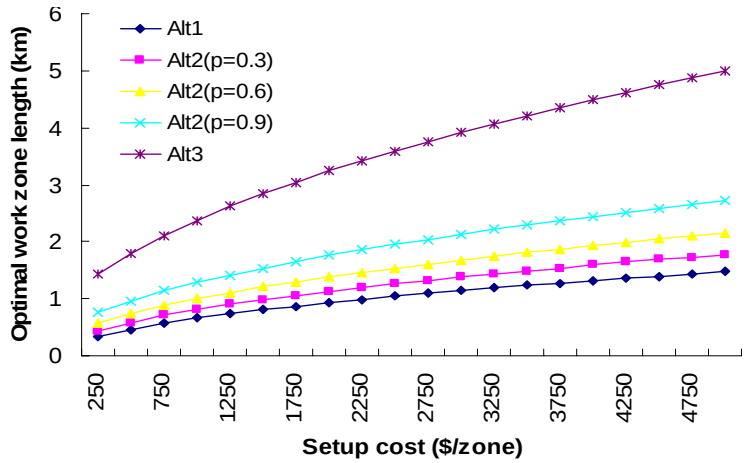


Figure 6 Optimal Zone Length versus Setup Cost z_1 (Q_1=400vph, Q_2=400vph)

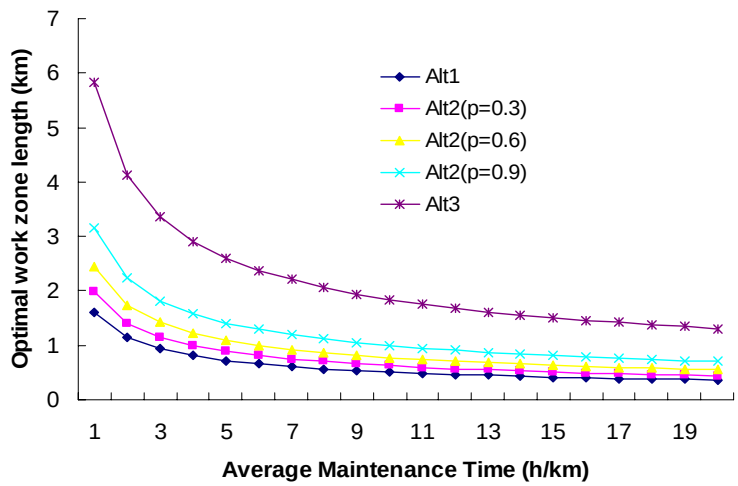


Figure 7 Optimal Zone Length versus Average Maintenance Time z_4 (Q_1=400vph, Q_2=400vph)

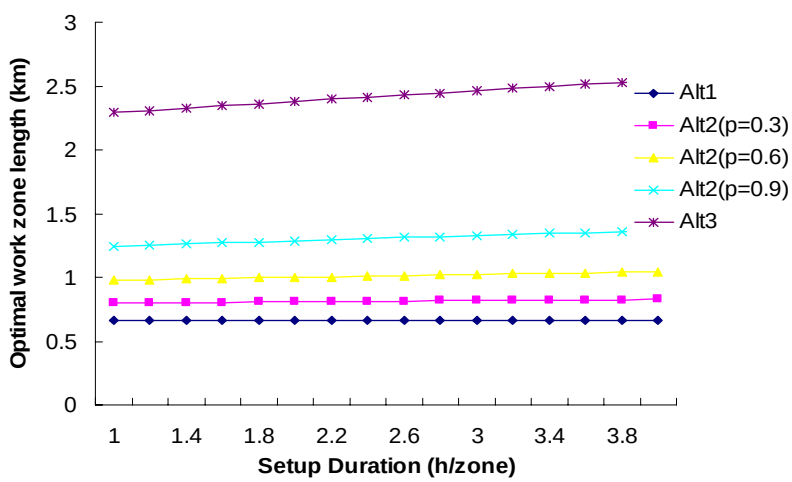


Figure 8 Optimal Zone Length versus Setup Duration z_3 (Q_1=400vph, Q_2=400vph)

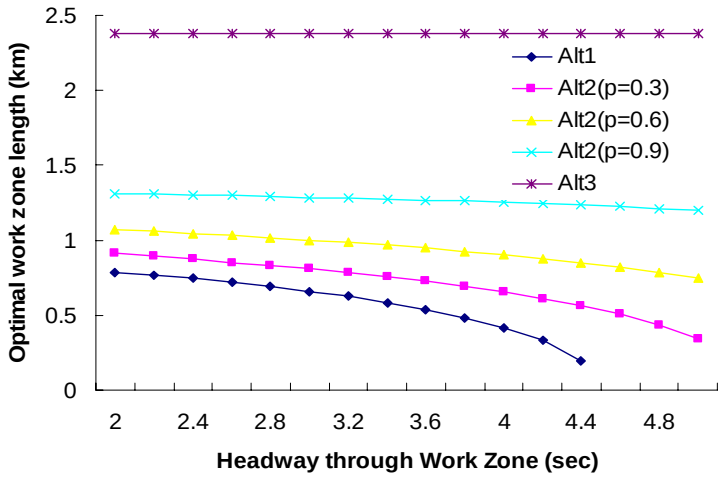


Figure 9 Optimal Zone Length versus Headway *H* (Q_1=400vph, Q_2=400vph)

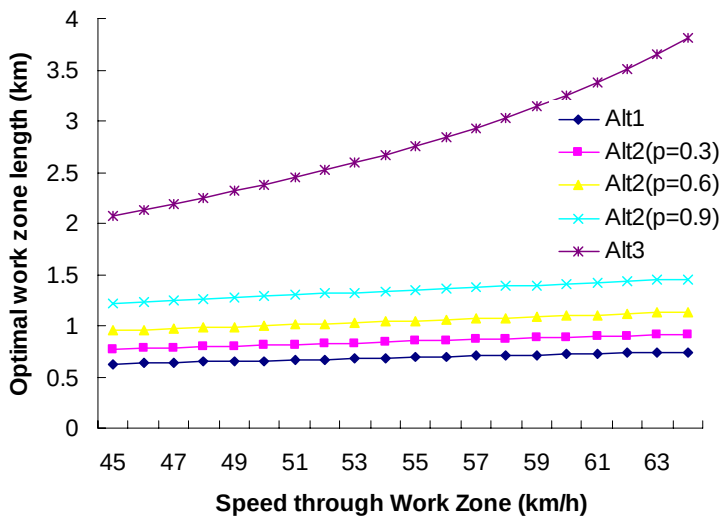


Figure 10 Optimal Zone Length versus Zone Speed *V* (Q_1=400vph, Q_2=400vph)

Table 4 Effects of Setup Cost and Setup Duration on Optimal Zone Length and Total Cost

Alternatives		Alt. 2.1		Alt. 2.2 (p=0.3)		Alt. 2.2 (p=0.6)		Alt.2.2 (p=0.9)		Alt. 2.3	
		Optimal length (km)	Min total cost ($/km)	Optimal length (km)	Min total cost ($/km)	Optimal length (km)	Min total cost ($/km)	Optimal length (km)	Min total cost ($/km)	Optimal length (km)	Min total cost ($/km)
Setup cost ($/zone)	1000	0.66	83804	0.81	83259	1.00	82844	1.29	82467	2.38	81556
	1500	0.81	84486	0.98	83817	1.21	83296	1.54	82820	2.84	81747
change	50%	0.15	0.81%	0.17	0.67%	0.21	0.55%	0.25	0.43%	0.46	0.23%
Setup duration (h/zone)	2	0.66	83804	0.81	83259	1.00	82844	1.29	82467	2.38	81556
	3	0.66	84188	0.82	83555	1.02	83074	1.33	82640	2.46	81625
Change	50%	0.00	0.46%	0.01	0.35%	0.02	0.28%	0.04	0.21%	0.08	0.08%

Figure 11 shows that the capacity of one lane through a work zone increases as the diverted fraction increases. Here the capacity for Alternative 2.1 is 1200 vph. As the diverted fraction increases, the combined flow discharge increases. The combined capacity is about 1450 vph for Alternative 2.2 (p=0.3) and about 1700 vph for Alternative 2.2 (p=0.6). The capacity of the one lane through the zone in Alternative 2.1 can be also obtained by dividing one hour (3600 seconds) by the headway (3 seconds) through the zone. Starting from Alternative 2.1 as the baseline, the additional capacity in Alternatives 2.2 and 2.3 is contributed by the detour. Higher diverted fractions increase the capacity through the zone.

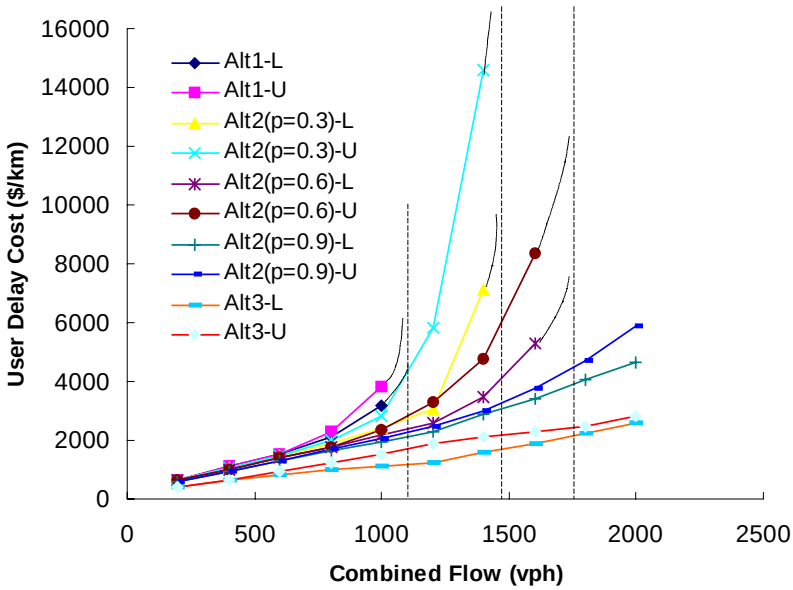


Figure 11 User Delay Costs versus Combined Flows

(2) Four-Lane Two-Way Highway Work Zone

The effects of various parameters on four-lane two-way highway work zone length and the preferable alternatives are examined in this section. The baseline numerical values for each variable in this section are defined in Table 5.

Table 5 Inputs for Numerical Example and Sensitivity Analysis for Four-Lane Two-Way Highway Work Zones

Variable	Description	Values
c_o	Maximum discharge rate without work zone	2,600vph
c_w	Maximum discharge rate with work zone	1,200vph
H	Average headway through work zone area	3 s
K_j	Jam density along AB and detour	200 veh/lane·km
L_{d1}	Length of first detour segment	0.5 km
L_{d2}	Length of second detour segment	5 km
L_{d3}	Length of third detour segment	0.5 km
L_t	Distance from A to B	5 km
n_a	Number of accidents per 100 million vehicle hour	40 acc/100mvh
Q_2	Hourly flow rate in direction 2	500 veh/hr
Q_3	Hourly flow rate in direction 3	500 veh/hr
V_w	Average work zone speed	50 km/hr
V_f	Free flow speed along AB and detour	80 km/hr
v_a	Average accident cost	142,000 $/acc
v_d	Value of user time	12 $/veh·hr
α	Reduction factor for two-lane maintenance	2.0
z_1	Fixed setup cost	1,000 $/zone
z_2	Average maintenance cost per lane·kilometer	80,000 $/lane·km
z_3	Fixed setup time	2 hr/zone
z_4	Average maintenance time per lane·kilometer	6 hr/lane·km

The optimized solutions for work zone length and total cost are shown in Table 6 for various Q_1 traffic flow. For Alternatives 4.1, 4.2 and 4.4, as Q_1 increases, the optimal zone length decreases. However, if optimal zone length exceeds the distance between the start and end of detour, L_t, the zone length would be set as L_t. Optimal zone length is

always equal to L_t for Alternative 4.3 when two lanes are closed for work. The optimal zone length ranges from 4.33 to 0.33 km for Alternatives 4.1 and 4.2, and 1.76 to 0.33 km for Alternative 4.4.

Table 6 Optimal Work Zone Lengths for Four-Lane Two-way Highway Work Zones and Total Costs for Different Flow Rates

Q_1	Alt. 4.1		Alt.4.2 (p=0.3)		Alt.4.2 (p=0.6)		Alt.4.2 (p=0.9)		Alt.4.3		Alt.4.4	
	Optimal length	Min. total cost	Optimal length	Min. total cost	Optimal length	Min. total cost	Optimal length	Min. total cost	Optimal length	Min. total cost	Optimal length	Min. total cost
100	4.30	80483	5.00	80433	5.00	80378	5.00	80323	5.00	80304	1.76	81247
200	3.07	80687	3.71	80648	4.97	80582	5.00	80493	5.00	80465	1.64	81343
300	2.52	80846	3.06	80818	4.13	80758	5.00	80642	5.00	80601	1.54	81436
400	2.20	80980	2.68	80968	3.63	80921	5.00	80791	5.00	80741	1.46	81522
500	1.98	81098	2.43	81103	3.31	81073	5.00	80942	5.00	80883	1.40	81602
600	1.82	81203	2.24	81227	3.07	81218	5.00	81094	5.00	81029	1.34	81677
700	1.69	81299	2.10	81343	2.89	81357	5.00	81247	5.00	81179	1.29	81747
800	1.59	81386	1.99	81451	2.75	81491	5.00	81402	5.00	81333	1.25	81813
900	1.51	81467	1.90	81552	2.64	81620	5.00	81559	5.00	81490	1.21	81874
1000	1.45	81541	1.82	81647	2.54	81746	5.00	81717	5.00	81652	1.18	81932
1100	1.39	81610	1.76	81736	2.47	81867	5.00	81876	5.00	81819	1.15	81985
1200	1.34	81674	1.70	81819	2.40	81984	5.00	82038	5.00	81991	1.13	82035
1300	0.39	114198	1.65	81896	2.35	82097	5.00	82201	5.00	82169	0.39	114476
1400	0.36	150510	1.61	81967	2.30	82206	5.00	82367	5.00	82352	0.36	150921
1500	0.35	193334	1.58	82033	2.27	82311	4.97	82534	5.00	82543	0.35	193914
1600	0.34	244690	1.55	82092	2.23	82411	4.94	82704	5.00	82740	0.34	245483
1700	0.34	307441	1.52	82145	2.21	82506	4.92	82877	5.00	82946	0.34	308501
1800	0.34	385866	0.44	101978	2.19	82597	4.91	83052	5.00	83161	0.34	387270
1900	0.34	486686	0.38	125530	2.17	82681	4.91	83231	5.00	83385	0.34	488541
2000	0.34	621103	0.36	151665	2.16	82760	4.92	83413	5.00	83621	0.34	623570
2100	0.34	809276	0.36	180984	2.15	82832	4.94	83598	5.00	83869	0.34	812611
2200	0.34	1091527	0.35	214147	2.14	82896	4.98	83788	5.00	84132	0.34	1096177
2300	0.33	1561935	0.35	251981	2.14	82953	5.00	83981	5.00	84411	0.33	1568791
2400	0.33	2502739	0.34	295559	2.15	82999	5.00	84180	5.00	84710	0.33	2514032
2500	0.33	5325141	0.34	346303	2.15	83036	5.00	84385	5.00	85031	0.33	5349777
2600	-	-	0.34	406147	2.17	83060	5.00	84596	5.00	85380	-	-

As in Figure 4, the zone lengths that minimize total costs are determined by trade-offs between the user and maintenance cost. The total cost vs. various work zone lengths for four-lane two-way highway work zones is shown in Figure 12 at the baseline condition. The optimal zone lengths for Alternatives 4.1, 4.2(0.3), 4.2(0.6), 4.2(0.9), 4.3

and 4.4 are 1.98 km, 2.43 km, 3.31 km, 5.00 km, 5.00 km and 1.40 km, respectively. Alternative 4.3 has the lowest cost and is thus preferred.

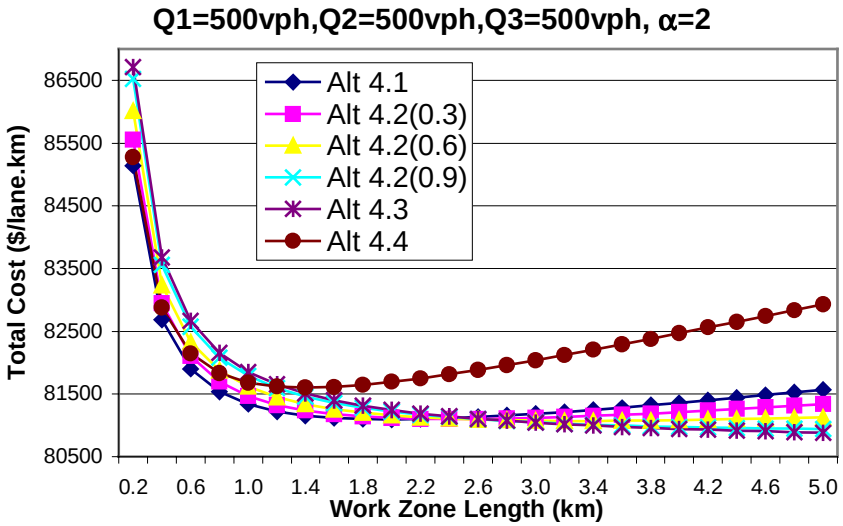


Figure 12 Total Costs versus Various Work Zone Lengths (Q_1=500vph, Q_2=500vph, Q_3=500vph, α=2)

Figure 13 shows that as Q_1 increase to 1000 vph, Alternative 4.1 reaches the lowest total cost and is the best alternative when other baseline values are unchanged. The optimal zone lengths for Alternatives 4.1, 4.2(0.3), 4.2(0.6), 4.2(0.9), 4.3 and 4.4 are 1.45 km, 1.82 km, 2.54 km, 5.00 km, 5.00 km and 1.18 km, respectively.

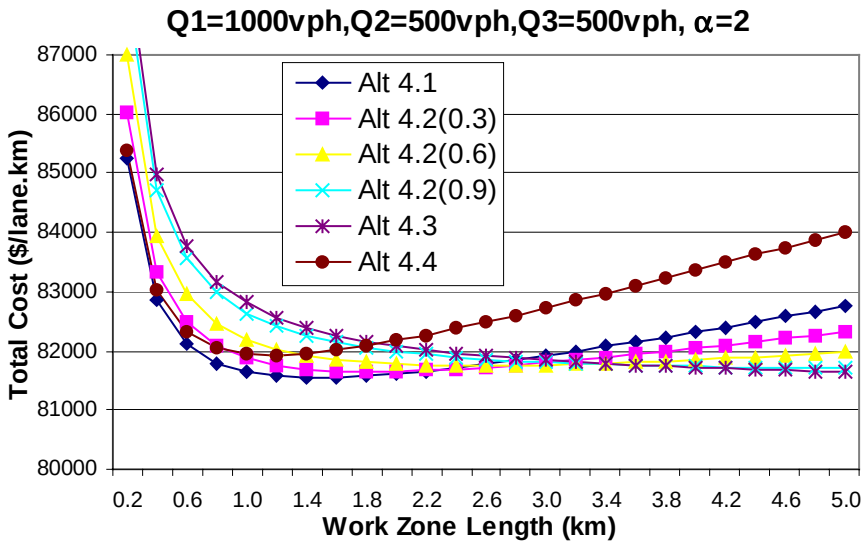


Figure 13 Total Costs versus Various Work Zone Lengths (Q_1=1000vph, Q_2=500vph, Q_3=500vph, α=2)

4.3 Selection Guidelines

(1) Two-Lane Two-Way Highway Work Zone

Thresholds among alternatives with respect to four variables, namely, detour length (L_d), length of main road between the beginning and end of detour (L_t), setup cost (z_1), and average maintenance time per kilometer (z_4), are solved numerically and presented below.

Figure 14 shows the relation between total cost and detour length when Q_1 and Q_2 are each 200 vph. The detour length threshold is 10.56 km, beyond which Alternative 2.1 (whose length L_t is 5 km, in Table 1) becomes preferable to Alternative 2.3.

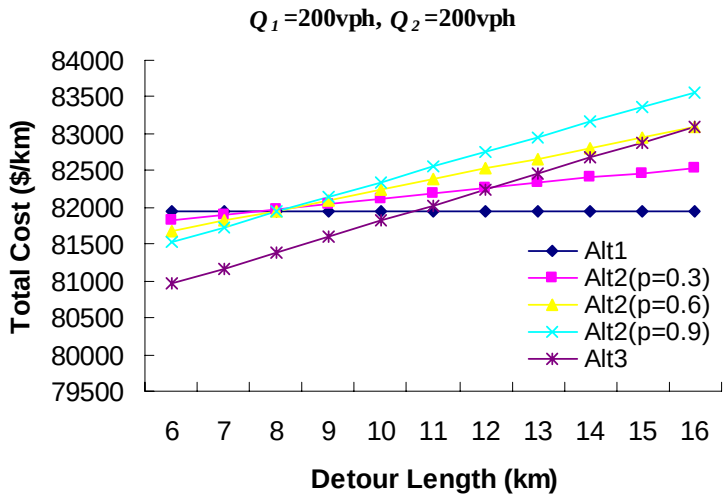


Figure 14 Total Cost versus Detour Length for Various Alternatives (Q_1=200vph, Q_2=200vph)

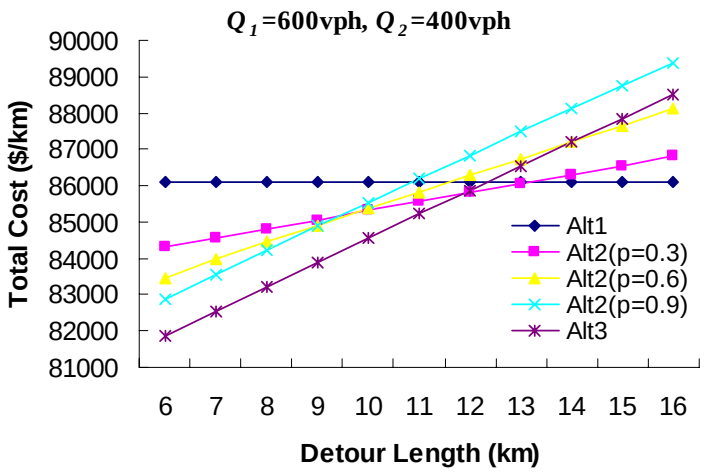


Figure 15 Total Cost versus Detour Length for Various Alternatives (Q_1=600vph, Q_2=400vph)

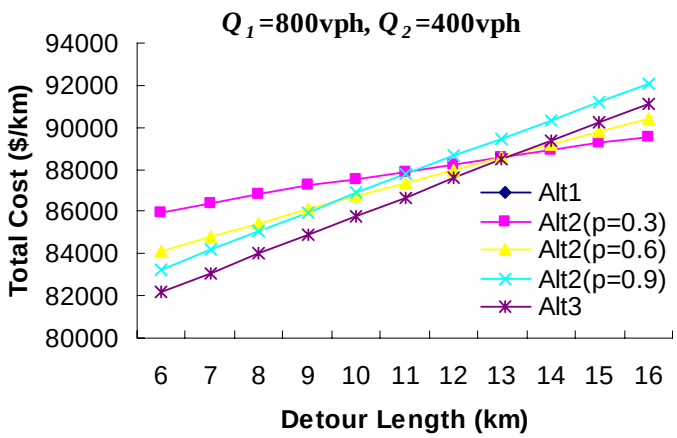


Figure 16 Total Cost versus Detour Length for Various Alternatives (Q_1=800vph, Q_2=400vph)

Figure 15 shows that there are two detour length thresholds and Alternatives 2.1, 2.2 and 2.3 are all on the lowest cost envelope. Figure 16 shows the relation between total cost and detour length when Q_1 and Q_2 are each 800 and 400 vph. The detour length threshold is 12.94 km, beyond which Alternative 2.2 becomes preferable to Alternative 2.3.

Defining circuity as the ratio of detour distance to maintained road distance = L_d / L_t, the circuity thresholds are shown for various flows in Table 7. The shadowed cells in Table 7 represent the preferred pair of alternatives that determine the threshold. If combined flow does not exceed 1000 vph, Alternatives 2.1 and 2.3 determine the lowest cost and Alternative 2.2 never becomes competitive, as illustrated in Figure 14.

If Q_1 is not below 600 vph and the combined flow is not below 1000 vph, there are two detour length thresholds and Alternatives 2.1, 2.2 and 2.3 all appear on the lowest cost envelope, e.g. in Figure 12. If combined flow exceeds 1000 vph, Alternatives 2.2 (p=0.3) and 2.3 become preferred, e.g. in Figure 16. Table 7 also shows that the circuity threshold increases as Q_2 increases. However, Q_1 has no obvious effect on the circuity threshold when Q_1 increases.

The thresholds with respect to setup cost, z_1, and average maintenance time per kilometer, z_4 in different flow rates can be obtained similarly to circuity ratio thresholds.

Table 7 Circuity Threshold at Different Flow Rates for Two-Lane Two-Way Highway Work Zones

$\Sigma(Q_1+Q_2)$	Q_1	Q_2	Circuity threshold		
			Alt1 & Alt3	Alt3 & Alt2(p=o.3)	Alt1& Alt2(p=o.3)
200	100	100	2.39	2.76	1.63
400	200	200	2.11	2.40	1.55
600	200	400	2.44	2.84	1.70
800	200	600	2.95	3.45	2.07
1000	200	800	4.14	4.65	3.31
1200	200	1000	-	12.37	-
600	400	200	1.85	2.03	1.53
800	400	400	2.21	2.40	1.87
1000	400	600	3.08	3.12	3.01
1200	400	800	-	5.85	-
1400	400	1000	-	-	-
800	600	200	1.81	1.91	1.63
1000	600	400	2.45	2.36	2.60
1200	600	600	-	3.68	-
1400	600	800	-	-	-
1600	600	1000	-	-	-
1000	800	200	1.95	1.88	2.07
1200	800	400	-	2.59	-
1400	800	600	-	9.86	-
1600	800	800	-	-	-
1800	800	1000	-	-	-
1200	1000	200	-	1.93	-
1400	1000	400	-	3.75	-
1600	1000	600	-	-	-
1800	1000	800	-	-	-
2000	1000	1000	-	-	-

(2) Four-Lane Two-Way Highway Work Zone

Using the total cost data from Table 6, the minimum total cost for each alternative at various flows is shown in Table 7. The shadowed cells in Table 7 represent the preferred alternative for the given flows. If Q_1 does not exceed 900 vph, Alternative 4.3 determines the lowest total cost. In this range of Q1, Alternative 4.3 has higher delay and lower maintenance cost than Alternative 4.1 because Alternative 4.1 has shorter zones.

Overall, the lower maintenance cost and higher delay effect for Alternative 4.3 still result in Alternative 4.3 being preferred.

If Q_1 is between 900 vph and 1200 vph, the delay cost of Alternative 4.3 increases much than the maintenance cost of Alternative 4.1 increases, so that Alternative 4.1 has lowest total cost. If Q_1 is between 1300 vph and 1700 vph, Alternative 4.2(0.3) is preferred. If Q_1 exceeds 1800 vph, Alternative 4.2(0.6) is preferred. It is also shown in Figure 17. This is because high Q_1 requires to detour some fraction of Q_1 to alternate route to decrease the queue delay by using the capacity of alternate route. Otherwise, large queue delay forms when Q_1 increases to approach the capacity of the road.

Table 8 Total Cost at Different Flow Rates for Four-Lane Two-Way Highway Work Zones (Q_2=500vph, Q_3=500vph, α=2)

Q1	Alt 4.1	Alt 4.2 (0.3)	Alt 4.2 (0.6)	Alt 4.2 (0.9)	Alt 4.3	Alt 4.4
100	80483	80433	80378	80323	80304	81247
200	80687	80648	80582	80493	80465	81343
300	80846	80818	80758	80642	80601	81436
400	80980	80968	80921	80791	80741	81522
500	81098	81103	81073	80942	80883	81602
600	81203	81227	81218	81094	81029	81677
700	81299	81343	81357	81247	81179	81747
800	81386	81451	81491	81402	81333	81813
900	81467	81552	81620	81559	81490	81874
1000	81541	81647	81746	81717	81652	81932
1100	81610	81736	81867	81876	81819	81985
1200	81674	81819	81984	82038	81991	82035
1300	114198	81896	82097	82201	82169	114476
1400	150510	81967	82206	82367	82352	150921
1500	193334	82033	82311	82534	82543	193914
1600	244690	82092	82411	82704	82740	245483
1700	307441	82145	82506	82877	82946	308501
1800	385866	101978	82597	83052	83161	387270
1900	486686	125530	82681	83231	83385	488541
2000	621103	151665	82760	83413	83621	623570
2100	809276	180984	82832	83598	83869	812611
2200	1091527	214147	82896	83788	84132	1096177
2300	1561935	251981	82953	83981	84411	1568791
2400	2502739	295559	82999	84180	84710	2514032
2500	5325141	346303	83036	84385	85031	5349777
2600	-	406147	83060	84596	85380	-

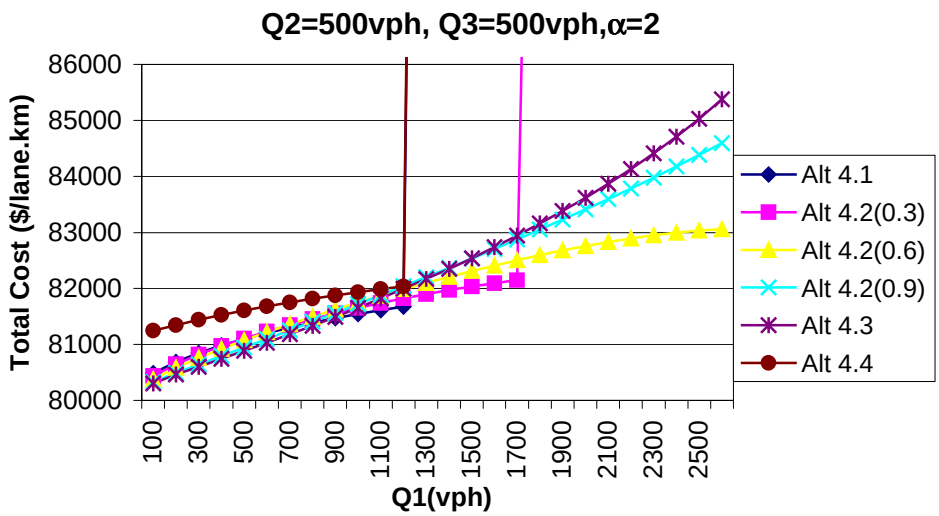


Figure 17 Total Cost versus Detour Length for Various Alternatives (Q_2=500vph, Q_3=500vph, α=2)

As the original flow on the detour traffic, Q_3, increases, the preferred range for Alternative 4.3 decreases, shown in Table 9 and Figure 18. If Q_1 does not exceed 400 vph, Alternatives 4.3 determines the lowest total cost. If Q_1 is between 500 vph and 1200 vph, Alternative 4.1 has lowest total cost. This is because Alternative 4.3 is most suitable when the sum of Q_1+Q_3 is relatively low. At a higher Q_3, the detoured flow from direction 1 will have higher delay than if it passes through the work zone along direction 1.

Table 9 Total Cost at Different Flow Rates for Four-Lane Two-Way Highway Work Zones (Q_2=500vph, Q_3=1000vph, α=2)

Q1	Alt 4.1	Alt 4.2(0.3)	Alt 4.2(0.6)	Alt 4.2(0.9)	Alt 4.3	Alt 4.4
100	80483	80436	80383	80330	80312	81247
200	80687	80674	80632	80571	80551	81343
300	80846	80858	80837	80760	80734	81436
400	80980	81021	81028	80953	80922	81522
500	81098	81171	81210	81149	81117	81602
600	81203	81311	81386	81349	81317	81677
700	81299	81442	81557	81552	81525	81747
800	81386	81566	81725	81760	81739	81813
900	81467	81683	81889	81972	81962	81874
1000	81541	81794	82050	82189	82194	81932
1100	81610	81900	82209	82411	82435	81985
1200	81674	82000	82365	82638	82687	82035
1300	114198	82095	82518	82872	82951	114476
1400	150510	82184	82669	83113	83227	150921
1500	193334	82268	82817	83362	83518	193914
1600	244690	82346	82962	83618	83826	245483
1700	307441	82417	83104	83885	84153	308501
1800	385866	102399	83243	84161	84501	387270
1900	486686	126005	83378	84450	84874	488541
2000	621103	152181	83510	84753	85276	623570
2100	809276	181537	83636	85071	85712	812611
2200	1091527	214736	83758	85407	86191	1096177
2300	1561935	252606	83874	85766	86722	1568791
2400	2502739	296219	83984	86149	87317	2514032
2500	5325141	346999	84086	86565	87999	5349777
2600		406879	84179	87019	88797	

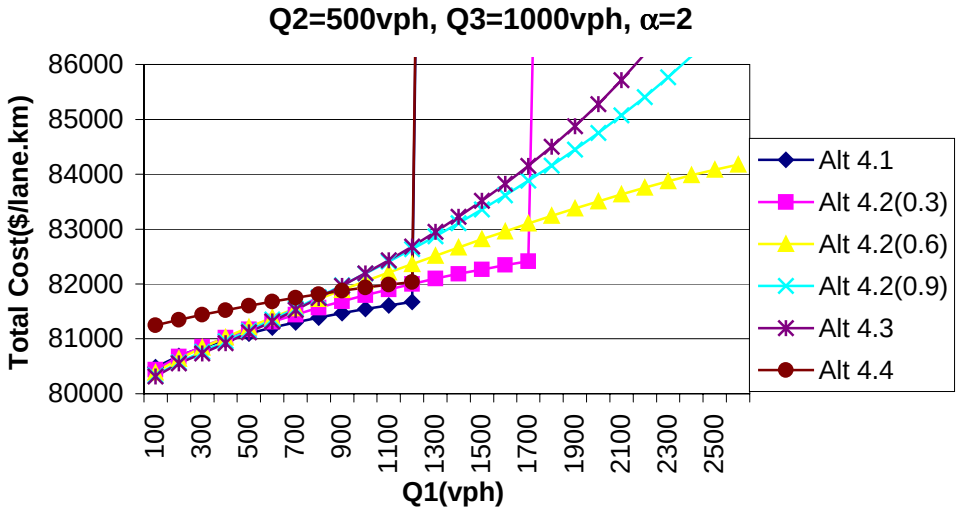


Figure 18 Total Cost versus Detour Length for Various Alternatives (Q_2=500vph, Q_3=1000vph, α=2)

If a cost reduction factor for two-lane maintenance is considered, the total cost for Alternatives 4.3 and 4.4 will be different from the costs in Tables 8 and 9. Tables 10 and 11 show the minimum total cost for Q_3=500 vph and 1000 vph using α=1.8. The shadowed cells indicate that only Alternatives 4.3 and 4.4 are preferred. When Q_3=500 vph, Alternative 4.3 is preferred for each Q_1 flow except Q_1 is between 1100 vph and 1200 vph. When Q_3=1000 vph, Alternative 4.3 is preferred for all Q_1 values except between 900 and 1200 vph. This is because when Q_1 does not exceed the work zone capacity, Alternative 4.3 has a lower delay from using the detour than the delay of Alternative 4.4, in which traffic crosses over to the opposite direction at low Q_1 volumes. If Q_1 is above 900 vph but still below the hourly work zone capacity 1200 vph, higher $Q_{1+}Q_3$ in direction 3 increases the delay more in Alternative 4.3 than in 4.4; therefore, Alternative 4.4 is preferred. However, if the Q_1 flow exceeds work zone capacity 1200 vph, the queue delay will increase sharply, especially in Alternative 4.4, which has one lane for each of two directions. Alternative 4.3 would then be preferred.

Table 10 Total Cost at Different Flow Rates for Four-Lane Two-Way Highway Work Zones (Q_2=500vph, Q_3=500vph, α=1.8)

Q1	Alt 4.1	Alt 4.2 (0.3)	Alt 4.2 (0.6)	Alt 4.2 (0.9)	Alt 4.3	Alt 4.4
100	80483	80433	80378	80323	72284	73190
200	80687	80648	80582	80493	72445	73282
300	80846	80818	80758	80642	72581	73371
400	80980	80968	80921	80791	72721	73454
500	81098	81103	81073	80942	72863	73531
600	81203	81227	81218	81094	73009	73603
700	81299	81343	81357	81247	73159	73670
800	81386	81451	81491	81402	73313	73733
900	81467	81552	81620	81559	73470	73792
1000	81541	81647	81746	81717	73632	73847
1100	81610	81736	81867	81876	73799	73898
1200	81674	81819	81984	82038	73971	73946
1300	114198	81896	82097	82201	74149	106217
1400	150510	81967	82206	82367	74332	142642
1500	193334	82033	82311	82534	74523	185628
1600	244690	82092	82411	82704	74720	237193
1700	307441	82145	82506	82877	74926	300208
1800	385866	101978	82597	83052	75141	378975
1900	486686	125530	82681	83231	75365	480245
2000	621103	151665	82760	83413	75601	615273
2100	809276	180984	82832	83598	75849	804313
2200	1091527	214147	82896	83788	76112	1087878
2300	1561935	251981	82953	83981	76391	1560493
2400	2502739	295559	82999	84180	76690	2505732
2500	5325141	346303	83036	84385	77011	5341478
2600		406147	83060	84596	77360	

Table 11 Total Cost at Different Flow Rates for Four-Lane Two-Way Highway Work Zones (Q_2=500vph, Q_3=1000vph, α=1.8)

Q1	Alt 4.1	Alt 4.2(0.3)	Alt 4.2(0.6)	Alt 4.2(0.9)	Alt 4.3	Alt 4.4
100	80483	80436	80383	80330	72292	73190
200	80687	80674	80632	80571	72531	73282
300	80846	80858	80837	80760	72714	73371
400	80980	81021	81028	80953	72902	73454
500	81098	81171	81210	81149	73097	73531
600	81203	81311	81386	81349	73297	73603
700	81299	81442	81557	81552	73505	73670
800	81386	81566	81725	81760	73719	73733
900	81467	81683	81889	81972	73942	73792
1000	81541	81794	82050	82189	74174	73847
1100	81610	81900	82209	82411	74415	73898
1200	81674	82000	82365	82638	74667	73946
1300	114198	82095	82518	82872	74931	106217
1400	150510	82184	82669	83113	75207	142642
1500	193334	82268	82817	83362	75498	185628
1600	244690	82346	82962	83618	75806	237193
1700	307441	82417	83104	83885	76133	300208
1800	385866	102399	83243	84161	76481	378975
1900	486686	126005	83378	84450	76854	480245
2000	621103	152181	83510	84753	77256	615273
2100	809276	181537	83636	85071	77692	804313
2200	1091527	214736	83758	85407	78171	1087878
2300	1561935	252606	83874	85766	78702	1560493
2400	2502739	296219	83984	86149	79297	2505732
2500	5325141	346999	84086	86565	79979	5341478
2600		406879	84179	87019	80777	

Chapter 5 Research Findings and Future Work

5.1 Research Findings

This study develops the work zone cost models for three possible alternative zone configurations with and without an alternate route. It determines the optimal zone length and preferred alternative for various combinations of variables. For a two-lane two-way highway work zone, when the traffic flows in two directions are steady, Alternative 2.1 has a higher user cost and shorter work zone length than other alternatives while Alternative 2.3 has a lower user cost and longer work zone length. When Q_1 or Q_2 increase, the optimal work zone length decreases for Alternatives 2.1 and 2.2. However, for Alternative 2.3, the optimal work zone length increases slightly as Q_1 increases, and decreases as Q_2 increases.

In the threshold analysis presented, Alternative 2.3 is the preferred alternative in the baseline condition. When detour length, L_d, the distance of the main road from the beginning to end of detour, L_t, setup cost, z_1, or the average maintenance time, z_4, increase beyond their threshold, Alternative 2.2 or Alternative 2.1 would be the preferred. This occurs because increasing L_d, L_t, z_1, or z_4 increases the user cost. Therefore, the preferred alternative will change when the total cost of Alternative 2.3 exceeds that of Alternative 2.2 or 2.1. Figure 14 shows the preferred alternatives for various combinations of variables.

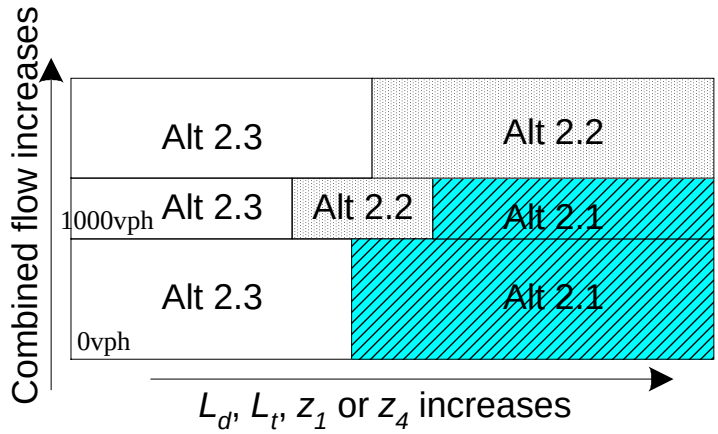


Figure 19 Preferred Alternatives Based on Combined Flow and Other Variables

For a four-lane two-way highway work zone, Alternative 4.3 is preferred when Q_1 is lower than 900 vph. As Q_1 increases but is still below work zone capacity, 1200 vph, Alternative 4.1 becomes preferable. When Q_1 exceeds 1200 vph, alternatives which detour some part of Q_1 are preferred. When Q_1 is between 1300 and 1700 vph, a 30% diversion of 0.3 of Q_1 is preferable; however, when Q_1 exceeds 1700 vph, higher diversion rates are required to minimize lowest total cost.

The developed analysis methods have been incorporated in a new software package. The developed software is based on the existing QuickZone version 1.0 available from FHWA, in order to provide compatibility with it. A user's manual for this software package is provided in Appendix I.

5.2 Future Work

The following improvements to the models and software developed in Phase 1 are proposed for Phase 2:

1. The current models, developed for 2-lane and 4-lane rural roads will be extended to analyze 6 and 8 lane rural roads as well as freeways with 4, 6 or 8 lanes.
2. The models will optimize the diversion rate instead of just evaluating given rates.
3. The models will consider diversion through more complex networks with multiple diversion paths instead of a single one, using equilibrium traffic assignment methods and a simulation model selected jointly with the SHA.
4. An optimal scheduling model will be incorporated to determine how resurfacing work might best be timed (e.g., in between traffic peaks, at night, in the off-season).
5. Work zone safety models will be developed or improved for the new type of roads considered in Task 1.
6. Improved models for resurfacing costs and work durations will be formulated and estimated. These models will take into account the tradeoffs between resurfacing frequency, pavement durability, serviceability and costs, as well as the extra costs required to speed-up the resurfacing work in critically congested sections of highway networks.
7. The use of these models in developing traffic control plans for pavement resurfacing projects will be demonstrated.

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Appendix I Work Zone Optimization Software User's Manual

1. Program Outline

The following program, "**Work Zone Optimization**", has been developed by the Department of Civil and Environmental Engineering at University of Maryland. The purpose of the work zone optimization software is to help highway agencies determine an optimal work zone length for varying work zone configurations with different road types. The program determines a minimum cost work zone length and a cycle phasing plan. This software is embedded to the QucikZone version 1.0 developed by Federal Highway Administration.

At this point, the program can optimize work zone lengths and cycle times for two-way two-lane rural highways, and only work zone lengths for four-lane divided rural highways. Also, users can choose the unit for inputs and outputs from either SI (metric) or English units.

2. Costs Considered in the Program

The total costs to be optimized by the program include maintenance costs, user delay costs and accident costs for four-lane divided rural highways, and maintenance costs and user delay costs for two-way two-lane rural highways.

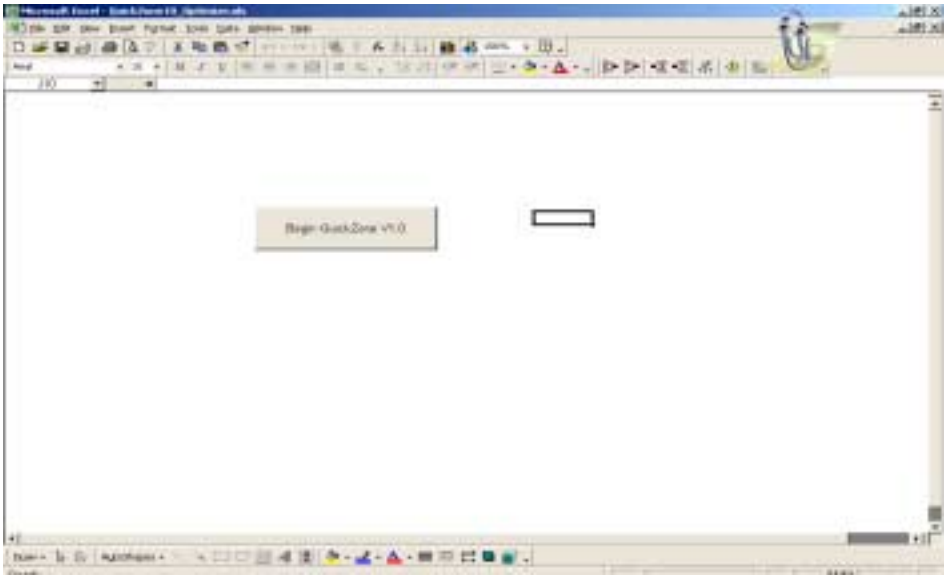
3. Program Installation

As mentioned earlier, the program is developed on the top of the QuickZone version 1.0 which is written in Visual Basic in connection with Microsoft Excel. Therefore all rules and instructions made for QuickZone version 1.0 apply for this program. Especially, as in running QuickZone, it is recommended that users "**Enable Macros**" within Excel when opening this program.

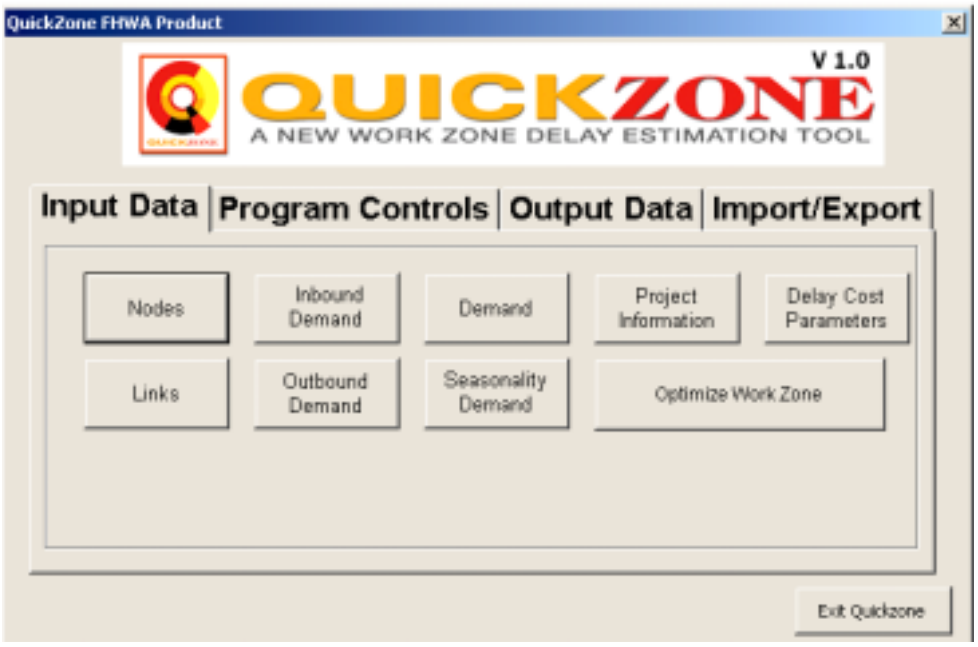
The program is named "**QuickZone10_Optimize.xls**". The users should copy this program into their own preferred directories before running it.

4. Start the application

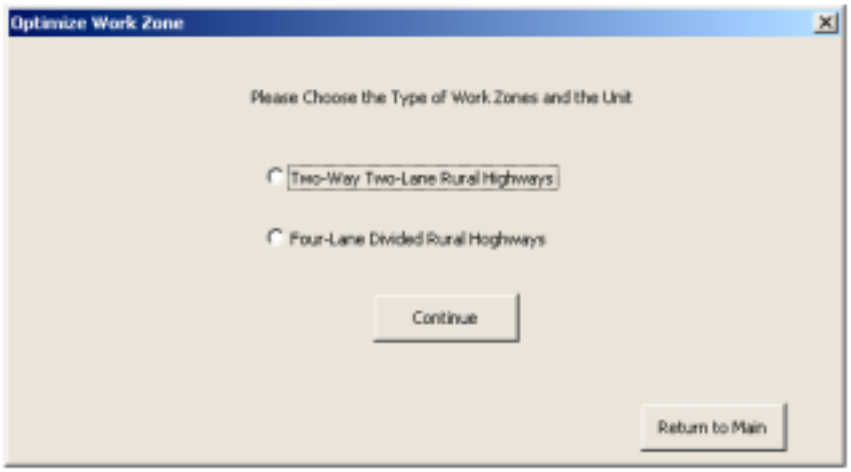
1. Double click the application file, "**QuickZone10_Optimize.xls**". The button for starting program will be shown.



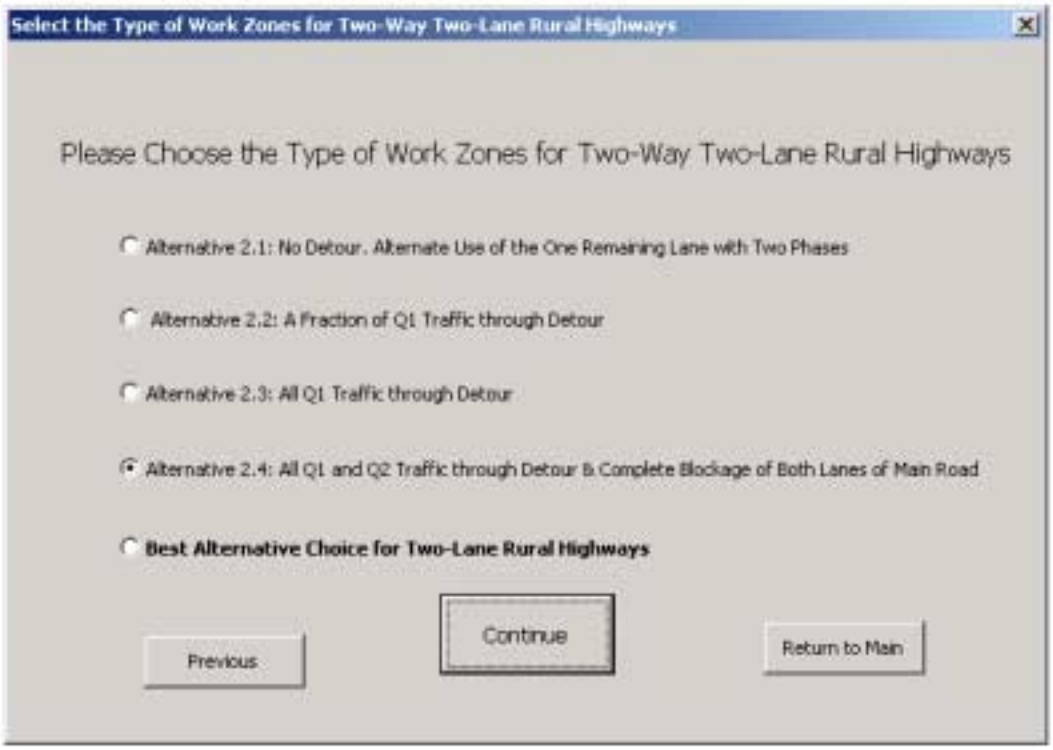
2. Click the button of "**Begin QuickZone V1.0**". The user will see the button for optimizing the work zone, "**Optimize Work Zone**" from the main menu. Click that button.



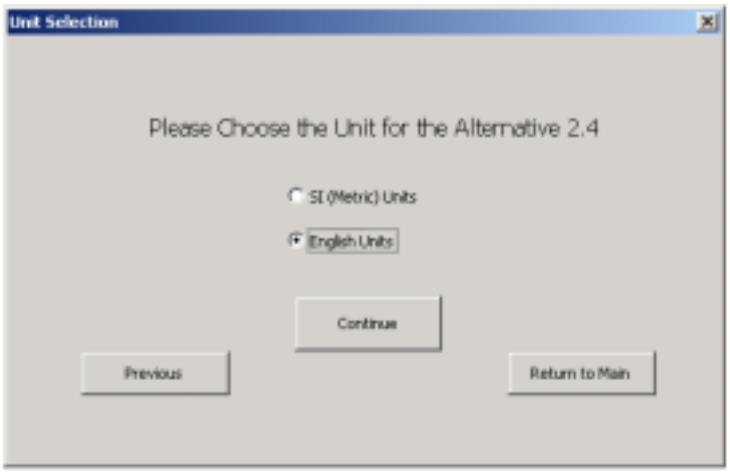
3. Choose the type of work zone to be optimized, and click the "**Continue**" button. The button "Return to Main" is provided for a user to return to the previous screen.



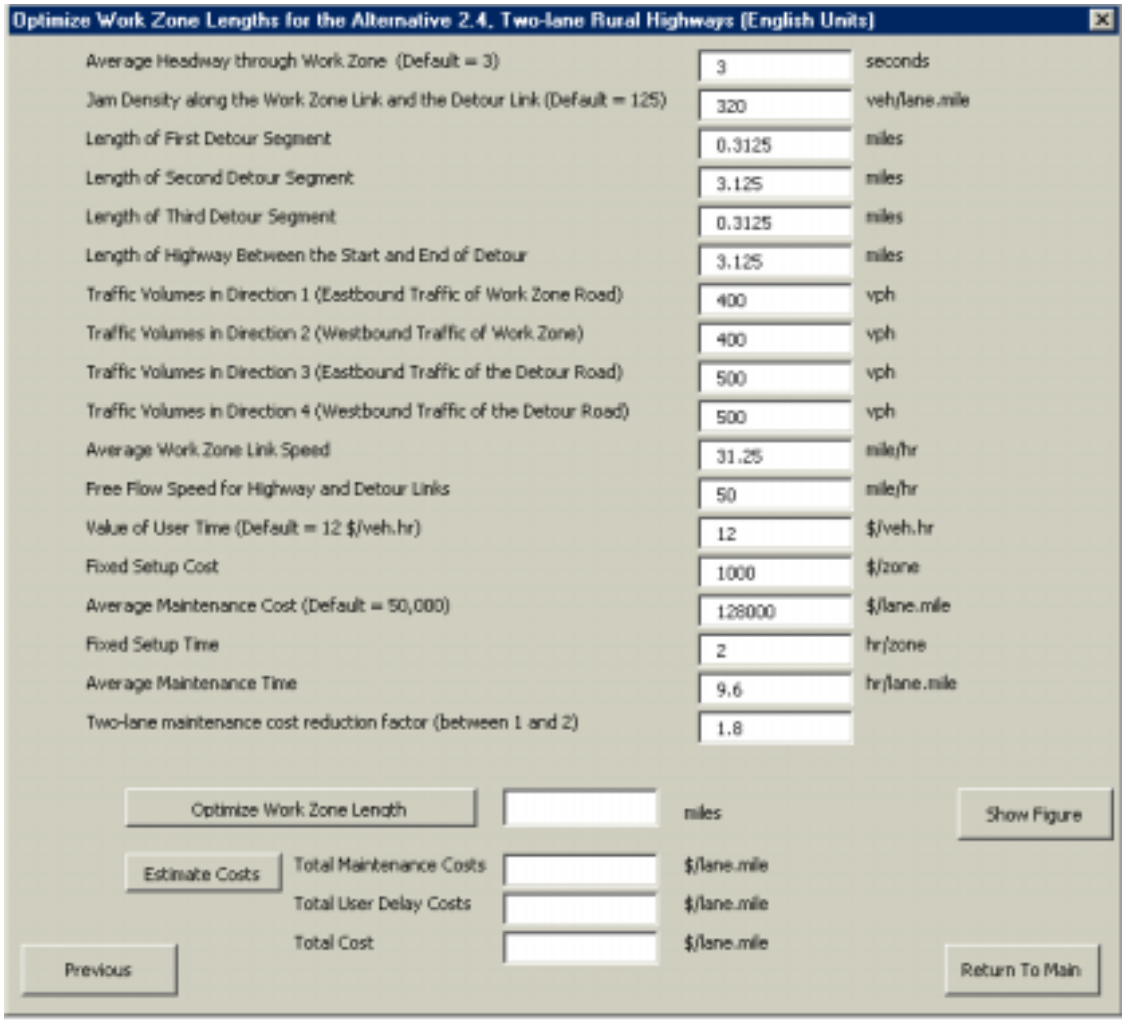
4. If a user chooses Two-Way Two-Lane Rural Highways, the following screen will be shown to select the configurations of the work zone. Four alternatives are analyzed for two-way two-lane rural highways (refer to the main report for each alternative).



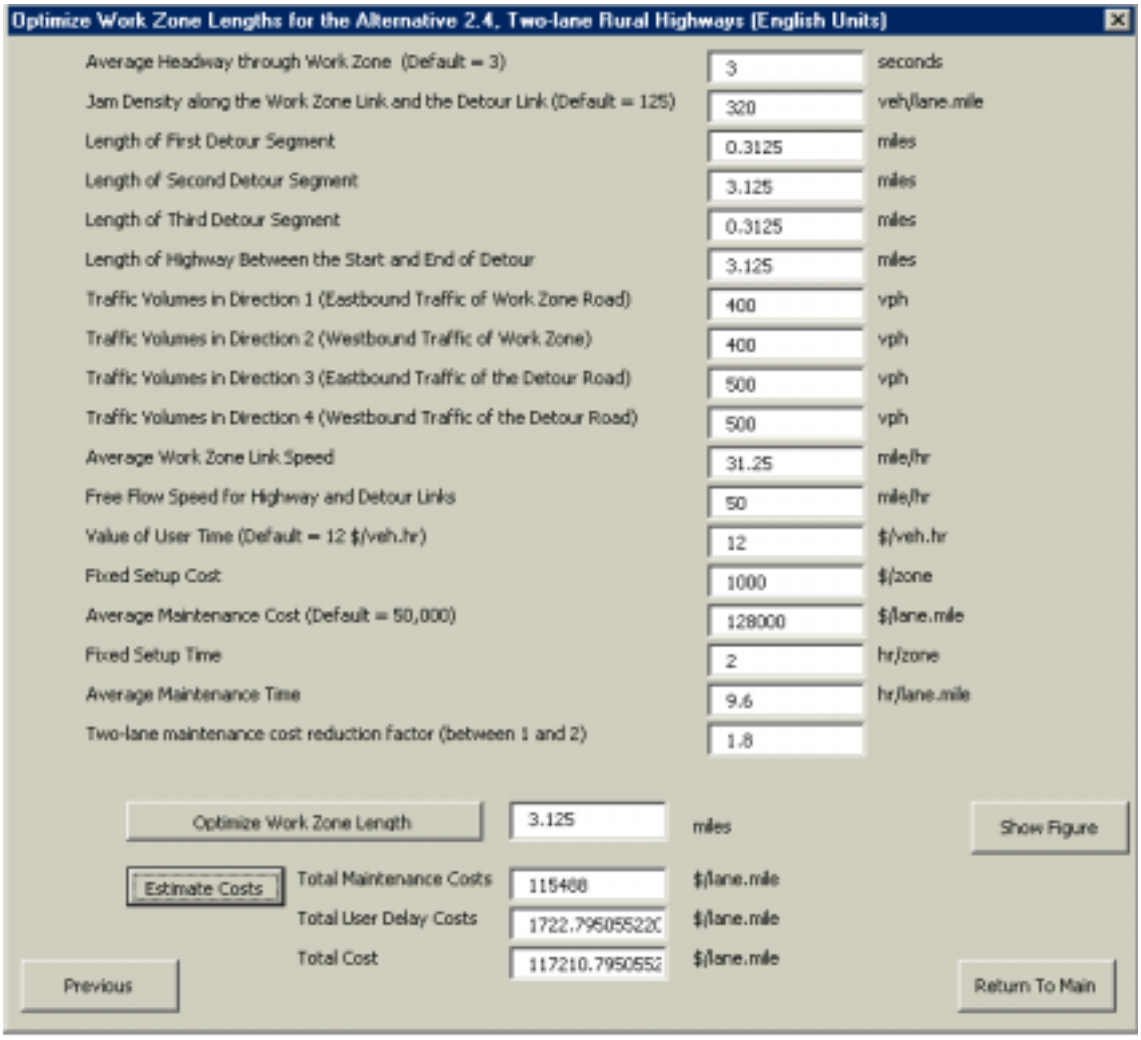
5. If a user selects Alternative 2.4 and clicks the "**Continue**" button, the following screen will be shown. On this screen, users can choose their preferred units.



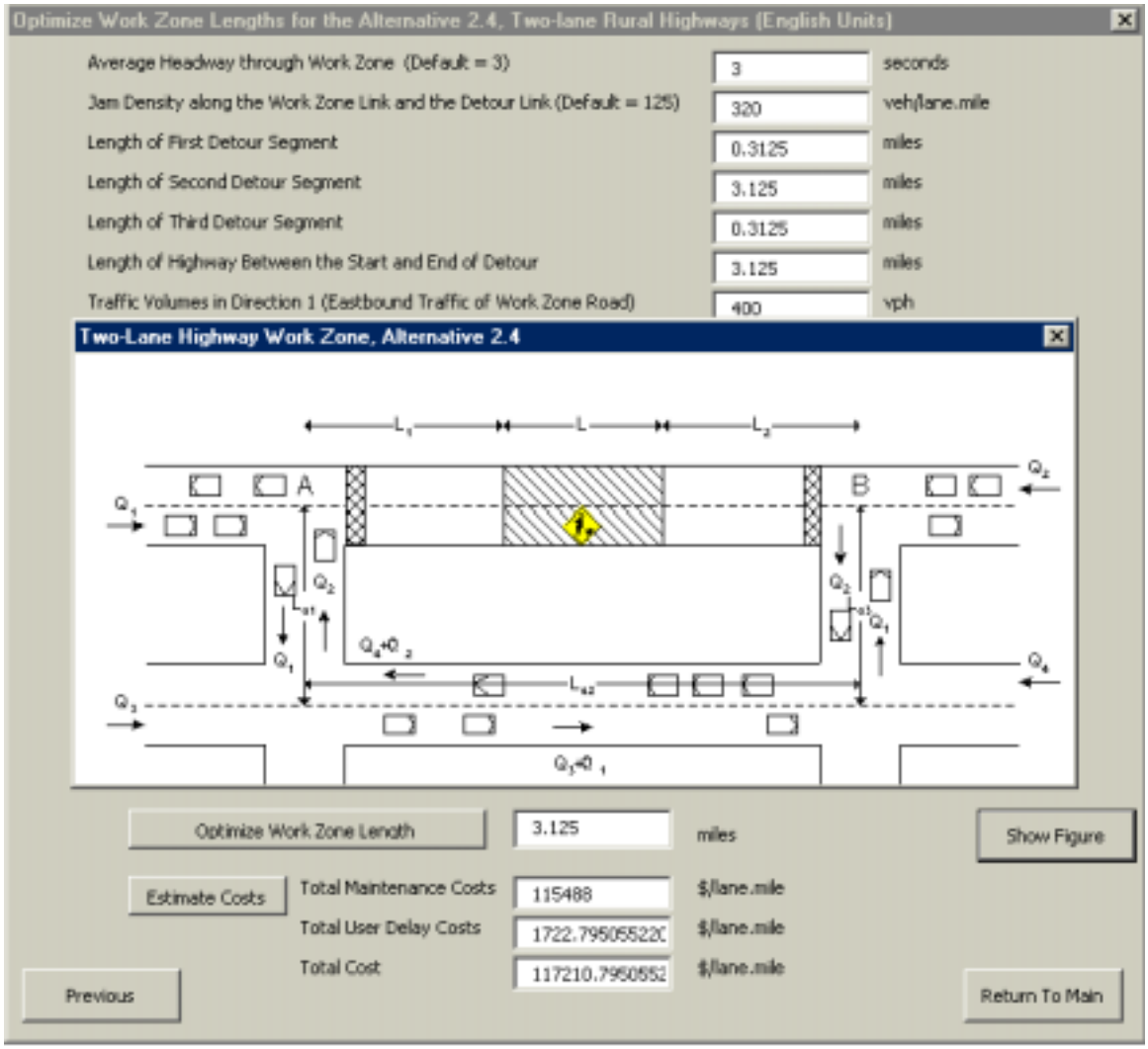
6. The following screen shows the dialog boxes for 7 work zone input variables for Alternative 2.4 of two-way two-lane rural highways.



7. Users can get the solutions by clicking the "**Optimize Work Zone Lengths and Cycle Time**" button after typing in the values for each box. The following screen shows an example result. Users can return to the main menu by clicking "**Return to Main**"



8. A user who is unfamiliar with the definitions of variables may click on "**Show Figure**". The Figure for Alternative 2.4 will then be shown on the screen.



5. Final Note

The work zone optimization program is a prototype program. There is much room for improving the model and algorithms. For detailed suggestions and recommendations for future development, to report any bugs in the program and for other suggestions, please contact one of the following persons:

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Chun-Hung "Peter" Chen (chpchen@wam.umd.edu)

Appendix II Selected Papers on Work Zone Optimization by the Report's Authors

1. Schonfeld, P. M., and Chien, I. J. (1999) "Optimal Work Zone Lengths for Two-Lane Highways." *Journal of Transp. Engrg*. ASCE, 125(1), 21-29.

2. Chien, S., and Schonfeld, P. (2001). "Optimal Work Zone Lengths for Four-Lane Highways." *Journal of Transp. Engrg*., ASCE, 127(2), 124-131.

3. Chen, C. H., and Schonfeld, P. (2002) "Work Zone Length for a Two-Lane Road with an Alternate Route." *TSC Report 2002-22*, University of Maryland, College Park.

4. Chen, C. H., and Schonfeld P. (2002) "Work Zone Length for Four-Lane Road with Alternate Routes." *TSC Report 2002-21*, University of Maryland, College Park.