INTEGRATED MANAGEMENT OF MAINTENANCE AND TRAFFIC

UNIVERSITY OF MARYLAND

SP107B45
FINAL REPORT

July 2002
The contents of this report reflect the views of the author who is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Maryland State Highway Administration. This report does not constitute a standard, specification, or regulation.
### 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.

### Key Words

- work zones
- QuickZone

Form DOT F 1700.7 (8-72) Reproduction of form and completed page is authorized.
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
July 2002
TABLE OF CONTENTS

| TABLE OF CONTENTS ........................................................................................................... | i |
| LIST OF TABLES ............................................................................................................. | ii |
| LIST OF FIGURES .......................................................................................................... | iii |

Chapter 1 Introduction ........................................................................................................ 1
  1.1 Motivation .................................................................................................................. 1
  1.2 Objectives ................................................................................................................ 2
  1.3 Scope ......................................................................................................................... 3
  1.4 Methodology ............................................................................................................. 3
  1.5 Organization of the Report ....................................................................................... 3

Chapter 2 Literature Review ............................................................................................... 5
  2.1 Work Zone Issues ..................................................................................................... 5
  2.2 Work Zone Cost Items ............................................................................................. 6
  2.3 Research Trends ....................................................................................................... 7
  2.4 Software and Information Sources for Work Zones ............................................... 11

Chapter 3 Optimization of Work Zones ............................................................................ 16
  3.1 Approach .................................................................................................................. 16
  3.2 Methodology and Assumptions ............................................................................... 18
  3.3 Model Formulation .................................................................................................. 22

Chapter 4 Threshold and Sensitivity Analysis .................................................................. 43
  4.1 Threshold Analysis .................................................................................................. 43
  4.2 Sensitivity Analysis ................................................................................................ 45
  4.3 Selection Guidelines ............................................................................................... 57

Chapter 5 Research Findings and Future Work ................................................................ 67
  5.1 Research Findings ................................................................................................... 67
  5.2 Future Work ............................................................................................................ 68

References ......................................................................................................................... 70

Appendix I Work Zone Optimization Software User’s Manual ....................................... 73

Appendix II Selected Journal Papers on Work Zone Optimization by the Report’s Authors .................................................................................................................. 81
LIST OF TABLES

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

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

Table 3 Comparison of the Delay Costs for Different Directional Flows in Alternative 2.2 ($p=0.6$)

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

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

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

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

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

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

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

Table 11 Total Cost at Different Flow Rates for Four-Lane Two-Way Highway Work Zones ($Q_2=500vph, Q_3=1000vph, \alpha=1.8$)
LIST OF FIGURES

Figure 1 Geometry of Analyzed Work Zone for Two-Lane Two-Way Highway .......... 19
Figure 2 Geometry of Analyzed Work Zone for Four-Lane Two-Way Highway .......... 21
Figure 3 Total Cost vs. Detour Length ........................................................................ 43
Figure 4 User Costs versus Various Zone Lengths (Q₁=400vph, Q₂=400vph) .......... 49
Figure 5 User, Maintenance, and Total Costs versus Various Work Zone Lengths (Q₁=400vph, Q₂=400vph) ................................................................................... 49
Figure 6 Optimal Zone Length versus Setup Cost z₁ (Q₁=400vph, Q₂=400vph) ...... 51
Figure 7 Optimal Zone Length versus Average Maintenance Time z₄ (Q₁=400vph, Q₂=400vph) ........................................................................................................ 51
Figure 8 Optimal Zone Length versus Setup Duration z₃ (Q₁=400vph, Q₂=400vph) ........................................................................................................ 51
Figure 9 Optimal Zone Length versus Headway H (Q₁=400vph, Q₂=400vph) ........ 52
Figure 10 Optimal Zone Length versus Zone Speed V (Q₁=400vph, Q₂=400vph) ...... 52
Figure 11 User Delay Costs versus Combined Flows....................................................... 53
Figure 12 Total Costs versus Various Work Zone Lengths (Q₁=500vph, Q₂=500vph, Q₃=500vph, α=2)................................................................................................ 56
Figure 13 Total Costs versus Various Work Zone Lengths (Q₁=1000vph, Q₂=500vph, Q₃=500vph, α=2)................................................................................................ 57
Figure 14 Total Cost versus Detour Length for Various Alternatives (Q₁=200vph, Q₂=200vph) ........................................................................................................ 58
Figure 15 Total Cost versus Detour Length for Various Alternatives (Q₁=600vph, Q₂=400vph) ........................................................................................................ 58
Figure 16 Total Cost versus Detour Length for Various Alternatives (Q₁=800vph, Q₂=400vph) ........................................................................................................ 58
Figure 17 Total Cost versus Detour Length for Various Alternatives (Q₂=500vph, Q₃=500vph, α=2)................................................................................................ 62
Figure 18 Total Cost versus Detour Length for Various Alternatives (Q₂=500vph, Q₃=1000vph, α=2).............................................................................................. 63
Figure 19 Preferred Alternatives Based on Combined Flow and Other Variables ........... 68
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 than 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 m² 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 (CO³) system to estimate the impact of traffic maintenance contract provisions on congestion, road user cost, and construction cost. CO³ 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 CO³ 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


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


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


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.
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 $Q_I$ traffic
2. A fraction of $Q_I$ traffic is diverted through detour
3. All of $Q_I$ is diverted through detour, allowing work zone on both lanes in direction 1
4. All of $Q_I$ 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:

$$C_T = C_M + C_U$$

(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):

$$C_U = YNv$$

(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:

\[
C_{UV}^1 = \frac{(z_3 + z_4 L)[Q_1(\frac{3600}{H} - Q_1) + Q_2(\frac{3600}{H} - Q_2)]v}{V(\frac{3600}{H} - Q_1 - Q_2)}
\]

where \( C_{UV}^1 \) = user delay cost per lane-kilometer for Alternative 1; \( z_j \) = 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 \( z_3 + z_4 L \) represents the maintenance duration per zone.

The maintenance cost per zone is assumed to be \( z_1 + z_2 L \), 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 \( L \)

\[
C_M = \frac{(z_1 + z_2 L)}{L} = \frac{z_1}{L} + z_2
\]

Then the total cost for Alternative 2.1, \( C_{T1}^1 \), is \( C_M + C_{UV}^1 \). 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:

\[
L^{*1} = \sqrt{\frac{z_3 V(\frac{3600}{H} - Q_1 - Q_2)}{z_4 [Q_1(\frac{3600}{H} - Q_1) + Q_2(\frac{3600}{H} - Q_2)]v}}
\]
The second derivative of $C_l^i$ 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 $Q_l$ in direction 1 is diverted to the alternate route. Then the user delay cost of the remaining flow in direction 1, $(1-p)Q_l$, and $Q_2$, denoted as $C_{1-p}$, has the same formulation as Eq.(3) but with $(1-p)Q_l$ substituted for $Q_l$.

$$C_{1-p} = \frac{(z_3 + z_4 L)(1-p)Q_l\left(\frac{3600}{H} - (1-p)Q_l\right) + Q_2 \left(\frac{3600}{H} - Q_2\right)}{V\left(\frac{3600}{H} - (1-p)Q_l - Q_2\right)} \quad (6)$$

The user delay cost of the diverted flow $pQ_l$ from direction 1, denoted as $C_p$, is equal to the flow $pQ_l$ multiplied by: (1) the average maintenance duration per kilometer, $\frac{z_3 + z_4}{L}$, which is the maintenance duration per zone, $z_3 + z_4 L$, 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, $\frac{L_z}{V_0}$, and (3) the value of time, $v$. Thus:

$$C_p = pQ_l\left(\frac{z_3 + z_4}{L}\right)\left[\frac{L_{d1} + L_{d3}}{V_0} + \frac{L_{d2}}{V_d^2} - \frac{L_z}{V_0}\right]v \quad (7)$$

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:

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

(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:

$$C_v^2 = C_{1-p} + C_p + C_{U3}$$

(9)

where

$C_v^2 = \text{user delay cost per kilometer per lane for Alternative 2.2}$

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

$C_{U1} = \text{user delay cost of diverted flow pQ_1}$

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

Then the total cost for Alternative 2.2, $C_T^2$, is $C_M + C_v^2$. 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:
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 \( pQ_1 \).

\[
C_{U1} = Q_1\left(\frac{z_3}{L} + z_4\right)[\frac{L_{d1} + L_{d3}}{V_0} + \frac{L_{d2}^3}{V_d^3} - \frac{L_d}{V_d}]v
\]

(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, \( \frac{L_1 + L_3}{V_0} + \frac{L}{V} \), and without the work zone, \( \frac{L}{V_0} \), and (3) the value of time, \( v \). Thus:

\[
C_{U2} = Q_2\left(\frac{z_3}{L} + z_4\right)(\frac{L_1 + L_3}{V_0} + \frac{L}{V} - \frac{L}{V_0})v
\]

(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 \( V_d^2 \).
The total user delay cost including original road and detour can be determined as follows:

\[ C^3_v = C_{U1} + C_{U2} + C_{U3} \]  \hspace{1cm} (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, \( C_M^3 \), is \( C_{M} + C_{U}^3 \). Its optimal work zone length \( L^{23} \) is then found to be:

\[ L^{23} = \frac{z_3 + Q_3z_3\left(\frac{L_{d1} + L_{d3} - L_i}{V_0} + \frac{L_{d2}}{V_{d0}}\right) + Q_1z_3\left(\frac{L_{d2}}{V_{d2}} - \frac{L_{d2}}{V_{d0}}\right)}{Q_2z_3\left(\frac{1}{V} - \frac{1}{V_0}\right)} \]  \hspace{1cm} (15)

Because the second derivatives \( \frac{\partial C_i^j}{\partial L^2}, \frac{\partial C_i^2}{\partial L^2}, \frac{\partial C_i^3}{\partial L^2} \) of the three objective functions \( C_1^i, C_2^i \) and \( C_3^i \) 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 $pQ_1$.

$$C_{U1} = Q_1 \left( \frac{z_3}{L} + z_4 \right) \left[ \frac{L_{d1} + L_{d3}}{V_0} + \frac{L_{d2}}{V_d^{*3}} - \frac{L_i}{V_0} \right]V$$

(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 $pQ_1$.

$$C_{U2} = Q_2 \left( \frac{z_3}{L} + z_4 \right) \left[ \frac{L_{d1} + L_{d3}}{V_0} + \frac{L_{d2}}{V_d^{*4}} - \frac{L_i}{V_0} \right]V$$

(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 $V_d^{*2}$.

$$C_{U3} = Q_3 \left( \frac{z_3}{L} + z_4 \right) \left( \frac{L_{d2}}{V_d^{*3}} - \frac{L_{d2}}{V_d^{*0}} \right)V$$

(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 $V_d^{*2}$.

$$C_{U4} = Q_4 \left( \frac{z_3}{L} + z_4 \right) \left( \frac{L_{d2}}{V_d^{*4}} - \frac{L_{d2}}{V_d^{*0}} \right)V$$

(19)
It is assumed here that $Q_3$ and $Q_4$ are equal so that the original detour speeds for directions 3 and 4 are equal, $V_{det}$, which will be derived by using Eq.(78).

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

$$C^4_u = C_{U1} + C_{U2} + C_{U3} + C_{U4}$$

where

$C^4_u = $ 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, $C^4_T$, is:

$$C^4_T = \frac{1}{2} \alpha (\frac{z_1}{L} + z_2) + C^4_u$$

Eq.(21) includes the parameter $\alpha$ which is reduction factor that is defined as the maintenance cost for two lanes divided by the maintenance cost for one lane. The $\frac{1}{2}$ 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 $C^4_T$ are then found to be:

$$\frac{\partial C^4_T}{\partial L} = -\alpha \frac{z_1}{2L^2} + \frac{Q_1z_3}{L^2} (\frac{L_{d1} + L_{d2} + L_{d3}}{V_0} \cdot \frac{L_{d1}}{V_{d1}} \cdot \frac{L_{d2}}{V_{d2}} \cdot \frac{L_{d3}}{V_{d3}}) + Q_2z_3 (\frac{L_{d1} + L_{d2} + L_{d3}}{V_0} + \frac{L_{d1} + L_{d2}}{V_{d1} + V_{d2}}) \cdot \frac{L_0}{V_0}$$

$$\frac{\partial^2 C^4_T}{\partial L^2} = \frac{Q_1z_3}{L^3} \left( \frac{L_{d1}}{V_{d1}^2} + \frac{L_{d2}}{V_{d2}^2} \right) + Q_2z_3 (\frac{L_{d1}}{V_{d1}^2} + \frac{L_{d2}}{V_{d2}^2} + \frac{L_{d3}}{V_{d3}^2}) < 0$$
\[
\frac{\partial^2 C_T^4}{\partial L^2} = \frac{\alpha c_0}{L^3} + 2 \frac{Q_1 z_3}{L^3} \left( \frac{L_{d1} + L_{d3}}{V_o} - \frac{L_{d2}}{V_{d2}^*} \right) V + 2 \frac{Q_1 z_3}{L^3} \left( \frac{L_{d1} + L_{d3}}{V_o} - \frac{L_{d2}}{V_{d2}^*} \right) V + 2 \frac{Q_1 z_3}{L^3} \left( \frac{L_{d2}}{V_{d2}^*} - \frac{L_{d2}}{V_{d0}^*} \right) V > 0
\]

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 \(L_q\).

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

\[
t_d = \frac{(Q_1 - c_w)D}{(c_0 - Q_1)}
\]

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 $L$.

$$C_q = \frac{t_q v_d}{L} \quad (25)$$

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:

$$t_q = \frac{1}{2} \left( D + t_d \right) \left( (Q_1 - c_w)D \right)$$

$$= \frac{1}{2} \left( 1 + \frac{Q_1 - c_w}{c_0 - Q_1} \right) (Q_1 - c_w) (z_3 + z_4 L)^2 \quad (26)$$

Then

$$C_q = 0 \quad \text{when } Q_1 \leq c_w$$

$$C_q = \frac{v_d}{2L} \left( 1 + \frac{Q_1 - c_w}{c_0 - Q_1} \right) (Q_1 - c_w) (z_3 + z_4 L)^2 \quad \text{when } Q_1 > c_w \quad (27)$$

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 $L$.

$$C_v = \frac{t_m v_d}{L} \quad (28)$$

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.

$$t_m = \left( \frac{L}{V_w} - \frac{L}{V_a} \right) Q_1 D \quad \text{when } Q_1 \leq c_w$$

$$t_m = \left( \frac{L}{V_w} - \frac{L}{V_a} \right) c_w D \quad \text{when } Q_1 > c_w \quad (29)$$
where $V_a = \text{average approaching speed}$; $V_w = \text{average work zone speed}$. 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

$$C_v = (\frac{1}{V_w} - \frac{1}{V_a})Q_1(z_j + z_w)\nu_d \quad \text{when } Q_1 \leq c_w$$  \hspace{1cm} (30)

$$C_v = (\frac{1}{V_w} - \frac{1}{V_a})c_w(z_j + z_w)\nu_d \quad \text{when } Q_1 > c_w$$

Total user delay per maintained lane kilometer $C_u$ is:

$$C_u = C_q + C_v$$  \hspace{1cm} (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

$$C_a = \frac{(t_q + t_m) n_a v_a}{L} \times 10^8$$ \hspace{1cm} (32)

Then

$$C_a = (\frac{1}{V_w} - \frac{1}{V_a})Q_1(z_j + z_w)\frac{n_a v_a}{10^8} \quad \text{when } Q_1 \leq c_w$$

$$C_a = (\frac{1}{2L}(1 + \frac{Q_1 - c_w}{c_0 - Q_1})(Q_1 - c_w)(z_j + z_w) + (\frac{1}{V_w} - \frac{1}{V_a})c_w(z_j + z_w)\frac{n_a v_a}{10^8} \quad \text{when } Q_1 > c_w$$  \hspace{1cm} (33)

Total cost is

$$C_T = C_M + C_u + C_a$$  \hspace{1cm} (34)

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

\[
L^{*41} = \sqrt{\frac{2z_1 + P_2P_3z_3^2}{P_1P_2P_3z_4^2 + 2P_3P_4z_4z_3}}
\]

when \( Q_j > c_w \)

where

\[ P_1 = Q_j - c_w \]  

(37)

\[ P_2 = 1 + \frac{Q_j - c_w}{c_0 - Q_j} \]  

(38)

\[ P_3 = v_d + \frac{n_a v_a}{10^5} \]  

(39)

\[ P_4 = \frac{1}{V_w} - \frac{1}{V_a} \]  

(40)

**Alternative 4.2: A Fraction of \( Q_j \) Traffic through Detour**

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

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

\[
C_u^{(1-p)} = C_q^{(1-p)} + C_v^{(1-p)}
\]

(41)
The user queue delay cost of the remaining flow in direction 1, \((1-p)Q_1\), denoted as \(C^{t_{q-p}}\), is the queue delay \(t_{q-p}\) for \((1-p)Q_1\) multiplied by the average delay cost \(v_d\) and divided by \(L\). \(t_{q-p}\) has the same formulation as equation (26) but with \((1-p)Q_1\) substituted for \(Q_1\):

\[
t_{q-p} = \begin{cases} 
0 & \text{when } (1-p)Q_1 \leq c_w \\
\frac{1}{2} \left( 1 + \frac{(1-p)Q_1 - c_w}{c_0 - (1-p)Q_1} \right) \left( (1-p)Q_1 - c_w \right) (z_j + z_dL)^2 & \text{when } (1-p)Q_1 > c_w 
\end{cases}
\]

\(C^{t_{q-p}}\) has the same formulation as equation (27) but with \((1-p)Q_1\) substituted for \(Q_1\):

\[
C^{t_{q-p}} = \begin{cases} 
0 & \text{when } (1-p)Q_1 \leq c_w \\
\frac{v_d (1 + (1-p)Q_1 - c_w)}{2L} \left( (1-p)Q_1 - c_w \right) (z_j + z_dL)^2 & \text{when } (1-p)Q_1 > c_w 
\end{cases}
\]

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

\[
t_{m-p} = \begin{cases} 
\left(\frac{L}{V_w} - \frac{L}{V_a}\right) (1-p)Q_1 D & \text{when } (1-p)Q_1 \leq c_w \\
\left(\frac{L}{V_w} - \frac{L}{V_a}\right) c_w D & \text{when } (1-p)Q_1 > c_w 
\end{cases}
\]

Then, \(C^{t_{v-p}}\) has the same formulation as equation (30) but with \((1-p)Q_1\) substituted for \(Q_1\):

\[
C^{t_{v-p}} = \begin{cases} 
\left(\frac{1}{V_w} - \frac{1}{V_a}\right) (1-p)Q_1 (z_j + z_dL)v_d & \text{when } (1-p)Q_1 \leq c_w \\
\left(\frac{1}{V_w} - \frac{1}{V_a}\right) c_w (z_j + z_dL)v_d & \text{when } (1-p)Q_1 > c_w 
\end{cases}
\]
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:

\[
C_u^p = C_q^p + C_v^p
\]  

(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, \( \frac{z_3 + z_4}{L} \), 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, \( \frac{L_{d1}}{V_a} + \frac{L_{d2}}{V_{d2}} \), and (3) the time vehicles through the original road AB without work zone, \( \frac{L}{V_a} \), and (3) the value of time, \( v_d \). Thus:

\[
C_v^p = pQ_1 \left( \frac{z_3 + z_4}{L} \right) \left[ \frac{L_{d1}}{V_a} + \frac{L_{d2}}{V_{d2}} - \frac{L}{V_a} \right] v_d
\]  

(47)

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

\[
C_u^p = C_q^p + C_v^p = pQ_1 \left( \frac{z_3 + z_4}{L} \right) \left[ \frac{L_{d1}}{V_a} + \frac{L_{d2}}{V_{d2}} - \frac{L}{V_a} \right] v_d
\]  

(48)

where \( V_{d2} \) 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

\[
C_{a}^{1-p} = \frac{(t_{a}^{1-p} + t_{u}^{1-p}) n_a V_a}{L 10^3}
\]  

(49)
Then,

\[ C_{a}^{t-p} = \left( \frac{I}{V_{a}} - \frac{I}{V_{a}}(1-p)Q_{i}(z_{j} + z_{d}L) \right) \frac{n_{a}V_{a}}{10^{b}} \quad \text{when } (1-p)Q_{i} \leq c_{w} \]

\[ C_{a}^{t-p} = I \frac{(1 + \frac{(1-p)Q_{i} - c_{w}}{c_{o} - (1-p)Q_{i}})((1-p)Q_{i} - c_{w})(z_{j} + z_{d}L)\frac{n_{a}V_{a}}{10^{b}}}{2L} + \frac{(1 - \frac{I}{V_{a}})c_{u}(z_{j} + z_{d}L)}{10^{b}} \quad \text{when } (1-p)Q_{i} > c_{w} \]  

(50)

The average accident cost per maintained kilometer for \( pQ_{i}, C_{a}^{p} \), is

\[ C_{a}^{p} = \left( \frac{t^{p} + t^{2}}{L} \right) \frac{n_{a}V_{a}}{10^{b}} \]  

(51)

where

\[ t^{p} = \frac{C_{a}^{p}L}{V_{a}} = (\frac{L_{d1}}{V_{a}} + \frac{L_{d3}}{V_{a}} + \frac{L_{d2}}{V_{a}} - \frac{L_{i}}{V_{a}})pQ_{i}(z_{j} + z_{d}L) \quad \text{when } pQ_{i} \leq c_{d} \]  

(52)

and \( t^{p} = 0 \). Then

\[ C_{a}^{p} = (\frac{L_{d1}}{V_{a}} + \frac{L_{d3}}{V_{a}} + \frac{L_{d2}}{V_{a}} - \frac{L_{i}}{V_{a}})pQ_{i}(\frac{z_{j}}{L} + z_{d}) \frac{n_{a}V_{a}}{10^{b}} \quad \text{when } pQ_{i} \leq c_{d} \]  

(53)

Another delay cost \( C_{t,3} \) 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).

\[ C_{t,3} = Q_{3}(\frac{z_{3}}{L} + z_{4})(\frac{L_{d2}}{V_{d}^{2}} - \frac{L_{d2}}{V_{d0}^{2}})V_{d} \]  

(8)

where \( V_{d}^{*2} \) is the detour speed affected by \( pQ_{i} \) in direction 3 in Alternative 4.2.

The total cost is:

\[ C_{t} = C_{M} + C_{u} + C_{a} = C_{M} + (C_{a}^{t-p} + C_{a}^{p}) + (C_{a}^{t-p} + C_{a}^{p}) \]  

(54)

Then
The optimal work zone length is:

\[
L^{*2} = \sqrt{ \frac{z_i + pQ_i(z_i + \frac{L_{adj} + L_{adj}}{V_a} + \frac{L_{adj}}{V_d} - \frac{L_i}{V_d})v_d + \frac{n_i v_i}{10^8} + Q_i(z_i + \frac{L_{adj} + L_{adj}}{V_a} + \frac{L_{adj}}{V_d} - \frac{L_i}{V_d})v_d}{(1 - p)Q_i(z_i + \frac{L_{adj} + L_{adj}}{V_a} + \frac{L_{adj}}{V_d} - \frac{L_i}{V_d})v_d + \frac{n_i v_i}{10^8}} }
\]

(56)

when \((1 - p)Q_i \leq c_w\)

The optimal work zone length is:

\[
L^{*2} = \sqrt{ \frac{z_i + [(1 - p)Q_i - c_w(1 - p)Q_i)](\frac{L_{adj} + L_{adj}}{V_a} + \frac{L_{adj}}{V_d} - \frac{L_i}{V_d})v_d + \frac{n_i v_i}{10^8} + Q_i(z_i + \frac{L_{adj} + L_{adj}}{V_a} + \frac{L_{adj}}{V_d} - \frac{L_i}{V_d})v_d}{(1 - p)Q_i(z_i + \frac{L_{adj} + L_{adj}}{V_a} + \frac{L_{adj}}{V_d} - \frac{L_i}{V_d})v_d + \frac{n_i v_i}{10^8} + (1 - p)Q_i(z_i + \frac{L_{adj} + L_{adj}}{V_a} + \frac{L_{adj}}{V_d} - \frac{L_i}{V_d})v_d + \frac{n_i v_i}{10^8}} }
\]

when \((1 - p)Q_i > c_w\)

**Alternative 4.3: All Q1 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:

$$C_T = \left( \frac{z_j}{L} + z_d \right)$$

$$+ Q_j \left( \frac{z_j}{L} + z_d \right) \left[ \frac{L_{d1} + L_{d3} + L_{d2}}{V_a} \frac{L_a}{V_a^2} - \frac{L_a}{V_a} \right] V_d$$

$$+ Q_j \left( \frac{z_j}{L} + z_d \right) \left[ \frac{L_{d2} + L_{d3}}{V_d^2} \frac{L_a}{V_a} \right] \left( \frac{z_j}{L} + z_d \right) \frac{n_a V_a}{10^5}$$

where $V_d^{**}$ 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:

$$\frac{\partial C_T}{\partial L} = -\frac{z_j}{L^2} + Q_j \frac{z_j}{L^2} \left( \frac{L_{d1} + L_{d3} + L_{d2}}{V_a} \frac{L_a}{V_a^2} - \frac{L_a}{V_a} \right) V_d + Q_j \frac{z_j}{L^2} \left( \frac{L_{d2} + L_{d3}}{V_d^2} \frac{L_a}{V_a} \right) \frac{n_a V_a}{10^5} < 0$$

$$\frac{\partial^2 C_T}{\partial L^2} = \frac{2z_j}{L^3} + 2 Q_j \frac{z_j}{L^2} \left( \frac{L_{d1} + L_{d3} + L_{d2}}{V_a} \frac{L_a}{V_a} \right) V_d + 2 Q_j \frac{z_j}{L^2} \left( \frac{L_{d2} + L_{d3}}{V_d^2} \frac{L_a}{V_a} \right) \frac{n_a V_a}{10^5}$$

$$+ 2 Q_j \frac{z_j}{L^3} \left( \frac{L_{d2} + L_{d3}}{V_d^2} \frac{L_a}{V_a} \right) V_d > 0$$

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.

\[
C_{q_1} = 0 \quad \text{when } Q_1 \leq c_w
\]

\[
C_{q_1} = \frac{v_d}{2L} \left( 1 + \frac{Q_1 - c_w}{c_0 - Q_1} \right) (Q_1 - c_w) (z_j + z_4L)^2 \quad \text{when } Q_1 > c_w \tag{60}\]

\[
C_{q_2} = 0 \quad \text{when } Q_2 \leq c_w
\]

\[
C_{q_2} = \frac{v_d}{2L} \left( 1 + \frac{Q_2 - c_w}{c_0 - Q_2} \right) (Q_2 - c_w) (z_j + z_4L)^2 \quad \text{when } Q_2 > c_w \tag{61}\]

\[
C_{v_1} = \left( \frac{1}{V_w} - \frac{1}{V_a} \right) Q_1 (z_j + z_4L) v_d \quad \text{when } Q_1 \leq c_w
\]

\[
C_{v_1} = \left( \frac{1}{V_w} - \frac{1}{V_a} \right) c_w (z_j + z_4L) v_d \quad \text{when } Q_1 > c_w \tag{62}\]

\[
C_{v_2} = \left( \frac{1}{V_w} - \frac{1}{V_a} \right) Q_2 (z_j + z_4L) v_d \quad \text{when } Q_2 \leq c_w
\]

\[
C_{v_2} = \left( \frac{1}{V_w} - \frac{1}{V_a} \right) c_w (z_j + z_4L) v_d \quad \text{when } Q_2 > c_w \tag{63}\]

\[
C_{a_1} = \left( \frac{1}{V_w} - \frac{1}{V_a} \right) Q_1 (z_j + z_4L) \frac{n_v u}{10^5} \quad \text{when } Q_1 \leq c_w
\]

\[
C_{a_1} = \left[ \frac{1}{2L} \left( 1 + \frac{Q_1 - c_w}{c_0 - Q_1} \right) (Q_1 - c_w) (z_j + z_4L)^2 \right. \\
\left. + \left( \frac{1}{V_w} - \frac{1}{V_a} \right) c_w (z_j + z_4L) \frac{n_v u}{10^5} \right] \quad \text{when } Q_1 > c_w \tag{64}\]
\[ C_{a_2} = \left( \frac{1}{V_w} - \frac{1}{V_a} \right) Q_2 (z_j + z_4 L) \frac{n_a v_a}{10^8} \quad \text{when} \quad Q_2 \leq c_w \]

\[ C_{a_2} = \left( \frac{1}{2L} \left( 1 + \frac{Q_2 - c_w}{c_0 - Q_2} \right) (Q_2 - c_w) (z_j + z_4 L)^2 \right. \]

\[ \left. + \left( \frac{1}{V_w} - \frac{1}{V_a} \right) c_w (z_j + z_4 L) \frac{n_a v_a}{10^8} \right) \quad \text{when} \quad Q_2 > c_w \]

The total cost is:

\[ C_T = C_M + C_u + C_a \]

\[ = C_M + (C_{q_1} + C_{v_1}) + (C_{q_2} + C_{v_2}) + (C_{a_1} + C_{a_2}) \quad (66) \]

\[ Q_1 \] 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. \( Q_1 \leq c_w, \quad Q_2 \leq c_w \)

\[ C_T = \left( \frac{z_j}{L} + z_2 \right) + \left[ 0 + \left( \frac{1}{V_w} - \frac{1}{V_a} \right) Q_1 (z_j + z_4 L) v_d \right] \]

\[ + \left[ 0 + \left( \frac{1}{V_w} - \frac{1}{V_a} \right) Q_2 (z_j + z_4 L) v_d \right] + \left( \frac{1}{V_w} - \frac{1}{V_a} \right) Q_1 (z_j + z_4 L) \frac{n_a v_a}{10^8} \quad (67) \]

\[ + \left( \frac{1}{V_w} - \frac{1}{V_a} \right) Q_2 (z_j + z_4 L) \frac{n_a v_a}{10^8} \]

\[ L^{44} = \sqrt{z_4 (Q_1 + Q_2) (V_a + \frac{n_a v_a}{10^8}) \left( \frac{1}{V_w} - \frac{1}{V_a} \right)} \quad (68) \]

2. \( Q_1 > c_w, \quad Q_2 \leq c_w \)

\[ C_T = \left( \frac{z_j}{L} + z_2 \right) + \left[ \frac{v_d}{2L} (1 + \frac{Q_2 - c_w}{c_0 - Q_2}) (Q_1 - c_w) (z_j + z_4 L)^2 + \left( \frac{1}{V_w} - \frac{1}{V_a} \right) c_w (z_j + z_4 L) v_d \right] \]

\[ + \left[ \frac{1}{2L} (1 + \frac{Q_2 - c_w}{c_0 - Q_2}) (Q_1 - c_w) (z_j + z_4 L)^2 + \left( \frac{1}{V_w} - \frac{1}{V_a} \right) c_w (z_j + z_4 L) \frac{n_a v_a}{10^8} \right] \quad (69) \]

\[ + \left( \frac{1}{V_w} - \frac{1}{V_a} \right) Q_2 (z_j + z_4 L) \frac{n_a v_a}{10^8} \]
\( L^{44} = \left[ \begin{array} \frac{z_j + \frac{z_j^2}{2} (1 + \frac{Q_2 - c_w}{c_0 - Q_2}) (Q_1 - c_w) (v_d + \frac{n_{v_a} \nu_a}{10^8})}{z_d (c_w + Q_2) (v_d + \frac{n_{v_a} \nu_a}{10^8}) + \frac{1}{V_w} - \frac{1}{V_a}} + \frac{1}{2L} \left( \frac{Q_1 - c_w}{c_0 - Q_1} \right) (z_j + z_d L)^2 \left( \frac{1}{V_w} - \frac{1}{V_a} \right) c_w (z_j + z_d L) v_d \right] \tag{70} \)

(3) \( Q_1 \leq c_w, \quad Q_2 > c_w \)

\[ L^{44} = \left( \frac{z_j}{L} + z_d \right) + \frac{v_d}{2L} \left( \frac{Q_2 - c_w}{c_0 - Q_2} \right) (Q_2 - c_w) (z_j + z_d L)^2 \left( \frac{1}{V_w} - \frac{1}{V_a} \right) c_w (z_j + z_d L) v_d \] \tag{71}

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

\[ L^{44} = \left[ \begin{array} \frac{z_j + \frac{z_j^2}{2} (1 + \frac{Q_2 - c_w}{c_0 - Q_2}) (Q_2 - c_w) (v_d + \frac{n_{v_a} \nu_a}{10^8})}{z_d (c_w + Q_1) (v_d + \frac{n_{v_a} \nu_a}{10^8}) + \frac{1}{V_w} - \frac{1}{V_a}} + \frac{1}{2L} \left( \frac{Q_1 - c_w}{c_0 - Q_1} \right) (z_j + z_d L)^2 \left( \frac{1}{V_w} - \frac{1}{V_a} \right) c_w (z_j + z_d L) v_d \right] \tag{72} \]

\[ L^{44} = \left( \frac{z_j}{L} + z_d \right) + \frac{v_d}{2L} \left( \frac{Q_1 - c_w}{c_0 - Q_1} \right) (Q_1 - c_w) (z_j + z_d L)^2 \left( \frac{1}{V_w} - \frac{1}{V_a} \right) c_w (z_j + z_d L) v_d \] \tag{73}

\[ L^{44} = \left[ \begin{array} \frac{z_j + \frac{z_j^2}{2} (v_d + \frac{n_{v_a} \nu_a}{10^8}) + \frac{v_d}{2L} \left( \frac{Q_1 - c_w}{c_0 - Q_1} \right) (Q_1 - c_w) (z_j + z_d L)^2 \left( \frac{1}{V_w} - \frac{1}{V_a} \right) c_w (z_d + z_d L) v_d \right] \tag{74} \]
3. Determination of Work Zone and Detour Speeds

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

$$Q = KV$$  \hspace{1cm} (75)

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

$$V = V_f - \frac{V_f}{K_j}K$$  \hspace{1cm} (76)

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

Substituting (76) into (75), we obtain

$$Q = K_jV - \frac{K_j}{V_f}V^2$$  \hspace{1cm} (77)

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

$$V = \frac{K_jV_f + \sqrt{(K_jV_f)^2 - 4K_jV_fQ}}{2K_j}$$  \hspace{1cm} (78)

Then, $V_0, V_{d0}$, $V_{d2}^*$ and $V_{d3}^*$ 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), $V = \frac{K_jV_f - \sqrt{(K_jV_f)^2 - 4K_jV_fQ}}{2K_j}$, which is congestion speed (Gerlough and Huber, 1975), is not applied because $V_0$, $V_{d0}$, $V_{d2}^*$ and $V_{d3}^*$ 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 ($V_{d0}$, $V_{d2}^*$ and $V_{d3}^*$) 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

\[ C_T^{*1}, C_T^{*2}, C_T^{*3} \text{ and } C_T^{*4} \] 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 \( L^{*1}, L^{*2} L^{*3} \text{ and } L^{*4} \). 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 \( T^{DL}_{32} \), beyond which Alternative 2.2 is preferable up to \( T^{DL}_{21} \).

![Figure 3 Total Cost vs. Detour Length](image-url)
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

$$C_T^{*2} = \left( \frac{z_1}{L^2} + z_2 \right) + \frac{(z_3 + z_4 L^2)(1 - p)Q_1(\frac{3600}{H} - (1 - p)Q_1) + Q_2(\frac{3600}{H} - Q_2)\nu}{V(\frac{3600}{H} - (1 - p)Q_1 - Q_2)}$$

$$+ pQ_1\left( \frac{z_3}{L^2} + z_4 \right)\left( \frac{L_{d1}}{V_0} + \frac{L_{d3}}{V_{d2}^2} - \frac{L_4}{V_0} \right)\nu$$

$$+ Q_3\left( \frac{z_3}{L^2} + z_4 \right)\left( \frac{L_{d2}}{V_{d2}^2} - \frac{L_{d3}}{V_{d0}} \right)\nu$$

(79)

$$= \left( \frac{z_1}{L} + z_2 \right) + Q_1\left( \frac{z_3}{L^3} + z_4 \right)\left( \frac{L_{d1}}{V_0} + \frac{L_{d3}}{V_{d2}^3} - \frac{L_4}{V_0} \right)\nu + Q_2\left( \frac{z_3}{L^3} + z_4 \right)\left( \frac{L_{d2}}{V_{d2}^3} - \frac{L_{d3}}{V_{d0}} \right)\nu$$

$$+ Q_3\left( \frac{z_3}{L^3} + z_4 \right)\left( \frac{L_{d2}}{V_{d2}^3} - \frac{L_{d3}}{V_{d0}} \right)\nu$$

$$= C_T^{*3}$$

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:
\[ T_{32}^{DL} = \]
\[ L_{d3} = \frac{1}{Q_j z_j \left( \frac{p}{V_d^2 L^2} - \frac{1}{V_d^3 L^3} \right) + Q_j z_j \left( \frac{p}{V_d^2 L^2} - \frac{1}{V_d^3 L^3} \right) + Q_j \left( \frac{1}{V_d^2 L^2} - \frac{1}{V_d^3 L^3} \right) + \frac{1}{V_d^3 L^3} \left( \frac{1}{V_d^3} - \frac{1}{V_d^0} \right) + z_j \left( \frac{1}{V_d^2} - \frac{1}{V_d^3} \right)} \]

\[ \frac{1}{V} \left( \frac{z_5}{L^3} - \frac{z_1}{L^3} + Q_j \left( \frac{1}{V_d} + L_{d3} - L_{d3} \right) - \frac{L_{d1} + L_{d1}}{V_0} - Q_j \left( \frac{1}{V_d^2} + L_{d3} - L_{d3} \right) - \frac{L_{d1} + L_{d1}}{V_0} \right) \]

\[ + Q_j \left( \frac{z_5}{L^3} + z_j \right) \left( \frac{L^3}{V} - \frac{L^3}{V_0} \right) - \frac{(z_5 + z_1 L^2)}{(1 - p)Q_j \left( \frac{3600}{H} \right) - (1 - p)Q_j + Q_j \left( \frac{3600}{H} - Q_j \right) + \frac{V(3600)}{H} - \frac{(1 - p)Q_j - Q_j}{V_0}} \]

\[ Q_j \left( L_{d1} + L_{d3} \right) \left[ \frac{z_5}{V_d^2} \left( \frac{1}{V_d^0} - \frac{1}{V_d^0} \right) - \frac{z_5}{V_d^3} \left( \frac{1}{V_d^3} - \frac{1}{V_d^0} \right) + z_j \left( \frac{1}{V_d^2} - \frac{1}{V_d^3} \right) \right] \]

\[ \left( \frac{3600}{H} - (1 - p)Q_j - Q_j \right) + Q_j \left( \frac{3600}{H} - Q_j \right) \]

where

\[ L_{d2} = L_d - (L_{d1} + L_{d3}) \]

\[ L_{d2} = L_d - (L_{d1} + L_{d3}) \]

\[ L_{d2} = L_d - (L_{d1} + L_{d3}) \]

Variable \( L_{d2} \), 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

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H$</td>
<td>Average headway through work zone area</td>
<td>3 s</td>
</tr>
<tr>
<td>$K_j$</td>
<td>Jam density along AB and detour</td>
<td>200 veh/lane·km</td>
</tr>
<tr>
<td>$L_{d1}$</td>
<td>Length of first detour segment</td>
<td>0.5 km</td>
</tr>
<tr>
<td>$L_{d2}$</td>
<td>Length of second detour segment</td>
<td>5 km</td>
</tr>
<tr>
<td>$L_{d3}$</td>
<td>Length of third detour segment</td>
<td>0.5 km</td>
</tr>
<tr>
<td>$L_t$</td>
<td>Distance from A to B</td>
<td>5 km</td>
</tr>
<tr>
<td>$Q_3$</td>
<td>Hourly flow rate in direction 3</td>
<td>500 veh/hr</td>
</tr>
<tr>
<td>$V$</td>
<td>Average work zone speed</td>
<td>50 km/hr</td>
</tr>
<tr>
<td>$V_f$</td>
<td>Free flow speed along AB and detour</td>
<td>80 km/hr</td>
</tr>
<tr>
<td>$V$</td>
<td>Value of user time</td>
<td>12 $/veh·hr</td>
</tr>
<tr>
<td>$Z_1$</td>
<td>Fixed setup cost</td>
<td>1,000 $/zone</td>
</tr>
<tr>
<td>$Z_2$</td>
<td>Average maintenance cost per lane-kilometer</td>
<td>80,000 $/lane·km</td>
</tr>
<tr>
<td>$Z_3$</td>
<td>Fixed setup time</td>
<td>2 hr/zone</td>
</tr>
<tr>
<td>$Z_4$</td>
<td>Average maintenance time per lane-kilometer</td>
<td>6 hr/lane·km</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>$\Sigma (Q_1 + Q_2)$</th>
<th>$Q_1$</th>
<th>$Q_2$</th>
<th>Alt. 2.1</th>
<th>Alt. 2.2 (p=0.3)</th>
<th>Alt. 2.2 (p=0.6)</th>
<th>Alt. 2.2 (p=0.9)</th>
<th>Alt. 2.3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Optimal length</td>
<td>Min. total cost</td>
<td>Optimal length</td>
<td>Min. total cost</td>
<td>Optimal length</td>
</tr>
<tr>
<td>200</td>
<td>100</td>
<td>100</td>
<td>1.78</td>
<td>81231</td>
<td>1.96</td>
<td>81159</td>
<td>2.20</td>
</tr>
<tr>
<td>400</td>
<td>200</td>
<td>200</td>
<td>1.18</td>
<td>81937</td>
<td>1.32</td>
<td>81811</td>
<td>1.52</td>
</tr>
<tr>
<td>600</td>
<td>200</td>
<td>400</td>
<td>0.90</td>
<td>82650</td>
<td>1.00</td>
<td>82457</td>
<td>1.13</td>
</tr>
<tr>
<td>800</td>
<td>200</td>
<td>600</td>
<td>0.70</td>
<td>83512</td>
<td>0.80</td>
<td>83154</td>
<td>0.92</td>
</tr>
<tr>
<td>1000</td>
<td>200</td>
<td>800</td>
<td>0.52</td>
<td>85118</td>
<td>0.63</td>
<td>84195</td>
<td>0.75</td>
</tr>
<tr>
<td>1200</td>
<td>200</td>
<td>1000</td>
<td>-</td>
<td>-</td>
<td>0.35</td>
<td>88710</td>
<td>0.55</td>
</tr>
<tr>
<td>600</td>
<td>400</td>
<td>200</td>
<td>0.90</td>
<td>82650</td>
<td>1.07</td>
<td>82401</td>
<td>1.32</td>
</tr>
<tr>
<td>800</td>
<td>400</td>
<td>400</td>
<td>0.66</td>
<td>83804</td>
<td>1.29</td>
<td>83259</td>
<td>1.00</td>
</tr>
<tr>
<td>1000</td>
<td>400</td>
<td>600</td>
<td>0.45</td>
<td>86057</td>
<td>0.61</td>
<td>84476</td>
<td>0.80</td>
</tr>
<tr>
<td>1200</td>
<td>400</td>
<td>800</td>
<td>-</td>
<td>-</td>
<td>0.39</td>
<td>87835</td>
<td>0.61</td>
</tr>
<tr>
<td>1400</td>
<td>400</td>
<td>1000</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>800</td>
<td>600</td>
<td>200</td>
<td>0.70</td>
<td>83512</td>
<td>0.90</td>
<td>83005</td>
<td>1.18</td>
</tr>
<tr>
<td>1000</td>
<td>600</td>
<td>400</td>
<td>0.45</td>
<td>86057</td>
<td>0.66</td>
<td>84258</td>
<td>0.90</td>
</tr>
<tr>
<td>1200</td>
<td>600</td>
<td>600</td>
<td>-</td>
<td>-</td>
<td>0.44</td>
<td>86884</td>
<td>0.70</td>
</tr>
<tr>
<td>1400</td>
<td>600</td>
<td>800</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1600</td>
<td>600</td>
<td>1000</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1000</td>
<td>800</td>
<td>200</td>
<td>0.52</td>
<td>85118</td>
<td>0.77</td>
<td>83692</td>
<td>1.08</td>
</tr>
<tr>
<td>1200</td>
<td>800</td>
<td>400</td>
<td>-</td>
<td>-</td>
<td>0.52</td>
<td>85828</td>
<td>0.81</td>
</tr>
<tr>
<td>1400</td>
<td>800</td>
<td>600</td>
<td>-</td>
<td>-</td>
<td>0.21</td>
<td>99491</td>
<td>0.60</td>
</tr>
<tr>
<td>1600</td>
<td>800</td>
<td>800</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1800</td>
<td>800</td>
<td>1000</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1200</td>
<td>1000</td>
<td>200</td>
<td>-</td>
<td>-</td>
<td>0.65</td>
<td>84616</td>
<td>1.00</td>
</tr>
<tr>
<td>1400</td>
<td>1000</td>
<td>400</td>
<td>-</td>
<td>-</td>
<td>0.34</td>
<td>90067</td>
<td>0.73</td>
</tr>
<tr>
<td>1600</td>
<td>1000</td>
<td>600</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1800</td>
<td>1000</td>
<td>800</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2000</td>
<td>1000</td>
<td>1000</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

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 \((p=0.6)\)

<table>
<thead>
<tr>
<th>(\Sigma(Q_1+Q_2))</th>
<th>(Q_1)</th>
<th>(Q_2)</th>
<th>Optimal Length</th>
<th>(C_T)</th>
<th>(C_M)</th>
<th>(C_U)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(\Sigma)</td>
<td>(C_{1-p})</td>
<td>(C_p)</td>
</tr>
<tr>
<td>1400</td>
<td>400</td>
<td>1000</td>
<td>0.29</td>
<td>92290</td>
<td>83469</td>
<td>8821</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100%</td>
<td>90.44%</td>
<td>9.56%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(pQ_1=240)</td>
<td>Flow ((1-p)Q_1+Q_2=1160)</td>
<td>Flow (Q_2=500)</td>
</tr>
<tr>
<td>1400</td>
<td>1000</td>
<td>400</td>
<td>0.73</td>
<td>84850</td>
<td>81366</td>
<td>3484</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100%</td>
<td>95.89%</td>
<td>4.11%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(pQ_1=600)</td>
<td>Flow ((1-p)Q_1+Q_2=800)</td>
<td>Flow (Q_2=500)</td>
</tr>
</tbody>
</table>
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 $z_1 (Q_1=400\text{vph}, Q_2=400\text{vph})$

Figure 7 Optimal Zone Length versus Average Maintenance Time $z_4 (Q_1=400\text{vph}, Q_2=400\text{vph})$

Figure 8 Optimal Zone Length versus Setup Duration $z_3 (Q_1=400\text{vph}, Q_2=400\text{vph})$
Figure 9 Optimal Zone Length versus Headway $H (Q_1=400\text{vph}, \ Q_2=400\text{vph})$

Figure 10 Optimal Zone Length versus Zone Speed $V (Q_1=400\text{vph}, \ Q_2=400\text{vph})$

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

<table>
<thead>
<tr>
<th>Alternatives</th>
<th>Alt. 2.1</th>
<th>Alt. 2.2 (p=0.3)</th>
<th>Alt. 2.2 (p=0.6)</th>
<th>Alt. 2.2 (p=0.9)</th>
<th>Alt. 2.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Setup cost ($/zone)</td>
<td>1000</td>
<td>0.66</td>
<td>83804</td>
<td>0.81</td>
<td>83259</td>
</tr>
<tr>
<td>Setup duration (h/zone)</td>
<td>2</td>
<td>0.66</td>
<td>83804</td>
<td>0.81</td>
<td>83259</td>
</tr>
<tr>
<td>Setup duration (h/zone)</td>
<td>3</td>
<td>0.66</td>
<td>84188</td>
<td>0.82</td>
<td>83555</td>
</tr>
<tr>
<td>Change</td>
<td>50%</td>
<td>0.00</td>
<td>0.46%</td>
<td>0.01</td>
<td>0.35%</td>
</tr>
</tbody>
</table>
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.

![Graph showing user delay costs versus combined flows](image)

**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

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_o$</td>
<td>Maximum discharge rate without work zone</td>
<td>2,600 vph</td>
</tr>
<tr>
<td>$c_w$</td>
<td>Maximum discharge rate with work zone</td>
<td>1,200 vph</td>
</tr>
<tr>
<td>$H$</td>
<td>Average headway through work zone area</td>
<td>3 s</td>
</tr>
<tr>
<td>$K_j$</td>
<td>Jam density along AB and detour</td>
<td>200 veh/lane-km</td>
</tr>
<tr>
<td>$L_{d1}$</td>
<td>Length of first detour segment</td>
<td>0.5 km</td>
</tr>
<tr>
<td>$L_{d2}$</td>
<td>Length of second detour segment</td>
<td>5 km</td>
</tr>
<tr>
<td>$L_{d3}$</td>
<td>Length of third detour segment</td>
<td>0.5 km</td>
</tr>
<tr>
<td>$L_t$</td>
<td>Distance from A to B</td>
<td>5 km</td>
</tr>
<tr>
<td>$n_a$</td>
<td>Number of accidents per 100 million vehicle hour</td>
<td>40 acc/100mvh</td>
</tr>
<tr>
<td>$Q_2$</td>
<td>Hourly flow rate in direction 2</td>
<td>500 veh/hr</td>
</tr>
<tr>
<td>$Q_3$</td>
<td>Hourly flow rate in direction 3</td>
<td>500 veh/hr</td>
</tr>
<tr>
<td>$V_w$</td>
<td>Average work zone speed</td>
<td>50 km/hr</td>
</tr>
<tr>
<td>$V_f$</td>
<td>Free flow speed along AB and detour</td>
<td>80 km/hr</td>
</tr>
<tr>
<td>$v_a$</td>
<td>Average accident cost</td>
<td>142,000 $/acc</td>
</tr>
<tr>
<td>$v_d$</td>
<td>Value of user time</td>
<td>12 $/veh-hr</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Reduction factor for two-lane maintenance</td>
<td>2.0</td>
</tr>
<tr>
<td>$Z_1$</td>
<td>Fixed setup cost</td>
<td>1,000 $/zone</td>
</tr>
<tr>
<td>$Z_2$</td>
<td>Average maintenance cost per lane-kilometer</td>
<td>80,000 $/lane-km</td>
</tr>
<tr>
<td>$Z_3$</td>
<td>Fixed setup time</td>
<td>2 hr/zone</td>
</tr>
<tr>
<td>$Z_4$</td>
<td>Average maintenance time per lane-kilometer</td>
<td>6 hr/lane-km</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>( Q_t )</th>
<th>Alt. 4.1</th>
<th>Alt. 4.2 (p=0.3)</th>
<th>Alt. 4.2 (p=0.6)</th>
<th>Alt. 4.2 (p=0.9)</th>
<th>Alt. 4.3</th>
<th>Alt. 4.4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Optimal length</td>
<td>Min. total cost</td>
<td>Optimal length</td>
<td>Min. total cost</td>
<td>Optimal length</td>
<td>Min. total cost</td>
</tr>
<tr>
<td>100</td>
<td>4.30</td>
<td>80483</td>
<td>5.00</td>
<td>80433</td>
<td>5.00</td>
<td>80378</td>
</tr>
<tr>
<td>200</td>
<td>3.07</td>
<td>80637</td>
<td>3.71</td>
<td>80648</td>
<td>4.97</td>
<td>80582</td>
</tr>
<tr>
<td>300</td>
<td>2.52</td>
<td>80846</td>
<td>3.06</td>
<td>80818</td>
<td>4.13</td>
<td>80758</td>
</tr>
<tr>
<td>400</td>
<td>2.20</td>
<td>80980</td>
<td>2.68</td>
<td>80968</td>
<td>3.63</td>
<td>80921</td>
</tr>
<tr>
<td>500</td>
<td>1.98</td>
<td>81098</td>
<td>2.43</td>
<td>81103</td>
<td>3.31</td>
<td>81073</td>
</tr>
<tr>
<td>600</td>
<td>1.82</td>
<td>81203</td>
<td>2.24</td>
<td>81227</td>
<td>3.07</td>
<td>81218</td>
</tr>
<tr>
<td>700</td>
<td>1.69</td>
<td>81299</td>
<td>2.10</td>
<td>81343</td>
<td>2.89</td>
<td>81357</td>
</tr>
<tr>
<td>800</td>
<td>1.59</td>
<td>81386</td>
<td>1.99</td>
<td>81451</td>
<td>2.75</td>
<td>81491</td>
</tr>
<tr>
<td>900</td>
<td>1.51</td>
<td>81467</td>
<td>1.90</td>
<td>81552</td>
<td>2.64</td>
<td>81620</td>
</tr>
<tr>
<td>1000</td>
<td>1.45</td>
<td>81541</td>
<td>1.82</td>
<td>81647</td>
<td>2.54</td>
<td>81746</td>
</tr>
<tr>
<td>1100</td>
<td>1.39</td>
<td>81610</td>
<td>1.76</td>
<td>81736</td>
<td>2.47</td>
<td>81867</td>
</tr>
<tr>
<td>1200</td>
<td>1.34</td>
<td>81674</td>
<td>1.70</td>
<td>81819</td>
<td>2.40</td>
<td>81984</td>
</tr>
<tr>
<td>1300</td>
<td>0.39</td>
<td>114198</td>
<td>1.65</td>
<td>81896</td>
<td>2.35</td>
<td>82097</td>
</tr>
<tr>
<td>1400</td>
<td>0.36</td>
<td>150510</td>
<td>1.61</td>
<td>81967</td>
<td>2.30</td>
<td>82206</td>
</tr>
<tr>
<td>1500</td>
<td>0.35</td>
<td>193334</td>
<td>1.58</td>
<td>82033</td>
<td>2.27</td>
<td>82311</td>
</tr>
<tr>
<td>1600</td>
<td>0.34</td>
<td>244690</td>
<td>1.55</td>
<td>82092</td>
<td>2.23</td>
<td>82411</td>
</tr>
<tr>
<td>1700</td>
<td>0.34</td>
<td>307441</td>
<td>1.52</td>
<td>82145</td>
<td>2.21</td>
<td>82506</td>
</tr>
<tr>
<td>1800</td>
<td>0.34</td>
<td>385866</td>
<td>0.44</td>
<td>101978</td>
<td>2.19</td>
<td>82597</td>
</tr>
<tr>
<td>1900</td>
<td>0.34</td>
<td>486666</td>
<td>0.38</td>
<td>125530</td>
<td>2.17</td>
<td>82681</td>
</tr>
<tr>
<td>2000</td>
<td>0.34</td>
<td>621103</td>
<td>0.36</td>
<td>151665</td>
<td>2.16</td>
<td>82760</td>
</tr>
<tr>
<td>2100</td>
<td>0.34</td>
<td>809276</td>
<td>0.36</td>
<td>180984</td>
<td>2.15</td>
<td>82832</td>
</tr>
<tr>
<td>2200</td>
<td>0.34</td>
<td>1091527</td>
<td>0.35</td>
<td>214147</td>
<td>2.14</td>
<td>82896</td>
</tr>
<tr>
<td>2300</td>
<td>0.33</td>
<td>1561935</td>
<td>0.35</td>
<td>251981</td>
<td>2.14</td>
<td>82953</td>
</tr>
<tr>
<td>2400</td>
<td>0.33</td>
<td>2520739</td>
<td>0.34</td>
<td>295559</td>
<td>2.15</td>
<td>82999</td>
</tr>
<tr>
<td>2500</td>
<td>0.33</td>
<td>3525141</td>
<td>0.34</td>
<td>346303</td>
<td>2.15</td>
<td>83036</td>
</tr>
<tr>
<td>2600</td>
<td>-</td>
<td>-</td>
<td>0.34</td>
<td>406147</td>
<td>2.17</td>
<td>83060</td>
</tr>
</tbody>
</table>

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

---

55
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 (Q1=500vph, Q2=500vph, Q3=500vph, α=2)](image)

Figure 12 shows that as Q1 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.
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 ($Q_1=200\text{vph}$, $Q_2=200\text{vph}$)

Figure 15 Total Cost versus Detour Length for Various Alternatives ($Q_1=600\text{vph}$, $Q_2=400\text{vph}$)

Figure 16 Total Cost versus Detour Length for Various Alternatives ($Q_1=800\text{vph}$, $Q_2=400\text{vph}$)
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 $= \frac{L_d}{L_t}$, 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

<table>
<thead>
<tr>
<th>Σ(Qi,Qj)</th>
<th>Qi</th>
<th>Qj</th>
<th>Circuity threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Alt1 &amp; Alt3</td>
</tr>
<tr>
<td>200</td>
<td>100</td>
<td>100</td>
<td>2.39</td>
</tr>
<tr>
<td>400</td>
<td>200</td>
<td>200</td>
<td>2.11</td>
</tr>
<tr>
<td>600</td>
<td>200</td>
<td>400</td>
<td>2.44</td>
</tr>
<tr>
<td>800</td>
<td>200</td>
<td>600</td>
<td>2.95</td>
</tr>
<tr>
<td>1000</td>
<td>200</td>
<td>800</td>
<td>4.14</td>
</tr>
<tr>
<td>1200</td>
<td>200</td>
<td>1000</td>
<td>-</td>
</tr>
<tr>
<td>600</td>
<td>400</td>
<td>200</td>
<td>1.85</td>
</tr>
<tr>
<td>800</td>
<td>400</td>
<td>400</td>
<td>2.21</td>
</tr>
<tr>
<td>1000</td>
<td>400</td>
<td>600</td>
<td>3.08</td>
</tr>
<tr>
<td>1200</td>
<td>400</td>
<td>800</td>
<td>-</td>
</tr>
<tr>
<td>1400</td>
<td>400</td>
<td>1000</td>
<td>-</td>
</tr>
<tr>
<td>800</td>
<td>600</td>
<td>200</td>
<td>1.81</td>
</tr>
<tr>
<td>1000</td>
<td>600</td>
<td>400</td>
<td>2.45</td>
</tr>
<tr>
<td>1200</td>
<td>600</td>
<td>600</td>
<td>-</td>
</tr>
<tr>
<td>1400</td>
<td>600</td>
<td>800</td>
<td>-</td>
</tr>
<tr>
<td>1600</td>
<td>600</td>
<td>1000</td>
<td>-</td>
</tr>
<tr>
<td>1000</td>
<td>800</td>
<td>200</td>
<td>1.95</td>
</tr>
<tr>
<td>1200</td>
<td>800</td>
<td>400</td>
<td>-</td>
</tr>
<tr>
<td>1400</td>
<td>800</td>
<td>600</td>
<td>-</td>
</tr>
<tr>
<td>1600</td>
<td>800</td>
<td>800</td>
<td>-</td>
</tr>
<tr>
<td>1800</td>
<td>800</td>
<td>1000</td>
<td>-</td>
</tr>
<tr>
<td>1200</td>
<td>1000</td>
<td>200</td>
<td>-</td>
</tr>
<tr>
<td>1400</td>
<td>1000</td>
<td>400</td>
<td>-</td>
</tr>
<tr>
<td>1600</td>
<td>1000</td>
<td>600</td>
<td>-</td>
</tr>
<tr>
<td>1800</td>
<td>1000</td>
<td>800</td>
<td>-</td>
</tr>
<tr>
<td>2000</td>
<td>1000</td>
<td>1000</td>
<td>-</td>
</tr>
</tbody>
</table>

(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 Qi 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 ($Q_2=500\text{vph}$, $Q_3=500\text{vph}$, $\alpha=2$)**

<table>
<thead>
<tr>
<th>$Q_1$</th>
<th>Alt 4.1</th>
<th>Alt 4.2 (0.3)</th>
<th>Alt 4.2 (0.6)</th>
<th>Alt 4.2 (0.9)</th>
<th>Alt 4.3</th>
<th>Alt 4.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>80483</td>
<td>80433</td>
<td>80378</td>
<td>80323</td>
<td>80304</td>
<td>81247</td>
</tr>
<tr>
<td>200</td>
<td>80687</td>
<td>80648</td>
<td>80582</td>
<td>80493</td>
<td>80465</td>
<td>81343</td>
</tr>
<tr>
<td>300</td>
<td>80846</td>
<td>80818</td>
<td>80758</td>
<td>80642</td>
<td>80601</td>
<td>81436</td>
</tr>
<tr>
<td>400</td>
<td>80980</td>
<td>80968</td>
<td>80921</td>
<td>80791</td>
<td>80741</td>
<td>81522</td>
</tr>
<tr>
<td>500</td>
<td>81098</td>
<td>81103</td>
<td>81073</td>
<td>80942</td>
<td>80883</td>
<td>81602</td>
</tr>
<tr>
<td>600</td>
<td>81203</td>
<td>81227</td>
<td>81218</td>
<td>81094</td>
<td>81029</td>
<td>81677</td>
</tr>
<tr>
<td>700</td>
<td>81299</td>
<td>81343</td>
<td>81357</td>
<td>81247</td>
<td>81179</td>
<td>81747</td>
</tr>
<tr>
<td>800</td>
<td>81386</td>
<td>81451</td>
<td>81491</td>
<td>81402</td>
<td>81333</td>
<td>81813</td>
</tr>
<tr>
<td>900</td>
<td>81467</td>
<td>81552</td>
<td>81620</td>
<td>81559</td>
<td>81490</td>
<td>81874</td>
</tr>
<tr>
<td>1000</td>
<td>81541</td>
<td>81647</td>
<td>81746</td>
<td>81717</td>
<td>81652</td>
<td>81932</td>
</tr>
<tr>
<td>1100</td>
<td>81610</td>
<td>81736</td>
<td>81867</td>
<td>81876</td>
<td>81819</td>
<td>81985</td>
</tr>
<tr>
<td>1200</td>
<td>81674</td>
<td>81819</td>
<td>81984</td>
<td>82038</td>
<td>81991</td>
<td>82035</td>
</tr>
<tr>
<td>1300</td>
<td>81498</td>
<td>81896</td>
<td>82097</td>
<td>82201</td>
<td>82169</td>
<td>114476</td>
</tr>
<tr>
<td>1400</td>
<td>150510</td>
<td>81967</td>
<td>82206</td>
<td>82367</td>
<td>82352</td>
<td>150921</td>
</tr>
<tr>
<td>1500</td>
<td>193334</td>
<td>82033</td>
<td>82311</td>
<td>82534</td>
<td>82543</td>
<td>193914</td>
</tr>
<tr>
<td>1600</td>
<td>244690</td>
<td>82092</td>
<td>82411</td>
<td>82704</td>
<td>82740</td>
<td>245483</td>
</tr>
<tr>
<td>1700</td>
<td>307441</td>
<td>82145</td>
<td>82506</td>
<td>82877</td>
<td>82946</td>
<td>308501</td>
</tr>
<tr>
<td>1800</td>
<td>385866</td>
<td>101978</td>
<td>82597</td>
<td>83052</td>
<td>83161</td>
<td>387270</td>
</tr>
<tr>
<td>1900</td>
<td>486866</td>
<td>125530</td>
<td>82681</td>
<td>83231</td>
<td>83385</td>
<td>488541</td>
</tr>
<tr>
<td>2000</td>
<td>621103</td>
<td>151665</td>
<td>82760</td>
<td>83413</td>
<td>83621</td>
<td>623570</td>
</tr>
<tr>
<td>2100</td>
<td>809276</td>
<td>180984</td>
<td>82832</td>
<td>83598</td>
<td>83869</td>
<td>812611</td>
</tr>
<tr>
<td>2200</td>
<td>1091527</td>
<td>214147</td>
<td>82896</td>
<td>83788</td>
<td>84132</td>
<td>1096177</td>
</tr>
<tr>
<td>2300</td>
<td>1561935</td>
<td>251981</td>
<td>82953</td>
<td>83981</td>
<td>84411</td>
<td>1568791</td>
</tr>
<tr>
<td>2400</td>
<td>2502739</td>
<td>295559</td>
<td>82999</td>
<td>84180</td>
<td>84710</td>
<td>2514032</td>
</tr>
<tr>
<td>2500</td>
<td>5325141</td>
<td>346303</td>
<td>83036</td>
<td>84385</td>
<td>85031</td>
<td>5349777</td>
</tr>
<tr>
<td>2600</td>
<td>406147</td>
<td>83060</td>
<td>84596</td>
<td>85380</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 17 Total Cost versus Detour Length for Various Alternatives ($Q_2=500\text{vph}$, $Q_3=500\text{vph}$, $\alpha=2$)

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

(Q2=500vph, Q3=1000vph, α=2)

<table>
<thead>
<tr>
<th>Q1</th>
<th>Alt 4.1</th>
<th>Alt 4.2(0.3)</th>
<th>Alt 4.2(0.6)</th>
<th>Alt 4.2(0.9)</th>
<th>Alt 4.3</th>
<th>Alt 4.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>80483</td>
<td>80436</td>
<td>80383</td>
<td>80330</td>
<td>80312</td>
<td>81247</td>
</tr>
<tr>
<td>200</td>
<td>80687</td>
<td>80674</td>
<td>80632</td>
<td>80571</td>
<td>80551</td>
<td>81343</td>
</tr>
<tr>
<td>300</td>
<td>80846</td>
<td>80858</td>
<td>80837</td>
<td>80760</td>
<td>80734</td>
<td>81436</td>
</tr>
<tr>
<td>400</td>
<td>80980</td>
<td>81021</td>
<td>81028</td>
<td>80953</td>
<td>80922</td>
<td>81522</td>
</tr>
<tr>
<td>500</td>
<td>81099</td>
<td>81171</td>
<td>81210</td>
<td>81149</td>
<td>81117</td>
<td>81602</td>
</tr>
<tr>
<td>600</td>
<td>81203</td>
<td>81311</td>
<td>81386</td>
<td>81349</td>
<td>81317</td>
<td>81677</td>
</tr>
<tr>
<td>700</td>
<td>81299</td>
<td>81442</td>
<td>81557</td>
<td>81552</td>
<td>81525</td>
<td>81747</td>
</tr>
<tr>
<td>800</td>
<td>81386</td>
<td>81566</td>
<td>81725</td>
<td>81760</td>
<td>81739</td>
<td>81813</td>
</tr>
<tr>
<td>900</td>
<td>81467</td>
<td>81683</td>
<td>81889</td>
<td>81972</td>
<td>81962</td>
<td>81874</td>
</tr>
<tr>
<td>1000</td>
<td>81541</td>
<td>81794</td>
<td>82050</td>
<td>82189</td>
<td>82194</td>
<td>81932</td>
</tr>
<tr>
<td>1100</td>
<td>81610</td>
<td>81900</td>
<td>82209</td>
<td>82411</td>
<td>82435</td>
<td>81985</td>
</tr>
<tr>
<td>1200</td>
<td>81674</td>
<td>82000</td>
<td>82365</td>
<td>82638</td>
<td>82687</td>
<td>82035</td>
</tr>
<tr>
<td>1300</td>
<td>114198</td>
<td>82095</td>
<td>82518</td>
<td>82872</td>
<td>82951</td>
<td>114476</td>
</tr>
<tr>
<td>1400</td>
<td>150510</td>
<td>82184</td>
<td>82669</td>
<td>83113</td>
<td>83227</td>
<td>150921</td>
</tr>
<tr>
<td>1500</td>
<td>193334</td>
<td>82268</td>
<td>82817</td>
<td>83362</td>
<td>83518</td>
<td>193914</td>
</tr>
<tr>
<td>1600</td>
<td>244690</td>
<td>82346</td>
<td>82962</td>
<td>83618</td>
<td>83826</td>
<td>245483</td>
</tr>
<tr>
<td>1700</td>
<td>307441</td>
<td>82417</td>
<td>83104</td>
<td>83885</td>
<td>84153</td>
<td>308501</td>
</tr>
<tr>
<td>1800</td>
<td>385866</td>
<td>102399</td>
<td>83243</td>
<td>84161</td>
<td>84501</td>
<td>387270</td>
</tr>
<tr>
<td>1900</td>
<td>486686</td>
<td>126005</td>
<td>83378</td>
<td>84450</td>
<td>84874</td>
<td>488541</td>
</tr>
<tr>
<td>2000</td>
<td>621103</td>
<td>152181</td>
<td>83510</td>
<td>84753</td>
<td>85276</td>
<td>623570</td>
</tr>
<tr>
<td>2100</td>
<td>809276</td>
<td>181537</td>
<td>83636</td>
<td>85071</td>
<td>85712</td>
<td>812611</td>
</tr>
<tr>
<td>2200</td>
<td>1091527</td>
<td>214736</td>
<td>83758</td>
<td>85407</td>
<td>86191</td>
<td>1096177</td>
</tr>
<tr>
<td>2300</td>
<td>1561935</td>
<td>252606</td>
<td>83874</td>
<td>85766</td>
<td>86722</td>
<td>1568791</td>
</tr>
<tr>
<td>2400</td>
<td>2502739</td>
<td>296219</td>
<td>83984</td>
<td>86149</td>
<td>87317</td>
<td>2514032</td>
</tr>
<tr>
<td>2500</td>
<td>5325141</td>
<td>346999</td>
<td>84086</td>
<td>86565</td>
<td>87999</td>
<td>5349777</td>
</tr>
<tr>
<td>2600</td>
<td>406879</td>
<td>84179</td>
<td>87019</td>
<td>88797</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Q2=500vph, Q3=1000vph, α=2

Figure 18 Total Cost versus Detour Length for Various Alternatives (Q2=500vph, Q3=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 $\alpha=1.8$. 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
\( (Q_2=500\text{vph}, Q_1=500\text{vph}, \alpha=1.8) \)

<table>
<thead>
<tr>
<th>Q1</th>
<th>Alt 4.1</th>
<th>Alt 4.2 (0.3)</th>
<th>Alt 4.2 (0.6)</th>
<th>Alt 4.2 (0.9)</th>
<th>Alt 4.3</th>
<th>Alt 4.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>80483</td>
<td>80433</td>
<td>80378</td>
<td>80323</td>
<td>72284</td>
<td>73190</td>
</tr>
<tr>
<td>200</td>
<td>80687</td>
<td>80648</td>
<td>80582</td>
<td>80493</td>
<td>72445</td>
<td>73282</td>
</tr>
<tr>
<td>300</td>
<td>80846</td>
<td>80818</td>
<td>80758</td>
<td>80642</td>
<td>72581</td>
<td>73371</td>
</tr>
<tr>
<td>400</td>
<td>80980</td>
<td>80968</td>
<td>80921</td>
<td>80791</td>
<td>72721</td>
<td>73454</td>
</tr>
<tr>
<td>500</td>
<td>81098</td>
<td>81103</td>
<td>81073</td>
<td>80942</td>
<td>72863</td>
<td>73531</td>
</tr>
<tr>
<td>600</td>
<td>81203</td>
<td>81227</td>
<td>81218</td>
<td>81094</td>
<td>73009</td>
<td>73603</td>
</tr>
<tr>
<td>700</td>
<td>81299</td>
<td>81343</td>
<td>81357</td>
<td>81247</td>
<td>73159</td>
<td>73670</td>
</tr>
<tr>
<td>800</td>
<td>81386</td>
<td>81451</td>
<td>81491</td>
<td>81402</td>
<td>73313</td>
<td>73733</td>
</tr>
<tr>
<td>900</td>
<td>81467</td>
<td>81552</td>
<td>81620</td>
<td>81559</td>
<td>73470</td>
<td>73792</td>
</tr>
<tr>
<td>1000</td>
<td>81541</td>
<td>81647</td>
<td>81746</td>
<td>81717</td>
<td>73632</td>
<td>73847</td>
</tr>
<tr>
<td>1100</td>
<td>81610</td>
<td>81736</td>
<td>81867</td>
<td>81876</td>
<td>73798</td>
<td>73898</td>
</tr>
<tr>
<td>1200</td>
<td>81674</td>
<td>81819</td>
<td>81984</td>
<td>82038</td>
<td>73971</td>
<td>73946</td>
</tr>
<tr>
<td>1300</td>
<td>114198</td>
<td>81896</td>
<td>82097</td>
<td>82201</td>
<td>74149</td>
<td>106217</td>
</tr>
<tr>
<td>1400</td>
<td>150510</td>
<td>81967</td>
<td>82206</td>
<td>82367</td>
<td>74332</td>
<td>142642</td>
</tr>
<tr>
<td>1500</td>
<td>193334</td>
<td>82033</td>
<td>82311</td>
<td>82534</td>
<td>74523</td>
<td>185628</td>
</tr>
<tr>
<td>1600</td>
<td>244690</td>
<td>82092</td>
<td>82411</td>
<td>82704</td>
<td>74720</td>
<td>237193</td>
</tr>
<tr>
<td>1700</td>
<td>307441</td>
<td>82145</td>
<td>82506</td>
<td>82877</td>
<td>74926</td>
<td>300208</td>
</tr>
<tr>
<td>1800</td>
<td>385866</td>
<td>101978</td>
<td>82597</td>
<td>83052</td>
<td>75141</td>
<td>378975</td>
</tr>
<tr>
<td>1900</td>
<td>486686</td>
<td>125530</td>
<td>82681</td>
<td>83231</td>
<td>75365</td>
<td>480245</td>
</tr>
<tr>
<td>2000</td>
<td>621103</td>
<td>151665</td>
<td>82760</td>
<td>83413</td>
<td>75601</td>
<td>615273</td>
</tr>
<tr>
<td>2100</td>
<td>809276</td>
<td>180984</td>
<td>82832</td>
<td>83598</td>
<td>75849</td>
<td>804313</td>
</tr>
<tr>
<td>2200</td>
<td>1091527</td>
<td>214147</td>
<td>82966</td>
<td>83788</td>
<td>76112</td>
<td>108787</td>
</tr>
<tr>
<td>2300</td>
<td>1561935</td>
<td>251981</td>
<td>82953</td>
<td>83981</td>
<td>76391</td>
<td>1560493</td>
</tr>
<tr>
<td>2400</td>
<td>2502739</td>
<td>295559</td>
<td>82999</td>
<td>84180</td>
<td>76690</td>
<td>2505732</td>
</tr>
<tr>
<td>2500</td>
<td>5325141</td>
<td>346303</td>
<td>83036</td>
<td>84385</td>
<td>77011</td>
<td>5341478</td>
</tr>
<tr>
<td>2600</td>
<td>406147</td>
<td>83060</td>
<td>84596</td>
<td>77360</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 11 Total Cost at Different Flow Rates for Four-Lane Two-Way Highway Work Zones
\((Q_2=500\text{vph}, Q_3=1000\text{vph}, \alpha=1.8)\)

<table>
<thead>
<tr>
<th>Q1</th>
<th>Alt 4.1</th>
<th>Alt 4.2(0.3)</th>
<th>Alt 4.2(0.6)</th>
<th>Alt 4.2(0.9)</th>
<th>Alt 4.3</th>
<th>Alt 4.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>80483</td>
<td>80436</td>
<td>80383</td>
<td>80330</td>
<td>72292</td>
<td>73190</td>
</tr>
<tr>
<td>200</td>
<td>80687</td>
<td>80674</td>
<td>80632</td>
<td>80571</td>
<td>72531</td>
<td>73282</td>
</tr>
<tr>
<td>300</td>
<td>80846</td>
<td>80858</td>
<td>80837</td>
<td>80760</td>
<td>72714</td>
<td>73371</td>
</tr>
<tr>
<td>400</td>
<td>80980</td>
<td>81021</td>
<td>81028</td>
<td>80953</td>
<td>72902</td>
<td>73454</td>
</tr>
<tr>
<td>500</td>
<td>81098</td>
<td>81171</td>
<td>81210</td>
<td>81149</td>
<td>73097</td>
<td>73531</td>
</tr>
<tr>
<td>600</td>
<td>81203</td>
<td>81311</td>
<td>81386</td>
<td>81349</td>
<td>73297</td>
<td>73603</td>
</tr>
<tr>
<td>700</td>
<td>81299</td>
<td>81442</td>
<td>81557</td>
<td>81552</td>
<td>73502</td>
<td>73670</td>
</tr>
<tr>
<td>800</td>
<td>81386</td>
<td>81566</td>
<td>81725</td>
<td>81760</td>
<td>73719</td>
<td>73733</td>
</tr>
<tr>
<td>900</td>
<td>81467</td>
<td>81683</td>
<td>81889</td>
<td>81972</td>
<td>73942</td>
<td>73792</td>
</tr>
<tr>
<td>1000</td>
<td>81541</td>
<td>81794</td>
<td>82050</td>
<td>82189</td>
<td>74174</td>
<td>73847</td>
</tr>
<tr>
<td>1100</td>
<td>81610</td>
<td>81900</td>
<td>82209</td>
<td>82411</td>
<td>74415</td>
<td>73898</td>
</tr>
<tr>
<td>1200</td>
<td>81674</td>
<td>82000</td>
<td>82365</td>
<td>82638</td>
<td>74667</td>
<td>73946</td>
</tr>
<tr>
<td>1300</td>
<td>114198</td>
<td>82095</td>
<td>82518</td>
<td>82872</td>
<td>74931</td>
<td>106217</td>
</tr>
<tr>
<td>1400</td>
<td>150510</td>
<td>82184</td>
<td>82669</td>
<td>83113</td>
<td>75207</td>
<td>142642</td>
</tr>
<tr>
<td>1500</td>
<td>193334</td>
<td>82268</td>
<td>82817</td>
<td>83362</td>
<td>75498</td>
<td>185628</td>
</tr>
<tr>
<td>1600</td>
<td>244690</td>
<td>82346</td>
<td>82962</td>
<td>83618</td>
<td>75806</td>
<td>237193</td>
</tr>
<tr>
<td>1700</td>
<td>307441</td>
<td>82417</td>
<td>83104</td>
<td>83885</td>
<td>76139</td>
<td>300208</td>
</tr>
<tr>
<td>1800</td>
<td>385866</td>
<td>102399</td>
<td>83243</td>
<td>84161</td>
<td>76481</td>
<td>378975</td>
</tr>
<tr>
<td>1900</td>
<td>486686</td>
<td>126005</td>
<td>83378</td>
<td>84450</td>
<td>76854</td>
<td>480245</td>
</tr>
<tr>
<td>2000</td>
<td>621103</td>
<td>152181</td>
<td>83510</td>
<td>84753</td>
<td>77256</td>
<td>615273</td>
</tr>
<tr>
<td>2100</td>
<td>809276</td>
<td>181537</td>
<td>83636</td>
<td>85071</td>
<td>77692</td>
<td>804313</td>
</tr>
<tr>
<td>2200</td>
<td>1091527</td>
<td>214736</td>
<td>83758</td>
<td>85407</td>
<td>78171</td>
<td>1087878</td>
</tr>
<tr>
<td>2300</td>
<td>1561935</td>
<td>252606</td>
<td>83874</td>
<td>85766</td>
<td>78702</td>
<td>1560493</td>
</tr>
<tr>
<td>2400</td>
<td>2502739</td>
<td>296219</td>
<td>83984</td>
<td>86149</td>
<td>79297</td>
<td>2505732</td>
</tr>
<tr>
<td>2500</td>
<td>5325141</td>
<td>346999</td>
<td>84086</td>
<td>86565</td>
<td>79979</td>
<td>5341478</td>
</tr>
<tr>
<td>2600</td>
<td>406879</td>
<td>84179</td>
<td>87019</td>
<td>80777</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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.
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.
References


_Hwy. and Transp._, 14-15.


A QuickZone Tailor-Made for Maryland web page, [www.tfhrc.gov/focus/mar01/quick.htm](http://www.tfhrc.gov/focus/mar01/quick.htm), January, 14th, 2002.


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 QuickZone 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:

Paul Schonfeld (pschon@eng.umd.edu)

Chun-Hung “Peter” Chen (chpchen@wam.umd.edu)
Appendix II Selected Papers on Work Zone Optimization by
the Report’s Authors


an Alternate Route.” TSC Report 2002-22, University of Maryland, College Park.

Alternate Routes.” TSC Report 2002-21, University of Maryland, College Park.