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Optimized scheduling of highway work zones

Yimin Tang
New Jersey Institute of Technology

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ABSTRACT

OPTIMIZED SCHEDULING OF HIGHWAY WORK ZONES

by
Yimin Tang

Highway maintenance activities usually require lane closures and disrupt traffic operations. Because of budget constraints, project deadlines, and the resulting traffic impact, the objective of this dissertation is to improve the efficiencies of traffic operation and maintenance work, and minimize the total project cost (i.e., agency cost and road user cost) by optimizing work zone schedules.

This dissertation focuses on the maintenance projects on multiple-lane highways. The objective total cost function is formulated while considering a discrete maintenance time-cost function and time-dependent traffic diversions. However, the work zone scheduling problem is a combinatorial optimization problem and difficult to solve analytically. This dissertation transformed the complicated problem into two separate steps: determining the time-dependent traffic diversion by the User Equilibrium Assignment, and minimizing the total project cost by a Genetic Algorithm. An iterative algorithm that integrates the two steps was developed. The optimized work zone schedule and the associated optimal diverted traffic flow can be found simultaneously after multiple iterations.

Case studies and extensive sensitivity analyses were conducted to analyze various scheduling scenarios with or without a time-cost function and traffic diversion. The relations among key decision variables were analyzed. Conclusions and recommendations are provided, and directions of future research efforts are discussed.

OPTIMIZED SCHEDULING OF HIGHWAY WORK ZONES

by
Yimin Tang

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APPROVAL PAGE

OPTIMIZED SCHEDULING OF HIGHWAY WORK ZONES

Yimin Tang

Dr. Steven I-Jy Chien, Dissertation Advisor — Date
Professor of Civil and Environmental Engineering, NJIT

Dr. Athanassios K. Bladikas, Committee Member — Date
Associate Professor and Chair of Industrial and Manufacturing Engineering, NJIT
Director of Interdisciplinary Program in Transportation, NJIT

Dr. Lazar N. Spasovic, Committee Member — Date
Professor of Civil and Environmental Engineering, NJIT

Dr. Paul M. Schonfeld, Committee Member — Date
Professor of Civil and Environmental Engineering, University of Maryland, College Park

Dr. Janice Daniel, Committee Member — Date
Associate Professor of Civil and Environmental Engineering, NJIT

Dr. Kyriacos Mouskos, Committee Member — Date
Research Professor, Transportation Institute, City College of New York

BIOGRAPHICAL SKETCH

Author: Yimin Tang

Degree: Doctor of Philosophy

Date: January 2008

Undergraduate and Graduate Education:

- Doctor of Philosophy in Transportation,
  New Jersey Institute of Technology, Newark, NJ, 2008

- Master of Science in Transportation,
  New Jersey Institute of Technology, Newark, NJ, 2001

- Master of Science in Highway Engineering,
  Southeast University, Nanjing, P. R. China, 1996

- Bachelor of Science in Highway Engineering,
  Southeast University, Nanjing, P. R. China, 1993

Major: Transportation

Presentations and Publications:

Yimin Tang and Steven Chien,
"Scheduling work zones for highway maintenance projects considering a discrete time-cost relation,"
Presentation at Transportation Research Board 87th Annual Meeting, Washington, D.C., 2008. (Forthcoming)

Yimin Tang and Steven Chien,
"Scheduling highway maintenance projects with Genetic Algorithms,"
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Wei Huang and Yimin Tang,
"A new regression equation for the tension stress in the middle-layer of a three-layer flexible pavement structure",
Journal of Chong Qing Jiao Tong University, Vol. 14, No. 1, 1995

To

My beloved wife and family

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LIST OF SYMBOLS

$AADT_m$, $AADT_a$	AADT on the mainline and the alternate route
A_j	Integer attributes defining work activity at interval j
B_i	Percentage of nighttime work in work zone i
C_{Ai}, C_{Vi}	Accident and vehicle operation costs of work zone i
C_M, C_I, C_U	Total maintenance, idling and road user costs
C_{Mi}^{k}	Maintenance cost of work zone i based on production option k
C_T	Total cost of a maintenance project
c_0	Capacity of the mainline
c_w	Capacity of the mainline with a work zone
D_i	Duration of work activity i
D_{min}	Minimum duration of work activities
D_{Mi}, D_{Qi}	Total moving delay and queuing delay of work zone i
D_M^j , D_A^j	Total moving delay on the mainline and alternate route at interval j
E_i , S_i	Ending and starting intervals of work zone i
f_{nc}	Nighttime cost factor
i	Index of work activities
j	Index of intervals
k	Index of production options
l_i	Length of work zone i
l_T	Total length of tapers and buffer
L	Project length

LIST OF SYMBOLS

m	Number of work activities in a work zone schedule
p_i^k	Work area length in work zone *i* using production option *k*
$p_{\min}$	Minimum work area length
$PD_{\max}$	Maximum project duration
P	Population size
P_{XO}, P_{MU}	Crossover ratio and Mutation ratio
Q_m^j, Q_a^j	Flow rates on the mainline and the alternate route at interval *j*
Q_d^j	Diverted traffic flow at interval *j*
q_1^j, q_2^j	Queue length at the beginning and end of interval *j*
r	Selection ratio for reproduction
r_a	Accident rate, number of accidents per 100 million veh-hours
T	Duration of intervals
$t_m{}^j, t_a{}^j$	Travel time on the mainline and the alternate route
$t_{XY}^0{}^j, t_{XY}{}^j$	Free-flow travel time, and travel time on link *XY*
V_f, V_a	Design speeds of the mainline and the alternate route
V_r, V_w	Average travel speeds on ramp and work zone
v	Value of users time in \$/vehicle-hour
v_a	Average cost per accident
v_d	Average idling cost per hour

LIST OF SYMBOLS

v_O	Average vehicle operation cost in dollar per vehicle-hour
z_1, z_3	Work zone setup cost and time
z_{2i}^{k}	Unit maintenance cost of production option *k* for work zone *i*
z_{4i}^{k}	Unit maintenance time of production option *k* for work zone *i*
α, β	Coefficients of BPR Function
θ_i	Cost coefficient of work zone *i*

CHAPTER 1

INTRODUCTION

1.1 Background

In recent years, surging traffic demand has deteriorated the performance of the highway system in the United States, and increased the needs of highway resurfacing, rehabilitation and restoration work (i.e., 3R projects). This increased traffic demand has caused more difficulties in traffic management and traffic control for the 3R projects. Maintenance activities not only disrupt traffic operations, but also introduce additional safety hazards to motorists, pedestrians, and workers.

The user delay caused by a work zone is frustrating and sometimes intolerable, especially during peak hours, and affects negatively public attitudes toward transportation agencies (Anderson and Ullman, 2000). The recent fuel price hikes also increase vehicle operating costs significantly, and make roadway users more sensitive to this traveling delay. The 2007 Urban Mobility Report (Texas Transportation Institute, 2007) indicated that the cost of traffic congestion to U.S. drivers was $78 billion in 2005, which is the result of 4.2 billion hours of delay and 2.9 billion gallons of wasted fuel. Ten percent of the total congestion cost is due to highway work zones (Federal Highway Administration, 2004). Furthermore, 1,010 people were killed in 2006 because of traffic accidents in work zones, and more than 40,000 people are injured each year (National Highway Traffic Safety Administration, 2007).

Because of the aforementioned adverse effects, traffic congestion and safety issues caused by highway maintenance activities have attracted concerns from Federal, state and local transportation agencies. Several studies and surveys (Federal Highway

Administration, 1998; Anderson and Ullman, 2000) provide nationwide strategies and statistics for mitigating work zone related delay as well as improving the safety of motorists and workers. Traffic management in highway work zones has been a critical component for mitigating these negative effects through the planning, design, and construction stages of projects.

The Highway Capacity Manual (2000) defines a work zone as a segment of highway in which maintenance and construction operations impinge on the number of lanes available to traffic or affect the operational characteristics of traffic flowing through the segment. A work zone may be a short-term maintenance work zone or a long-term construction zone, which can be distinguished by the nature of the barriers used to demarcate the work area (Highway Capacity Manual 2000). Long-term construction zones are generally established with concrete barriers, while short-term construction zones use standard channeling devices, such as traffic cones and drums according to the Manual on Uniform Traffic Control Devices (MUTCD, 2003). Additionally, the duration of capacity reduction is considered to be another major distinction. Long-term work zones utilized in highway reconstruction projects (e.g., bridge deck rehabilitation and replacement, highway widening, etc.) usually require significant amount of construction time. The size and schedule of long-term work zones are usually determined by the construction stages of a project.

Many other maintenance activities (e.g., pavement resurfacing, concrete pavement joint repairing, pothole repairing, utility work, etc.) may be performed by scheduling a number of temporary or short-term work zones along a maintenance project to reduce the traffic impact. To this end, the size and schedule of short-term work zones are determined by the work production rate (e.g., linear meters per hour), hourly traffic fluctuation, and construction time windows. Since highway maintenance projects are usually subject to budget constraints and project deadlines, and generate adverse traffic impacts, work zones should be well scheduled to mitigate the inconvenience to the public, and to reduce the total project cost. However, most research on scheduling maintenance projects did not jointly consider variable construction production rates and maintenance time-cost relations. Therefore, this research focuses on developing a sound optimization model that can handle such a complicated work zone scheduling problem.

1.2 Problem Statement

When planning and designing short-term maintenance projects, it is desirable to optimize time windows (or schedules) for maintenance activities to reduce delay. For example, work zone activities may be scheduled during off-peak periods, nighttime, and weekends. State and local transportation authorities usually grant designated time windows for lane closures. Limited construction time during daylight may restrict the size of work zones and thus increase the maintenance-related costs and project duration for the following reasons:

- Repetitive setup and removal of work zones as well as interrupted working processes may slow down the project progress and increase the overall project duration and cost.
- Frequent mobilizations due to work breaks inhibit productivity and may affect construction quality (Dunston, Savage, and Mannering, 1999).
- Nighttime operations may increase safety and productivity concerns, while weekend activities may cause problems in scheduling crews and neither have been popular (Denney and Levine, 1984).

- The appropriate length of lane-closures and the magnitude of the associated impacts (e.g., vehicular queue) have not been regulated explicitly by transportation agencies, which may cause more adverse impacts than necessary.

Additionally, transportation agencies are under increasing pressure to reduce construction time and minimize the impact of work zones to the traveling public and local businesses due to the surging traffic in recent years (Anderson and Ullman, 2000). By applying road user cost and incentive/disincentive fees, innovative contracting methods (e.g., A+B Bidding, Incentive/Disincentive Method, etc.) can increase contractors' productivities and reduce project duration. However, accelerating construction and compressing schedules are expensive because more work crews and equipment are required. On the other hand, a conservative estimation of project duration will also cause overpayment of the incentive fee (Herbsman et al. 1995).

The advent of Intelligent Transportation Systems (ITS), such as advanced traveler information systems (ATIS) and advanced traffic management systems (ATMS), enables today's travelers to take advantage of real-time traffic information (e.g., congestion, traffic accident and roadway construction) to plan their trips accordingly. Before approaching a congested area, such as a work zone, motorists are able to avoid delay by using alternate routes. Thus, the route choice and the associated traffic impact on a mainline with a work zone and alternate routes should be taken into consideration while planning maintenance activities.

Due to these aforementioned concerns, the relationship between work zone schedules, traffic impact, project duration and total cost should be thoroughly investigated. Typical questions that should be considered are:

- How many work zones should be scheduled to reduce the overall system cost, including the agency cost (i.e., maintenance and idling costs) and user costs?

- When should a work zone start, and how long should it take to complete the task with and without traffic diversion?
- How will the different production rates and maintenance costs affect the total cost and schedule with or without traffic diversion?
- What is the cost-effective production rate for a maintenance task?
- How will a compressed project duration affect work zone schedules and the total cost while considering maintenance time-cost relations and traffic diversion?
- What is the threshold of mainline traffic conditions that would justify diverting traffic?
- What are the effects on the total cost when improving an alternate route (e.g., capacity increase)?

The above questions can be answered by solving a combinatorial work zone scheduling optimization problem as formulated in this dissertation.

As discussed in Chapter 2, work zone optimization in previous studies mainly focused on the following directions:

- Optimizing crew assignment by minimizing total traffic delay (Fwa and Cheu, 1998; Chang, et al. 2001);
- Optimizing the length of a single work zone by minimizing total agency and user cost (McCoy, et al. 1980,1987,1998; Schonfeld and Chien, 1999; Chien and Schonfeld, 2001; Jiang and Adeli, 2003; Tien and Schonfeld, 2006);
- Optimizing schedules of multiple work zones for a maintenance project (Chien, Tang and Schonfeld, 2002; Chen and Schonfeld, 2004); and
- Optimizing work zone schedules and traffic diversions (Chen, 2003 and 2006).

However, the solutions of minimum system-wide total cost or minimum total delay under the assumption of a fixed construction production rate and unit cost may not be realistic in innovative contracting methods, because the over-simplified time-cost function may not reflect the interaction between the reduction in construction time (i.e., reduced road user cost) and the addition of construction cost incurred by accelerated construction. In addition to that, dynamic traffic diversions due to different work zone schedules was either ignored or over-simplified.

A sophisticated work zone scheduling model that incorporates dynamic traffic diversion requires large data collection efforts (e.g., O-D data) and computation resources, which may impede the implementation in medium or small scale maintenance projects, due to budget and time constraints. Hence, an efficient work zone optimization model, which can utilize existing data sources (e.g., AADT) as well as link early planning efforts and construction practices more closely by jointly considering time-dependent traffic diversion and maintenance time-cost relation, is highly desirable.

1.3 Objectives and Research Approach

By considering the aforementioned background and needs, this dissertation focuses on improving traffic operations and maintenance work efficiencies, and minimizing the overall project cost. Therefore, the proposed model will optimize work zone schedules by minimizing the total cost including agency and roadway user costs. The joint effects of maintenance time-cost relations and dynamic traffic diversions are incorporated into the formulation of the total cost function. The objectives of this study are to:

- Optimize work zone schedules by minimizing total cost including agency and user costs while incorporating time-dependent traffic diversions. A discrete time-cost relation will be utilized.
- Determine the time-dependent traffic diversion scheme to an alternate route at an upstream exit of the mainline roadway with a work zone by utilizing the User-Equilibrium (UE) Principle.

To achieve its objectives, this research transforms the complicated problem into two separate steps. The first step utilizes the UE Principle to solve the time-dependent traffic diversion problem based on the initial work zone schedules. The optimal diversion ratio is obtained when the predicted travel times on both the mainline and the alternate route are equal at the end of each interval. The second step evaluates the total cost and utilizes a Genetic Algorithm to reproduce improved work zone schedules. An iterative algorithm that integrates the two steps is developed to optimize work zone schedules by minimizing total cost including agency and user costs. Optimized work zone schedules and associated optimal time-dependent diverted flow can be found simultaneously after multiple iterations. The proposed optimization framework is illustrated in Figure 1.1.

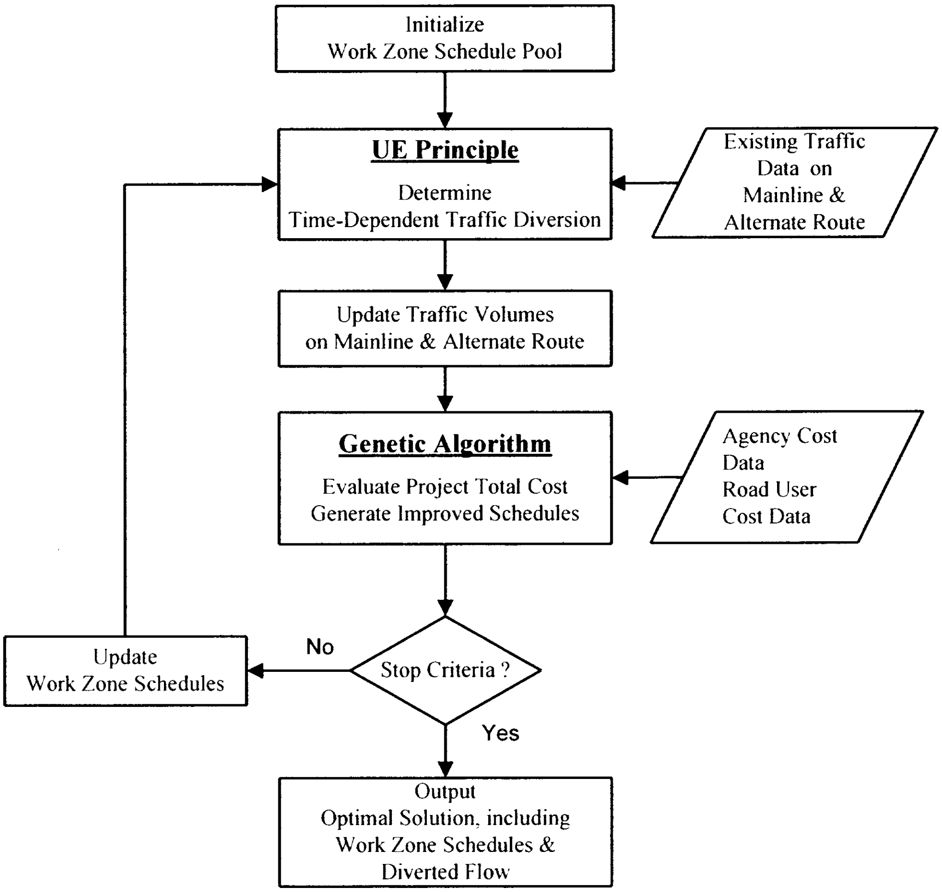


Figure 1.1 Framework of the proposed optimization model.

1.4 Scope of Work

The work scope of this research includes the development of a work zone scheduling optimization model for maintenance projects on multiple-lane highways. The proposed model will be focused on optimizing work zone schedules while considering a discrete time-cost relation and time-dependent traffic diversions to an alternate route. The scope of this research includes the following items:

- Formulate the objective total cost function for multiple-lane highway maintenance projects with one lane closure under time-dependent traffic conditions while considering a discrete time-cost relation;
- Develop link performance functions for a multiple-lane highway with a work zone and alternate routes.
- Determine time-dependent traffic diversions from the mainline road with a work zone to an alternate route based upon the User-Equilibrium (UE) principle.
- Optimize the work zone scheduling optimization problem, in which the developed objective total cost function is minimized subject to various constraints (e.g., maximum project duration).
- Collect real world data (e.g., construction costs and contractor production rates) for various types of maintenance activities and user time values.
- Calibrate the developed model and evaluate the performance of the solution algorithm and the quality of results.
- Analyze critical factors affecting the work zone schedules while considering time-dependent traffic diversions and discrete time-cost functions.
- Develop the guidelines for the implementation of the developed model.

1.5 Dissertation Organization

The dissertation is organized into six chapters. Chapter 1 introduces the background and the needs of developing a work zone scheduling model, and discusses the objective and the scope of this research. Chapter 2 summarizes the efforts of previous studies related to various aspects of highway work zones, such as traffic operations at work zones, optimization of work zone operations, current practices and optimization algorithms, etc. Chapter 3 presents the formulation of the objective total cost function for multiple-lane highway maintenance projects with and without traffic diversion to an alternate route. The development and validation of the developed Genetic Algorithm are presented in Chapter 4. In Chapter 5, a case study is presented with four different scenarios, i.e., a constant or a discrete maintenance time-cost function with or without traffic diversion. Extensive sensitivity analyses are conducted to explore the relationship between work zone schedules and the key decision variables. Finally, conclusions and suggestions for future studies are presented in Chapter 6.

CHAPTER 2

LITERATURE REVIEW

In the past two decades, the interest of federal, state and local transportation engineers, consultants and researchers in mitigating traffic disruptions due to maintenance activities has been increasing, and many studies have been conducted in this field. A comprehensive literature review has been conducted and the results are summarized herein. The literature review covers the following major aspects: traffic operations and measures in work zones, current practices in maintenance management, innovative contracting methods, construction scheduling methods, and work zone optimization.

2.1 Traffic Operations and Measures

This section discusses the previous studies related to traffic operations and measures in highway work zones, including speed and capacity in work zone, delay and queue estimation, traffic diversion and tools for planning work zones.

2.1.1 Speed and Capacity

The reduction of speed and capacity are primary factors affecting traffic flow through a work zone. This is the key information for determining traffic management strategies and planning work zone schedules.

While studying traffic characteristics within work zones on Illinois freeways, Rouphail and Tiwari (1985) evaluated the effects of the work intensities and the locations of maintenance activities on the mean travel speeds through work zones. The results showed that the mean speed decreased as the intensity of maintenance activities increased and as the maintenance activity was closer to the moving traffic in the open lane. Pain, McGee, and Knapp (1981) conducted a speed study in work zones, and found that the mean speed varied with several factors, such as traffic demand (e.g., peak or off-peak hours), lane closure configuration (e.g., right lane closure, left lane closure, or two-lane bypass), traffic control devices (e.g., cones, tubular cones, barricades and vertical panels), and location of the work zone. Rouphail, Yang, and Fazio (1988) derived various mean speeds and their coefficients of variation to describe speed changes in work zones. They found that the mean speed within a work zone does not vary considerably under light traffic demand conditions. Moreover, the speed recovery time increased as traffic demand increased. Based upon the traffic data collected at Indiana's four-lane two-way freeway work zones, Jiang (1999a) found that vehicle speeds at work zones remain stable and close to posted work zone speed limit under uncongested conditions. However, under congested traffic conditions, vehicle speed remains low and inconsistent with a drop, ranging from 32 to 56 percent.

A number of previous studies related to work zone capacity were based on field data. Dudek and Richard (1982) estimated work zone capacity based on the data collected from a number of work zones on freeways in Houston and Dallas, Texas. They considered various lane closure strategies and obtained cumulative distributions of observed work zone capacities. Krammes and Lopez (1994) estimated the baseline value capacity, 1600 pc/hour/lane, for all short-term freeway work zones based on 45 hours of traffic counts at 33 work zones in Texas. A procedure to adjust highway capacity for work zones was suggested, while the effects of work zone activities intensity, percentage of heavy vehicles, and the presence of entrance ramps were considered. However, the above data were collected under uncongested conditions. It was found that the queue discharge rate was 10~20% lower than the capacity in uncongested conditions based upon the data collected from Indiana's freeway work zones (Jiang, 1999a) and two freeway bottlenecks near Toronto, Canada (Cassidy, 1999). The aforementioned work zone capacity can be considered as a criterion to identify the traffic operational condition (i.e., congested or uncongested) associated with a work zone. Instead of using the work zone capacity, the queue discharge rate should be utilized in calculating the queuing delay caused by a work zone while traffic demand exceeds the work zone capacity.

Considering that the work zone capacity may be affected by numerous site-specific factors (e.g., percentage of heavy vehicle, roadway geometry, work zone speed, work time, etc), several mathematical models (e.g., regression models and Artificial Neutral Network models) have been developed recently to estimate the capacity. Kim, Lovell and Paracha (2001) developed a linear regression model based upon the field data collected from 12 freeway work zones in Maryland. This regression model was developed based upon the mathematical relationship among work zone capacity and several independent factors, such as location of work zone, number of closed lanes, percentage of heavy vehicles and lateral distance to the opened lanes, work zone length and grades as well as the intensity of work activity.

Karim and Adeli (2003) developed a Radial Basis Function Neural Network (RBFNN) to estimate the capacity of freeway work zones by considering 11 factors including number of lanes, number of open lanes, layout, length, lane width, percentage trucks, grade, speed, work intensity, darkness factor, and proximity of ramps. The RBFNN model was trained using 40 field data sets of work zone capacity and tested by

27 data sets. It was found that a large deviation (20~71%) occurred between the estimated and actual work zone capacity because different truck traffic may affect work zone capacity significantly. The truck percentages in the test data sets were beyond the maximum range of truck percentages in the training data. Later, Adeli and Jiang (2003) developed a Neural-Fuzzy Logic model and added six factors (i.e., location, duration, work day, weather, pavement condition and driver composition) into the previous RBFNN model (Karim and Adeli, 2003). A total of 168 data sets collected from various work zones in several states of the United States and Toronto in Canada were used to develop the Neural-Fuzzy Logic model. The prediction error was reported within a range of 0.9~13.5% based upon 14 sets of testing data.

2.1.2 Delay and Queue Estimation

Queuing delay incurred by motorists traveling through work zones is a primary component of total delay. Two well-known methods are used to determine the effects of queuing, which are deterministic queuing theory (Dudek and Richards, 1982; Schonfeld and Chien, 1999; Jiang, 2001) and shock wave theory (Wirasinghe, 1978; Newell, 1993).

Deterministic queuing theory, which has been in practice for decades, is usually implemented by using a queuing diagram consisting of two cumulative curves for arrival and departure vehicles respectively. Employing deterministic queuing theory, Cassidy and Han (1993) estimated the average delay caused by work zones on a two-lane, two-way highway with one opened lane. Later, to consider the stochastic nature of traffic operations, Cassidy et al. (1994) employed Monte-Carlo simulation and statistical estimation to identify the distribution of average delay. It was found that using the deterministic queuing theory could achieve a reasonable mean value of average delay.

Son (1999) extended Newell's model (1969), which was developed based on the theory of fluid approximation, for estimating delay at an intersection of a one-way street controlled by an actuated traffic signal. Son's model was validated based upon data collected from a two-lane two-way highway. However, the oversaturated traffic condition was not considered. Jiang (2001) developed a model to estimate traffic delay of freeway work zones by considering deceleration and acceleration delay, queuing delay, and speed reduction delay. Deterministic queuing theory was utilized to estimate the maximum and average queue lengths, and the time for completely discharging the queue.

In addition to traffic delay, queue length has been used as a measure of roadway congestion, and is utilized by transportation agencies to determine the optimal control strategy. However, queue length as defined in previous studies was a conceptual vertical (or point) queue based upon deterministic queuing theory, which cannot represent the physical queue length in real world operations.

The shock wave theory, also called the L-W-R model, was developed by Lighthill and Whitham (1955), and by Richards (1956). The shock wave theory assumes that traffic flow is analogous to fluid flow, and utilizes a flow-speed-density relationship to analyze the transition of traffic flow over time and space. Therefore, the shock wave theory could be used to analyze the length of physical queues based on deterministic demand and capacity. It is particularly well suited to evaluate the space occupied by the queuing processes and the interaction between the queuing processes (May, 1990).

Wirasinghe (1978) developed a model to estimate total delay caused by an incident based upon shock wave theory. It was indicated in a graphical interpretation that the queue length is usually underestimated by the deterministic queuing theory in which only two traffic flow states (i.e., free-flow and jam) were considered, but the transition between the two states was neglected.

Al-Deek, Garib and Radwan (1995) utilized the time-space domain determined by shock wave theory to identify the influence of single and multiple freeway incidents. Based upon the speed data collected by loop detectors located in the congested domain, the cumulative delay caused by single and multiple incidents can be calculated respectively. This method was implemented on Route I-880 in California, and achieved satisfactory results.

Chin (1996) compared the estimated delay and queue length at a freeway bottleneck by using both deterministic queuing theory and shock wave theory. It was found that both theories can generate comparable results of delay and congestion duration. The shock wave theory was found to estimate physical queue length more accurately. Lovell and Windover (1999) further clarified the definitions of queue in both theories, and emphasized that the total delay and queue length estimated by the two theories are consistent and accurate. At any given time, the queue defined in queuing theory is a conceptual point queue representing those vehicles that would like to have departed from the bottleneck by that time, but have not yet been able to pass the bottleneck (Lovell and Windover, 1999). The point queue does not include the vehicles that are slowly moving and impeded by the back of the point queue. However, the queue considered in the shock wave theory is defined as the real physical vehicular queue including those vehicles in transition from the state of free flow to the state of congestion.

In this dissertation, the deterministic queuing theory will be employed to estimate queuing delay considering the time-dependent traffic volumes and roadway capacity.

2.1.3 Traffic Diversion

Today's travelers are able to obtain accurate roadway information through various media (e.g., variable message signs, highway advisory radio and other advanced traveler information systems), and then choose preferable routes accordingly to bypass roadway construction. In addition, traffic demand management (TDM) strategies are used to encourage travelers to take alternate route(s) or mode(s) to alleviate traffic congestion due to major roadway construction work. Thus, the applicability of traffic diversion becomes an important factor that influences the decision-making of work zone schedules.

A field study on I-140 in San Antonio, Texas, indicated that traffic diversion usually occurs at urban freeway work zones where frontage roads were adjacent to the freeway (Ullman, 1996). It was found that traffic volume was significantly reduced (up to 40%) at entrance ramps before reaching the freeway queue. Moreover, an even higher reduction of traffic volume (up to 90%) was observed on the entrance ramps within the jammed freeway section. However, at the exit ramps located within the queued freeway segment, the variations of exiting traffic volume were fluctuating due to many factors, such as traffic diversion at upstream entrance ramp, traffic flow characteristics, and capacity of the exit ramp. For the exit ramps upstream of the freeway queue, the observed traffic volumes were not significantly affected by downstream congestion.

Later, Ullman and Dudek (2003) developed a macroscopic traffic flow model based on an analogy to fluid-flow theory in a permeable pipe to predict the queue propagation caused by a short-term work zone with traffic diversion in an urban area. A permeability factor was defined to represent the effect of natural diversion along a corridor in an urban area. However, the factor is a site-specified parameter that needs to be calibrated with a large amount of field data. Therefore, that model is not applicable to analyzing work zone delay.

Chen (2003 and 2006) optimized work zone lengths, schedules and traffic diversion ratios of detour routes as well as traffic control alternatives (i.e., partial, full or crossover lane closures) by minimizing the total cost consisting of transportation agency and user costs. In Chen's study (2003), the optimal diversion ratios were obtained numerically based upon the system optimum assignment, i.e., minimum total cost. However, by considering time-dependent traffic volumes, the assumption of a constant traffic diversion ratio in the presence of a work zone may be relaxed.

Besides work zone schedules, other factors affecting traffic diversion at work zones include time-dependent traffic demand, user's route choices, and different Origin-Destinations pairs. A dynamic traffic assignment model (e.g., Jayakrishnan, et al. 1995; Tong et al. 2000; Kuwahara et al. 2001) considered the distribution of traffic flows over time in a roadway network, while assuming different traveler's preferences of shortest-path, such as the dynamic system-optimal assignment (DSO) that minimizes network total travel cost; the reactive dynamic user-optimal assignment (RDUO) that minimizes any individual instantaneous travel cost, and the predictive dynamic user-optimal assignment (PDUO) that minimizes any individual actual travel cost (Tong, 2000).

Given a work zone schedule on the mainline, optimizing the traffic diversion to alternate route(s) can be handled independently in order to simplify the complexity of the scheduling problem. This dissertation develops an iterative algorithm, which optimizes work zone schedules and time-dependent diverted traffic flow sequentially and iteratively. The proposed optimization framework is depicted in Figure 1.1.

2.1.4 Tools in Work Zone Planning

Memmott and Dudek (1984) developed a computer model, called Queue and User Cost Evaluation of Work Zones (QUEWZ) that has been used to estimate average speeds in work zones and calculate user costs, including delay costs and vehicle operating costs. QUEWZ-98 is the latest version of QUEWZ, and was developed by the Texas Transportation Institute and the Texas Department of Transportation. The QUEWZ-98 model, designed for freeway facilities or multilane divided highways, can determine the number of hours available for a lane-closure without causing excessive congestion based on time-varying hourly traffic demand. The excess emissions due to the lane closure can also be estimated.

QuickZone (Mitretek System, 2000), a key component of the Strategic Work-Zone Analysis Tools (SWAT) Program, was developed by FHWA. QuickZone is a Microsoft Excel spreadsheet-based tool, which adopts the deterministic queuing theory to estimate traffic impact (e.g., delay and queue length) in the network during the entire project duration based upon a set of input parameters, such as hourly demand, traffic diversion ratios, the capacities of work zones and existing roadways in the study network, and the schedule and length of work zones.

However, neither QUEWZ nor QuickZone are capable of optimizing the work zone schedule while considering time-dependent traffic diversion and the trade-off between transportation agency and user costs subject to budget and time constraints.

The Construction Analysis for Pavement Rehabilitation Strategies (CA4PRS) software is a comprehensive production analysis tool designed to estimate the maximum probable length of highway pavement reconstruction and compare different pavement alternatives and construction methods (Lee, et al. 2005a, 2005b). Marco- and microscopic traffic simulation models may be integrated with CA4PRS to quantify road user costs for different construction plans and sequences. This software was designed based on California's practices of Portland Cement Concrete (PCC) pavement rehabilitation, and is suitable for scheduling long-term construction zones for reconstructing PCC pavement.

2.2 Current Practices in Maintenance Management

Managing surging traffic demand at highway work zones has been a challenging task. The practices of maintenance management including techniques, methods and processes of state transportation agencies have been discussed in several previous studies (Burns, 1990; FHWA, 1998; Anderson and Ullman, 2000).

Many transportation agencies have devoted much attention to schedule various types of maintenance activities, such as bridge deck and joint repairs, pavement patching, sweeping, pavement marking and resurfacing (Burns, 1990). In addition, new technologies have been adopted for maintenance activities to alleviate congestion and to enhance traffic safety, such as moveable barriers (Satterfield, 2001) and Intelligent Transportation Systems (ITS) (Lasek, 1999). A moveable barrier brings a quick, easy and cost saving option to setup or relocate a short-term work zone in accordance with the designated schedule. ITS technologies allow traffic engineers to adjust the pre-determined work zone schedules based upon historical or real-time traffic data.

Table 2.1 contains the results from a survey (Burns, 1990) of 28 transportation agencies in 18 states of the United States and one province in Canada. The majority (89 percent) of the agencies scheduled moving and short-term maintenance activities during daytime off-peak hours. However, it was reported that an increasing amount of work is being scheduled during nighttime and weekend hours due to the limited daytime off-peak hours. Thus, a sound scheduling model is desirable to schedule work zones to mitigate the traffic impact due to insufficient daytime off-peak hours.

Table 2.1 Surveys of Agency Scheduling Practices

	Type of Work Zone							
	Moving		**Short Term**		**Long Term**		**Close Freeway**	
	No.	%	No.	%	No.	%	No.	%
Daytime Off Peak	25	89	25	89	15	54	3	11
Nighttime	7	25	10	36	13	46	7	25
Weekend	9	32	12	43	12	43	7	25
No Restrictions	0	0	2	0.7	2	0.7	1	0.3

[Source]: Burns, E.N. "Managing Urban Freeway Maintenance," NCHRP, Synthesis of Highway Practice 170, pp.7, 1990.

Another survey conducted in 1998 (Dunston et al. 1999) indicated that single lane closure was the prevailing choice in the practice of six States (i.e., Illinois, California, Georgia, Massachusetts, Texas, and Florida), whereas the choice of working hours during nighttime and daylight was roughly even. The survey also found that multilane closure was not frequently utilized because it was considered as a low rank alternative and preferred only for nighttime work. The single lane-closure work zone is considered as the primary type of work zone in this dissertation.

To accommodate increasing maintenance workloads, many agencies have implemented Maintenance Management Systems (MMS) to coordinate their resources, equipment and crew (Burns, 1990). The MMS utilizes productivity standards (i.e., the production rate) to generate the required work duration for each type of maintenance work and then the workloads can be managed efficiently. Furthermore, it was found that more than 50 percent of transportation agencies use both their own crews and contractors to perform pavement-patching work on their urban freeways. Table 2.2 summarizes the prevailing production rates of several typical roadway maintenance items adopted in resurfacing projects by the New Jersey Department of Transportation (NJDOT, 2001a). The production rate herein is defined as the amount of work completed in a 8-hour working day per crew.

Table 2.2 Itemized Production Rates in Resurfacing Projects

Item	**Production Rate (per 8-hour working day per crew)**	
	English	Metric
Removal of Vertical Curb	400 Linear Foot	120 Linear Meter
Removal of Bituminous Concrete Overlay	2500 Sq. Yard	2090 Sq. Meter
Bituminous Concrete Base or Surface Course	1300 Tons	1180 Mega Gram
Milling (up to 2 inches thick)	6000 Sq. Yard	5000 Sq. Meter
Concrete Barrier Curb	250 Linear Foot	75 Linear Meter
Concrete Vertical Curb	300 Linear Foot	90 Linear Meter
Electrical Conduit	150 Linear Foot	45 Linear Meter
Fiber Optic Conduit	1000 Linear Foot	300 Linear Meter
Beam Guide Rail	500 Linear Foot	150 Linear Meter

[Source]: NJDOT Capital Program Management, Construction Scheduling Standard Coding and Procedures for Designer and Contractors Manual, BDC01T-5, 2001.

A higher production rate may be used if construction needs to be accelerated to meet a tight project schedule. For example, NJDOT utilizes a production rate of 1.20 times the standard production rate to accelerate construction processes if I/D contracting method and A+B Bidding are not applicable. Under the Incentive/Disincentive (I/D) method, 1.33 times the standard production rate may be utilized to establish the time savings that can be achieved with I/D provisions. Similarly, 1.25 times the standard production rate will be applied to establish construction duration with A+B Bidding.

It is worth noting that a higher production rate is usually accompanied by higher construction cost, which suggests that the work zone schedule be optimized to minimize project total cost. For example, accelerated construction may reduce lane occupancy charges, and offset the additional construction cost due to high production rate. Thus, subject to budget constraint and project deadline, developing a model to optimize the schedule of maintenance activities is desirable. This dissertation is focused on optimizing work zone schedules to minimize total cost while considering a discrete maintenance time-cost relation.

2.3 Innovative Contracting Methods

When a maintenance project proceeds into the construction stage, the road user cost (RUC) associated with traffic congestion is not sensitive to the contractor's total cost. To mitigate the congestion impact on roadway users by regulating work zone schedules, time-based lane occupancy charges may be used to increase contractor's productivity and reduce contract time by employing innovative contracting methods, such as cost-plus-time bidding (A+B), Incentive/Disincentive (I/D), A+B bidding plus I/D and lane-rental, which are introduced briefly below:

2.3.1 Cost Plus Time (A+B) Bidding

The bid price of the Cost plus Time (A+B) bidding method is the summation of construction costs (i.e., Component A), and the product of total proposed construction duration times road user cost per day, which is pre-determined by the transportation agency (i.e., Component B). To win a contract, contractors must determine the tradeoff between construction cost and time to minimize the total combined bid. After awarding the project to the winning contractor, Component A and the proposed construction duration will become the official contract budget and duration, respectively.

A+B Bidding has two versions, which are A+B Only and A+B plus Incentive/Disincentive (I/D) clauses. When implementing A+B with I/D method, contractors may receive an incentive for early project completion; however, the liquidation damage for late completion are applicable to both versions.

A+B Bidding is suitable for highway maintenance projects requiring traffic restrictions, lane closures and detours that may result in high road user costs and significant impacts to local communities. As indicated in a survey of 101 projects conducted by Herbsman (1995b), 24 States have implemented A+B Bidding. It was found that the average reduction in project duration was ranged from 6% to 83% of the original projection durations regarding of the above different types of projects. However, the reduction in project duration due to A+B Bidding is usually achieved by extending work schedules, such as work during night and weekend; therefore, the lane occupancy may not be reduced in the same proportion as the total time saving of overall construction (Anderson and Ullman, 2000). According to the survey, A+B Bidding with an I/D clause has been popular and used in 94% of the above projects.

2.3.2 Incentive/Disincentive (I/D) Method

In the Incentive/Disincentive (I/D) method, the target duration of a project (i.e., contract time) is fixed and determined by transportation agencies. The incentive fee is awarded to the contractor if the date of completion is earlier than the target date. Otherwise, the contractor has to pay a disincentive charge as a penalty for delay. The previous survey (Herbsman et. al., 1995a) indicated that 35 States have implemented I/D contracting, and the most popular I/D fees were between $2,500/day and $5,000/day. The I/D fee may be quite high for liquidated damages on reconstruction projects performed under heavy traffic conditions, where the impact on road users is substantial (Anderson and Ullman, 2000). Some States (e.g., New Jersey and Iowa, etc) calculate I/D fees as a percentage of total project cost as depicted in Table 2.3 (Herbsman, 1995a). Furthermore, most states utilize the same value for incentive and disincentive fees.

Table 2.3 Schedule of Daily I/D Fees Utilized by NJDOT

Total Project Cost (in millions of dollars)	I/D Rates ($/day)	Converted I/D Rates ($/hour)
0~0.5	$1,000	$45
0.5~1.5	$2,000	$85
1.5~5.0	$5,000	$210
5.0~10.0	$6,000	$250
10.0~15.0	$8,000	$330
15.0~20.0	$10,000	$420
20.0~30.0	$13,000	$550
30.0~40.0	$16,000	$670
40.0~50.0	$17,000	$710
50.0+	0.03% of total project cost	N/A

[Source]: Herbsman, (1995a). The hourly I/D rates are converted from daily I/D rates by dividing 1 day =24 hours.

In fact, contractors may earn incentive because of conservative engineers' time estimates (Herbsman et al. 1995a). Therefore, an overestimated project duration may increase the total costs to transportation agencies; whereas an underestimated project duration may not generate contractors' incentives because they will not be able to earn any. Therefore, the key of I/D contracts is to accurately estimate project duration prior to advertising a project, because the project duration serves as a benchmark to determine the incentive payment or disincentive charge. The optimization model proposed in this dissertation may assist transportation agencies to develop optimal project durations for short-term highway maintenance projects, and establish the time restrictions of lane closures.

2.3.3 Lane Rental Method

The lane rental method designates project duration and a schedule of lane rental fee before the bidding processes. The lane rental fee is defined as a daily-based or hourly-based charge, an example of which is presented in Table 2.4. Contractors are required to pay the rental fee for closing any travel lanes for construction, as if they rented the right-of-way of the lanes for a temporary duration. Thus, contractors have to minimize the combined construction and lane rental costs to determine a competitive bid price by deploying appropriate construction methods and lane closure schedules. However, the lane rental cost will be included into the contractor's construction cost (Herbsman et al. 1998), and will be eventually paid by transportation agencies.

Table 2.4 Examples of Lane Rental Fee

Lane Type	Daily Fees (dollars/day)	Hourly Fees (6:30 AM~9:00AM) (dollars/hour)	Hourly Fees (9:00 AM~3:00PM) (dollars/hour)
One lane	20,000	2,000	500
One shoulder	5,000	500	125
One lane and shoulder	25,500	2,500	625
Two lanes	45,000	4,500	1,250
Two lanes and shoulder	50,000	5,000	1,375

[Source]: Anderson and Ullman, (2000). "Reducing and mitigating impacts of lane occupancy during construction and maintenance," NCHRP, Synthesis 293, pp. 27.

Lane closures are unavoidable in most highway 3-R projects, such as pavement resurfacing and roadway widening. Because of the lane rental method, a contractor would have an economic motivation to reduce the duration of lane closures to minimize the lane rental charges. An optimized work zone schedule can bring substantial benefits to contractors because of the potential reduction in lane rental charges. The lane rental method can save 23~38% of construction cost and lane closure duration on the basis of

British experiences, although it raises pressures on resource allocation and manpower management (Herbsman et al. 1998).

By employing innovative contracting methods, the reduction of contract time can be either achieved by the competition between bidding contractors (i.e., A+B Bidding) or encouraged by financial rewards (e.g., I/D method). Time delay may be penalized by using I/D and lane-rental methods (Herbsman, et al. 1995a). However, as a result of innovative contracting, the accelerated progress of construction may result in higher cost so that a time-cost tradeoff analysis is desirable. Note that there is little effort on optimizing work zones while jointly considering the agency cost, user cost, and time-cost tradeoff, which is considered in this dissertation.

2.4 Construction Scheduling Methods

A number of network scheduling methods, such as Critical Path Method (CPM) and Program Evaluation and Review Technique (PERT), have been extensively used for scheduling and monitoring the progress of construction projects.

Based upon the fixed duration of each task, CPM is used to determine the duration of the entire project as well as deadlines for each task so that they will not delay the entire project. PERT has been utilized to estimate the probability of completing a project subject to a time constraint while considering the variations in the duration of each task. However, the traditional network scheduling methods (i.e., CPM and PERT) only analyze network-wide construction activities for identifying critical path(s) and project duration (Liu, et al. 1995); however, project cost and duration minimization are not considered.

A Repetitive Scheduling Method (RSM), such as the Linear Scheduling Method (LSM), is suitable for scheduling repetitive tasks, e.g., carpeting each floor in a high-rise building construction project and paving multiple highway segments in highway construction projects. RSM may compensate for the drawback of CPM where continuous utilization of resources across repetitive tasks cannot be assured (Harris and Ioannou, 1998). Adeli and Karim (1997) developed a mathematical model to minimize direct construction cost while considering both non-repetitive and repetitive tasks. From the standpoint of contractors, the above study was particularly focusing on the optimization of project duration and direct construction cost for a large-scale construction project based upon the fixed duration of each task. However, while considering the constraints of allowable construction time windows and road user cost in highway maintenance projects, the optimal duration and minimal cost of different tasks that require lane-closures (e.g., pavement resurfacing) need to be re-evaluated.

Furthermore, as an enhancement of CPM, time-cost trade-off analyses (Liu, et al. 1995; Adeli and Karim, 1997; Li and Love, 1997; Feng, et al. 2000) minimized the contractor's total cost and project duration by balancing direct (e.g., material, labor and equipment, etc) and indirect (i.e., overhead) costs for a construction project. The above time-cost trade-off analyses were conducted from a contractor's stand point, which did not consider road user cost.

A pilot study that combined construction planning with the A+B bidding method was conducted by El-Rayes (2001), where a dynamic programming model was employed to optimize resource utilization for long-term highway construction projects. Given several highway sections and a number of construction activities associated with each highway section, the minimum total combined bid, including direct cost, indirect cost and road user cost was achieved through optimal crew formation and continuity for each construction activity. However, that study focused on planning a set of repetitive activities across multiple highway construction sections, in which the road user cost and the restrictions of lane closures associated with highway 3R projects were not considered.

2.5 Work Zone Optimization

A number of studies related to work zone optimization have been conducted in the past two decades, such as the optimization of long-term work zones (McCoy et al. 1980, 1987, 1998, etc), short-term work zones (Chien et al. 2001, 2002, etc) and crew assignment (Fwa et al. 1998; Chang et al. 2001; Wang et al. 2002). The objective functions in the above studies were to minimize either the total cost (e.g., agency's cost, user cost, etc) or the total delay (e.g., queuing delay and speed reduction delay), as discussed below.

2.5.1 Work Zone Length

McCoy, Pang, and Post (1980) developed a framework to optimize the length of a work zone with crossover (i.e., two-lane two-way operation) on existing four-lane divided highways by minimizing the total cost, including speed reduction delay cost, accident cost, additional vehicle operating cost and traffic control costs based on 1979 data in Nebraska. Average Daily Traffic (ADT) was utilized to estimate the delay cost during a given work zone duration. Because of changes in road user cost and accident rates, McCoy and Peterson (1987) obtained the optimal work zone length that was about 60 percent longer than what was found in his Nebraska study (McCoy, 1980). Martinelli and Xu (1996) integrated the queuing delay cost into McCoy's model (1980), and concluded that the optimal work zone length is not affected by queuing delay for long-term work zones. To enhance McCoy's model (1980), McCoy and Mennenga (1998) formulated a new cost function considering installation, relocation, maintenance and removal costs of traffic control devices. An optimal work zone length with partial lane closure (i.e., single lane closure along one travel direction) was derived.

Schonfeld and Chien (1999) jointly optimized work zone lengths and the associated traffic control cycles for two-lane two-way highways by minimizing the total cost (e.g., maintenance and user delay costs) considering static traffic conditions. The moving delay due to speed reduction within a work zone was neglected. It was found that the optimal work zone length is significantly affected by traffic volumes, travel speed within the work zone, maximum discharge rate and work zone setup cost. A sensitivity analysis was also conducted and results showed that as traffic flow increases, the reduction of work zone length offers a way to increase the discharge rate that may reduce the user delay cost, albeit at increased maintenance cost. Later, Chien and Schonfeld (2001) optimized work zone length for four-lane highways by minimizing the total cost including agency cost, accident cost, and user delay cost. The optimal work zone length was optimized analytically by assuming a uniform hourly traffic distribution. It was found that the total cost is very sensitive to the optimal work zone length under heavy traffic conditions.

Jiang and Adeli (2003) optimized work zone length for multi-lane freeways by minimizing the total cost considering the same cost components in Chien's model (2001), while darkness and seasonal demand factors were introduced to reflect the extra cost incurred by nighttime work and seasonal traffic variation.

Tien and Schonfeld (2006) optimized a single work zone length under assumptions of static traffic demand, a hyperbolic maintenance time-cost function and a fixed traffic diversion ratio per work zone. However, the simplified hyperbolic time-cost relation may not be applicable to real world practices.

2.5.2 Work Zone Schedule

Several studies (Chien, Tang, and Schonfeld, 2002; Chen, 2003 and 2006) have been conducted to optimize work zone schedules at a project level by dividing the total project length into smaller work zones for reducing the impact on roadway users. The optimal schedules of work zones and work breaks were obtained by minimizing the total agency and user costs.

To consider possible maintenance breaks, Chien, Tang, and Schonfeld (2002) introduced labor and equipment idling costs into the total cost function developed by Schonfeld and Chien (1999) for two-lane two-way highways. This enhancement enables the model to handle more practical conditions (e.g., scheduling a maintenance break to avoid peak hours). A sequential search method was developed to optimize the project starting time and the schedule of work zones (e.g., timing and length) subject to time-dependent traffic demand.

Considering traffic diversion through detour routes, Chen (2003) developed an optimization model for scheduling work zones on four-lane two-way and two-lane two-way highways. Four alternatives were evaluated, including (1) one-lane closure, (2) one-lane closure with single or multiple detour route(s) carrying partial traffic on the same direction, (3) full closure on one direction while all traffic diverted to single or multiple detour route(s), and (4) full closure on one direction with the crossover of all traffic into the opposite direction. By minimizing project total cost, a preferable combination of alternatives was selected for each work zone of the project. Chen (2006) included a time constraint into the previous optimization model (2003) to reflect the allowable lane closure time in construction practice. A high penalty cost is imposed on the work zone schedules that violate the time constraints.

The schedule of work zones, however, may be affected by other factors and constraints that were not discussed in previous studies. For example, a discrete maintenance time-cost relation and a project deadline may have a significant influence on total project cost and work zone schedules. Therefore, the proposed optimization model discussed in this dissertation will address the relation between work zone schedule and road user cost, total cost and project duration, as well as their combined impacts on the work zone schedules.

2.5.3 Job-Shop Problem in Maintenance Scheduling

A few studies were conducted in the field of Pavement Management Systems (PMS) and Maintenance Management Systems (MMS), which focused on scheduling crew assignments for multiple routine maintenance tasks (e.g., patching, utility works, etc) in a roadway network. These studies are very similar to "Job-Shop" problems, i.e., assigning multiple maintenance jobs to fewer crews, in which the maintenance activities were simplified as temporary isolated jobs with given durations. The cost, work zone length, time restriction of construction and project deadline were not taken into account.

By employing Genetic Algorithms (Fwa and Cheu, 1998), a crew scheduling problem was optimized by minimizing total traffic delay (i.e., speed reduction and queuing delay) based on limited working hours of each crew. However, time restriction of lane closures was not considered. Later, Ma, Cheu and Lee (2004) developed a hybrid Genetic Algorithm-Simulation approach to solve a daily maintenance work assignment problem. The microscopic simulation software PARAMICS was utilized to estimate the total network delay caused by simultaneously on-going maintenance activities. However, the advantage of the robust searching ability in Genetic Algorithm was restricted due to excessive computation time, which resulted in the optimized schedule not being available in a timely fashion (e.g., within a day) even using a very small population size. Chang, Sawaya and Ziliaskopoulos (2001) proposed a Tabu-search approach to optimize the schedule of maintenance jobs by minimizing total traffic delay in a roadway network. A dynamic traffic assignment model was integrated to assess the network traffic delay while considering the effects of multiple work zones.

2.5.4 Optimization Algorithms

As indicated in a previous study (Chien, Tang and Schonfeld, 2002), the work zone scheduling problem is a large combinatorial optimization problem where the solution space consists of multiple decision variables, i.e., starting and ending times of the project, work zone lengths, and maintenance breaks. Therefore, a powerful searching algorithm, such as the Genetic Algorithm, is desirable to find a near optimum solution. Potential optimization techniques, such as Genetic Algorithm (GA), Tabu-Search (TS), and Simulated Annealing (SA) are suitable for solving this combinatorial problem.

Genetic Algorithm (GA) is a stochastic algorithm whose searching methods mimic natural phenomena: genetic inheritance and Darwinian strife for survival (Michalewicz, 1999). A Genetic Algorithm includes several major components: a genetic representation of potential solutions, a fitness function (i.e., objective function) for performance evaluation, a selection mechanism for evolution, and a reproduction function to generate offspring (i.e., new solutions). Genetic Algorithm shows good performance in solving large combinatorial optimization problems in many transportation research areas, such as pavement maintenance scheduling problems (Fwa, et al. 1998 and 2000;), transit route planning and design (Chien, et al. 2001; Ngamchai and Lovell, 2003), highway geometric design (Fwa, et al. 2002; Jong and Schonfeld, 2003) and traffic signal timing optimization (Park, et al. 1999). The common characteristic of the above optimization problems is to find the best combination or sequence of decision variables (e.g., working schedules, transit route links, highway alignment elements, and signal phases with varied timing splits, etc) to achieve a maximum or minimum objective value.

The simulated annealing (SA) algorithm derived from statistical mechanics was developed by Kirkpatrick et al. (1983) based upon the strong analogy between the physical annealing process of solids and the problem of solving large combinatorial optimization problems. The states of solid represent the feasible solutions of optimization problems, in which the energy associated with each state corresponds to the objective function value of each feasible solution. Accordingly, the minimum energy of the crystal state corresponds to the optimal solution while rapid quenching can be considered as a local optimization. A standard simulated annealing algorithm includes four principle portions, i.e., solution representation, objective function, generation mechanism of neighbor solutions and cooling schedule. SA has been proven effective for fine-tuning a local optimal search, and is utilized to solve many optimization problems in transportation related fields, such as traffic signal timing (Hadi et al., 1994; Lee, et al., 1997), work zone optimization (Chen, 2003; Jiang and Adeli; 2003), and berth scheduling (Kim and Moon, 2003). However, a good initial solution and cooling schedule are very critical in finding the optimal solution.

The literature review revealed that each algorithm has its own advantages in solving particular types of optimization problems. It was found that Genetic Algorithm outperforms SA and TS in solving the traveling salesman problem (Pham and Karaboga, 2000). However, a comparative study of SA, GA and TS was conducted in solving machine-grouping problems by Zolfaghari and Liang (2002), and the results indicated that SA outperforms both GA and TS for large-scale problems, while GA is slightly better than TS for the comprehensive grouping problems.

2.6 Summary

The findings and conclusions on the comprehensive literature review were:

(1) Several earlier research efforts optimized work zone length (McCoy, et al. 1980 and 1987; Martinelli and Xu, 1996) and crew assignment (Fwa and Cheu, 1998; Change, et al. 2001; Ma, et al. 2004) to minimize total travel delay. However, the agency cost was not included. This dissertation developed an objective total cost function, including agency and road user costs because the trade-off between both costs needs to be considered.

(2) The practices of maintenance management and innovative contracting methods suggest that accelerated construction can induce productivity and reduce project duration. However, a higher construction cost may be incurred. It was found that the time-cost relation was either simplified or ignored by previous studies. A discrete maintenance time-cost function is adopted in this dissertation.

(3) Deterministic queuing theory will be used to estimate queuing delay caused by work zones because the key input parameters, i.e., work zone capacity and time-varying traffic volumes, may be collected directly from field observations (e.g., traffic volumes) and estimated based upon similar work zone layouts (e.g. work zone capacity).

(4) Traffic diversion due to work zones and the associate effects on traffic operations and total cost were studied by several researchers. However, the following limitations were found:

- Site-specific parameters and large amounts of data are required for calibration (i.e., Ullman and Dudek, 2003), and therefore it is not applicable to the work zone scheduling problem in this study;
- Microscopic simulation model was utilized to reflect traffic diversion and estimate delay (Ma, et al. 2004). However, the excessive computation time (i.e., more than 60 hours on a 4-CPU computer) is much longer than the daily operational requirement of scheduling maintenance activities; and
- The simplified assumption of constant traffic diversion ratio per work zone (Chen, 2003) may not reflect time-dependent diversions.

Therefore, this study developed a User Equilibrium assignment model to determine time-dependent traffic diversions.

(5) By reviewing the characteristics of the work zone scheduling problem, the superiorities of Genetic Algorithm can be summarized as follows,

- Genetic Algorithm can solve almost any type of objective functions, such as nonlinear, integer, logical, or discontinuous functions or constraints (Dandy and Engelhardt, 2001). The work zone optimization problem discussed here has a discontinuous objective function.
- The schedule of work zones for a maintenance project can be directly transformed to an integer genetic representation, which is the key element of developing an efficient Genetic Algorithm. This feature can reduce the possibility of generating invalid solutions as well as the difficulties of encoding and decoding binary solutions, and thereby save a large amount of computation time.

- The total cost of a maintenance project is a function of work zone schedule and time-dependent traffic demand. Therefore, by exchanging a randomly selected segment of two different solution strings (i.e., schedules), the newly generated solution may present a more cost effective schedule than its predecessors. According to this characteristic, an efficient crossover operator can be easily devised for the Genetic Algorithm.

- The number of work zones can be self-adjusted during the evolutionary process by means of genetic operations (i.e., crossover and mutation), which means all decision variables (i.e., the number of work zones and associated schedules) can be solved simultaneously. This advantage provides flexibility and efficiency in solving large combinatorial problems where the number of decision variables may be varied.

- A Genetic Algorithm performs a multi-directional search by maintaining a population of potential solutions and encourages information formation and exchange between these directions (Michalewicz, 1999). This advantage helps to explore enormous solution spaces of the work zone scheduling problem.

Therefore, Genetic Algorithm is adopted in this study to develop an iterative algorithm that can jointly optimize the work zone schedule and time-dependent diverted flow as discussed in Chapter 4.

CHAPTER 3

METHODOLOGY

With the rapid growth of traffic demand in highway systems, work zone schedules and the associated traffic impacts become critical factors during project planning, designing and construction stages. Subject to the constraints of budget, project deadline, roadway capacity as well as the availability of alternate routes, developing cost-effective work zone schedules is highly desirable to accommodate various traffic conditions and reduce total cost. Therefore, this dissertation formulates a work zone scheduling problem, and the objective is to minimize the total cost while considering dynamic traffic diversion.

This chapter discusses the formulation of the objective total cost function, which consists of maintenance cost and road user cost (see Section 3.1). The work zone related delay costs without or with considering an alternate route are discussed in Sections 3.2 and 3.3, respectively.

3.1 Objective Function

As discussed in previous studies (Schonfeld and Chien, 1999; Chien, Tang and Schonfeld, 2002), longer work zones usually cause higher user cost; however maintenance work can be performed more efficiently with less repetitive work zone setups. To balance the interests of both the transportation agency and roadway users, the objective of this dissertation is to optimize a work zone schedule by minimizing the total cost consisting of agency cost and road user cost.

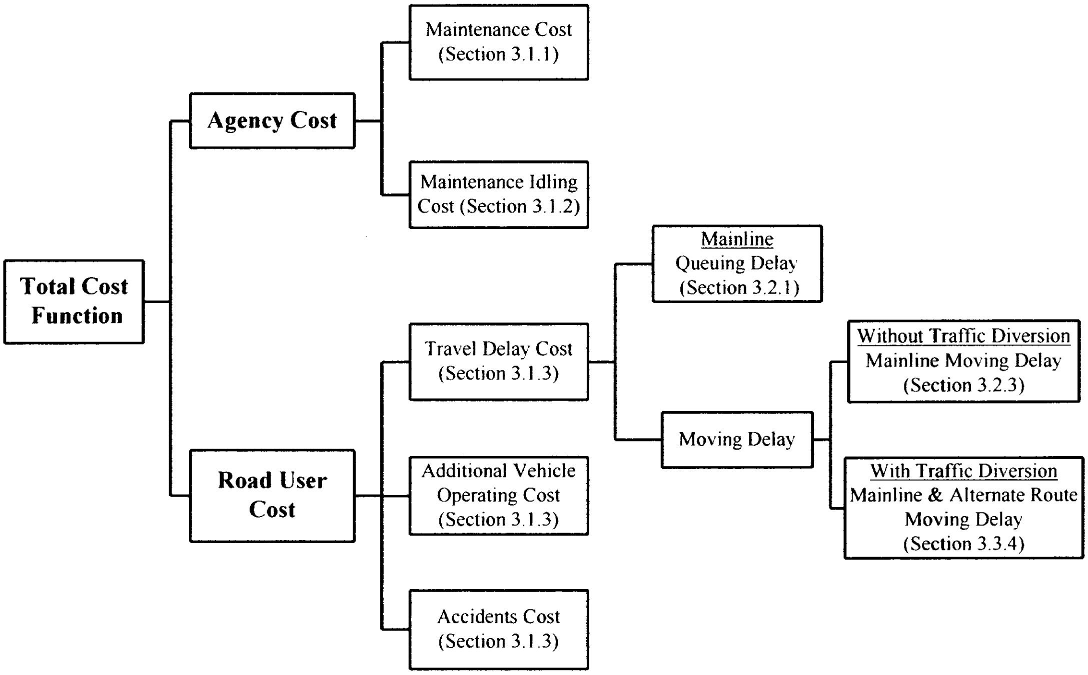


Figure 3.1 Cost components in the objective function.

Figure 3.1 presents all cost components included in the objective total cost function. The transportation agency cost, including material, labor and equipment costs, is a function of work zone length and unit maintenance cost. The length of work zone is represented by a maintenance duration, which is determined by the starting and ending times of the work zone and the associated unit production time as discussed in Section 3.1.1.

The road user cost, consisting of additional travel delay, additional vehicle operating and traffic accident costs due to maintenance activities, is a function of work zone schedule as traffic flow varies over time.

It is worth noting that the highway maintenance project discussed in this dissertation will be focusing on scheduling work zones with single lane-closure. The assumptions below are made for developing the objective total cost functions for multi-lane highway maintenance projects.

1. The traffic volume approaching a work zone is given, which may be obtained from a traffic demand analysis model that considers the equilibrium of traffic time on the mainline roadway with work zones and alternate route(s).

2. Different vehicle classifications are not considered in this dissertation. The equivalent of passenger cars can be obtained based upon the methodology in Highway Capacity Manual when the percentage of heavy vehicles is known;

3. A work zone with a single lane-closure is considered in this dissertation. In accordance with MUTCD (2003), a work zone consists of an advance warning area (l_W), an upstream merging taper (l_{T1}), an upstream buffer area (b_1), a working area (p_i) and a downstream buffer area (b_2) as well as a downstream taper (l_{T2}), as shown in Figure 3.2. Thus, the length of work zone, denoted as l_i is a sum of the above components, i.e., $l_i = p_i + l_W + l_{T1} + b_1 + b_2 + l_{T2}$. Given a operating speed, the lengths of l_W , l_{T1} and b_1 can be determined based upon MUTCD(2003); and b_2 and l_{T2} are considered as constants. Thus, the total lengths of warning area, tapers and buffers are constant, denoted as l_T (i.e., $l_T = l_W + l_{T1} + b_1 + b_2 + l_{T2}$), and the work zone length is derived as $l = p + l_T$.

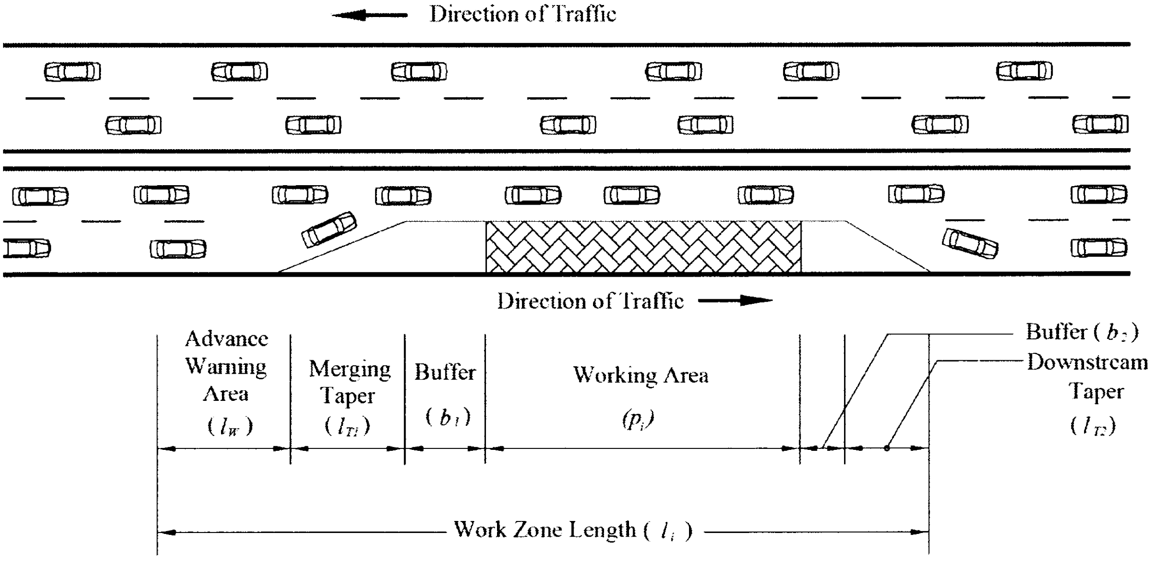


Figure 3.2 Configuration of a single lane closure work zone on a four-lane highway.

4. There are no geometric changes (e.g., entrance ramp and exit ramp) within the vicinity of the project.

5. Traffic moves at a reduced speed through a work zone. The reduced speed also causes the moving delay due to vehicle acceleration and deceleration.

6. Limited working hours, and nighttime restrictions are not considered as constraints in this dissertation, because crews may be scheduled according to the optimized solutions of the developed model. The additional maintenance cost due to nighttime work may be considered by applying a cost factor during the nighttime period.

The total cost (C_T) of a maintenance project discussed in this dissertation has three components: maintenance cost (C_M), idling cost (C_I), and user cost (C_U). Each component is a sum of the costs associated with individual work zones and maintenance work breaks. Thus,

$$\text{Minimize } C_T = C_M + C_I + C_U = \sum_{i=1}^{m}(C_{Mi} + C_{Ii}) + \sum_{i=1}^{m} C_{Ui} \tag{3.1a}$$

Subject to

Maximum duration of project: $\sum_{i=1}^{m} D_i \leq PD_{\max} \quad \forall i$ (3.1b)

Minimum duration of work activity: $D_i \geq D_{\min} \quad \forall i$ (3.1c)

User specified project length: $\sum_{i=1}^{m} p_i = L \quad \forall i$ (3.1d)

where the number of work zones scheduled to complete the maintenance project, denoted as *m,* is one of the decision variables to be optimized. *L* is the project length. p_i is the length of work area in work zone *i*. $PD_{\max}$ represents the maximum duration of the project, which may be determined by the project deadline or contract provisions. In addition, $D_{\min}$ is the minimum duration required by a work activity, which represents two user specified constants for work zones and work breaks, respectively. The minimum duration of a work zone, denoted as $D^1_{\min}$, is determined by the required maintenance procedure, e.g., work zone setup time and minimum production per setup. The minimum duration of a work break, denoted as $D^0_{\min}$, may be determined by the duration of traffic peak hours or the duration of other work activities that crew may need to perform. All components in C_T depicted in Equation 3.1 are discussed next.

3.1.1 Maintenance Cost

The maintenance cost (C_{Mi}^{k}) of work zone i consists of material, equipment and labor, which is a function of working area length p_i^k and unit maintenance cost z_{2i}^{k}. Therefore C_{Mi}^{k} can be formulated as in Equation 3.2:

$$C_{Mi}^{k} = z_1 + \theta_i \cdot z_{2i}^{k} \cdot p_i^k \quad \forall i,k \tag{3.2a}$$

where z_1 is the fixed cost for setting and removing a work zone; and z_{2i}^{k} represents the unit maintenance cost in \$/lane-km. The superscript k in Equation 3.2a is an index of feasible production options to perform a given type of maintenance work. Thus, the variable z_{2i}^{k} represents the unit maintenance cost associated with production option k. θ_i is utilized here as a cost coefficient that can reflect actual maintenance cost due to nighttime work.

The cost coefficient θ_i can be determined by the percentage of nighttime work. Thus,

$$\theta_i = 1 + (f_{nc} - 1) \cdot B_i \quad \forall i \tag{3.2b}$$

where f_{nc} is a nighttime cost factor specified by the additional unit maintenance cost at nighttime, i.e., $f_{nc} \geq 1.0$, and B_i is the percentage of work completed at night in work zone i. Note that the coefficient $\theta_i \geq 1.0$, with $\theta_i = 1.0$ representing work performed entirely during the daytime or no additional cost for nighttime work.

The duration of work zone i, denoted as D_i, is the elapse time between the starting time (S_i) and ending time (E_i). Thus,

$$D_i = E_i - S_i \quad \forall i \tag{3.3a}$$

where D_i can also be expressed in terms of p_i^k and unit production time z_{4i}^k. Thus,

$$D_i = z_3 + z_{4i}^k \cdot p_i^k \quad \forall i,k \tag{3.3b}$$

in which z_3 is the time required for setting and removing a work zone, and z_{4i}^k is a unit production time associated with production option k, and defined as the amount of time spent per lane-kilometer (e.g., hour/lane-km) for a maintenance activity.

Note that $D_i \geq D_{\min}^1$ as defined in Equation 3.1c. Thus, given a specified minimum length of a work zone, denoted as $p_{\min}$, the minimum duration of a work zone can be derived as

$$D_{\min}^1 = z_3 + z_{4i}^k \cdot p_{\min} \quad \forall i,k \tag{3.3c}$$

According to Equations 3.3a and 3.3b, p_i^k is derived as

$$p_i^k = \frac{E_i - S_i - z_3}{z_{4i}^k} \quad \forall i,k \tag{3.4}$$

By substituting Equation 3.4 into Equation 3.2a, the maintenance cost C_{Mi}^k is derived as:

$$C_{Mi}^k = z_1 + \frac{z_{2i}^k}{z_{4i}^k} \cdot \theta_i \cdot (E_i - S_i - z_3) \quad \forall i,k \tag{3.5}$$

Note that the unit maintenance cost z_{2i}^k and unit production time z_{4i}^k usually have an inverse relation, i.e., less unit production time z_{4i}^k (i.e., higher production rate) results in higher unit maintenance cost, because more crew and equipment are deployed. This relation may be represented by a continuous or a discrete function (Adeli and Karim, 1997). Additionally, the extra maintenance cost may be offset by reduced unit production time and the resultant saving in road user cost. Thus, the choice of option k will affect the total cost and project duration, and thereby is considered as a decision variable in this study.

This dissertation adopts a discrete time-cost function as illustrated in Figure 3.3, which may be realistically used to real world projects. Each point in Figure 3.3 represents a feasible production option k corresponding to a unique pair of unit maintenance cost z_{2i}^k and unit production time z_{4i}^k, which can be determined based on the total cost and production of an 8-hour working day per crew (RS Means, 2005).

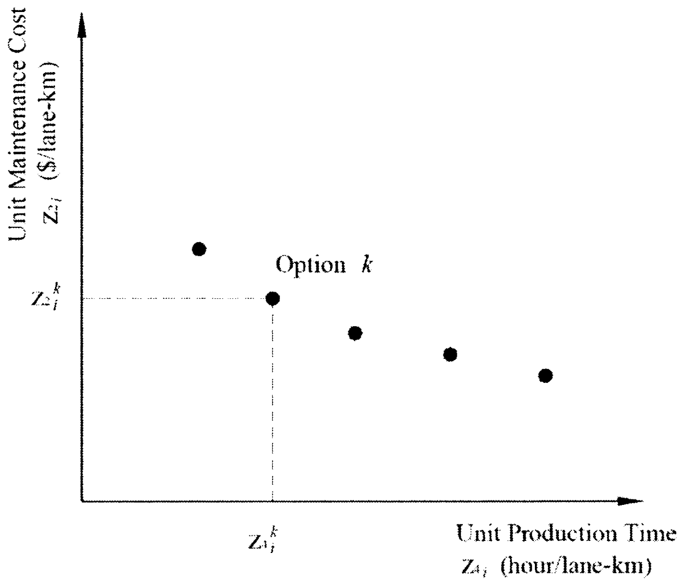


Figure 3.3 Unit maintenance cost versus unit production time.

In accordance with Assumption 3, the length of a work zone (l_i) is equal to the sum of the length of working area (p_i^k) derived in Equation 3.5, and the fixed length of tapers and buffer areas at both ends of the work zone (l_T). Thus,

$$l_i = \frac{E_i - S_i - z_3}{z_{4i}^k} + l_T \tag{3.6}$$

where l_T is specified in the Manual on Uniform Traffic Control Devices (MUTCD, 2003).

3.1.2 Idling Cost

The idling cost discussed here is incurred by equipment and crew during maintenance work breaks. The work break is a time period between two consecutive work periods. This break is usually scheduled during peak hours to reduce the congestion impacts to road users.

To unify the definition of "work zone" and "work break", a work break is defined as a dummy work zone, in which there is no maintenance activity performed. Thus, the length of a work break is zero. All equipment and crews are considered to be idle during a work break. The idling cost is additional to the maintenance cost, and is the product of work break duration denoted as D_i and the average idling cost denoted as v_d. Thus,

$$C_{Ii} = v_d D_i = v_d (E_i - S_i) \qquad \forall i \tag{3.7}$$

where i represents a work break. Note that $D_i \geq D^0_{\min}$ as defined in Equation 3.1c. $D^0_{\min}$ is a user specified constant, which may be determined by the duration of traffic peak hours or the duration of other work activities to which crew may be re-assigned. However, if a work break exceeds a specified duration (e.g., 4 hours) and the maintenance crews may be shifted to other work sites, the average idling cost (v_d) may be negligible. Note that C_{Ii} is always greater than or equal to zero. When $v_d = 0$, it means that work breaks may be easily scheduled without additional idling cost.

3.1.3 Road User Cost

The road user cost (C_U) defined here is incurred by motorists approaching and traveling through a work zone, which consists of delay cost, vehicle operating cost, and accident cost, denoted as C_{Di}, C_{Vi} and C_{Ai} respectively in Equation 3.8.

$$C_{Ui} = C_{Di} + C_{Vi} + C_{Ai} \qquad \forall i \tag{3.8}$$

The cost components within C_{Ui} are discussed next.

Delay Cost

The delay cost of work zone *i*, denoted as C_{Di}, is the product of total delay and the value of users time (v). Thus,

$$C_{Di} = (D_{Qi} + D_{Mi} + D_{Ai}) \cdot v \quad \forall i \tag{3.9}$$

where $D_{Q\,i}$ is the total queuing delay incurred by motorists waiting in a queue before entering a work zone; $D_{M\,i}$ is the total moving delay due to the reduced speed limit on the mainline within a work zone. $D_{A\,i}$ represents the total moving delay of an alternate route incurred by the diverted traffic. The formulation of $D_{Q\,i}$ and $D_{M\,i}$ are presented in Section 3.2, while $D_{A\,i}$ is discussed in Section 3.3.5.

Vehicle Operating Cost

The vehicle operating cost (VOC) is a vehicle-hour based cost caused by queuing delay ($D_{Q\,i}$), which is additional to the VOC under existing traffic conditions without a work zone. The vehicle operating cost, denoted as C_{Vi}, can be formulated as the product of work zone queuing delay denoted as $D_{Q\,i}$ and unit vehicle idling cost denoted as v_O.

$$C_{Vi} = D_{Qi} \cdot v_O \quad \forall i \tag{3.10}$$

As indicated in NCHRP Report No. 133 (1972), vehicle idling costs in 1970 were 0.1819, 0.2017 and 0.2166 \$/vehicle-hour for cars, single unit trucks and combination trucks, respectively. However, no recent official updates of the vehicle idling costs were found to reflect the enhancements in contemporary automobile technologies. Thus, this dissertation converts the 1970 dollar value into the current value through an inflation factor.

The inflation factor can be calculated by the CPI inflation calculator (Bureau of Labor Statistics, 2007) provided on the website of the U.S. Bureau of Labor Statistics, which uses the average Consumer Price Index (CPI) for a given calendar year. The inflation factor is 5.37, which means that one dollar in 1970 is equivalent to 5.37 dollars in 2007. This factor also represents the price change of all goods and services consumed by urban households. However, if the transportation sector only is considered, the inflation factor may be calculated by dividing 187.69, which is the current "Transportation Component" of CPI for All Urban Consumers (i.e., CPI-U) in July, 2007, by the 1970 annual average "Transportation Component" of CPI-U 37.5. The ratio is equal to 5.00, and this is the inflation factor used in this dissertation, making the vehicle idling cost 0.91, 1.01 and 1.08 \$/vehicle-hour respectively for cars, single unit trucks and combination trucks.

Accident Cost

The accidents considered here are those occurring in and adjacent to a work zone. The accident cost can be estimated from the accident rate (r_a), which is the number of accidents per 100 million vehicle hours, multiplied by the product of the work zone delay and the average cost per accident (v_a). Thus,

$$C_{Ai} = (D_{Qi} + D_{Mi}) \cdot r_a \cdot v_a \quad \forall i \tag{3.11}$$

Note that the accident rates are available from references such as McCoy and Peterson (1987), Pigman and Agent (1990), and Chien and Schonfeld (2001).

Finally, the total road user cost (C_{Ui}) of a work zone i can be derived from the sum of delay cost, additional VOC and traffic accident cost of Equation 3.12a.

$$\begin{aligned} C_{Ui} &= (D_{Qi} + D_{Mi})\, v + D_{Qi} v_O + (D_{Qi} + D_{Mi})\, r_a v_a \\ &= D_{Qi}(v + v_O + r_a v_a) + D_{Mi}(v + r_a v_a) \quad \forall i \end{aligned} \tag{3.12a}$$

Therefore, the total road user cost, denoted as C_U, can be derived as

$$C_U = \sum_{i=1}^{m} C_{Ui} \qquad \forall i \tag{3.12b}$$

where m represents the total number of work zones.

3.2 Work Zone Delays

Given a work zone on a mainline roadway, the associated delay consists of queuing delay and moving delay on the mainline, and the delays along alternate routes caused by diverted traffic. This section formulates the additional queuing delay and moving delay caused by a work zone while considering time-dependent traffic conditions. The moving delay considering traffic diversion is discussed in Section 3.3.4.

3.2.1 Queuing Delay on the Mainline

The determination of queuing delay at a multiple-lane highway work zone is based on Figure 3.4(a), which illustrates a time-dependent relation between demand and capacity represented by a solid line and a dashed line, respectively.

The capacity drop between points S_i and E_i indicates that work zone i is active in period $[S_i, E_i]$, during which a reduced work zone capacity (c_w) is in effect. As shown in Figure 3.4(b), the vehicular queue starts to form at t_1 and t_4 as soon as traffic demand exceeds roadway capacity, and the queue starts to dissipates at t_2 and t_5 when demand is less than capacity. Note that all vehicles in the queue have been discharged at t_3 and R_i.

The total queuing delay can be defined as the area below the solid lines in Figure 3.4(b). In the absence of a work zone, the roadway capacity shown in Figure 3.4(a) is a constant c_0. The existing queuing delay, denoted as D_R, starts at t_4 when $Q_4 > c_0$, which is represented by the shaded area in Figure 3.4(b). To estimate the actual work zone related delay, D_R is excluded from the total delay to be considered for optimizing work zones.

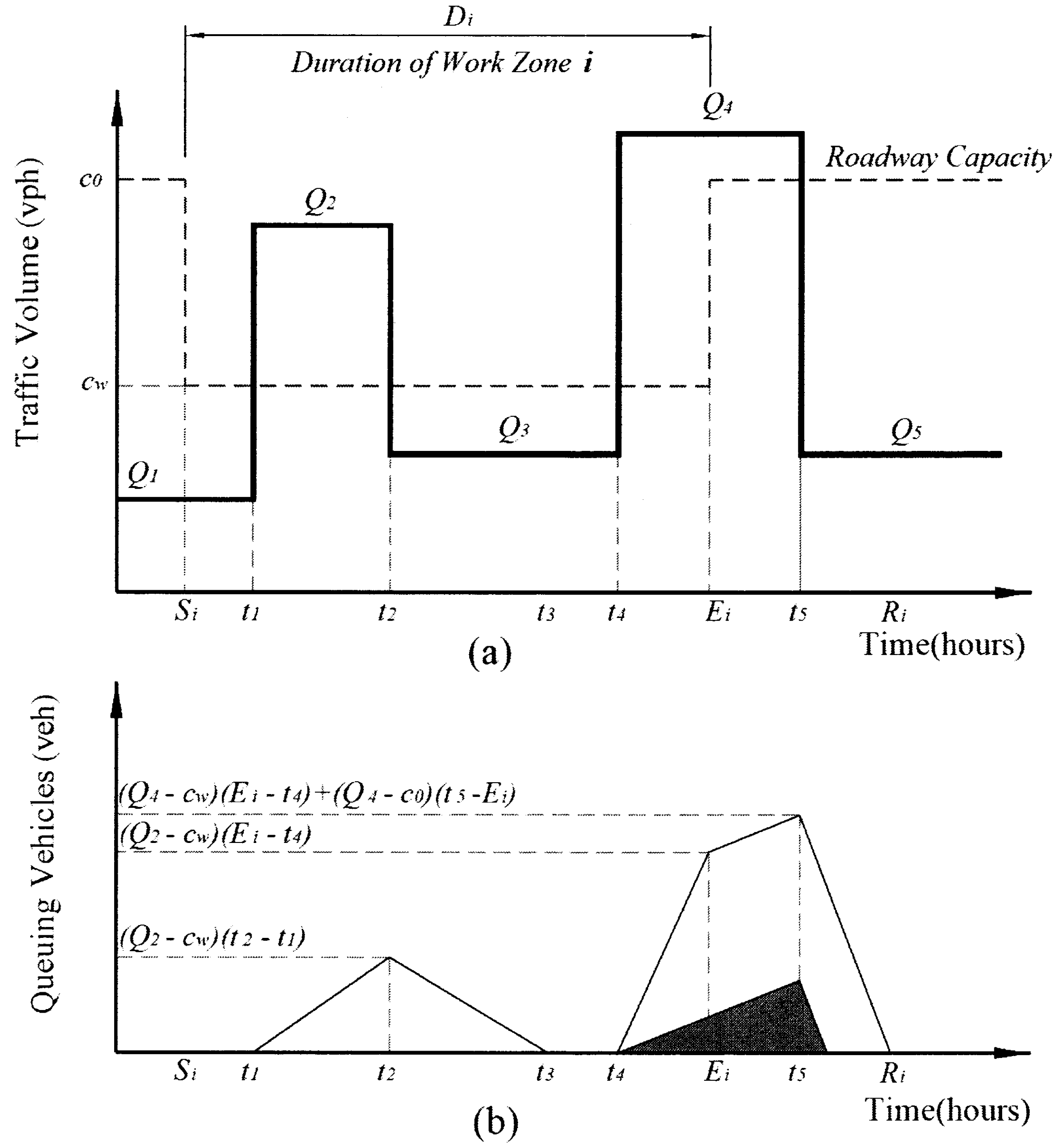


Figure 3.4 Diagram of traffic demand, roadway capacity and queue.

While traffic demand varies over time, it is assumed that the demand is uniform within any small time intervals (i.e., 15 minutes). The queuing delay within interval j, denoted as D_{Qi}^{j} in Equation 3.13, is the average number of vehicles in queue within interval j multiplied by the interval duration, denoted as T. Thus,

$$D_{Qi}^{j} = \frac{q_1^{\,j} + q_2^{\,j}}{2} \cdot T \quad \forall i, j \tag{3.13}$$

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

$$q_2^{\,j} = \left\{ \begin{matrix} q_1^{\,j} + (Q_m^{\,j} - Q_d^{\,j} - c_w)\,T & \text{if } q_2^{\,j} > 0) \\ 0 & \text{if } q_2^{\,j} \leq 0 \end{matrix} \right\} \quad \forall j \tag{3.14}$$

where $Q_m^{\,j}$ is the traffic flow rate on the mainline during interval *j*; and $Q_d^{\,j}$ is the diverted traffic flow rate from the mainline to alternate routes during interval *j*. Note that $Q_d^{\,j} = 0$ indicates that there is no traffic diversion during interval *j*.

After work zone *i* is removed at time E_i, all queued vehicles are discharged at time R_i shown in Figure 3.4. R_i can be calculated by using Equation 3.14 iteratively until all queued vehicles are discharged. For example, in Figure 3.4b, R_i can be obtained by dividing the total queued vehicles during $[E_i\,,\, t_5]$ by roadway capacity c_0, as in Equation 3.15a.

$$R_i = \frac{q_1^{E_i} + (Q_4 - c_0)(t_5 - E_i)}{c_0} \quad \forall i \tag{3.15a}$$

In Equation 3.15b, the total queuing delay of work zone *i* (D_{Qi}) is calculated as the sum of the queuing delay between the work zone starting time S_i and the queue ending time R_i. Note that the existing queuing delay D_R is excluded. Thus,

$$D_{Qi} = \sum_{j=S_i}^{R_i} D_{Qi}^{j} - D_R = \sum_{j=S_i}^{R_i} \left(\frac{q_1^{\,j} + q_2^{\,j}}{2}\right) \cdot T - D_R \quad \forall i \tag{3.15b}$$

3.2.2 BPR Function

A commonly used link performance function was developed by the U.S. Bureau of Public Roads. The so called BPR function is,

$$t = t^0 \times \left(1 + \alpha \cdot \left(\frac{x}{c} \right)^\beta \right) \tag{3.16}$$

where t and x are the travel time and flow of a link, respectively. In Equation 3.16, c represents the practical capacity of the link, which is different from the theoretical maximum throughput of the link. α and β are model parameters, and their typical values are $\alpha = 0.15$ and $\beta = 4.0$ (Sheffi, 1985). The BPR function is adopted in this dissertation to estimate travel times and formulate the link performance function of the mainline and service road.

3.2.3 Moving Delay on the Mainline without Traffic Diversion

The moving delay is the excess travel time experienced by motorists due to speed reduction within a work zone. Without traffic diversion, the moving delay on the mainline during the presence of work zone i, denoted as D_{Mi}, can be formulated as,

$$D_{Mi} = \sum_{j=S_i}^{E_i} D_{Mi}^j = \sum_{j=S_i}^{E_i} (t_{wi} - t_e^j) \cdot T \cdot \min(Q_m{}^j, c_w) \quad \forall i \tag{3.17a}$$

where t_{wi} is the average travel time within the work zone derived in Equation 3.17b; t_{ei}^j represents the existing travel time without a work zone during interval j, which can be calculated as in Equation 3.17c by using the BPR function; V_f is the free-flow speed of the mainline. V_w is the average travel speed in the work zone.

$$t_{wi} = \frac{l_i}{V_w}. \quad \forall i \tag{3.17b}$$

$$t_{ei}^{j} = \frac{l_i}{V_f}\cdot[\,1+\alpha\cdot\left(\frac{Q_m^j}{c_0}\right)^{\beta}\,] = \frac{l_i}{V_f}\cdot\delta^j \quad \forall i,j \tag{3.17c}$$

By introducing Equation 3.6 into Equation 3.17a, the moving delay of work zone *i* can be represented as a function of work zone starting time (*S_i*), ending time (*E_i*) and the unit production time z_{4i}^k. Thus,

$$D_{Mi} = \sum_{j=S_i}^{E_i} D_{Mi}^j = (\frac{E_i - S_i - z_3}{z_{4i}^k} + l_T)\sum_{j=S_i}^{E_i}(\frac{1}{V_w} - \frac{\delta^j}{V_f})\cdot T\cdot\min(Q_m{}^j, c_w) \quad \forall i \tag{3.17d}$$

3.3 Traffic Diversion

When congestion occurs on the mainline due to a work zone, motorists may choose alternate routes to bypass the congested segment. Subsequently, travel time on the alternate routes will increase, and the route choice between the mainline and an alternate route may vary over time. Therefore, travel time is utilized as the measure of link performance. The User-Equilibrium (UE) principle, a widely applied route choice model, is employed in this dissertation to approximate dynamic traffic diversion.

Several assumptions are made in order to formulate the link performance functions of the mainline and an alternate route and a UE assignment.

1. Only one alternate route is considered in this dissertation. The alternate route is a service road of the mainline. Traffic may bypass a work zone on the mainline through an exit ramp before the work zone, and return on the mainline;
2. The existing traffic on the exit ramp is not affected by the traffic diversion, and it is combined with the existing traffic on the service road;
3. Traffic volume will not exceed the capacity of service road and ramps, thus queuing delay on the alternate route is not considered; and
4. The existing condition of the mainline and the alternate route represents a state of UE. Traffic diversion from the mainline to an alternate route occurs only if the travel time of the mainline exceeds that of the alternate route due to the vehicular

queue or the reduced speed caused by a work zone. In addition, traffic diversion from an alternate route to the mainline is not considered.

3.3.1 Link Performance Function of the Mainline

As illustrated in Figure 3.5, the mainline considered here is link *AD* between an upstream exit ramp *AE* and a downstream entrance ramp *FD*. When a work zone is scheduled, link *AD* is divided into three segments, which are link *AB* before the work zone, link *BC* the actual work zone and link *CD* after the work zone. Thus, the total travel time on the mainline during interval *j*, denoted as t_m^j, is the sum of travel time on the three links, denoted as t_{AB}^j, t_{BC}^j and t_{CD}^j, respectively.

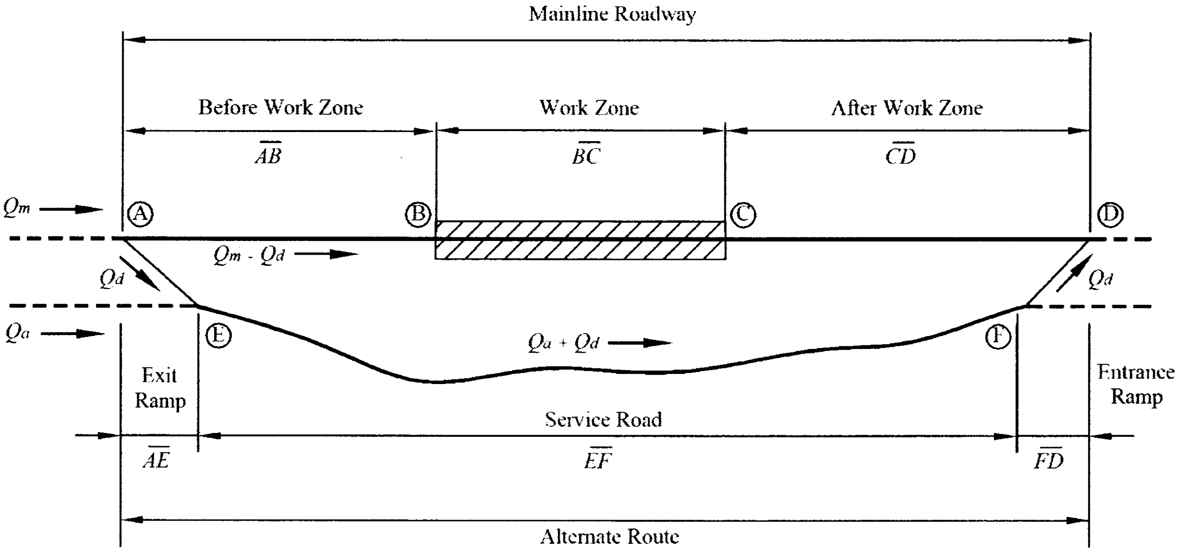


Figure 3.5 Diagram of the mainline and alternate route.

The travel time on the approach to the work zone, denoted as t_{AB}^j, can be calculated as the travel time on link *AB* plus the average individual queuing delay caused by the work zone. Thus,

$$t_{AB}{}^{j} = t_{AB}^{0} \times \left(1 + \alpha \cdot \left(\frac{Q_m{}^{j} - Q_d{}^{j}}{c_0} \right)^{\beta} \right) + t_q{}^{j} \tag{3.18}$$

where the first term represents the travel time on link *AB* without queue, and may be calculated by the BPR function; t_{AB}^{0} and c_0 are the free-flow travel time on link *AB* and the capacity of the mainline, respectively. $Q_m{}^{j}$ is the existing flow on the mainline, and $Q_d{}^{j}$ is the diverted flow. *T* is the interval duration. In Equation 3.18, $t_q{}^{j}$ is the average individual queuing delay within interval *j*, which represents the average waiting time in queue, and can be derived by dividing the total queuing delay by the total number of vehicles during interval *j*. Thus,

$$t_q{}^{j} = \frac{D_{Qi}{}^{j}}{(Q_m{}^{j} - Q_d{}^{j}) \cdot T} \tag{3.19}$$

where $D_{Qi}{}^{j}$ is the total queuing delay (i.e., vehicle-hour) occurred during interval *j* due to work zone *i* as calculated by Equation 3.13.

The travel time within the work zone, denoted as $t_{BC}{}^{j}$, is equal to the length of the work zone *i*, denoted as l_i, divided by the regulated work zone speed V_w. Thus,

$$t_{BC}{}^{j} = \frac{l_i}{V_w} \tag{3.20}$$

Finally, the travel time after the work zone, denoted as $t_{CD}{}^{j}$, can be calculated by the BPR function below,

$$t_{CD}{}^{j} = t_{CD}^{0} \times \left(1 + \alpha \cdot \left(\frac{Q_m{}^{j} - Q_d{}^{j}}{c_0} \right)^{\beta} \right) \quad if \;\; Q_m{}^{j} - Q_d{}^{j} \le c_w \tag{3.21a}$$

$$t_{CD}{}^{j} = t_{CD}^{0} \times \left(1 + \alpha \cdot \left(\frac{c_w}{c_0} \right)^{\beta} \right) \quad if \;\; Q_m{}^{j} - Q_d{}^{j} > c_w \tag{3.21b}$$

where t_{CD}^{0} is the free-flow travel time on link *CD*, and c_w is the reduced roadway capacity due to a work zone.

Thus, the total travel time on the mainline ($t_m^{\,j}$) is derived as a function of the diverted flow $Q_d^{\,j}$.

$$t_m^{\,j} = t_{AB}^{\,j} + t_{BC}^{\,j} + t_{CD}^{\,j} \qquad \forall j \tag{3.22}$$

3.3.2 Link Performance Function of the Alternate Route

As shown in Figure 3.5, the alternate route considered here includes the exit ramp *AE*, the service road link *EF* and the entrance ramp *FD*. Hence, the travel time on the alternate route, denoted as $t_a^{\,j}$, is the sum of the travel times on links *AE*, *EF* and *FD*.

The travel time on service road link *EF*, denoted as $t_{EF}^{\,j}$, is also a function of the diverted flow from the mainline, denoted as $Q_d^{\,j}$,, and can be calculated by the BPR function as,

$$t_{EF}^{\,j} = t_{EF}^{0} \times \left(1 + \alpha \cdot \left(\frac{Q_a^{\,j} + Q_d^{\,j}}{c_a} \right)^{\beta} \right) \tag{3.23}$$

where t_{EF}^{0} and c_a are the free-flow travel time and capacity of the service road link *EF*, respectively. Note that $Q_a^{\,j}$ is the existing flow on the service road link *EF* during interval j.

The total travel time on the exit ramp *AE* and entrance ramp *FD*, denoted as t_{ramp}, is considered as a constant, and equal to the length of both ramps divided by the average speed of the ramps. Thus,

$$t_{ramp} = \frac{l_{AE} + l_{FD}}{V_r} \tag{3.24}$$

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

Thus, the total travel time on the alternate route can be derived as,

$$t_a^j = t_{EF}^j + t_{ramp} \tag{3.25}$$

3.3.3 User Equilibrium Assignment

Based upon Assumption 4 in Section 3.3, the User-Equilibrium assignment will be triggered when the travel time on the mainline exceeds that of the alternate route because of the queuing delay and reduced speed caused by a work zone. By diverting a portion of mainline traffic to the alternate route at interval *j*, the state of equilibrium is achieved by the same travel times between Node A and D through the mainline and the alternate route. Thus,

$$t_m^j - t_a^j = 0 \tag{3.26}$$

As discussed earlier, the travel times of the mainline and the alternate route are both a function of diverted traffic flow Q_d^j. The traffic flow within any small time interval *j* (e.g., duration of 15 minutes) is uniform, thus the diverted traffic flow Q_d^j during interval *j* can be optimized by solving Equation 3.26. Finally, by substituting Q_d^j into Equation 3.14, the queuing delay with traffic diversion on the mainline can be calculated.

3.3.4 Total Moving Delay

After optimizing the diverted flow $Q_d{}^j$, the total moving delay on the mainline and the alternate route can be obtained by comparing the difference of travel times on the mainline and alternate route with and without a work zone.

Thus, the total moving delay of the mainline, denoted as $D_M{}^j$, can be formulated as

$$D_M{}^j = (Q_m{}^j - Q_d{}^j)(t_m^j - t_m^{j'}) \qquad \forall j \tag{3.26}$$

where $t_m{}^j$ and $t_m^j{}'$ are the travel times through the mainline link AD with and without a work zone. Note that $t_m{}^j$ can be obtained from Equation 3.22; and $t_m^j{}'$ can be calculated by the BPR function as

$$t_m^{j'} = t_{AD}^0 \times \left(1 + \alpha \cdot \left(\frac{Q_m{}^j}{c_0} \right)^{\beta} \right) \tag{3.27}$$

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

On the other hand, the total moving delay of the alternate route, denoted as $D_A{}^j$, includes the moving delay incurred by the existing flow $Q_a{}^j$ on service road link EF and the diverted traffic $Q_d{}^j$, which are formulated below.

The moving delay of the existing flow, denoted as $D_{EF}{}^j$, can be derived as

$$D_{EF}{}^j = Q_a{}^j \cdot (t_{EF}{}^j - t_{EF}^{j}{}') \tag{3.28}$$

where $t_{EF}{}^j$ and $t_{EF}^j{}'$ are the travel times through the service road link EF with and without considering the diverted flow $Q_d{}^j$. Note that $t_{EF}{}^j$ can be obtained from Equation 3.23; and $t_{EF}^j{}'$ can be calculated by the BPR function as

$$t_{EF}^{j}{}' = t_{EF}^{0} \times \left(1 + \alpha \cdot \left(\frac{Q_a^{\,j}}{c_a} \right)^{\beta} \right) \tag{3.29}$$

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

The moving delay of the diverted traffic, denoted as $D_d^{\,j}$, can be derived as,

$$D_d^{\,j} = Q_d^{\,j} \cdot (t_a^{\,j} - t_m^{j}{}') \tag{3.30}$$

where $t_a^{\,j}$ and $t_m^{j}{}'$ represent the travel times of the diverted flow $Q_d^{\,j}$ on the alternate route *AEFD* and on the mainline *AD* without a work zone, respectively. Note that $t_a^{\,j}$ is derived using Equation 3.25; and $t_m^{j}{}'$ can be calculated using Equation 3.27.

Thus, the total moving delay of the alternate route, denoted as $D_A^{\,j}$, can be derived as

$$D_A^{\,j} = D_{EF}^{\,j} + D_a^{\,j} \tag{3.31}$$

By substituting $D_M^{\,j}$ and $D_A^{\,j}$ into Equation 3.9, the total delay cost C_{Di} considering the availability of an alternate route and time-dependent traffic diversion can be obtained.

3.4 Summary

In this chapter, the objective total cost function of the work zone scheduling optimization problem was formulated, while a discrete maintenance time-cost function and additional nighttime maintenance cost were considered. The total cost (C_T) of a maintenance project consists of maintenance cost (C_M), idling cost (C_I), and road user cost (C_U), which were discussed in Section 3.1. The road user cost includes delay cost, additional VOC and accident cost. The delay costs with or without an alternate route were derived in Section 3.2 and Section 3.3, respectively.

While considering time-dependent traffic diversions to an alternate route, the link performance functions of the mainline and an alternate route were formulated in Section 3.3. Given the schedule of a work zone on the mainline, the diverted flow Q_d^j can be optimized by a UE assignment when traffic diversion occurs. The resultant total moving delay on the mainline and alternate route was also formulated.

With the developed objective function in Equation 3.1, the optimized variables are the starting time (S_i), ending time (E_i) and the production option (k_i) of work zone i as well as the number of work activities (m). Thus, the total number of decision variables in this optimization problem is (3m+1). Because of the various combinations and interdependent relation among these decision variables, this optimization problem has an enormous solution space to be explored. By employing the Genetic Algorithm developed in Chapter 4, the combinatorial work zone scheduling problem can be solved.

CHAPTER 4

OPTIMIZATION ALGORITHM

As discussed previously, the objective of this dissertation is to minimize the total cost function formulated in Equation 3.1, in which the decision variables include the starting time (S_i), ending time (E_i) , index of production option (k_i) for each work zone i (i = 1 to m) and the number of work zones (m). The total number of decision variables in this optimization problem is ($3m$+1). The combination and the interdependent relations among these decision variables form a combinatorial optimization problem that is difficult to optimize analytically. Therefore, a solution algorithm is developed in this chapter to search for the optimal solution.

This chapter first presents a numerical sequential searching method. Due to several limitations, the sequential search method was unable to jointly optimize the schedule of work zones in a maintenance project. Subsequently, a Genetic Algorithm (GA) based on an integer string representation was developed to search optimal work zone schedules simultaneously. However, the variable production option discussed in Chapter 3 was not considered as an additional decision variable by the GA. Therefore, an enhance GA based on a linked list representation was developed for solving the work zone scheduling optimization problem formulated in Chapter 3. This chapter discusses the two different genetic representations and other components of the developed GA, which include reproduction process, evaluation criterion, selection mechanisms and constraint handling methods, respectively. Finally, by conducting a benchmark analysis, the model parameters of the GA were calibrated, and the optimal solution found by the developed GA was validated.

4.1 Sequential Search Method

A sequential search method is developed to optimize the work zone lengths and schedule by minimizing the average cost per lane-kilometer (Chien, Tang and Schonfeld, 2002) in which a fixed relation of unit maintenance cost (z_{2i}^{k}) and unit production time (z_{4i}^{k}) was assumed, and the discrete maintenance time-cost function discussed in Section 3.1.1 was not considered. As a result, the joint effects of accelerated construction and the associated maintenance cost as well as the potential reduction in road user cost were not discussed.

The objective function (total cost) of a work zone *i* was developed in Chapter 3 and includes maintenance cost (C_{Mi}), idling cost (C_{Ii}) and user delay cost (C_{Ui}), where C_{Mi} can be determined by Equation 3.5, if the work zone starting time (S_i) and ending time (E_i) are known; C_{Ui} is a function of queuing delay(D_{Qi}) and moving delay(D_{Mi}) defined in Equation 3.8; and the idling cost (C_{Ii}) can be obtained after the duration of work break is determined. Thus, the work zone length l_i^* can be optimized by starting at a reasonably short length (e.g., 0.100 km), and then calculating its total cost for each time interval increment (e.g., 15 minutes). By comparing the average cost of each increment of work zone length, the work zone length that achieves the minimum total cost can be found.

Given a starting time for the maintenance project, the optimal schedule of work zones was obtained by optimizing the length of each work zone sequentially. The best project starting time is determined by enumerating the project starting times in 15-minute intervals until the minimum total cost is found. The procedure of the optimization process is shown in Figure 4.1.

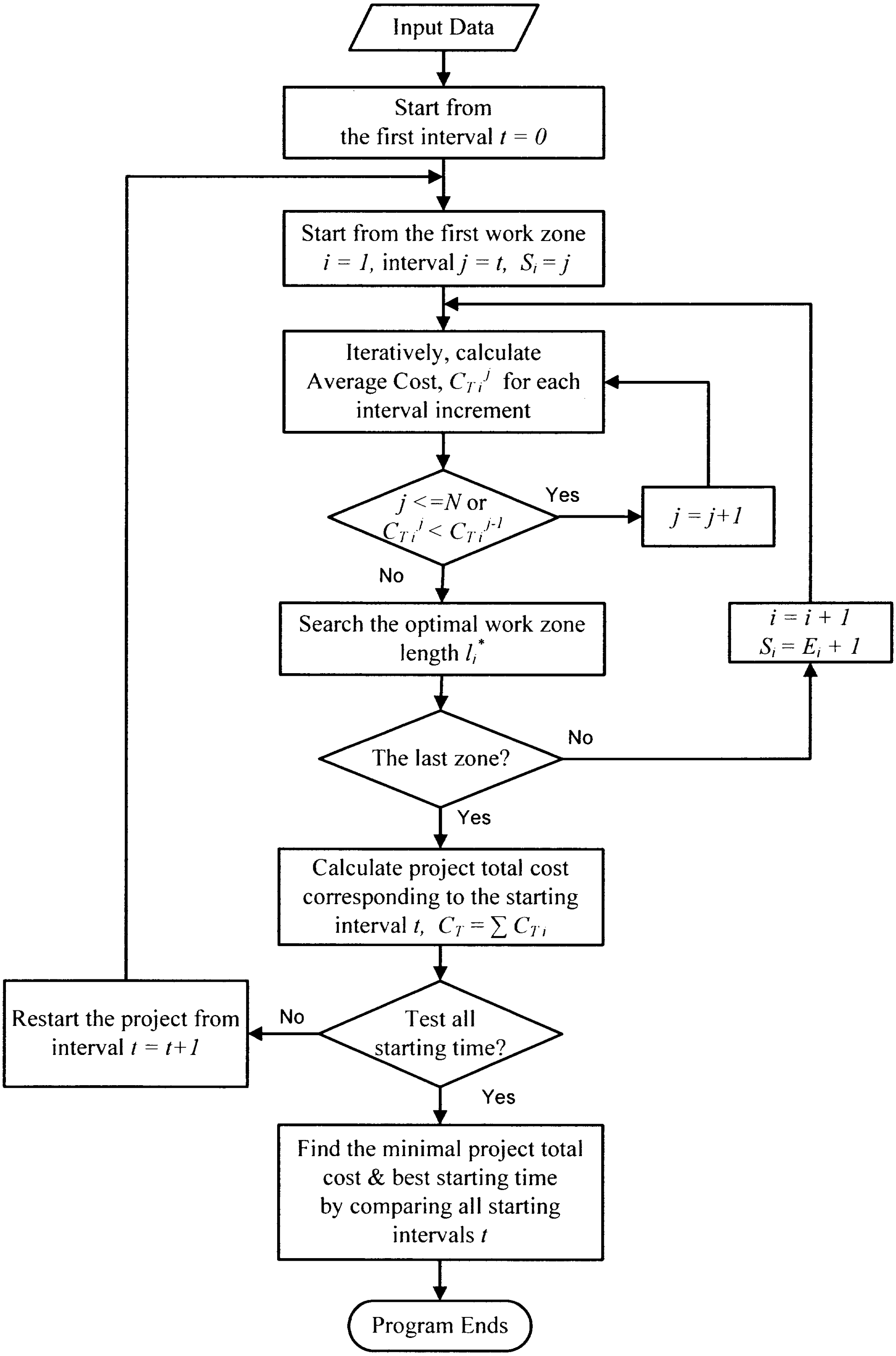


Figure 4.1 Flow chart of the sequential search method.

The sequential search method may not find the global optimal solution that minimizes the total cost because it does not simultaneously consider the solution space for all decision variables. In addition, the length of the last work zone may not be optimal before the length of the project is fixed.

4.2 Genetic Algorithm

The Genetic Algorithm (GA) is a stochastic algorithm which mimics the natural phenomena of genetic inheritance and Darwinian strife for survival (Michalewicz, 1999) to search for the optimal solution. A GA includes five major components:

- A criterion for evaluating the performance of a solution. The objective total cost function developed in Chapter 3 is the criterion.
- A genetic representation for encoding feasible solutions. An efficient genetic representation needs to accommodate all decision variables and reduce the difficulties of encoding and decoding a solution, which is a key component of a GA. An efficient data structure can also facilitate the processes of generating new valid solutions and reducing computation time. This dissertation develops an integer string representation in Section 4.3 and a linked list representation in Section 4.4 to transform a work zone scheduling problem into a GA.
- Reproduction processes to produce offspring solutions. Crossover and mutation operations corresponding to the integer string representation and linked list genetic representation were developed to generate new solutions in the potential solution space, and are discussed in Sections 4.3.2 and 4.4.2, respectively.
- A selection mechanism for promoting the evolution of good solutions. The elitist selection method is utilized for both developed genetic representations and is discussed in Section 4.6.
- A constraint handling method to direct the search to a feasible solution space. Repair methods were developed for the constraints defined in Section 4.7, which are applicable to both integer and linked list genetic representations.

The optimization procedure of the developed GA is summarized below and depicted in Figure 4.2.

Step 1: A group of random feasible solutions is generated by the GA. Then, the GA starts from the initial group of solutions, so called population pool.

Step 2: If there is no alternate route, go to Step 3. Otherwise, a UE assignment is used for each solution (i.e., work zone schedule) in the population pool to distribute traffic between the mainline and the alternate route based upon existing traffic conditions and the methodology discussed in Section 3.3. After the UE assignment, updated traffic volumes are obtained on the mainline and alternate route.

Step 3: The objective value of each solution (i.e. total cost) is calculated based upon the work zone schedule and the updated traffic volumes on the mainline and the alternate route.

Step 4: In accordance with the elitist selection discussed in Section 4.6, the solutions having good performance will be chosen to reproduce new solutions (i.e., offspring) in Step 5.

Step 5: Crossover and mutation will be used for the solutions selected in Step 4, and new solutions will be generated. The developed repair methods discussed in Section 4.7 verify that each new solution conforms to the constraints.

Step 6: The new solutions will replace their parent solutions in the population pool. The solutions that cannot be repaired will be discarded, and their parent solutions will remain in the population pool. Thus, a new population pool is formed for the next iteration.

Step 7: If the predefined stop-criteria (e.g., maximum iterations) is reached, terminate the GA processes and output the optimized solution. Otherwise, go to Step 2.

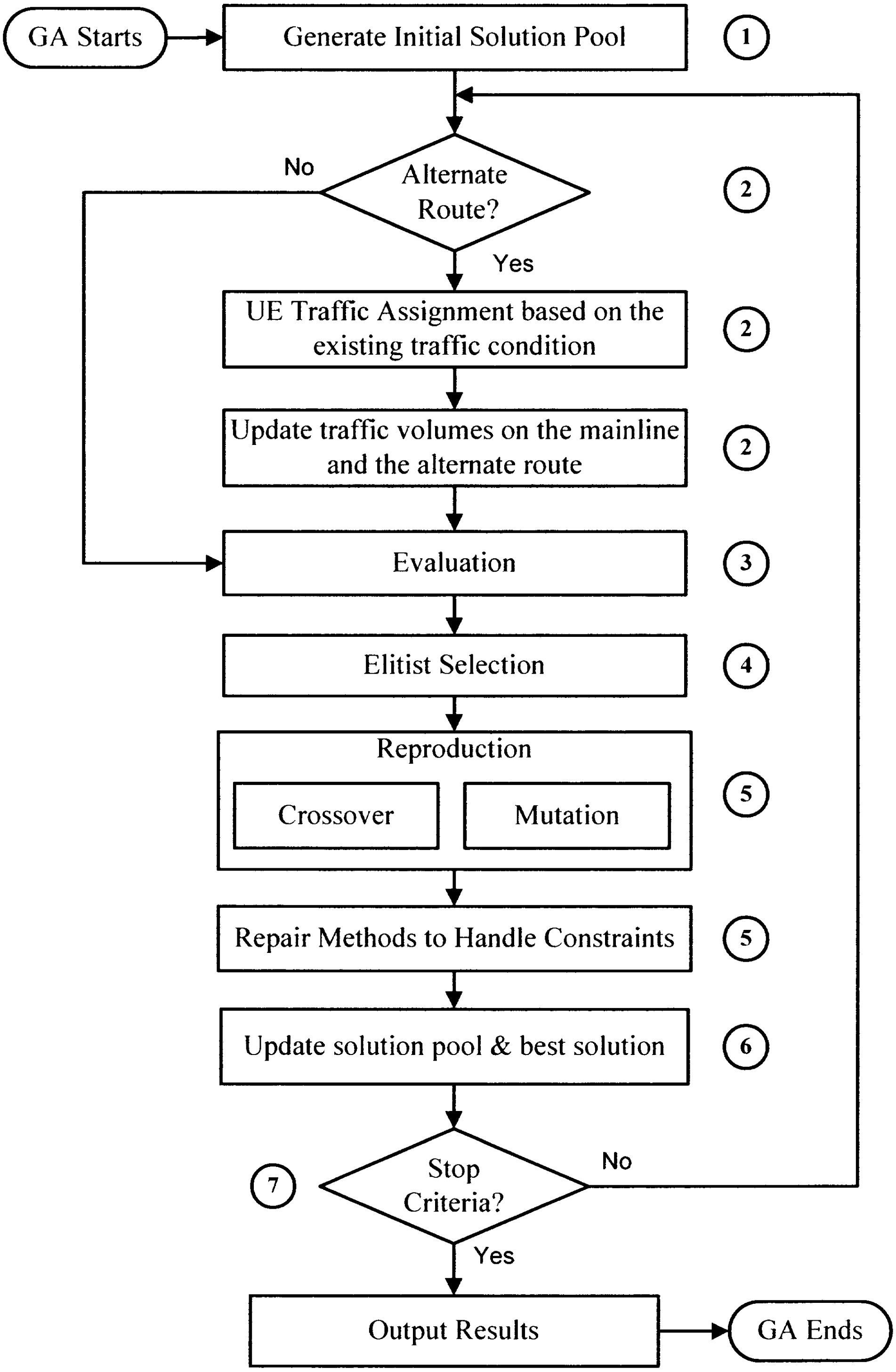


Figure 4.2 Flow chart of the developed GA.

4.3 Integer String Genetic Representation

A Genetic Algorithm utilizing an integer string representation was developed to solve for the optimized work zone schedule for two-lane two-way highway maintenance projects (Tang and Chien, 2007). The developed GA is further enhanced herein, so that the four-lane two-way highway work zone scheduling problem can be solved. This section introduces the encoding and decoding scheme of the genetic representation, the procedures of crossover and mutation as well as the mechanisms to correct invalid cell combinations.

4.3.1 Encoding and Decoding Schemes

An integer string, also called solution string, consists of a series of cells, and is designed to represent a series of consecutive intervals in which potential work zone schedules may be arranged. The duration of each interval *j*, denoted by *T*, may be determined based on the required solution accuracy. (15-minute is used in this dissertation). In general, a shorter interval may gain higher solution accuracy, but consumes more computing time.

An integer attribute, denoted as A_j, is assigned to interval *j* to define the status of a maintenance activity at interval *j*, as indicated in Equation 4.1.

$$A_j = \begin{cases} 0, & \text{work break at interval j;} \\ 1, & \text{work zone at interval j; and} \\ 2, & \text{two work zones in transition at the end of interval j.} \end{cases} \tag{4.1}$$

Hence, a solution string of $(A_1, \ldots, A_j, \ldots, A_N)$ can represent the schedules of work activities by various combinations of attributes of *N* intervals. Note that the maximum number of intervals in a solution string, denoted as *N*, is determined by the maximum project duration $PD_{\max}$, divided by the interval duration *T*. Thus,

$$N = \frac{PD_{\max}}{T} \tag{4.2a}$$

Figure 4.3 illustrates an encoding scheme example of an integer string, which depicts a two-day maintenance schedule for five contiguous work zones and two work breaks. Note that each cell in Figure 4.3 represents a two-hour interval. The starting and ending times of a work zone (or a work break) can be decoded by the position of "0" (or "2") in the solution string. The length of each work zone can, therefore, be solved by Equation 3.6.

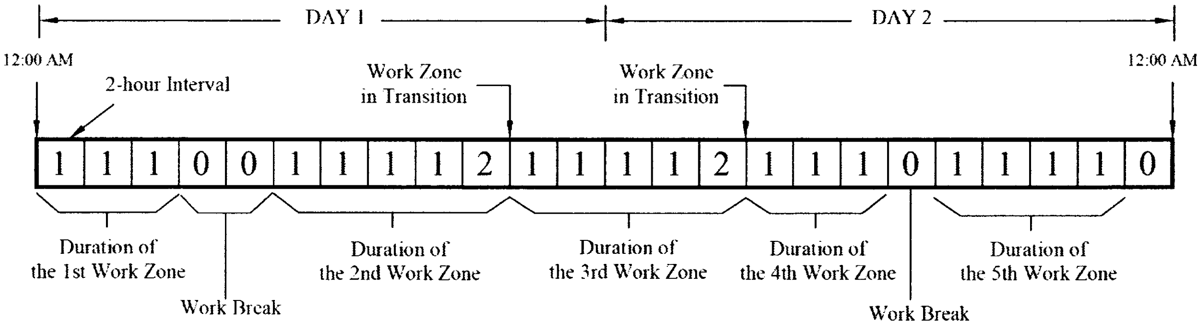


Figure 4.3 Encoding scheme of an integer string genetic representation.

The integer string genetic representation encodes the studied work zone scheduling problem into a series of intervals, so that the impact of time-dependent traffic demand to work zone schedule can be properly analyzed. For instance, a work zone with a fixed duration may result in different user delay costs if the work zone starts at a different cell in a solution string. Another advantage of the integer string genetic representation is that the constraint of the maximum project duration is always satisfied by a pre-defined number of intervals in the solution string.

4.3.2 Crossover and Mutation

During reproduction, the classic genetic operators (i.e., crossover and mutation) are adopted to reproduce new solutions by altering their parent solutions (i.e., solution strings in a previous population pool). Because GA is a stochastic algorithm, the probabilities of performing the crossover and mutation operations are defined as crossover ratio and mutation ratio, denoted as P_{XO} and P_{MU} respectively, which are two pre-determined model parameters. For example, the crossover operator is triggered when a random fractional number generated by GA exceeds the crossover ratio. The procedures of crossover and mutation are illustrated in Figures 4.4(a) and 4.4(b).

Two-point crossover generates two offsprings (i.e., new solution) by exchanging the cells between two random crossover points in two parent solution strings, as illustrated in Figure 4.4(a).

The mutation operator randomly selects a cell (e.g., $A_j = 1$) in a parent solution string and alters its attribute (i.e., $A_j = 0$ or 2) as below. Thus, a new offspring can be generated as depicted in Figure 4.4(b).

$$A_j = \begin{cases} 0 \\ 1 \\ 2 \end{cases} \xrightarrow[\Rightarrow]{\text{mutation}} A_j = \begin{cases} 1 \text{ or } 2 \\ 0 \text{ or } 2 \\ 0 \text{ or } 1 \end{cases} \tag{4.2b}$$

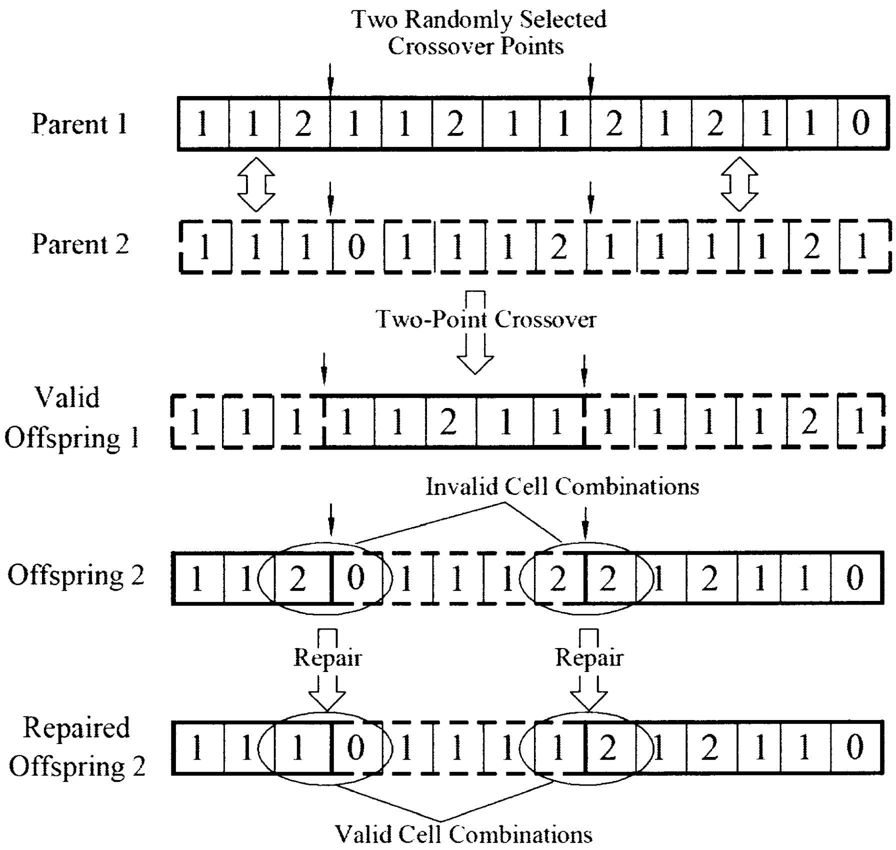


Figure 4.4(a) Crossover operations and the associated repair patterns.

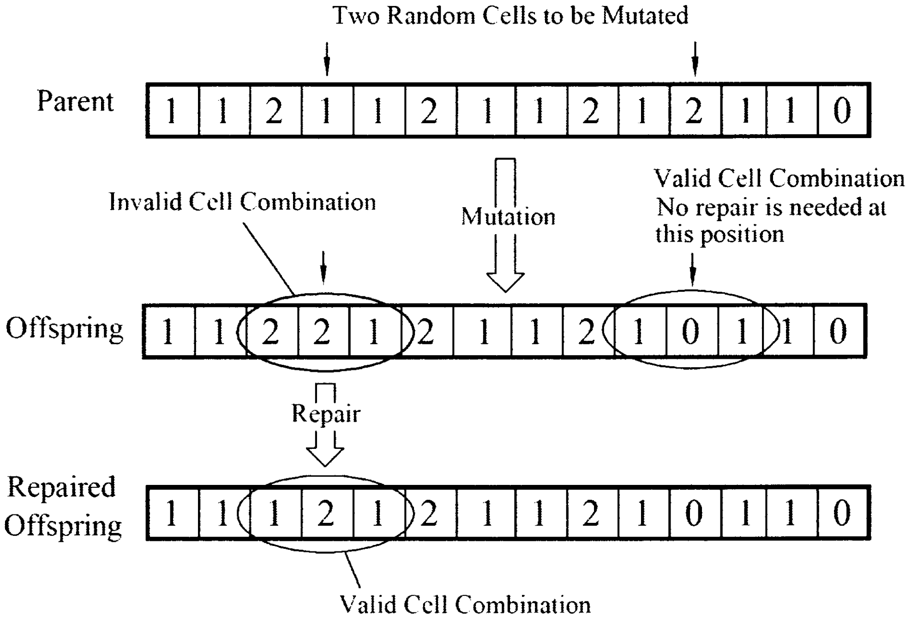


Figure 4.4(b) Mutation operations and the associated repair patterns.

4.3.3 Invalid Cell Combinations

Invalid cell combinations, which violate the encoding rules defined in Equation 4.1, may exist in an offspring string due to the exchange of cells through crossover and the alteration of cells by mutation. It is worth noting that an invalid cell combination in an offspring solution only exists at the positions where crossover and mutation are applied because the parent strings in the past generation always contain valid cell combinations. Thus, an invalid cell combination can be easily identified according to the attributes of adjacent cells and the repair pattern corresponding to each invalid cell combination is developed for crossover and mutation respectively.

Table 4.1 Repair Patterns for Crossover

	After Crossover	**Status**	**After Repair**
1	0 | 0	Valid	/
2	0 | 1	Valid	/
3	**0 | 2**	**Invalid**	**0 | 1**
4	1 | 0	Valid	/
5	1 | 1	Valid	/
6	1 | 2	Valid	/
7	**2 | 0**	**Invalid**	**1 | 0**
8	2 | 1	Valid	/
9	**2 | 2**	**Invalid**	**1 | 2**

Note: "|" represents a random crossover point.
"0" – maintenance work break at interval j;
"1" – work zone at interval j; and
"2" – two work zones in transition at the end of interval j.

An example of invalid cell combinations generated by crossover is illustrated in Figure 4.4(a). After the crossover operation, nine cell combinations (i.e., 3×3) at the crossover point may be generated in an offspring solution as shown in Table 4.1. In accordance with the genetic representation defined in Equation 4.1, three combinations in bold text (i.e., "0|2", "2|0" and "2|2") in Table 4.1 are identified as invalid combinations, because a cell (i.e., an interval) having an attribute of "2" represents a work zone in transition which cannot link to the cells having the attributes of "0" and "2". Otherwise, the combinations are identified as an invalid combination.

Table 4.2 Repair Patterns for Mutation

Before Mutation	**After Mutation**[1]	**After Repair**
0 $\underline{0}$ 0	0 $\underline{1}$ 0	/[2]
	0 $\underline{2}$ 0	0 $\underline{1}$ 0
0 $\underline{0}$ 1	0 $\underline{1}$ 1	/
	0 $\underline{2}$ 1	0 $\underline{1}$ 1
0 $\underline{0}$ 2	Invalid combination [3]	
0 $\underline{1}$ 0	0 $\underline{0}$ 0	/
	0 $\underline{2}$ 0	0 $\underline{0}$ 0
0 $\underline{1}$ 1	0 $\underline{0}$ 1	/
	0 $\underline{2}$ 1	0 $\underline{0}$ 1
0 $\underline{1}$ 2	**0 $\underline{0}$ 2**	0 $\underline{0}$ 1
	0 $\underline{2}$ 2	0 $\underline{1}$ 1
0 2 0	Invalid combinations [3]	
0 2 1		
0 2 2		
1 $\underline{0}$ 0	1 $\underline{1}$ 0	/
	1 $\underline{2}$ 0	1 $\underline{1}$ 0
1 $\underline{0}$ 1	1 $\underline{1}$ 1	/
	1 $\underline{2}$ 1	/
1 0 2	Invalid combination [3]	
1 $\underline{1}$ 0	1 $\underline{0}$ 0	/
	1 $\underline{2}$ 0	1 $\underline{0}$ 0
1 $\underline{1}$ 1	1 $\underline{0}$ 1	/
	1 $\underline{2}$ 1	/
1 $\underline{1}$ 2	**1 $\underline{0}$ 2**	1 $\underline{2}$ 1
	1 $\underline{2}$ 2	1 $\underline{2}$ 1

Before Mutation	**After Mutation**[1]	**After Repair**
1 2 0	Impossible combination [3]	
1 $\underline{2}$ 1	1 $\underline{0}$ 1	/
	1 $\underline{1}$ 1	/
1 2 2	Invalid combinations [3]	
2 0 0		
2 0 1		
2 0 2		
2 $\underline{1}$ 0	**2 $\underline{0}$ 0**	1 $\underline{0}$ 0
	2 $\underline{2}$ 0	1 $\underline{1}$ 0
2 $\underline{1}$ 1	**2 $\underline{0}$ 1**	1 $\underline{1}$ 1
	2 $\underline{2}$ 1	1 $\underline{2}$ 1
2 $\underline{1}$ 2	**2 $\underline{0}$ 2**	1 $\underline{0}$ 1
	2 $\underline{2}$ 2	1 $\underline{2}$ 1
2 2 0	Invalid combinations [3]	
2 2 1		
2 2 2		

Note:
[1] Mutation occurs at the middle cell indicated by a underscore "_".
[2] Valid and no repair is needed.
[3] It is an invalid combination, and cannot exist in a parent solution string.

Figure 4.4(b) depicts an example of invalid cell combinations generated by the mutation. Given three possible attributes for a cell (i.e., interval), three consecutive cells may form a total of 27 combinations (i.e., 3×3×3) in a parent solution string as shown in the "before mutation" column of Table 4.2, where only 14 cell combinations may appear and the remaining 13 cell combinations are indicated as invalid combinations that cannot exist in the parent string.

As shown in Table 4.2, the 14 cell combinations in the "before mutation" column may generate 28 possible cell combinations (i.e., 14×2) according to the mutation pattern discussed in Section 4.3.2. Among the 28 possible combinations, there are 16 invalid cell combinations indicated by the bold texts in column "after mutation". A repair method is developed to correct all invalid cell combinations listed in column "after repair" in Table 4.2.

The developed GA based on the integer string representation outperformed the sequential search method discussed in Section 4.1 in solving the work zone scheduling problem on a two-lane two-way highway (Tang and Chien, 2007). However, it was unable to accommodate the discrete maintenance time-cost function discussed in Chapter 3. Thus, an enhanced genetic representation and data structure are developed to search for an optimal work zone schedule as well as production options corresponding to a discrete time-cost function.

4.4 Linked List Genetic Representation

As discussed in previous sections 4.1 and 4.3, the sequential search method did not jointly optimize the work zone schedules subject to the constraint of fixed project length, and the developed GA based on the integer string representation was unable to accommodate the discrete maintenance time-cost function. This section developed an enhanced GA representation, and the corresponding crossover and mutation operations are discussed in the following sections.

4.4.1 Linked List Data Structure

A general solution of the work zone scheduling problem may be represented by a list, denoted as SL and called the solution list.

$$SL=\{(S_1,E_1,k_1),\ \ldots\ldots\ ,(S_i,E_i,k_i),\ \ldots\ldots\ ,(S_m,E_m,k_m)\} \tag{4.3}$$

where S_i and E_i represent the starting and ending intervals of work activity i (i=1 to m), respectively. Note that k_i in Equation 4.3 is the index of production options associated with work activity i, and $k_i = 0$ represents a work break.

The list of intervals with an identical duration T are arranged in an ascending order starting from interval zero to N. Note that N represents the total number of intervals based on the maximum project duration, and can be obtained by Equation 4.2. Thus, the solution list SL can be abstracted as a "linked list" data structure, where (S_i, E_i, k_i) represents a node i. The number of nodes in the list represents the number of work activities for a maintenance project. Figure 4.5 illustrates a sample project schedule. The information containing in each node includes the starting interval (S_i), ending interval (E_i) and production option (k_i) of each work activity.

In Figure 4.5, if an interval lasts 15 minutes, a two-day project duration can be represented by 192 intervals. The project schedule consists of four work zones and three work breaks. The maintenance work starts at interval 8 and ends at interval 166. The first work break indicates a late start of the project, and the last work break indicates an early completion of the project.

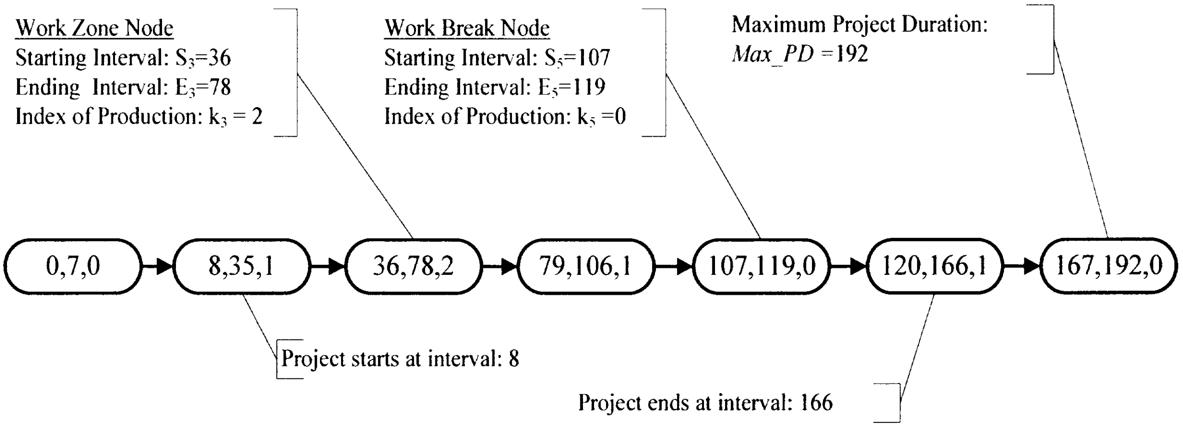


Figure 4.5 A linked list genetic representation.

By retrieving the work zone schedule from the solution list *SL*, the length of each work area (p_i), the associated queuing delay (D_{Qi}), and moving delay (D_{Mi}) can be determined by Equations 3.4, 3.15b and 3.17, respectively. Hence, all cost components in Equation 3.1 can be obtained.

4.4.2 Crossover and Mutation

Similar to the integer string representation discussed in Section 4.3, the two-point crossover and mutation operators are utilized. However, the procedures of crossover and mutation are modified to accommodate the different data structure of the linked list genetic representation.

Two-point Crossover Operator

As illustrated in Figure 4.6, the crossover operator divides each parent solution list into three segments between two random points, and exchanges the second segment (i.e., the middle segment) with another parent solution. Thus, two new solutions are created, which inherit the schedule information from their parent solutions. The crossover ratio, i.e., the probability of applying the crossover, was discussed in Section 4.3.2.

It is worth noting that the crossover operator also merges the two adjacent nodes from different parent solutions at the crossover points only if the two nodes employ the same production option. The shaded nodes in Figure 4.6 represent the merged nodes. For example, through the crossover operation, the shaded node 3 (36, 64, 2) in offspring 1 is generated by merging node 3 (36, 45, 2) in parent solution 1 and node 4 (46, 64, 2) in parent solution 2 because they employ the same production option 2. The shaded node 3 represents that a work zone employing production option 2 starts from interval 36 (i.e., $S_3 = 36$) and ends at interval 64 (i.e. $E_3 = 64$), which has an extended duration in comparison with node 3 (36, 45, 2) in parent solution 1.

This example demonstrates that the developed two-point crossover operator not only creates two new solutions, but also can adjust the schedule of work activities. In addition, the merge operation prevents the two-point crossover operator from creating repetitive short duration activities (i.e., nodes) in an offspring solution that may cause additional maintenance costs.

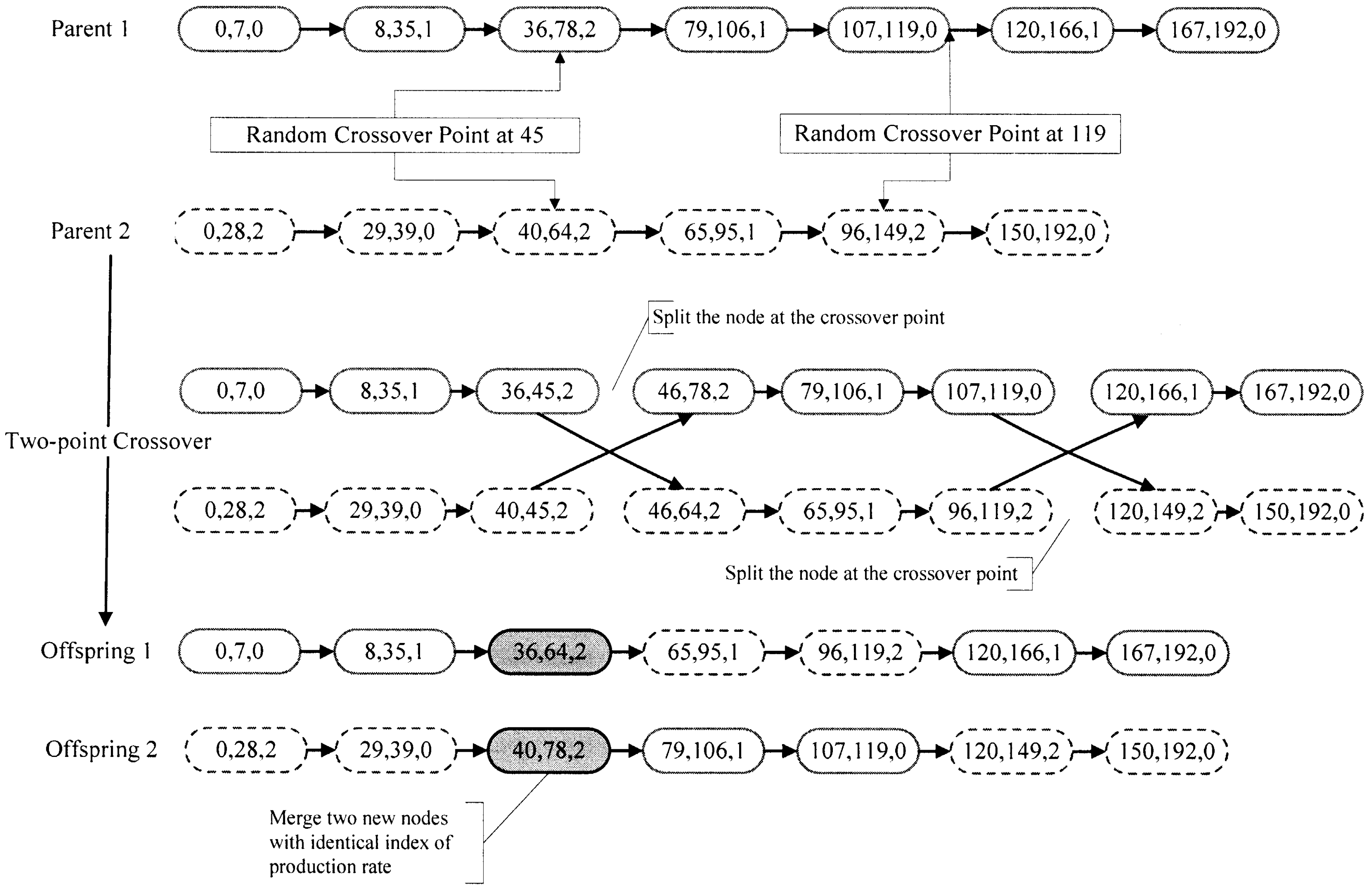


Figure 4.6 Illustration of the two-point crossover operation.

Mutation Operator

A mutation operator splits a node into two new nodes at a randomly selected interval and assigns a random value of a production option (i.e., *k*) to either of the two new nodes. Thus, the parent solution is altered by adding a new node. Based upon this procedure, a larger work zone (with a longer work duration) tends to have a greater possibility of being divided into two smaller zones with different production options. The mutation ratio, i.e., the probability of applying the mutation, was discussed in Section 4.3.2. The mutation operator creates diversity within a new population pool, which also prevents the searching process from being trapped into local optimal solutions.

The linked list data structure is a direct representation, which can be directly used as a GA solution (Michalewicz, 1999). The linked list representation simplifies the decoding process required by the integer string representation discussed in Section 4.3. In addition, the linked list eliminates all invalid cell combinations, and therefore the computation time and the efficiency of the developed GA are improved.

4.5 Evaluation Criterion

The performance of a GA solution is ranked by the objective value in terms of total cost based on the schedule decoded from the GA solution. For the optimization of the work zone scheduling problem discussed in this dissertation, the solution that achieves the least total cost is deemed as the best solution. By implementing the elitist selection discussed in the next section, the better solutions have a higher possibility to evolve into the next generation of the population pool.

4.6 Elitist Selection

The elitist selection, developed by Michalewicz (1999), is utilized to guarantee that the current generation solutions with good performance can always evolve into the next generation. The elitist selection is applicable to both genetic representations discussed in Sections 4.3 and 4.4.

Figure 4.7 illustrates the process of selection, where the population size and the ratio of selection are denoted as P and r, respectively, and are two pre-determined model parameters. Prior to the selection process, the solutions in the current generation (i.e., i^{th} generation) are sorted in an ascending order based on their objective values. The first solution in the generation represents the best schedule in terms of the lowest total cost. As shown in Figure 4.7, the top ($P \times r$) parent solutions in the i^{th} generation are chosen to reproduce exact ($P \times r$) new offspring in the $(i+1)^{th}$ generation, and the worst ($P \times r$) solutions in the i^{th} generation are discarded. Then, the original top ($P \times r$) and the remaining $P \times (1-2r)$ solutions are replicated to the population pool of the $(i+1)^{th}$ generation to maintain a constant population size P. The elitist selection will be used with each generation during the iteration process before the developed GA reaches the criteria of terminating the search processes.

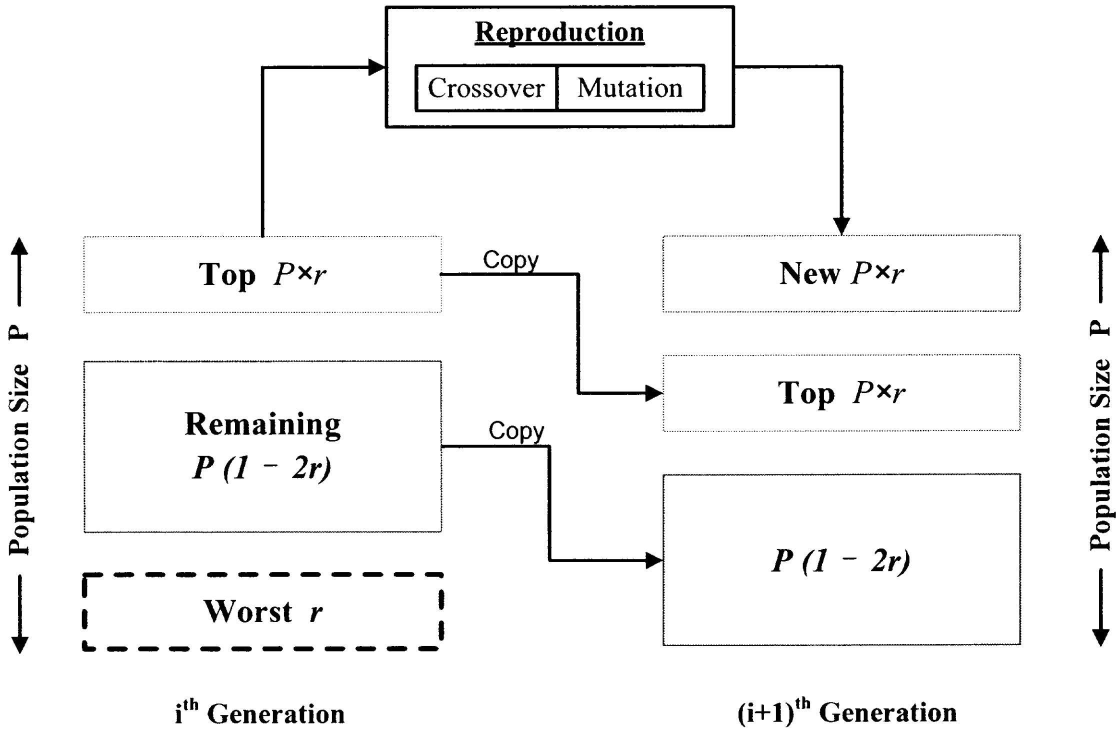


Figure 4.7 Elitist selection mechanism.

4.7 Constraint Handling Methods

The objective total cost function formulated in Equation 3.1a is bounded by three conditions: (A) maximum project duration, i.e., Equation 3.1b; (B) minimum duration of work activities, i.e., Equation 3.1c; and (C) user specified project length, i.e., Equation 3.1d.

The common constraint handling methods in GA include a penalty function method and a repair method (Chan, Fwa and Hoque, 2001). The penalty function method applies a large penalty value to the objective value of the solution violating a constraint(s).

Thus, infeasible solutions may be discarded during the evolution process. Although the penalty function method is easy to apply, good genetic structures in promising solutions may be scraped due to a minor violation of constraints.

Instead, a repair method corrects invalid solutions generated by crossover and mutation operations. Thus, a repair method can overcome the aforementioned drawback of a penalty function method subject to more computing time. In addition, it is difficult to formulate a general repair rule for complicated constraints. However, the special design of genetic representation may ease the design of a repair method. For example, the developed genetic representation can eliminate the constraint of maximum project duration (i.e., Constraint A) by defining the maximum number of intervals in a feasible solution. In addition, three general repair procedures can be formulated by utilizing the developed genetic representation, and thus adopted by the developed GA.

4.7.1 Constraint A: Maximum Project Duration

As formulated in Equation 3.1b, Constraint A ensures that all maintenance work must be completed within the specified maximum project duration, denoted as $PD_{\max}$. For the aforementioned integer string and linked list genetic representations, the maximum number of intervals in a solution list, denoted as N in Equation 4.2a, can always satisfy the constraint of maximum project duration, and no additional repairs are required.

4.7.2 Constraint B: Minimum Duration of Work Activities

As formulated in Equation 3.1c, Constraint B stipulates that the duration of a work activity must be no less than the minimum duration $D_{\min}$ required by construction practices. The minimum duration of a work zone, denoted as $D^{1}_{\min}$, was derived in

Equation 3.3c. The minimum duration of a work break, denoted as $D_{\min}^{0}$, is a user specified parameter, which may be determined by the duration of traffic peak period or the duration of other work activities that an idling crew may be re-assigned.

Crossover and mutation operations may generate short duration work activities that violate Constraint B. These short work activities may be considered as isolated fragments (i.e., nodes) in a work zone schedule, and they will be "absorbed" by their preceding and subsequent activities because forcing these fragments to satisfy the constraint may distort other good schedule information inherited from parent solutions. The repair procedure developed for Constraint B is illustrated in Figure 4.8.

Step 1: Check the current node *i*. If node *i* is a work zone, go to Step 4; otherwise, node *i* is a work break, go to Step 2;

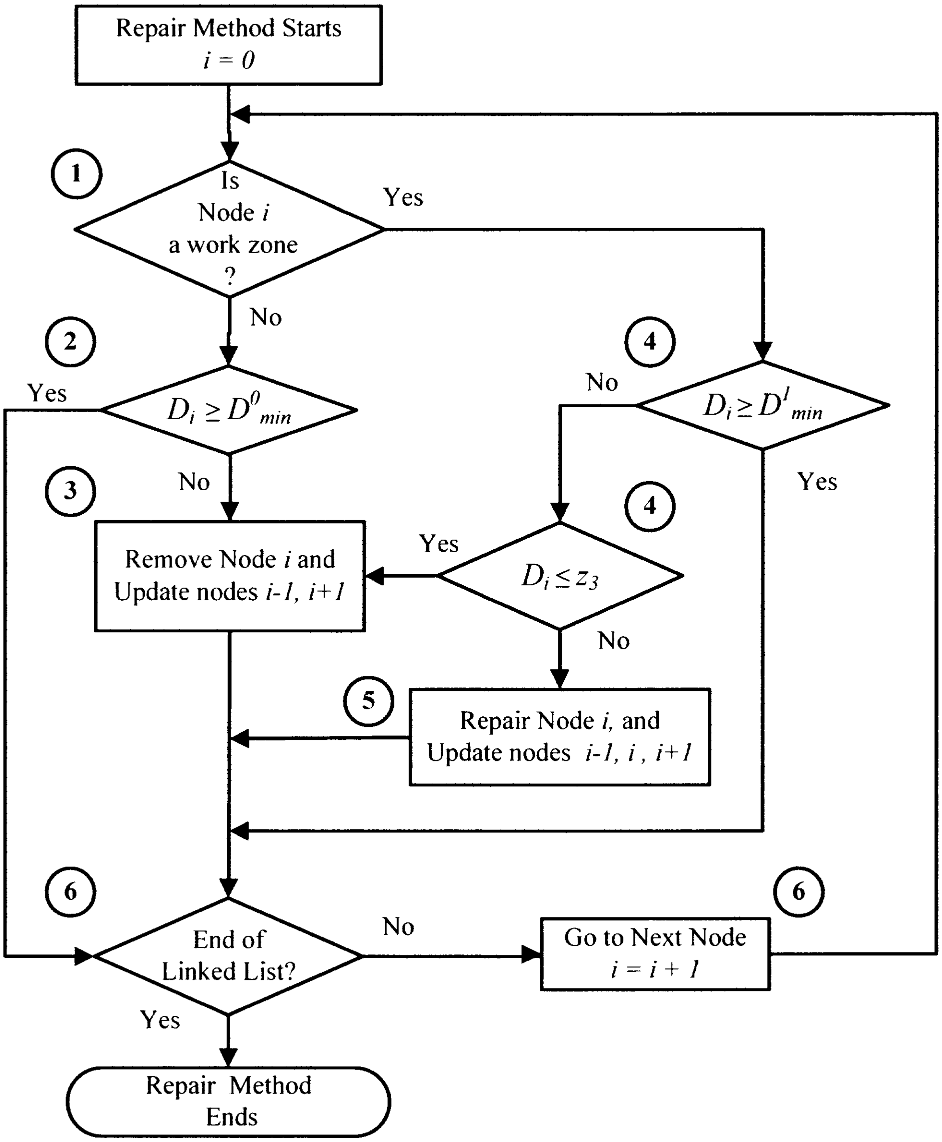
Step 2: if $D_i \geq D_{\min}^{0}$, Constraint B is satisfied, go to Step 6; otherwise, go to Step 3;

Step 3: Remove node *i*, and assign the intervals of node *i* to adjacent nodes *i-1* and *i+1*. Update the starting and ending intervals nodes *i-1, i+1*, then go to Step 6;

Step 4: If $D_i \geq D_{\min}^{1}$, Constraint B is satisfied, and go to Step 6; Then, if $D_i \leq z_3$, work zone node *i* is also treated as a fragment to be removed, go to Step 3; Otherwise, if $D_{\min}^{1} > D_i > z_3$, work zone node *i* is to be repaired, go to Step 5; Note that z_3 is the fixed setup time of a work zone.

Step 5: Repair node *i* by taking additional intervals from adjacent nodes *i-1* and *i+1*. Update the starting and ending intervals in nodes *i-1, i, i+1*, then go to Step 6;

Step 6: If the last node of the linked list is reached, the repair method ends; otherwise, check the next node (i.e., $i \Leftarrow i+1$), then go to Step 1.



i: Index of nodes;

D_i : Duration of node i (i.e. work activity i);

$D^0_{\min}$: Minimum duration of a work break

$D^1_{\min}$: Minimum duration of a work zone;

z_3: Fixed setup time of a work zone

Figure 4.8 Repair procedure for Constraint B.

4.7.3 Constraint C: User Specified Project Length

Constraint C defines that the work area length (p_i) is equal to the total project length *(L)*, which was derived in Equation 3.1c. Total length derived from a solution list is denoted as *TL*, i.e., $TL = \sum_{i=1}^{m} p_i$. Two repair procedures C1 and C2 are developed to correct the solutions violating Constraint C. If *TL>L*, repair procedures C1 will be used; otherwise, repair procedure C2 will be used.

Repair Procedure C1

Repair procedure C1 corrects the condition that total length *TL* exceeds a specified project length *L*. The excessive length and the associated work zone nodes will be discarded to satisfy Constraint C. Repair procedure C1 is shown in Figure 4.9.

Step 1: If node *i* is a work zone, calculate the length of work area (p_i) and the total length $TL = \sum_i p_i$; If node *i* is a work break, go to Step 3;

Step 2: Locate the node where *TL* exceeds *L*. If *TL<L*, go to Step 3; otherwise, *TL≥L*, go to Step 4;

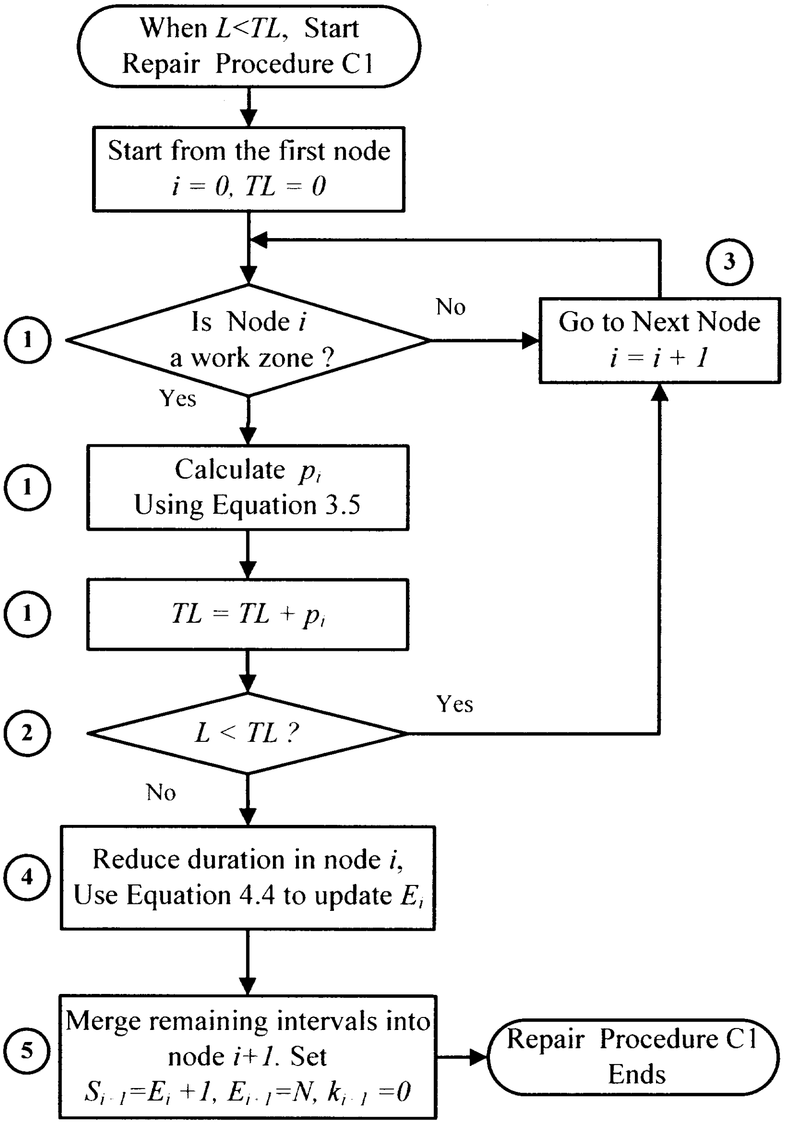
Step 3: Check the next node (i.e., $i \Leftarrow i+1$), then go to Step 1;

Step 4: Reduce the work zone duration in node *i*, and update the ending interval E_i by Equation 4.4;

$$E_i \Leftarrow E_i - (TL - L) \cdot z_{4i}^{p} / T \tag{4.4}$$

where z_{4i}^{p} is the unit production time of node *i* with respect to production option $k_i = p$; and T is the interval duration;

Step 5: Merge the remaining intervals after E_i (i.e., E_i+1 to N) into node $i+1$, and set $k_{i+1} = 0$; Repair procedure C1 ends.



TL: Total length of work areas;
E_i: Ending interval of nodes i;
i: Index of nodes, i.e., work activities;
L: Total project length;
N: Total number of intervals in a solution;
p_i: Work area length of node i;
S_i: Starting interval of node i.

Figure 4.9 Repair procedure C1 for Constraint C.

Repair Procedure C2

The total work area length (TL) decoded from a solution may be less than the project total length (L). To satisfy Constraint C, the shortage in project length, denoted as $\Delta L (= L - TL)$, will be compensated by extending the duration of work zones and reducing the duration of work breaks. Thus, the maximum project duration can still be remained (i.e., Constraint A).

Repair procedure C2 examines each work break to determine the amount of additional work, denoted as g_i, that may be completed while converting the entire duration of work break i to working hours. The addition work g_i is calculated based on the greater unit production time of work zones *i-1* and *i+1*. Thus,

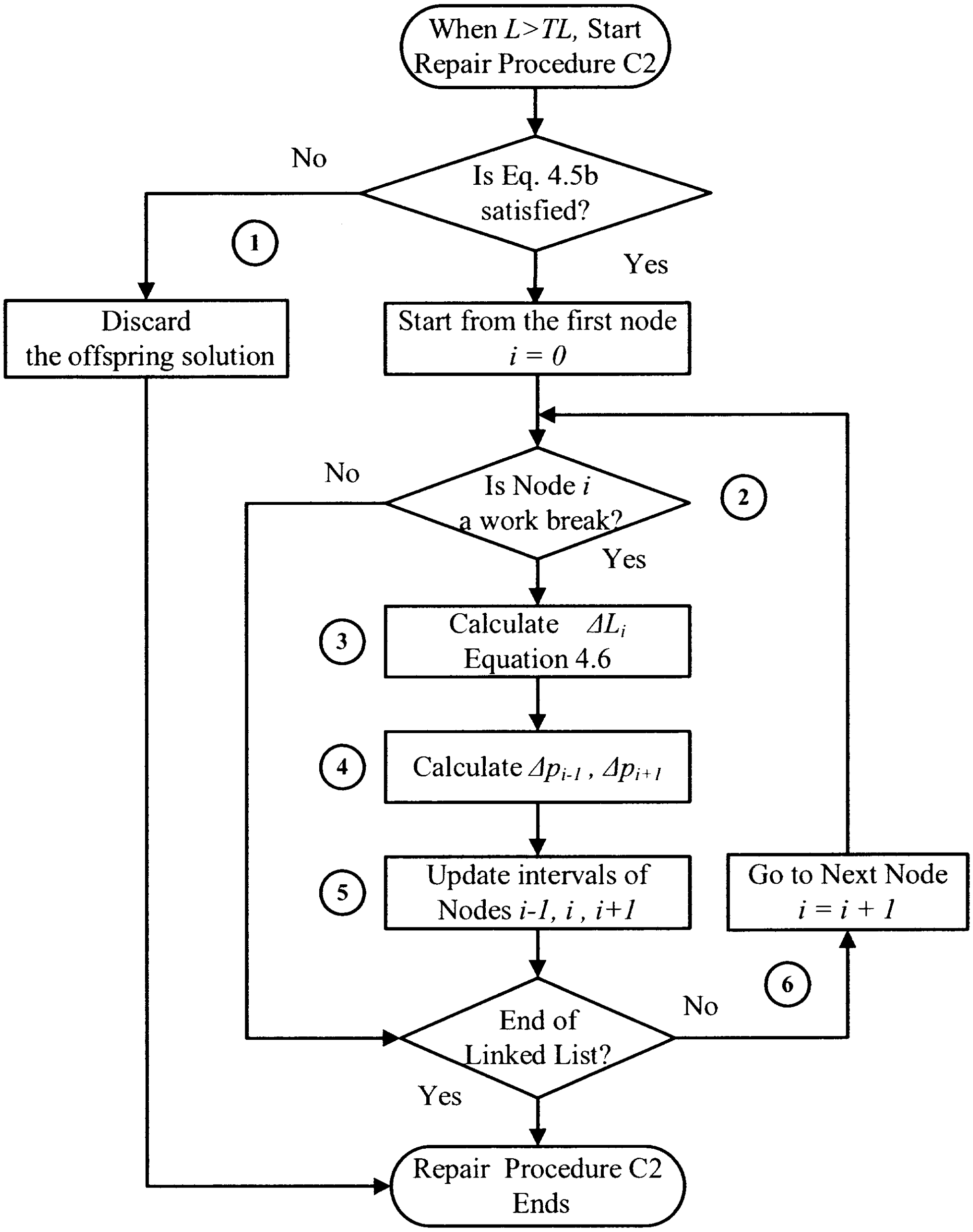
$$g_i = \frac{D_i^0}{\max(z_{4\,i-1}^{p}, z_{4\,i+1}^{r})} \tag{4.5a}$$

in which D_i^0 is the duration of work break i; p and r are the index of production option; and $z_{4\,i-1}^{p}$ and $z_{4\,i+1}^{r}$ represents the unit production time (i.e., hour per lane-km) of work zones *i-1* and *i+1*.

To satisfy Constraint C, the sum of the additional work should be no less than the shortage ΔL, which is derived as,

$$\sum_i g_i \geq \Delta L \tag{4.5b}$$

The criterion defined in Equation 4.5b ensures that the sufficient work break time can be allocated to compensate the shortage in project length, and it must be satisfied before starting repair procedure C2. Any offspring solutions not satisfying Equation 4.5b will be discarded. The flow chart of repair procedure C2 is illustrated in Figure 4.10.



i: Index of nodes;

ΔL_i: Additional work area length assigned to work break i;

$\Delta p_i, \Delta p_{i+1}$: Additional work area length allocated to work zones $i-1$ and $i+1$;

Figure 4.10 Repair procedure C2 for Constraint C.

Step 1: Check a new solution. If a solution satisfies Equation 4.5b, go to Step 2; If not, the solution cannot be corrected, and should be discarded; Repair procedure ends;

Step 2: If node *i* is a work break, go to Step 3; otherwise, go to Step 6;

Step 3: Distribute the total shortage in work area length (ΔL) to each work break *i*. The additional work area length assigned to work break *i*, denoted as ΔL_i, is calculated by Equation 4.6.

$$\Delta L_i = \frac{g_i}{\sum_i g_i} \times \Delta L \qquad (4.6)$$

Step 4: Assign the additional work area length (ΔL_i) to work zones *i-1* and *i+1* proportionally based upon the corresponding lengths of p_{i-1} and p_{i+1}, as shown in Equations 4.7a and 4.7b, respectively.

$$\Delta p_{i-1} = \frac{p_{i-1}}{p_{i-1} + p_{i+1}} \times \Delta L_i \qquad (4.7a)$$

$$\Delta p_{i+1} = \frac{p_{i+1}}{p_{i-1} + p_{i+1}} \times \Delta L_i \qquad (4.7b)$$

Step 5: Extend the working hours of work zones *i-1* and *i+1* according to Equations 4.8a and 4.8b, where E'_{i-1} represents the updated ending interval of work zone *i-1* and S'_{i+1} is the updated starting interval of work zone *i+1*; and *T* is the interval duration. Then, the starting and ending intervals of work break *i* also need to be updated by using Equations 4.9a and 4.9b. Then go to Step 6;

$$E'_{i-1} = E_{i-1} + \frac{\Delta p_{i-1} \cdot z^{p}_{4\,i-1}}{T} \qquad (4.8a)$$

$$S'_{i+1} = S_{i+1} - \frac{\Delta p_{i+1} \cdot z'^{r}_{4\ i+1}}{T} \tag{4.8b}$$

$$S'_{i} = E'_{i-1} + 1 \tag{4.9a}$$

$$E'_{i} = S'_{i+1} - 1 \tag{4.9b}$$

Step 6: If the last node is reached, repair method C2 ends; otherwise, check the next node (i.e., $i \Leftarrow i+1$), then go to Step 2.

4.8 Model Calibration

This section utilizes a hypothetical two-lane two-way highway maintenance project to validate the developed GA model. Chen (2003) analyzed this example by the Simulated Annealing Algorithm. The optimal solution achieved by the simulated annealing algorithm is adopted as a benchmark.

4.8.1 Example Case and Benchmark Solution

A 7.50-km maintenance project on a two-lane two-way highway will be performed by closing one travel lane at a time. The Annual Average Daily Traffic (AADT) on the studied highway is 15,000 vehicles, and the hourly traffic distribution is depicted in Table 4.3. The baseline values of input parameters are summarized in Table 4.4.

Table 4.3 Mainline AADT and Hourly Traffic Volumes for Benchmark Solution

Hours	Volumes (both directions)	Q_1 (vph)	Q_2 (vph)	Hours	Volumes (both directions)	Q_1 (vph)	Q_2 (vph)
0-1	349	167	182	**12-13**	600	300	300
1-2	350	168	182	**13-14**	552	287	265
2-3	349	157	192	**14-15**	650	332	318
3-4	350	185	165	**15-16**	852	452	400
4-5	349	185	164	**16-17**	1100	539	561
5-6	350	186	164	**17-18**	844	397	447
6-7	552	315	237	**18-19**	750	353	397
7-8	900	504	396	**19-20**	702	330	372
8-9	1152	645	507	**20-21**	600	276	324
9-10	1002	541	461	**21-22**	500	240	260
10-11	800	408	392	**22-23**	349	167	182
11-12	649	331	318	**23-24**	349	167	182

Source: Chen (2004).

Table 4.4 Baseline Values of Input Parameters for Benchmark Solution

Variables	**Descriptions**	**Baseline Input Value**
H	Average headway through work zone	3 seconds
$AADT$	Annual average daily traffic	15,000
V_a	Travel speed under normal condition	80 km/hour
V_w	Average work zone speed	50 km/hour
l_i	Length of work zone i	--
p_i	Length of work area for work zone i	--
l_T	Total length of tapers and buffers	0 km (N/A)
v	Value of user time	12 \$/veh-hour
v_d	Average idling cost per hour	800 \$/hour
v_O	Vehicle operating cost	0 \$/veh-hr (N/A)
z_1	Fixed setup cost	1,000 \$/zone
z_3	Fixed total time of setting and removing a work zone	2.0 hours/zone
z_2^k	Unit maintenance cost per lane-kilometer	80,000\$/lane-km
z_4^k	Unit production time per lane-kilometer	6 hr/lane-km
k	Index of production options	-- (N/A)
L	Project length	7.500 km

Note that the work zone taper length, vehicle operating cost and variable production options were not considered in Chen's model (2003), thus these parameters are set to zero or are "Not Applicable".

The benchmark solution in Table 4.5 indicates that the best project starting time is 11:00 and the minimized total cost of 627,688 \$/project is achieved by scheduling 9 work zones and 4 work breaks. The optimized lengths of work zone 1 through 9 are 0.53, 0.77, 1.07, 0.82, 0.76, 1.08, 0.71, 0.45 and 1.34 km, respectively. The project duration is 66.95

hours including 63.00 hours spend in work zones and 3.95 hours of work breaks. The optimized schedule and the resulting cost components are summarized in Table 4.5.

Table 4.5 Benchmark Solution Achieved by Simulated Annealing

Zone No.	**Optimal Length (km)**	**Duration (Hours)**	**Starting Time (0~23.99)**	**Ending Time (0~23.99)**	**Idling Time (Hours)**	**Total Cost ($/zone)**
1	0.53	5.16	11.00 (11:00)	16.16 (16:10)	-	44,154
2	0.77	6.60	17.00 (17:00)	23.60 (23:36)	0.84	64,502
3	1.07	8.40	23.60 (23:36)	8.00 (08:00)	0.00	88,147
4	0.82	6.90	9.09 (9:06)	15.99 (16:00)	1.09	69,612
5	0.76	6.54	16.99 (17:00)	23.53 (23:32)	1.00	63,817
6	1.08	8.46	23.53 (23:32)	7.99 (08:00)	0.00	88,968
7	0.71	6.24	9.01 (9:00)	15.25 (15:15)	1.02	60,207
8	0.45	4.68	15.25 (15:15)	19.93 (19:56)	0.00	38,271
9	1.34	10.02	19.93 (19:56)	5.95 (05:57)	0.00	110,011
Total		63.00			3.95	627,688
Maintenance Cost						609,000
Queuing Delay Cost						12,842
Moving Delay Cost						2,612
Idling Cost						3,162
Accident Cost						72
Total Cost						**627,688**
Total Cost/project-km						**83,691**

Source: Chen (2004), Table 7, pp. 105.

The starting and ending times within parentheses were converted to “hh:mm” format by Tang.

4.8.2 Optimized Solution in GA

The GA model utilizes 15-minute intervals to run the example. The maximum project duration is defined as 90 hours containing 360 intervals. The population size is 1,600. The value of selection ratio *r* is 0.45, and the ratios of two-point crossover and mutation are 0.65 and 0.02, respectively. The stop-criterion is set at 100 generations for each run.

Because GA is a stochastic algorithm, the optimal solutions may vary with the random operations in generating different initial population pools and performing crossover and mutation. Given a randomly generated population pool, 10 model runs were performed by using different random number seeds. The solution that achieves the lowest total cost is deemed as the optimum solution. Table 4.6 lists the minimized total cost achieved by the optimized work zone schedule.

Table 4.6 Optimized Work Zone Schedule Achieved by GA

Zone No.	Optimal Length (km)	Duration (Hours)	Starting Time	Ending Time	Idling Time (Hours)	Total Cost ($/zone)
1	0.583	5.50	10:45	16:15	0	48,967
2	0.000	0.75	16:15	17:00	0.75	600
3	0.750	6.50	17:00	23:30	0	62,462
4	1.084	8.50	23:30	08:00	0	89,533
5	0.000	1.00	08:00	09:00	1.00	800
6	0.458	4.75	09:00	13:45	0	38,655
7	0.458	4.75	13:45	18:30	0	39,245
8	0.875	7.25	18:30	01:45	0	72,339
9	0.708	6.25	01:45	08:00	0	58,675
10	0.000	1.00	08:00	09:00	1.00	800
11	0.708	6.25	09:00	15:15	0	59,549
12	0.458	4.75	15:15	20:00	0	39,268
13	1.418	10.50	20:00	06:30	0	116,690
Total	7.500	67.75	--	--	2.75	627,583
Maintenance Cost						610,000
Queuing Delay Cost						12,734
Moving Delay Cost						2,577
Idling Cost						2,200
Accident Cost						72
Vehicle Operating Cost						--
Total Cost						**627,583**
Total Cost/project-km						**83,678**

The developed GA found the optimized solution at the 49th generation, and the minimized total cost of 627,583 $/project is slightly lower than the benchmark solution (i.e., 627,688$/project). The best project starting time is found at 10:45 AM, and 10 work zones and 3 work breaks are scheduled to complete the project. The total duration of work breaks is 2.75 hours. Comparing with the benchmark solution, the total delay cost may be reduced if an additional work zone is included in the schedule. The additional work zone setup cost (i.e., 1,000 \$/zone) is offset by the saving in idling cost (i.e., \$ 962). The resulting project duration is 67.75 hours, and is 0.8 hours longer than the benchmark solution because of the setup time of the additional work zone.

The comparison between the benchmark and the GA solution indicates that the total number of work activities (i.e., 10 work zones and 3 work breaks) found by the GA is equal to that of the benchmark solution (i.e., 9 work zones and 4 work breaks). The slight differences in the minimized total costs and the numbers of work zones may be caused by the different project starting time. The optimized solution obtained by the GA is consistent with the benchmark solution summarized in Table 4.4.

4.8.3 Reliability of the Developed GA

The developed GA is written in C programming language and compiled by the Microsoft® Visual C++ 2005 Express Edition. To verify the reliability of the developed GA, 30 random population pools were tested for the benchmark example. The 30 program runs took approximately 9.5 minutes on a 2.40 GHz Intel® Core™ 2 Duo CPU.

Given the stop criteria of 100 generations for each run, the developed GA converged to the minimized total costs between the 32nd and the 69th generation during the 30 model runs. The minimized total costs achieved by the GA range from \$627,583 to \$628,213 as illustrated in Figure 4.11. The best project starting time varies from 10:00 AM to 12:00 PM among the 30 replications. Not considering the constant portion of the maintenance cost (i.e., 80,000 \$/lane-km × 7.5 km = 600,000 \$/lane), the variation in the minimized total costs is 2.28% due to different project starting times and various combinations of work zone lengths.

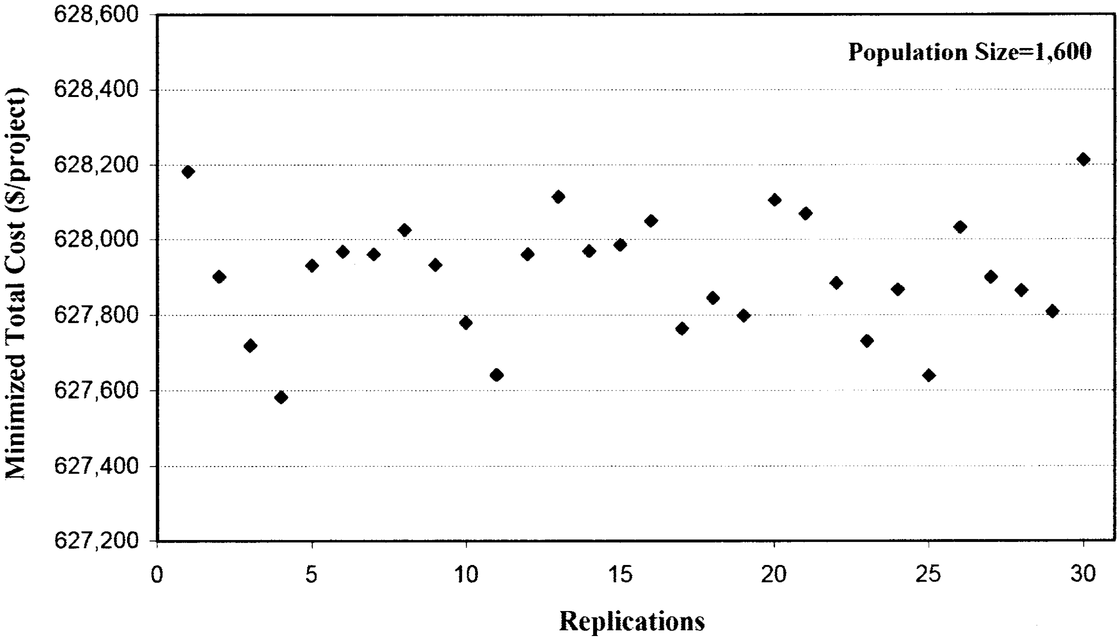


Figure 4.11 Minimized total costs over 30 replications.

Population size affects the GA performance and the quality of optimal solutions. Larger populations may improve the ptimal solution quality subject to more computation time. Thus, the minimized total costs obtained by the GA are tested over a range of population sizes from 600 to 1,700 incrementally. For a given population size, thirty replications (i.e., 30 random population pools) were performed, and the lowest total cost achieved by the GA model is illustrated in Figure 4.12. In this example, the develop GA model gains lower minimized total cost while the population size increases, and a stable range of the minimized total cost can be achieved when the population size is over 900.

The results suggest that the appropriate range of population size (P) is approximately 2.5~3.5 times the total number of intervals (N) in a solution (i.e., P = $2.5N$~$3.5N$). Increasing population size above the upper limit of this range will not improve the solution quality noticeably. The case study conducted in Chapter 5 uses a population size of $4N$.

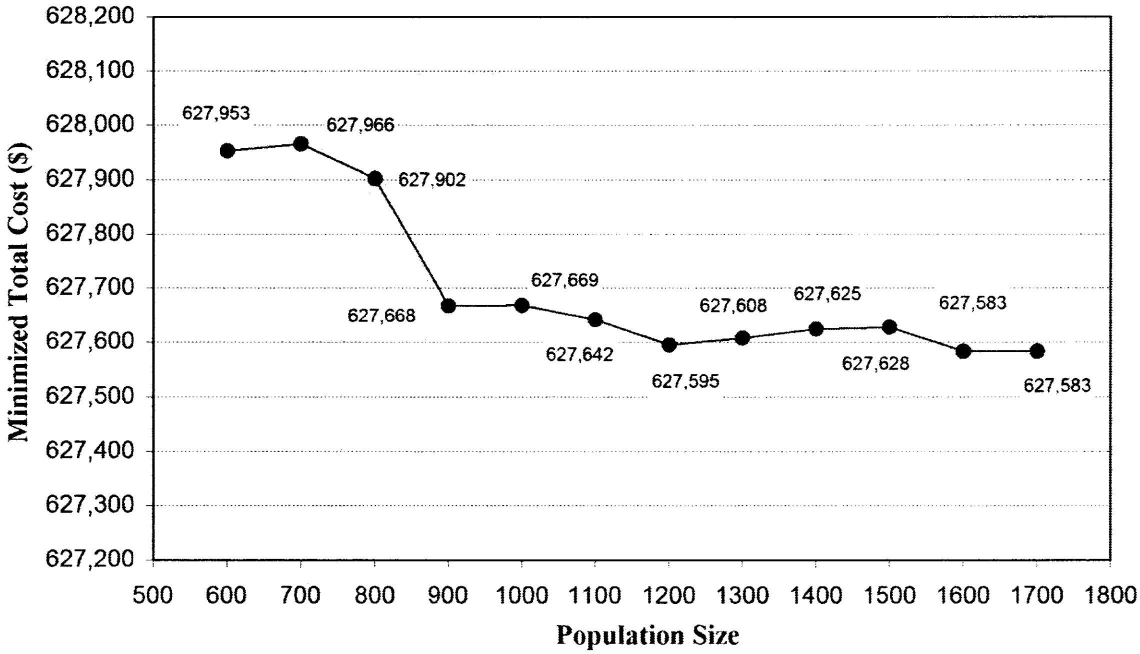


Figure 4.12 Minimized total costs versus population size.

CHAPTER 5

CASE STUDY

5.1 Introduction

By deploying crews capable of a high production rate, highway maintenance work may be accelerated so as to reduce total road user cost and project duration. In addition, the traffic on the mainline may be diverted to alternate routes, which allows a longer time window and less repetitive work zone setups for roadway maintenance. However, accelerating construction is usually expensive, and diverting traffic may increase the travel time on the alternate routes. Thus, the two strategies should be evaluated jointly while considering different traffic conditions (e.g., AADT) of the mainline as well as alternate routes subject to various constraints (e.g., maximum project duration).

As shown in Table 5.1, this chapter developed four scenarios listed below, which include a constant or a discrete maintenance time-cost function with or without traffic diversion to an alternate route.

- Scenario A1: No traffic diversion and a constant maintenance time-cost function (i.e., fixed unit maintenance cost z_2^k and unit maintenance time z_4^k for an entire project) is used.
- Scenario A2: No traffic diversion and a discrete maintenance time-cost function is used.
- Scenario B1: An alternate route is available and a constant maintenance time-cost function is used.
- Scenario B2: An alternate route is available and a discrete maintenance time-cost function is used.

Table 5.1 Definition of Studied Scenarios

Maintenance Time-Cost Function	[A] No Traffic Diversion	[B] Traffic Diversion
[1] Constant z_2^k, z_4^k	Scenario A1	Scenario B1
[2] Discrete time-cost function	Scenario A2	Scenario B2

Based upon a set of input parameters with given baseline values, the work zone schedules for the aforementioned four scenarios were optimized by minimizing the total project cost. The optimized solutions were analyzed to evaluate the applicability and benefits of the accelerated construction and traffic diversion. Section 5.2 discuses the scenarios without traffic diversion (i.e., A1 and A2), and the scenarios with traffic diversion (i.e., B1 and B2) are discussed in Section 5.3. Furthermore, a sensitivity analysis for several key parameters is presented in Section 5.4.

5.1.1 Parameters of Traffic and Work Activities

A maintenance project will be conducted on a Principle Arterial with 2 travel lanes in each direction in Middlesex County, New Jersey. The maintenance work will be scheduled to close one travel lane at a time for resurfacing a 5.00-km long highway segment with 2-inch asphalt concrete pavement. This case study demonstrates the optimized work zone schedules for the maintenance work along one travel lane, and the optimized schedules for the remaining lanes can be obtained by the same approach.

The Annual Average Daily Traffic of the studied highway, denoted as $AADT_m$, is 45,000 vehicles per day (vpd), and the hourly traffic volume distribution and the directional split in Table 5.2 are obtained from the Road User Cost Manual developed by the New Jersey Department of Transportation (2001), and illustrated in Figure 5.1. For the purpose of sensitivity analyses, Table 5.2 summarizes the hourly volumes with respect to $AADT_m$ ranging from 30,000 to 60,000 vpd.

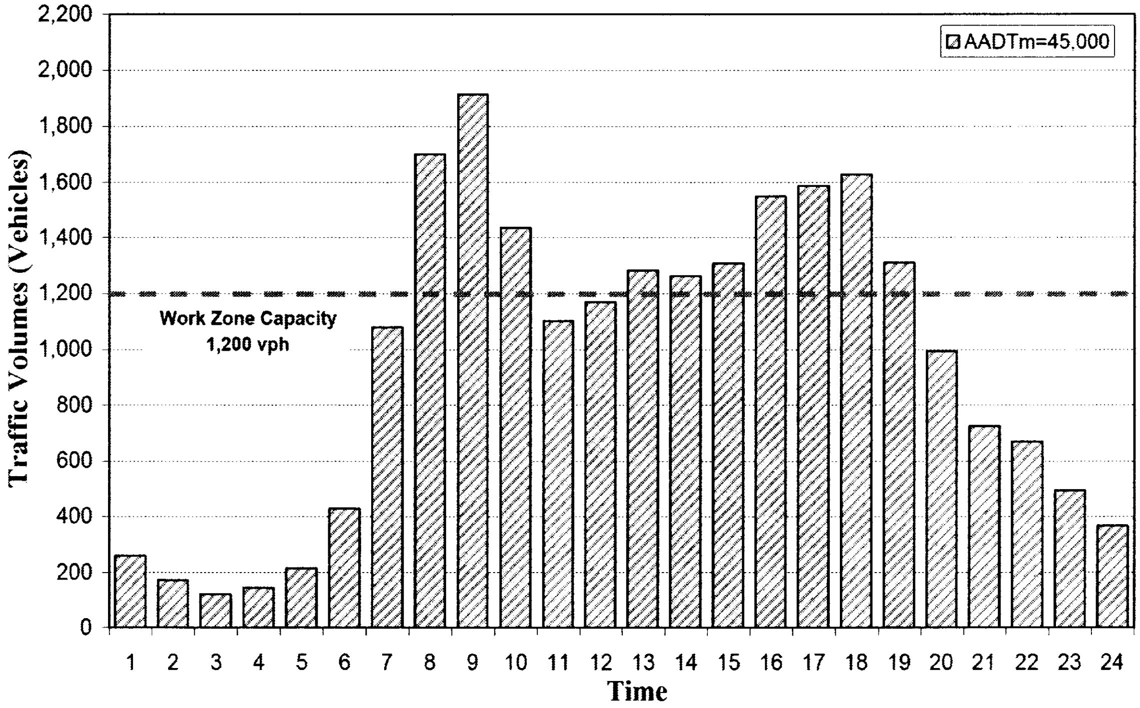


Figure 5.1 Weekday hourly traffic volume distribution on the mainline.

The capacity of the studied highway is 4,500 vehicles per hour (vph), and the roadway capacity is reduced to 1,200 vph with one lane closure for construction. The design speed is 80 km/hour, and the posted work zone speed limit is 50 km/hour. The total length of the merge taper and downstream taper as well as work buffer areas is 0.20-km.

The work zone setup and removal time is 2 hours and the associated cost is \$1,000 per zone. The idling cost for work breaks between work zones is \$800 per hour. For constructing 2-inch asphalt concrete pavement, the baseline values of unit maintenance cost z_2^k and production time z_4^k (i.e., Crew "B-25B" shown in Table 5.3) are obtained the *Means Heavy Construction Cost Data 2006* (RS Means, 2006). The alternative production options 1, 3 and 4, i.e., Crews "M-1", "M-3" and "M-4" shown in Table 5.3 were developed by adjusting the baseline labor/equipment cost and daily production of the Crew "B-25B". For example, the most productive Crew "M-4" consists of more skillful workers and equipment, thus the highest production rate can be provided with the highest unit maintenance cost. The hypothetical unit costs and unit production times may be substituted by contractor's historical construction time-cost data.

Table 5.2 Mainline AADT($AADT_m$) and Hourly Traffic Volumes

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

Note: Directional split is for the travel direction impacted by work zone.

Table 5.3 Unit Maintenance Cost and Production Time for Pavement Resurfacing

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

The baseline values of other input parameters are summarized in Table 5.4. They are introduced to demonstrate the developed model rather than to represent any specific site.

5.1.2 Parameters of the Developed GA

The parameters for the developed GA model were calibrated previously in Section 4.8 Model Calibration. The designed population size is 1,000. The value of selection ratio r is 0.45, and the ratios of two-point crossover and mutation are 0.65 and 0.025, respectively. The stop-criterion is set at 100 generations for each run. A feasible solution in GA contains 256 intervals with an interval of 15 minutes, which represents the maximum project duration $PD_{\max} = 64$ hours.

The optimal solution achieved in this example is based upon 30 program runs (i.e., 3 random population pools times 10 runs per population pool), which takes approximately 1.0~1.5 minutes on a 2.40 GHz Intel® Core™ 2 Duo CPU.

Table 5.4 Baseline Values of Input Parameters for Scenario A

Variables	Descriptions	Baseline Values
$AADT_m$	AADT on the mainline	45,000 vpd
c_0	Capacity of the mainline	4,500 vph
c_w	Capacity of the mainline with work zone	1,200 vph
V_f	Design speed of the mainline	80 km/hour
V_w	Average work zone speed	50 km/hour
l_i	Length of work zone i	To be determined
p_i	Length of work area for work zone i	To be determined
l_T	Total length of tapers and buffers	0.400 km
v	Value of user time	15 $/veh-hour
v_d	Average idling cost per hour	800 $/hour
v_O	Additional vehicle operating cost	0.91 $/veh-hour
z_1	Fixed setup cost	1,000 $/zone
z_3	Fixed total time of setting and removing a work zone	2.0 hours/zone
z_2^k	Unit maintenance cost per lane-kilometer	$/lane-km (Table 5.3)
z_4^k	Unit production time per lane-kilometer	hr/lane-km (Table 5.3)
k	Index of production options	To be determined
f_{nc}	Nighttime maintenance cost factor	1.00
L	Project length	5.000 km
$PD_{\max}$	Maximum project duration	64 hours
D_{min}	Minimum duration of work zone and work break	3 hours and 2 hours
P	Population size	1,000
r	Selection ratio for reproduction	0.45
P_{XO}	Crossover ratio	0.65
P_{MU}	Mutation ratio	0.025

5.2 Optimized Work Zone Schedules without Traffic Diversion

For the maintenance project defined in Section 5.1, this section discussed two scenarios, i.e., A1 and A2, in which traffic diversion from the mainline to alternate routes is not considered. Scenario A1 assumes that the maintenance project will be conducted by utilizing a designated production option through the entire project, where the unit maintenance cost z_2^k and production time z_4^k are fixed for all work zones. With the given production option, the work zone schedule is optimized to minimize the total cost. Instead, in Scenario B2, the production option of each work zone is a decision variable, and is jointly optimized with the work zone schedule to minimize the total cost. The optimal solutions of each scenario are discussed and compared in the following sections.

5.2.1 Scenario A1

Given that $AADT_m$ = 45,000 vpd and $PD_{\max}$ =64 hours, the work zone schedule is optimized with respect to each production option listed in Table 5.3, where Production Option 1 represents the lowest productive option at the least unit cost, while Production Option 4 is the most productive but expensive option. Four optimized schedules (i.e., Schedule "A1-1", "A1-2", "A1-3" and "A1-4") and their associated cost components are presented in Tables 5.5 through 5.8.

Schedule "A1-1" in Table 5.5 indicates that the project must start at 0:00 when the Production Option 1 is deployed, thus the project can be completed without exceeding the maximum project duration. The resulting project duration is 55.25 hours. The maintenance work is scheduled into five work zones over three off-peak periods (i.e., 0:00~7:15 on Day 1, 18:00~7:15 on Day 2 and Day 3) and two mid-day off-peak periods (i.e., 9:45~14:45 in Day 1 and Day 2). Four work breaks are scheduled to avoid peak hours and reduce excessive travel delay and the associated user costs. The minimized project total cost is $157,366, consisting of $129,300, $9,200 and $18,866 of maintenance, idling and road user costs, respectively.

Table 5.5 Optimized Schedule "A1-1" ($AADT_m$ = 45,000, Option 1)

Work Zone i	Work Zone Start & End Times	Duration (Hours)	Work Area Length p_i (km)	Maintenance Cost ($)	User Cost ($)	Idling Cost ($)	Total Cost ($)
1	00:00–07:15	7.25	0.778	20,336	611	0	20,947
2	07:15–09:45	2.50	Work Break	0	45	2,000	2,045
3	09:45–14:45	5.00	0.444	12,049	5,647	0	17,695
4	14:45–18:00	3.25	Work Break	0	128	2,600	2,728
5	18:00–07:15	13.25	1.667	42,433	3,286	0	45,719
6	07:15–09:45	2.50	Work Break	0	45	2,000	2,045
7	09:45–14:45	5.00	0.444	12,049	5,647	0	17,695
8	14:45–18:00	3.25	Work Break	0	128	2,600	3,074
9	18:00–07:15	13.25	1.667	42,433	3,286	0	45,719
	Total	55.25	5.000	129,300	18,866	9,200	**157,366**
Itemized User Cost							
Queuing Delay Cost ($)		13,190					
Moving Delay Cost ($)		4,807					
Vehicle Operating Cost($)		800					
Accident Cost ($)		68					

The optimized work zone schedule "A1-2" summarized in Table 5.6 indicates that the best project start time is 0:00 and the resulting project duration is 53.50 hours when employing Production Option 2. The optimized schedule is similar to Schedule "A1-1", in which the maintenance work is scheduled for five work zones during three off-peak periods (i.e., 0:00~7:00, 18:45~7:00 and 18:45~5:30) and two mid-day off-peak periods (i.e., 9:45~13:30 in Day 1 and Day 2). Two work breaks (i.e., 7:00~9:45 and 13:30~18:45) in each day are arranged to avoid peak traffic, and then excessive travel delay and the associated user costs can be reduced. Compared to Schedule "A1-1", deploying Production Option 2 can accelerate the maintenance work and allows longer work breaks to avoid peak traffic, achieving a significant reduction of $11,324 in user cost. The idling cost increases by $3,600 due to the extended work breaks; however, it may be offset by the reduction of road user cost. Thus, Production Option 2 saves $ 7,109 in total cost, which reduces the minimized project total cost to $150,257, consisting of $129,915, $12,800 and $7,542 of maintenance, idling and road user costs, respectively.

Table 5.6 Optimized Schedule "A1-2" ($AADT_m$ = 45,000, Option 2)

Work Zone	**Work Zone**	**Duration**	**Work Area Length** p_i	**Maintenance Cost**	**User Cost**	**Idling Cost**	**Total Cost**
i	**Start & End Times**	**(Hours)**	**(km)**	**($)**	**($)**	**($)**	**($)**
1	00:00–07:00	7.00	0.909	23,712	357	0	24,069
2	07:00–09:45	2.75	Work Break	0	0	2,200	2,200
3	09:45–13:30	3.75	0.318	8,949	2,188	0	11,137
4	13:30–18:45	5.25	Work Break	0	32	4,200	4,232
5	18:45–07:00	12.25	1.864	47,559	1,610	0	49,169
6	07:00–09:45	2.75	Work Break	0	0	2,200	2,200
7	09:45–13:30	3.75	0.318	8,949	2,188	0	11,137
8	13:30–18:45	5.25	Work Break	0	32	4,200	4,232
9	18:45–05:30	10.75	1.591	40,746	1,136	0	41,882
	Total	53.50	5.000	129,915	7,542	12,800	**150,257**
Itemized User Cost							
Queuing Delay Cost ($)		3,665					
Moving Delay Cost ($)		3,628					
Vehicle Operating Cost($)		222					
Accident Cost ($)		28					

Given the maximum project duration of 64 hours, both Schedules "A-1" and "A-2" suggest an immediate start of construction at 0:00 of Day 1, thus all maintenance work can be completed before the morning peak hour in Day 3. Otherwise, the remaining work will be extended to the daytime peak or mid-day off-peak hours, and that inevitably causes additional user costs and work zone setup costs.

The optimized Schedule "A1-3" summarized in Table 5.7 indicates that the project starts at 18:30, and the resulting project duration is 36.50 hours while deploying a more productive but expensive Production Option 3. The accelerated construction allows less repetitive work activities and shorter work breaks. Hence, the entire maintenance work can be completed within two overnight off-peak periods (i.e., 18:30~7:30 and 18:30~7:00) and one mid-day off-peak period (i.e., 9:45~14:00) with two work breaks (i.e., 7:30~9:45 and 14:00~18:30). Comparing this with Production Option 2, the saving in work zone setup cost (i.e., $2,000) can compensate the additional $1,300 maintenance cost due to the increased maintenance cost required by Production Option 3. The reduction of $7,400 in idling cost can fully offset the additional $1,679 user cost. Finally, the reductions in the total cost and project duration are $ 6,421 and 17 hours when deploying Production Option 3.

Table 5.7 Optimized Schedule "A1-3" ($AADT_m = 45{,}000$, Option 3)

Work Zone i	**Work Zone** **Start & End Times**	**Duration** **(Hours)**	**Work Area Length** p_i **(km)**	**Maintenance Cost** **($)**	**User Cost** **($)**	**Idling Cost** **($)**	**Total Cost** **($)**
1	18:30–07:30	13.00	2.316	59,457	3,446	0	62,904
2	07:30–09:45	2.25	Work Break	0	179	1,800	1,979
3	09:45–14:00	4.25	0.474	12,957	3,356	0	16,313
4	14:00–18:30	4.50	Work Break	0	53	3,600	3,653
5	18:30–07:00	12.50	2.211	56,800	2,188	0	58,988
	Total	36.50	5.000	129,215	9,221	5,400	**143,836**
Itemized User Cost							
Queuing Delay Cost ($)		4,489					
Moving Delay Cost ($)		4,426					
Vehicle Operating Cost($)		272					
Accident Cost ($)		34					

The optimized work zone schedule of "A1-4" summarized in Table 5.8 indicates that the best project start time is 19:15 in Day 1 and the resulting project duration is 34 hours by utilizing the most expensive but productive Option 4. Similar to Schedule "A1-3", the maintenance work is performed within two overnight off-peak periods (i.e., 19:15~7:00 and 18:45~5:15) and one mid-day off-peak period (i.e., 9:45~13:00) with two work breaks (i.e., 7:30~9:45 and 13:00~18:45). However, in comparison with Schedule "A1-3", the project total cost is increased by $1,592 because the savings in user cost cannot compensate the increased maintenance and idling costs.

Table 5.8 Optimized Schedule "A1-4"($AADT_m$ = 45,000, Option 4)

Work Zone *i*	**Work Zone** **Start & End Times**	**Duration** **(Hours)**	**Work Area Length** p_i **(km)**	**Maintenance Cost** **($)**	**User Cost** **($)**	**Idling Cost** **($)**	**Total Cost** **($)**
1	19:15–07:00	11.75	2.500	66,528	1,778	0	68,305
2	07:00–09:45	2.75	Work Break	0	0	2,200	2,200
3	09:45–13:00	3.25	0.321	9,401	1,360	0	10,761
4	13:00–18:45	5.75	Work Break	0	17	4,600	4,617
5	18:45–05:15	10.50	2.179	58,127	1,418	0	59,545
	Total	34.00	5.000	134,055	4,573	6,800	**145,428**
Itemized User Cost							
Queuing Delay Cost ($)		1,085					
Moving Delay Cost ($)		3,405					
Vehicle Operating Cost($)		66					
Accident Cost ($)		17					

The above analyses demonstrate that the selection of production options may significantly affect work zone schedule and total cost. The minimized total costs and project duration associated with the four optimized schedules (i.e., Schedules "A1-1" through "A1-4") are illustrated in Figures 5.2 and 5.3, respectively. The comparisons indicate that Options 3 and 4 outperform Options 1 and 2 in terms of reduced total cost and project duration when $AADT_m$ = 45,000 vpd. The reduced project duration results from less repetitive setups and shorter work breaks.

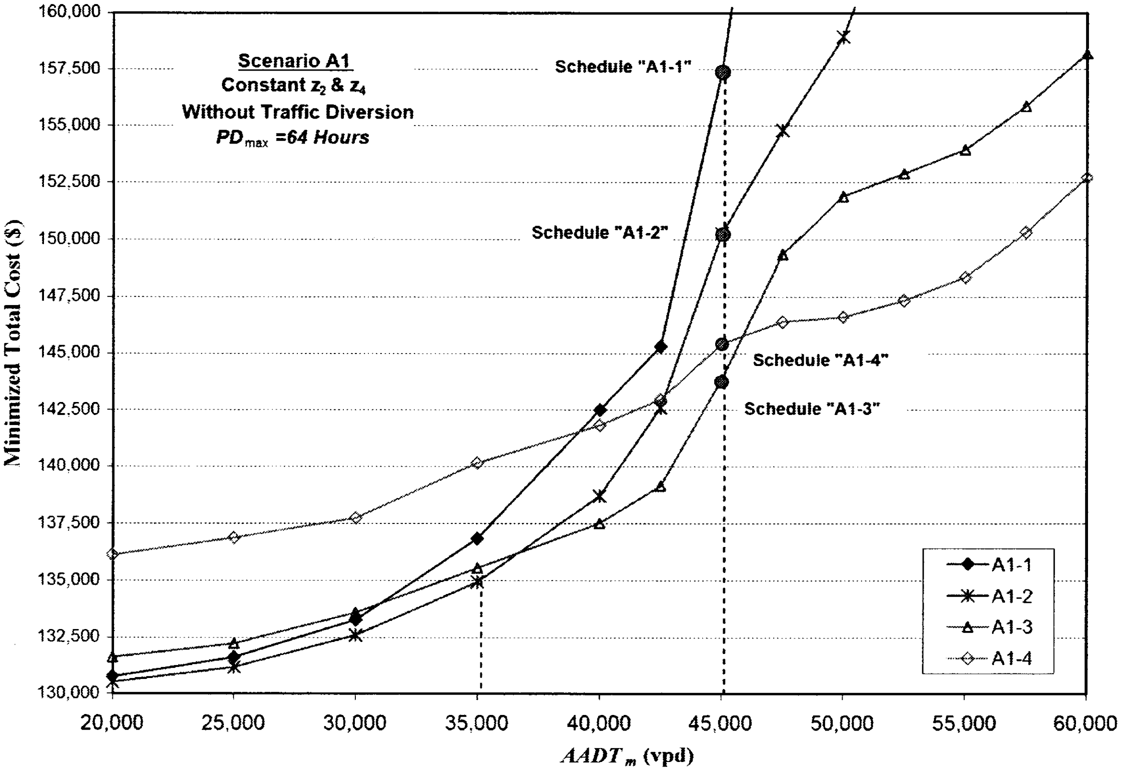


Figure 5.2 Scenario A1: minimized total cost vs. $AADT_m$ for various production options (PD_{max} = 64 hours).

Note that $AADT_m$ may affect the performance of production options. To study the relation among the total cost, project duration and production options for various traffic conditions (i.e., $AADT_m$), sensitivity analyses were conducted and the results are shown in Figures 5.2 and 5.3.

Figure 5.2 indicates that $AADT_m$ is a critical factor in determining a cost-efficient production option. The minimized total costs associated with Production Options 1, 2, 3 and 4 increase +176%, +51%, +20% and +12%, respectively as the $AADT_m$ increases from 20,000 vpd to 60,000 vpd. Note that significant increases in total cost occur if Production Options 1 and 2 are applied when $AADT_m$ exceeds 30,000 vpd. A similar trend was observed for Production Option 3 when $AADT_m$ exceeds 42,500 vpd. The minimized total cost associated with Production Option 4 is relatively not sensitive to $AADT_m$.

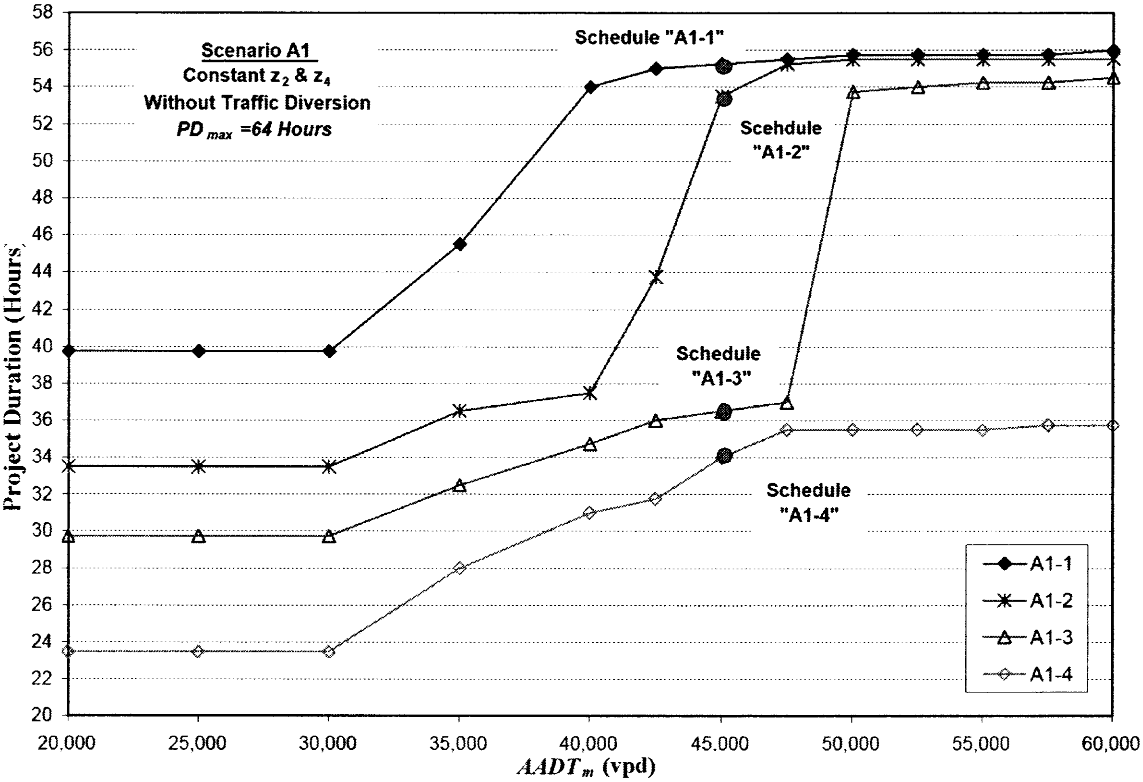


Figure 5.3 Scenario A1: project duration vs. $AADT_m$ for various production options ($PD_{\max}$ = 64 hours).

As illustrated in Figure 5.3, the project duration increases as $AADT_m$ increases, because of longer work break time and more repetitive work zone setups needed to be scheduled to avoid work during peak periods. Furthermore, the less productive Options 1 or 2 causes a sharp increase in project duration.

It was found that the project duration is not sensitive to $AADT_m$ if $AADT_m$ < 30,000 vpd or $AADT_m$ > 47,500 vpd. However, it is worth noting that the stabilized project durations in the above ranges represent two different schedules. When $AADT_m$ < 30,000 vpd, the increase of $AADT_m$ does not change the optimized work zone schedules and project duration because the traffic volumes are lower than the work zone capacity, and the slight increase of minimized total cost depicted in Figure 5.2 merely results from the increased moving delay in the work zones. However, when $AADT_m$ exceeds 47,500 vpd, the project durations and work zone schedules are constrained by the maximum project duration $PD_{\max}$ when Production Options 1, 2 and 3 are employed. Note that the 5.00 km maintenance project can be completed within 56 hours, but due to the constrained project duration, it cannot be extended to the next off-peak period. Consequently, the dramatic increase in the minimized total cost shown in Figure 5.2 is caused by excessive queuing delay. Within the studied range of $AADT_m$ between 20,000 vpd and 60,000 vpd, it was found that the constraint of $PD_{\max}$ has a relatively minor impact on Options 4. The trend suggests that $PD_{\max}$ needs to be determined carefully according to different production options and traffic conditions; otherwise, it may adversely affect work zone schedules and project total cost. The sensitivity analysis regarding $PD_{\max}$ will be presented later in Section 5.4.

The above analyses reveal that Options 1, 2 and 3 achieve a similar minimized total costs when $AADT_m$ is below 35,000 vpd, although employing Option 3 reduces project duration. In many situations, Option 3 may be the preferred option. When $AADT_m$ is between 35,000 vpd and 45,000 vpd, Option 3 is the most cost-effective option as demonstrated by the previous examples (i.e., Schedule "A1-3"). The most productive and expensive Option 4 would be preferred when the $AADT_m$ exceeds 45,000 vpd because the savings in user costs on a heavily traveled highway is sufficient to compensate for the additional maintenance cost.

5.2.1 Scenario A2

The assumption of fixed unit maintenance cost z_2^k and production time z_4^k is relaxed while for Scenario A2. Thus, the production option of each work zone is an integer decision variable together with the work zone schedule. The developed GA was used to search for the optimal solution with respect to $AADT_m$ ranging from 20,000 to 60,000 vehicles per day. The minimized total costs for various demand and production options for Scenario A1 and Scenario A2 are illustrated in Figure 5.4.

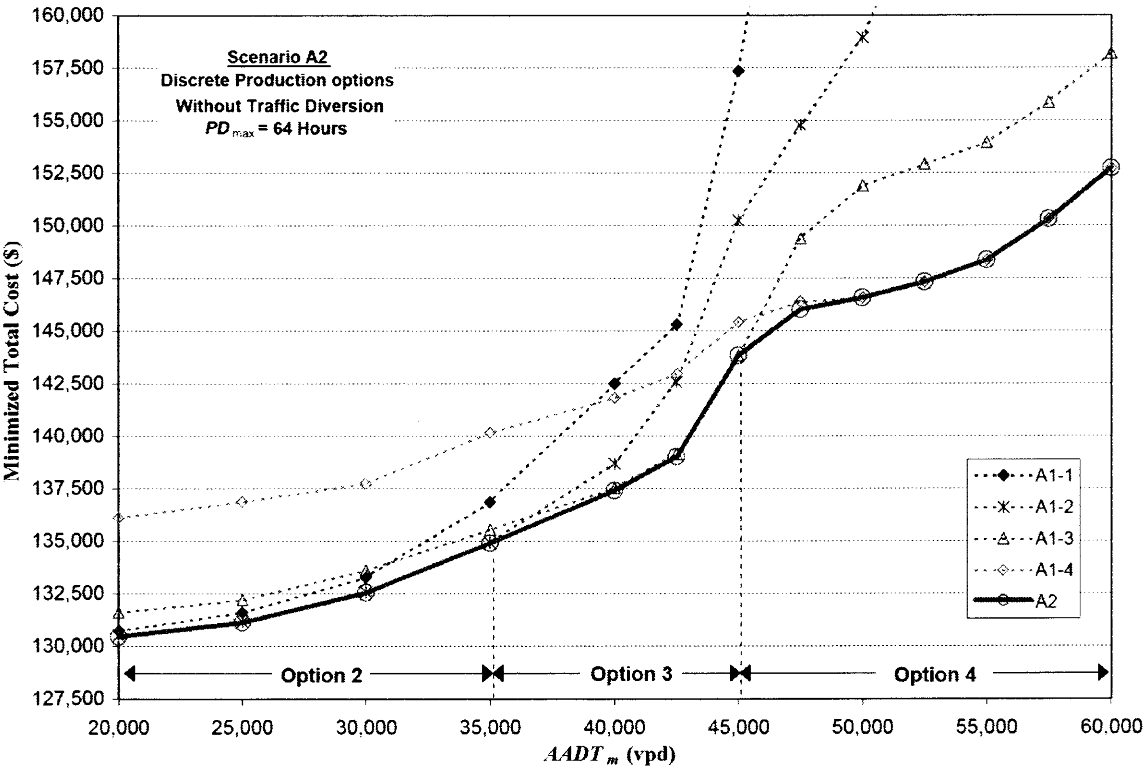


Figure 5.4 Scenario A2 and comparison with Scenario A1 options: minimized total cost versus various $AADT_m$ (PD_{max} = 64 hours).

The comparison demonstrates that the minimized total cost of Scenario A2 achieved by the developed GA model are consistent with the lowest total costs of Scenario A1 for various demand levels. The developed GA is capable of identifying appropriate production options to minimize the total cost while considering a discrete time-cost function.

5.2.3 Findings

Section 5.2 explored the relations among project total cost, $AADT_m$, maintenance production options and maximum project duration while traffic diversion was not considered. The findings are summarized below,

(1) Given that $AADT_m$ = 45,000 vpd and $PD_{\max}$ = 64 hours, four optimized schedules (i.e., Schedule “A1-1”, “A1-2”, “A1-3” and “A1-4”) were achieved. The minimized total costs, cost components and project durations are summarized in Table 5.9a. It was found that Options 3 and 4 outperform Options 1 and 2 in terms of reduced total cost and project duration when $AADT_m$ = 45,000 vpd. The reduced project duration results from less repetitive setups and shorter work breaks.

Table 5.9a Summary of Cost Components for Various Production Options ($AADT_m$ = 45,000)

Options	Optimized Schedules	Maintenance Cost ($)	Idling Cost ($)	Queuing Delay Cost ($)	Moving Delay Cost ($)	VOC& Accident Cost ($)	Minimized Total Cost ($)	Project Duration (Hours)
1	A1-1	129,300	9,200	13,190	4,807	868	157,366	55.25
2	A1-2	129,915	12,800	3,665	3,628	250	150,257	53.50
3	A1-3	129,215	5,400	4,489	4,426	306	143,836	36.50
4	A1-4	134,055	6,800	1,085	3,405	83	145,428	35.00

(2) Traffic volume is a critical factor in determining cost-effective production options for a maintenance project. It was found that the most cost-effective production option varies with traffic demand as summarized in Table 5.9b. It was found that Production Option 1 is not recommended because it is slightly cheaper but much slower than Production Option 2.

Table 5.9b Scenario A: Suggested Production Options for Various $AADT_m$

Cost-effective Production Option	**Economical Ranges of $AADT_m$ (vpd)**
Option 2	$AADT_m < 35{,}000$
Option 3	$35{,}000 \leq AADT_m \leq 45{,}000$
Option 4	$AADT_m > 45{,}000$

(3) The maximum project duration $PD_{\max}$ needs to be determined carefully for the different production options and traffic volumes; otherwise, a constrained work schedule may increase total project cost. The sensitivity analysis of $PD_{\max}$ is discussed in Section 5.4.

5.3 Optimized Work Zone Schedules with an Alternate Route

As concluded in Section 5.2, the traffic volume on the mainline not only affects the total project cost, but also is a critical factor in determining a cost-effective production option. Therefore, diverting traffic from the mainline with work zones to alternate routes may be a cost-effective approach to optimize work zone schedules.

This section optimizes the work zone schedules, considering time-dependent traffic diversions to an alternate route, i.e., Scenario B defined in Table 5.1. Scenario B1 represents a fixed unit maintenance cost z_2^k and production time z_4^k through the entire project while this assumption will be relaxed for the analysis of Scenario B2. The alternate route considered here is a minor arterial with one travel lane in each direction, which functions as a service road parallel to the mainline. Figure 5.5 illustrates the conceptual layout of the mainline and the alternate route.

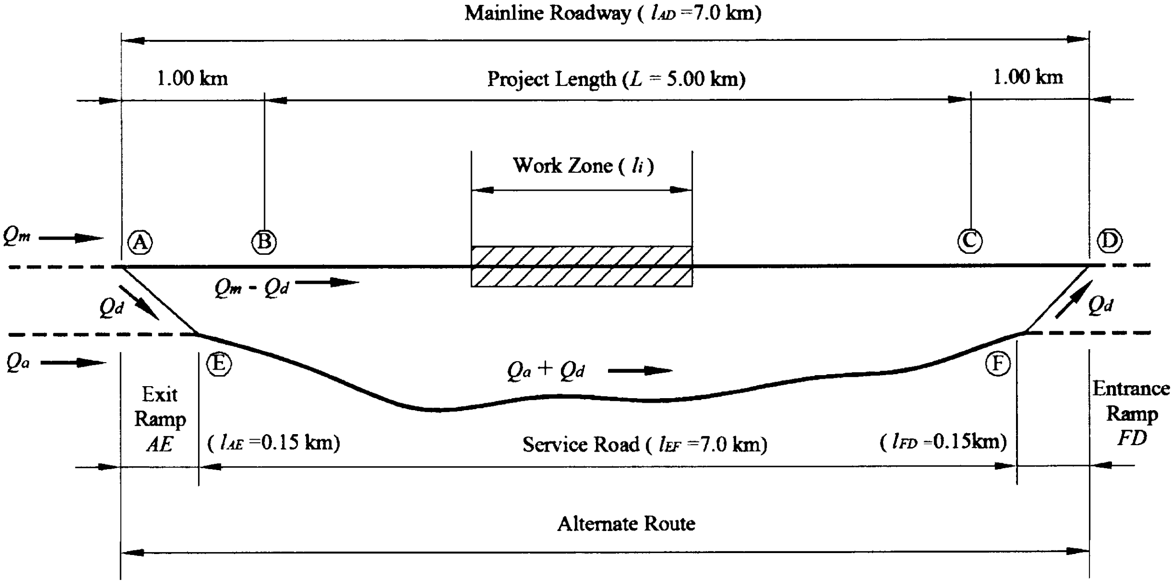


Figure 5.5 Conceptual layout of the mainline with a work zone and an alternate route.

As shown in Figure 5.5, the studied 5.00 km maintenance project is situated between an upstream exit ramp *AE* and a downstream entrance ramp *FD* on the 7.00-km long mainline segment *AD,* where the project is located at 1.00 km downstream of the exit ramp *AE.* The diverted traffic may exit from the off-ramp *AE* and return onto the mainline through the 7.00-km long service road *EF* and the on-ramp *FD.* The service road has a design speed of 55 km per hour, and carries 25,000 vehicles per day. The capacity of the service road is 1,700 vehicles per hour (vph). The baseline values of input parameters for Scenario B are summarized in Table 5.10, and the input parameters of the mainline and the planned maintenance work can be found in Tables 5.3 and 5.4 of Section 5.2.

Table 5.10 Baseline Values of Input Parameters for Scenario B

Variables	Descriptions	Baseline Input Values
$AADT_m$	AADT on the mainline	45,000 vpd
$AADT_a$	AADT on the service road	25,000 vpd
c_a	Capacity of the alternate route	1,700 vph
V_a	Design speed of service road	55 km/hr
V_r	Average speed of ramps *AE* and *FD*	40 km/hr
L_{AB}	Distance between ramp *AE* and the maintenance project	1.00 km
L_{CD}	Distance between ramp *FD* and the maintenance project	1.00 km
L_{AD}	Travel distance on mainline segment *AD*	7.00 km
L_{AE}	Travel distance on exit ramp *AE*	0.15 km
L_{EF}	Travel distance on service road *EF*	7.00 km
L_{FD}	Travel distance on entrance ramp *FD*	0.15 km
α, β	Coefficients of BPR function for mainline and service road	α=0.15, β=4.0

The hourly volumes on the service road for an $AADT_a$ ranging from 15,000 to 30,000 vehicles per day are summarized in Table 5.11. Note that traffic data of the mainline and alternate route were obtained from the Road User Cost Manual (2001) developed by the New Jersey Department of Transportation.

Table 5.11 Hourly Traffic Volumes of the Service Road for Various $AADT_a$

Hours	**Percentage of $AADT_a$**	**Directional Split [1]**	**$AADT_a$ on Alternate Route**			
			15,000	**20,000**	**25,000**	**30,000**
0-1	0.70%	0.48	50	67	84	101
1-2	0.60%	0.48	43	58	72	86
2-3	0.40%	0.45	27	36	45	54
3-4	0.40%	0.53	32	42	53	64
4-5	0.60%	0.53	48	64	80	95
5-6	1.60%	0.53	127	170	212	254
6-7	4.40%	0.57	376	502	627	752
7-8	6.00%	0.54	486	648	810	972
8-9	5.30%	0.56	445	594	742	890
9-10	5.10%	0.56	428	571	714	857
10-11	5.20%	0.51	398	530	663	796
11-12	5.70%	0.51	436	581	727	872
12-13	6.30%	0.5	473	630	788	945
13-14	6.50%	0.52	507	676	845	1014
14-15	6.40%	0.51	490	653	816	979
15-16	6.20%	0.53	493	657	822	986
16-17	6.20%	0.49	456	608	760	911
17-18	6.30%	0.47	444	592	740	888
18-19	6.50%	0.47	458	611	764	917
19-20	6.00%	0.47	423	564	705	846
20-21	4.60%	0.46	317	423	529	635
21-22	3.80%	0.48	274	365	456	547
22-23	2.90%	0.48	209	278	348	418
23-24	2.30%	0.48	166	221	276	331

Note: Directional split is for the same travel direction of the mainline work zone.

5.3.1 Scenario B1

This section presents the optimized work zone schedules associated with Production Options 1 through 4 while considering time-dependent traffic diversions.

The optimal diverted traffic flow rate for each interval is solved simultaneously with the optimized schedules "B1-1" through "B1-4" in accordance with the UE principle derived in Chapter 4. The optimal temporal diverted flow rate and the remaining mainline traffic flow rate are illustrated in Figures 5.8 through 5.11 in bold and slim solid lines, respectively, while the existing traffic demand on the mainline and the service road are shown in dashed lines.

As shown in Figures 5.8 to 5.11, traffic diversion is triggered when the travel time of the mainline exceeds that of the alternate route, due to the queuing and moving delays on the mainline. By diverting traffic to the alternate route, UE can be reached at the end of each interval when the travel times on the both routes are equal. The optimal diverted flow rate varies over time because of the variable queue length and travel time at the end of each interval on the mainline.

Table 5.12 presents an example of calculating time-dependent travel time and diverted flow rate during the presence of the first work zone of Schedule "B1-1" (i.e., 17:30~12:00 in Table 5.12). For instance, without traffic diversion, the travel times on the mainline and alternate route will be 11.60 and 8.13 minutes at 18:00. By diverting 219 vehicles within a 15-minute interval (i.e., 875 vph × 0.25 hour) to the alternate route, the same travel time of 9.03 minutes on both the mainline and the alternate route will be experienced by motorists. Note that an allowable travel time variation of 0.05 minutes between the routes was adopted to find UE.

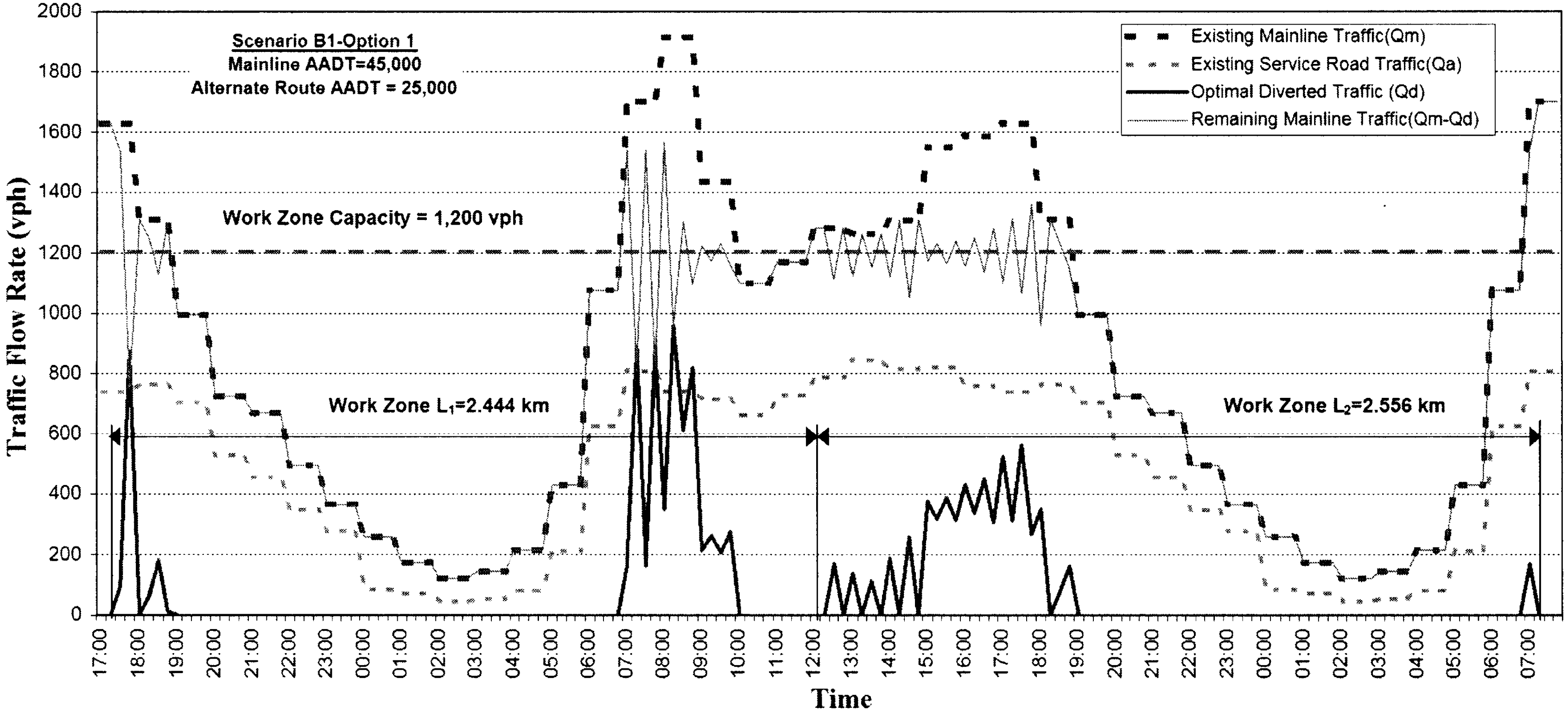


Figure 5.6 Optimal diverted traffic flow in Schedule “B1-1”.

Table 5.12 Example of Diverted Traffic Flow, Travel Time of Mainline and Alternate Route (Schedule "B1-1")

Intervals		Without Traffic Diversion				Diverted Traffic Flow Q_d (vph)	Queue Length at the end of Interval (veh)	With Traffic Diversion					
		Mainline		Alternate Route				Mainline Travel Time (minutes)					Alternate Route Travel Time (min.)
Start Time	End Time	Q_m (vph)	Travel Time (min.)	Q_a (vph)	Travel Time (min.)			Before Work Zone	Average Queuing Delay (min./veh)	Within Work Zone	After Work Zone	Total	
17:15	17:30	1628	6.54	740	8.13	**0**	0	2.52	0.00	3.41	0.60	**6.54**	**8.13**
17:30	17:45	1628	8.51	740	8.13	**93**	83.75	2.52	1.64	3.41	0.60	**8.17**	**8.15**
17:45	18:00	1628	11.60	740	8.13	**875**	0	2.52	2.50	3.41	0.60	**9.03**	**9.02**
18:00	18:15	1311	7.17	764	8.13	**0**	27.75	2.52	0.64	3.41	0.60	**7.17**	**8.13**
18:15	18:30	1311	8.44	764	8.13	**62**	40.00	2.52	1.63	3.41	0.60	**8.16**	**8.15**
18:30	18:45	1311	9.00	764	8.13	**181**	22.50	2.52	1.66	3.41	0.60	**8.19**	**8.20**
18:45	19:00	1311	8.20	764	8.13	**12**	47.25	2.52	1.61	3.41	0.60	**8.14**	**8.14**
19:00	19:15	994	7.84	705	8.12	**0**	0	2.52	1.31	3.41	0.60	**7.84**	**8.12**
No Traffic Diversion between 19:00 and 7:00, because $Q_m < C_w$													
06:45	07:00	1077	6.53	627	8.11	**0**	0	2.52	0.00	3.41	0.60	**6.53**	**8.11**
07:00	07:15	1701	8.75	810	8.15	**162**	84.75	2.52	1.65	3.41	0.60	**8.19**	**8.21**
07:15	07:30	1701	11.74	810	8.15	**890**	0	2.52	2.73	3.41	0.60	**9.26**	**9.23**
07:30	07:45	1701	8.75	810	8.15	**162**	84.75	2.52	1.65	3.41	0.60	**8.19**	**8.21**
07:45	08:00	1701	11.74	810	8.15	**890**	0	2.52	2.73	3.41	0.60	**9.26**	**9.23**
08:00	08:15	1915	9.34	742	8.13	**350**	91.25	2.52	1.75	3.41	0.60	**8.28**	**8.28**
08:15	08:30	1915	12.20	742	8.13	**958**	30.50	2.52	3.82	3.41	0.60	**10.35**	**9.23**
08:30	08:45	1915	10.30	742	8.13	**612**	56.25	2.52	2.00	3.41	0.60	**8.53**	**8.55**
08:45	09:00	1915	11.11	742	8.13	**818**	30.50	2.52	2.37	3.41	0.60	**8.90**	**8.90**
09:00	09:15	1436	9.04	714	8.12	**212**	36.50	2.52	1.64	3.41	0.60	**8.17**	**8.19**
09:15	09:30	1436	9.29	714	8.12	**262**	30.00	2.52	1.70	3.41	0.60	**8.23**	**8.21**
09:30	09:45	1436	9.02	714	8.12	**206**	37.50	2.52	1.65	3.41	0.60	**8.18**	**8.18**
09:45	10:00	1436	9.33	714	8.12	**275**	27.75	2.52	1.69	3.41	0.60	**8.22**	**8.22**
10:00	10:15	1101	7.37	663	8.11	**0**	3.00	2.52	0.84	3.41	0.60	**7.37**	**8.11**

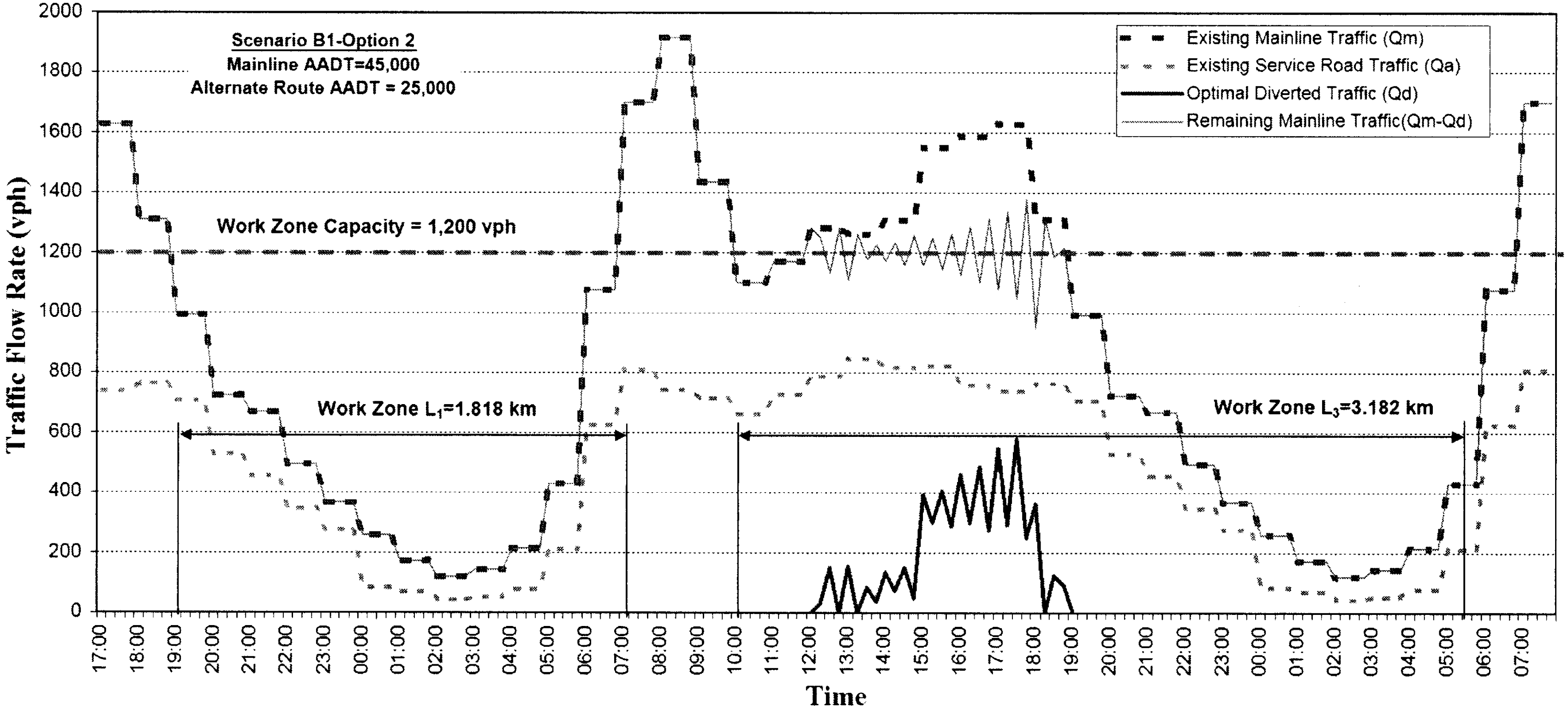


Figure 5.7 Optimal diverted traffic flow in Schedule “B1-2”.

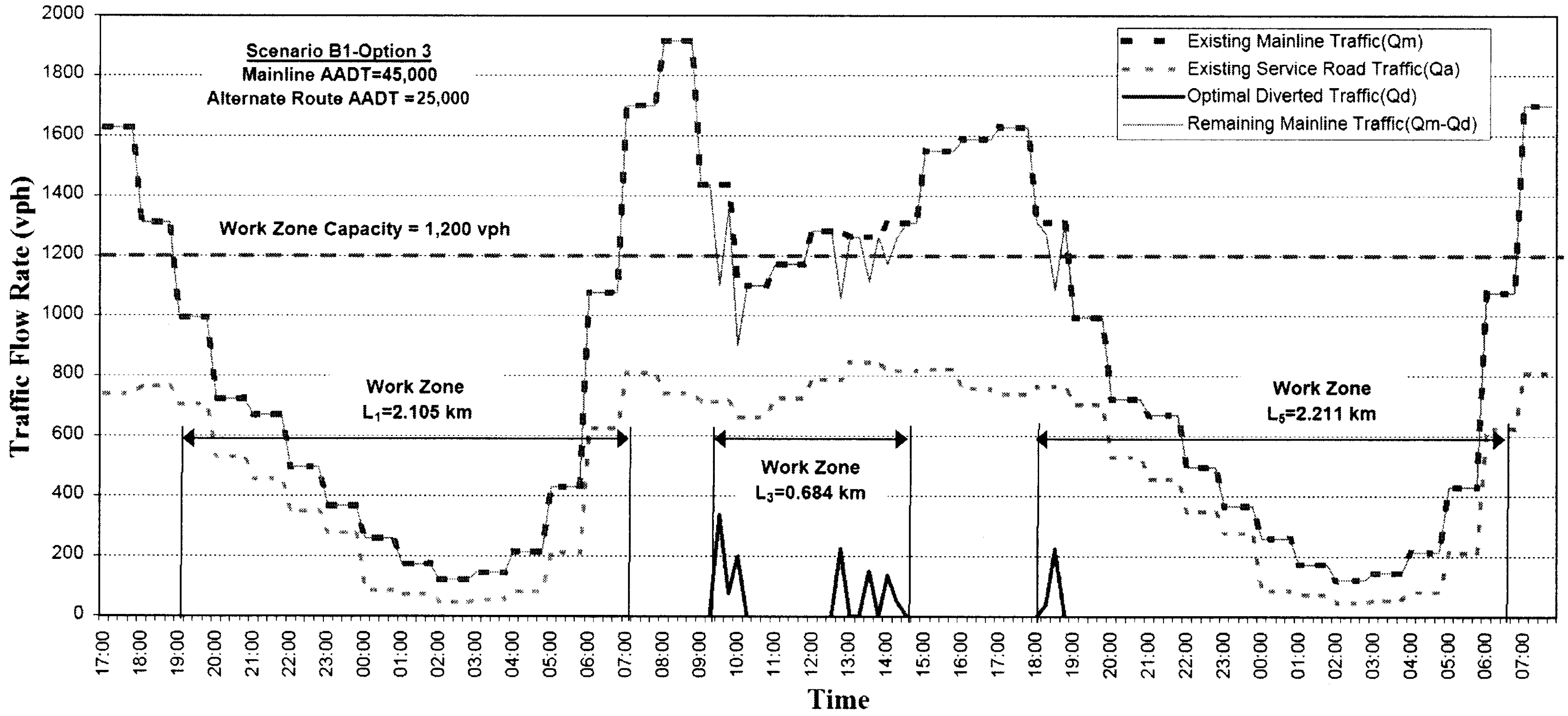


Figure 5.8 Optimal diverted traffic flow in Schedule “B1-3”.

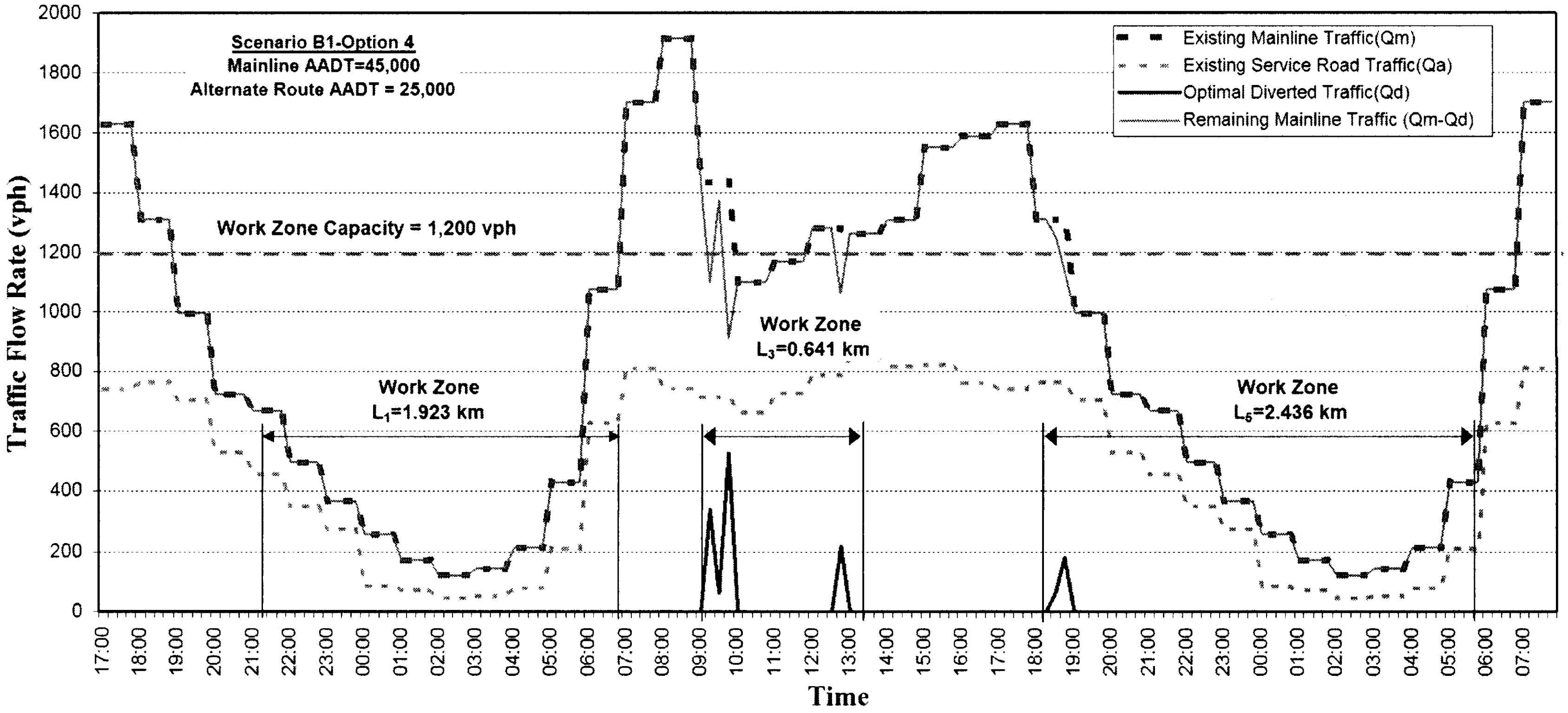


Figure 5.9 Optimal diverted traffic flow in Schedule “B1-4”.

The optimized Schedule "B1-1" presented in Table 5.13 indicates that the best project starting time is 17:30 and the project duration is 37.75 hours if Production Option 1 is used. Two consecutive work zones are scheduled. A total of 3,305 vehicles are diverted to the alternate route during the time periods of 17:30~19:00, 7:00~10:00, 12:30~19:00 and 7:00~7:15 as shown in Figure 5.6, which represents 22% of the existing traffic volumes during these time periods. Thus, the maintenance work can be performed uninterruptedly in longer work zones, and the repetitive setup time and costs as well as idling cost can be reduced. However, it is worth noting that greater work zone length increases diverted traffic volumes, which results in increased moving delays on both the mainline and the alternate route.

Table 5.13 Optimized Schedule "B1-1" ($AADT_a$ = 25,000, Option 1)

No. i	Work Zone Start & End Times	Duration (Hours)	Work Area Length p_i (km)	Maintenance Cost ($)	User Cost ($)	Idling Cost ($)	Total Cost ($/zone)
1	17:30–12:00	18.50	2.444	61,769	9,482	0	71,251
2	12:00–07:15	19.25	2.556	64,531	10,276	0	74,807
	Total	37.75	5.000	126,300	19,778	0	**146,078**
Itemized User Cost							
Total Queuing Delay Cost ($)				6,118			
Total Mainline Moving Delay Cost ($)				8,786			
Total Alternate Route Moving Delay Cost ($)				4,429			
Vehicle Operating Cost($)				372			
Accident Cost ($)				73			

When deploying Production Option 2, the maintenance work starts at 19:00 and the project can be completed within 34.50 hours by scheduling two work zones and one work break during the AM peak hours (i.e., 7:00 ~ 10:00). A total of 1,509 vehicles are diverted to the alternate route, which is approximately 11 % of the total traffic volume within the time periods indicated in Figure 5.7. By using the more productive Option 2, a work break can be scheduled during the AM peak hour without extending the project duration, and the queuing delay on the mainline can be reduced noticeably (i.e., \$3,313 or 54%). In the mean time, the moving delay on the alternate route can also be reduced (i.e., \$2,554 or 57%) because of less diverted traffic. A total reduction of \$7,528 in road user cost (i.e., approximately 38% of the user cost in Schedule "B1-1") can offset the increased maintenance and idling costs, and a total cost saving of \$4,513 comparing to that of Schedule "B1-1" can be achieved.

Table 5.14 Optimized Schedule "B1-2" ($AADT_a$ = 25,000, Option 2)

No. i	**Work Zone Start & End Times**	**Duration (Hours)**	**Work Area Length** p_i **(km)**	**Maintenance Cost (\$)**	**User Cost (\$)**	**Idling Cost (\$)**	**Total Cost (\$/zone)**
1	19:00–07:00	12.00	1.818	46,424	1,419	0	47,842
2	07:00–10:00	3.00	Work break	0	0	2,400	2,400
3	10:00–05:30	19.50	3.182	80,491	10,831	0	91,322
	Total	34.50	5.000	126,915	12,250	2,400	**141,565**

Itemized User Cost	
Total Queuing Delay Cost (\$)	2,805
Total Mainline Moving Delay Cost (\$)	7,354
Total Alternate Route Moving Delay Cost (\$)	1,875
Vehicle Operating Cost(\$)	170
Accident Cost (\$)	46

The optimized schedule "B1-3" summarized in Table 5.15 suggests that three smaller work zones and two work breaks should be arranged. By using Production Option 3, the maintenance project can start at 19:00 and can be completed within 35.5 hours. It is worth noting that 360 vehicles are diverted to the alternate route, representing 12% of the existing volume during the time periods of 9:30~10:15, 12:45~14:30 and 18:15~18:45 as illustrated in Figure 5.8. Consequently, the moving delay occurring on the alternate route is not significant. The road user cost is reduced further in comparison with Option 2, including a reduction of \$3,176(43.2%) and \$1,450(77.3%) in moving delay cost on the mainline and the alternate route, respectively, and a slight decrease in queuing delay cost was also observed. The total reduction in road user cost is sufficient to compensate for the increased maintenance and idling costs, making Option 3 the most cost-effective production option.

Table 5.15 Optimized Schedule "B1-3" ($AADT_a = 25{,}000$, Option 3)

No.	Work Zone	Duration	Work Area Length p_i	Maintenance Cost	User Cost	Idling Cost	Total Cost
i	Start & End Times	(Hours)	(km)	(\$)	(\$)	(\$)	(\$)
1	19:00–07:00	12.00	2.105	54,143	1,602	0	55,745
2	07:00–09:15	2.25	Work break	0	0	1,800	1,800
3	09:15–14:30	5.25	0.684	18,272	3,376	0	21,647
4	14:30–18:00	3.50	Work break	0	9	2,800	2,809
5	18:00–06:30	12.50	2.211	56,800	2,470	0	59,271
	Total	35.50	5.000	129,215	7,457	4,600	**141,272**
Itemized User Cost							
Total Queuing Delay Cost (\$)				2,665			
Total Mainline Moving Delay Cost (\$)				4,178			
Total Alternate Route Moving Delay Cost (\$)				425			
Vehicle Operating Cost(\$)				162			
Accident Cost (\$)				28			

With Production Option 4, the optimized schedule "B1-4" summarized in Table 5.16 suggests that the project starts at 21:15 on Day 1 and is completed in 32.5 hours, which is shorter than the duration of Schedule "B1-3". As indicated in Figure 5.9, 347 vehicles (i.e., 12% of the existing volumes) were diverted to the alternate route between 9:15 and 15:15. In comparison with Schedule "B1-3", Schedule "B1-4" results in a

$3,976 increase in the total cost because the reduction of $1,864 in road user cost cannot compensate for the additional $4,840 and $1,000 in maintenance and idling costs.

Table 5.16 Optimized Schedule "B1-4" ($AADT_a$ = 25,000, Option 4)

No.	**Work Zone**	**Duration**	**Work Area Length** p_i	**Maintenance Cost**	**User Cost**	**Idling Cost**	**Total Cost**
i	**Start & End Times**	**(Hours)**	**(km)**	**($)**	**($)**	**($)**	**($)**
1	21:15–06:45	9.50	1.923	51,406	923	0	52,328
2	06:45–09:00	2.25	Work break	0	0	1,800	1,800
3	09:00–13:30	4.50	0.641	17,802	2,535	0	20,337
4	13:30–18:15	4.75	Work break	0	9	3,800	3,809
5	18:15–05:45	11.50	2.436	64,847	2,127	0	66,974
	Total	31.00	5.000	134,055	5,593	5,600	**145,248**
Itemized User Cost							
Total Queuing Delay Cost ($)				1,809			
Total Mainline Moving Delay Cost ($)				3,234			
Total Alternate Route Moving Delay Cost ($)				420			
Vehicle Operating Cost($)				110			
Accident Cost ($)				21			

The above examples demonstrate how the selection of a production option and traffic diversion may affect the optimization of work zone schedules as well as total project cost. As indicated in the aforementioned optimized schedules "B1-1" through "B1-4", the user cost can be reduced while a more productive option is deployed; although the maintenance and idling costs (i.e., agency cost) may increase. This trend is clearly indicated in Figure 5.10, where Production Option 3 is deemed as the most cost-effective. It was also found that the best option also diverts the least traffic to the alternate route. There are 360 vehicles diverted to the alternate route under Production Option 3 compared to 3,305, 1,509 and 466 vehicles corresponding to Production Options 1, 2 and 4 respectively.

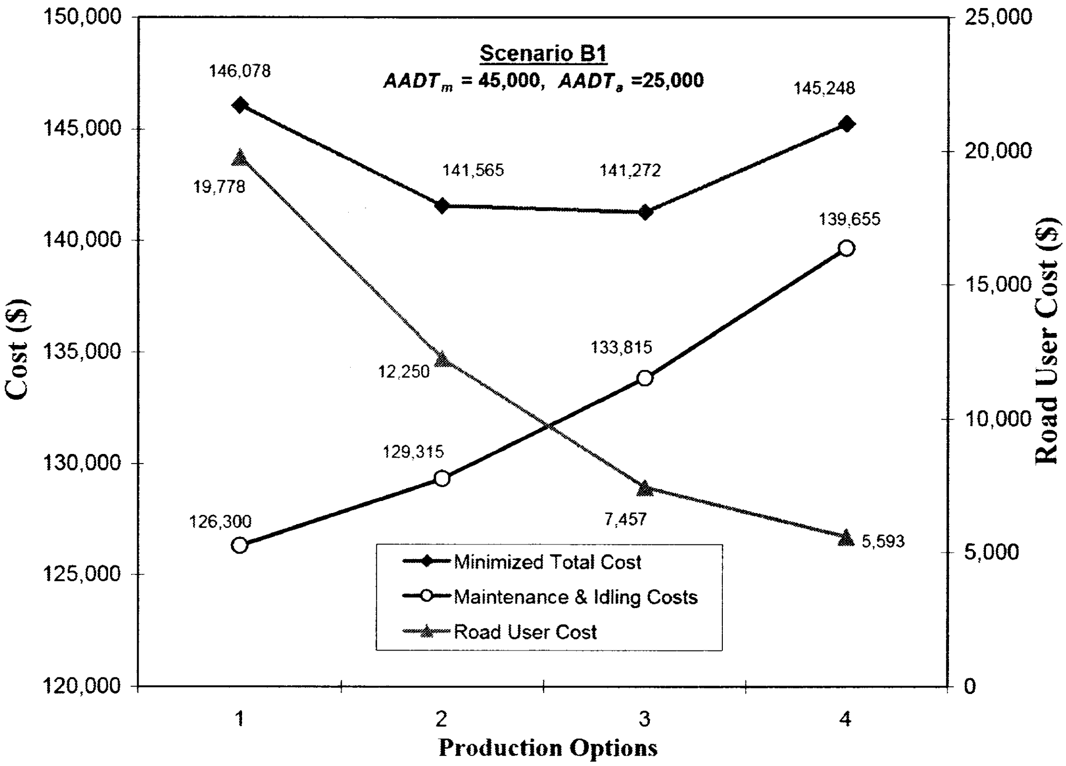


Figure 5.10 Maintenance, idling and road user costs versus production options.

Sensitivity analyses were conducted with respect to each production option as $AADT_m$ increases from 30,000 vpd to 60,000 vpd and $AADT_a$ remains at 25,000 vpd. As shown in Figure 5.11(a), the approximately proportional increase of the minimized total cost as $AADT_m$ increases is contributed by the increased moving delay cost because the excessive queuing delay cost is significantly reduced by diverting traffic to the alternate route during peak periods.

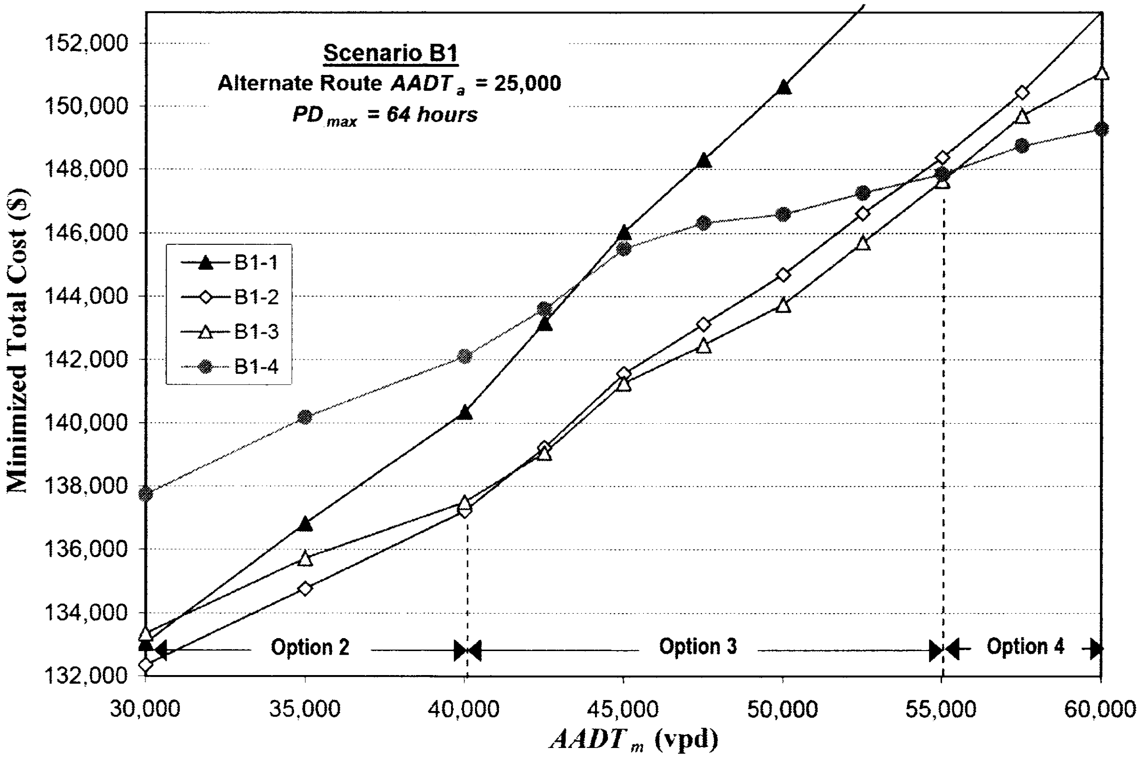


Figure 5.11(a) Scenario B1: minimized total cost versus various $AADT_m$.

As indicated by Figure 5.11(a), Options 1, 2 and 3 achieved similar total cost when $AADT_m$ < 30,000 vpd, which is consistent with the results of Table 5.2 discussed in Scenario A1. The most productive but expensive Option 4 may not be necessary when the $AADT_m$ is lower than 30,000 vpd, because the saving in road user cost cannot offset the increased maintenance cost.

It was also found that when $AADT_m$ < 40,000 vpd, employing Production Option 2 can achieve the lowest total cost. However, as $AADT_m$ continuously increases, Option 3 becomes the most cost-effective option until $AADT_m$ reaches 55,000 vpd, where Option 4 becomes the optimal choice. Production Option 1 is not recommended because it is slightly cheaper but much slower than Production Option 2, as indicated in Table 5.3.

The thresholds of $AADT_m$ to determine a cost-effective production option are summarized in Table 5.17.

Table 5.17 Suggested Economical Ranges of $AADT_m$ for Each Production Option ($AADT_a$ = 25,000)

Cost-effective Production Option	**Economical Range of $AADT_m$ (vpd)**	
	Without Traffic Diversion (Scenario A)	**With Traffic Diversion (Scenario B)**
Option 2	$AADT_m < 35{,}000$	$AADT_m < 40{,}000$
Option 3	$35{,}000 \le AADT_m \le 45{,}000$	$40{,}000 \le AADT_m \le 55{,}000$
Option 4	$AADT_m > 45{,}000$	$AADT_m > 55{,}000$

In Table 5.17, by comparing the thresholds of $AADT_m$ in Scenario A1 (see Figure 5.4) with those in Scenario B1 (see Figure 5.11(a)), it was found that the threshold of $AADT_m$ corresponding to each production increases while traffic diversion is taken into account. Therefore, a production option, say Option 3, may be applicable for a wider range of $AADT_m$ (i.e., 40,000 vpd to 55,000 vpd).

The economical range of $AADT_m$ for each production option may serve as a guideline for planning highway maintenance activities. Note that the thresholds of $AADT_m$ may vary with a series of site-specified parameters, such as $AADT_a$, capacities, travel speeds and traffic distributions of the mainline and alternate route, value of users' time. The developed model can assist transportation agencies to identify these thresholds based on the above site-specific data.

5.3.2 Scenario B2

Scenario B2 uses the discrete time-cost function defined in the previous section, and the assumptions of fixed unit maintenance cost z_2^k and production time z_4^k is relaxed. Work zone schedules were optimized using the developed GA with respect to a range of $AADT_m$ from 30,000 vpd to 60,000 vpd. For the purpose of comparison, the minimized total costs of Scenario B2 and Scenario B1 (i.e., Options 1 through 4) are illustrated together in Figure 5.11(b), in which the optimal production option is obtained by the developed GA to achieve the lowest total cost.

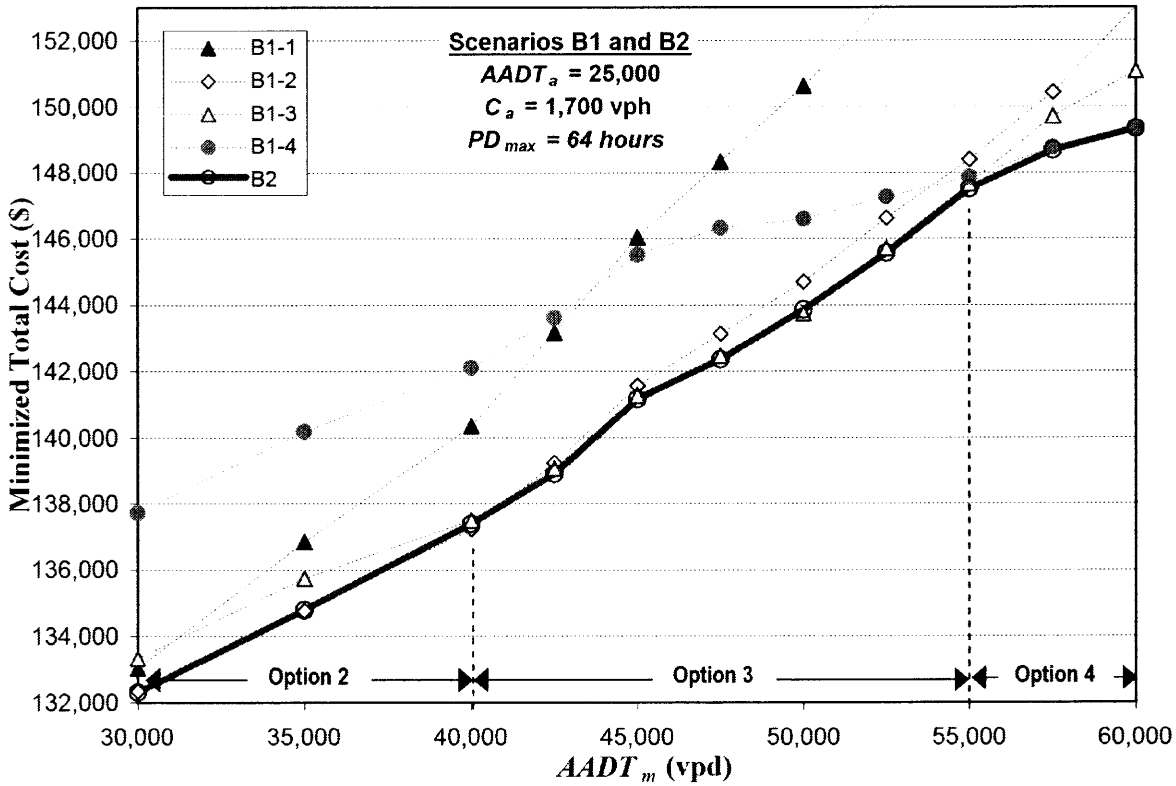


Figure 5.11(b) Scenario B2 and comparison with Scenario B1 options: minimized total cost versus various $AADT_m$ ($PD_{\max}$ = 64 hours).

The optimized schedule “B2” in Table 5.18 indicates the significance of selecting appropriate production options to minimize total cost. By comparing Schedule “B2” with the best Schedule “B1-3” shown in Table 5.7, it was found that Option 2 should be adopted for the third work zone of Schedule “B2” during the overnight off-peak period (i.e.,18:15~7:00), instead of the more expensive Option 3 employed in the previous Schedule “B1-3”. Thus, Schedule “B2” outperforms Schedule “B1-3” in terms of a slightly lower total cost. It is worth noting that the cost saving of Schedule “B2” is not significant, however, the mixed utilization of different production options in Schedule “B2” may offer additional flexibilities in scheduling work zones if considerable cost difference exists among different options.

Table 5.18 Optimized Schedule “B2” ($AADT_a = 25{,}000$)

No.	**Work Zone**	**Duration**	**Work Area Length** p_i	**Index of Options**	**Maintenance Cost**	**User Cost**	**Idling Cost**	**Total Cost**
i	**Start & End Times**	(Hours)	(km)	***k***	($)	($)	($)	($)
1	19:00–07:15	12.25	2.155	3	55,394	1,947	0	57,340
2	07:15–09:00	1.75	Work break	0	0	25	1,400	1,425
3	09:00–15:15	6.25	0.893	3	23,553	4,499	0	28,053
4	15:15–18:15	3.00	Work break	0	0	15	2,400	2,415
5	18:15–07:00	12.75	1.952	2	49,760	2,172	0	51,933
	Total	35.25	5.000	/	128,708	8,658	3,800	**141,166**

Itemized User Cost	
Total Queuing Delay Cost ($)	3,210
Total Mainline Moving Delay Cost ($)	4,484
Total Alternate Route Moving Delay Cost ($)	737
Vehicle Operating Cost($)	195
Accident Cost ($)	32

5.3.3 Comparisons between Scenarios A and B

To evaluate the applicability and benefits of traffic diversion, Scenarios A1 and B1 were compared based on the optimized schedules discussed in previous sections. The cost components associated with each option are summarized in Table 5.19.

In comparison with Schedules "A1-1" and "A1-2", reductions of 7.2% and 5.8 % in the minimized total costs were achieved in Schedule "B1-1" and "B1-2", which were mainly contributed by the reduced maintenance and idling costs. With traffic diversion, maintenance work can be performed more efficiently in longer work zones with less repetitive setups; consequently, the project duration was also reduced noticeably by 50%. In comparison with Schedule "A1-3", Schedule "B1-3" reduced the minimized total cost by 1.8%, which was a result of the reduced idling and road user costs. However, Schedule "B1-4" achieved a minimized total cost slightly lower than that of Schedule "A1-4".

Table 5.19 Scenarios A and B: Summary of Cost Components for Various Production Options ($AADT_m$ = 45,000 and $AADT_a$ = 25,000)

Scenarios	Optimized Schedules	Maintenance Cost ($)	Idling Cost ($)	Queuing Delay Cost ($)	Moving Delay Cost ($)	VOC& Accident Cost ($)	Minimized Total Cost ($)	Project Duration (Hours)
[A] Without Traffic Diversion	A1-1	129,300	9,200	13,190	4,807	868	157,366	55.25
	A1-2	129,915	12,800	3,665	3,628	250	150,257	53.50
	A1-3	129,215	5,400	4,489	4,426	306	143,836	36.50
	A1-4	134,055	6,800	1,085	3,405	83	145,428	34.00
[B] With Traffic Diversion	B1-1	126,300	0	6,118	13,215	445	146,078	37.75
	B1-2	126,915	2,400	2,805	9,229	216	141,565	34.50
	B1-3	129,215	4,600	2,665	4,603	190	141,272	35.50
	B1-4	134,055	5,600	1,809	3,654	131	145,248	32.50

It is worth nothing that the optimized work zone schedules in Scenario B did not necessarily reduce the road user cost when compared with Scenario A. It was found that the road user costs associated with Schedules "B1-1", "B1-2" and "B1-4" increased while applying traffic diversion because of the additional moving delay, which occurred on both the mainline and the alternate route. However, all optimized schedules of Scenario B1 can still outperform those of Scenario A1 in terms of lower minimized total cost and shorter project duration. For $AADT_m$ = 45,000 vpd utilized in this example, the resultant cost reductions due to traffic diversion are not significant, but as $AADT_m$ grows, considerable reduction in total cost may be achieved.

To study the potential benefit of traffic diversion, sensitivity analyses were conducted as the mainline $AADT_m$ increases from 30,000 vpd to 60,000 vpd while the alternate route $AADT_a$ remains at 25,000. The minimized total costs associated with each production option in Scenarios A1 and B1 are depicted in Figures 5.12(a) and (b).

In Figure 5.12(a), the $AADT_m$ = 35,000 vpd threshold can be identified, at which Scenario B1 outperforms A1 in terms of the lower total cost even though the reduction is not significant. However, as $AADT_m$ exceeds 42,500vpd, traffic diversion may significantly reduce the total cost when employing Options 1 and 2. In Figure 5.12(b), the total cost reductions associated with the more productive Options 3 and 4 are not as significant as those of Options 1 and 2. The thresholds of $AADT_m$ = 42,500 vpd and 52,500 vpd are found for Options 3 and Option 4, respectively. The results suggest that traffic diversion would be highly favorable when employing less productive options on heavily traveled highways.

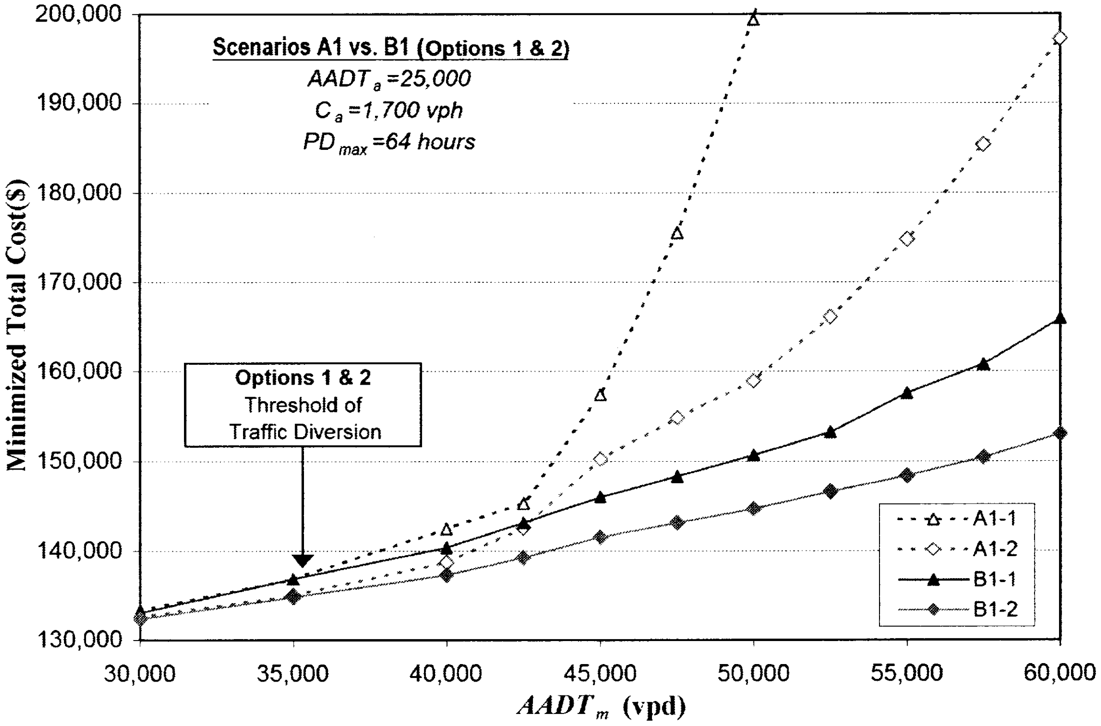


Figure 5.12(a) Scenarios A1 and B1: minimized total costs versus $AADT_m$ (Options 1 and 2).

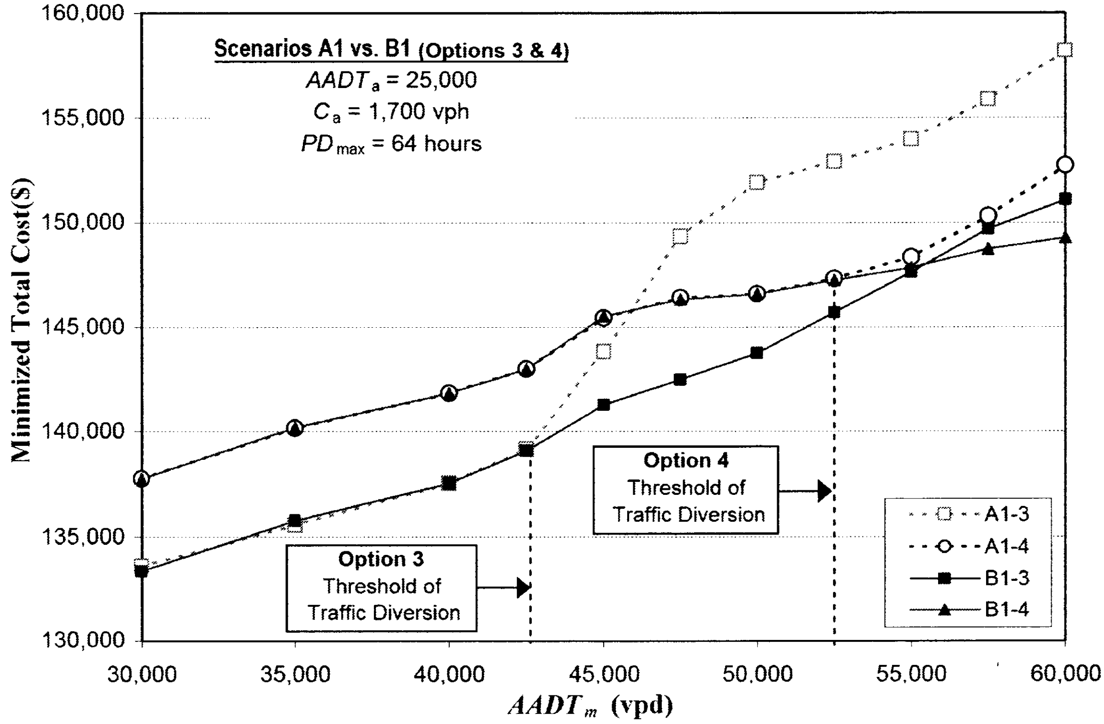


Figure 5.12(b) Scenarios A1 and B1: minimized total costs versus $AADT_m$ (Options 3 and 4).

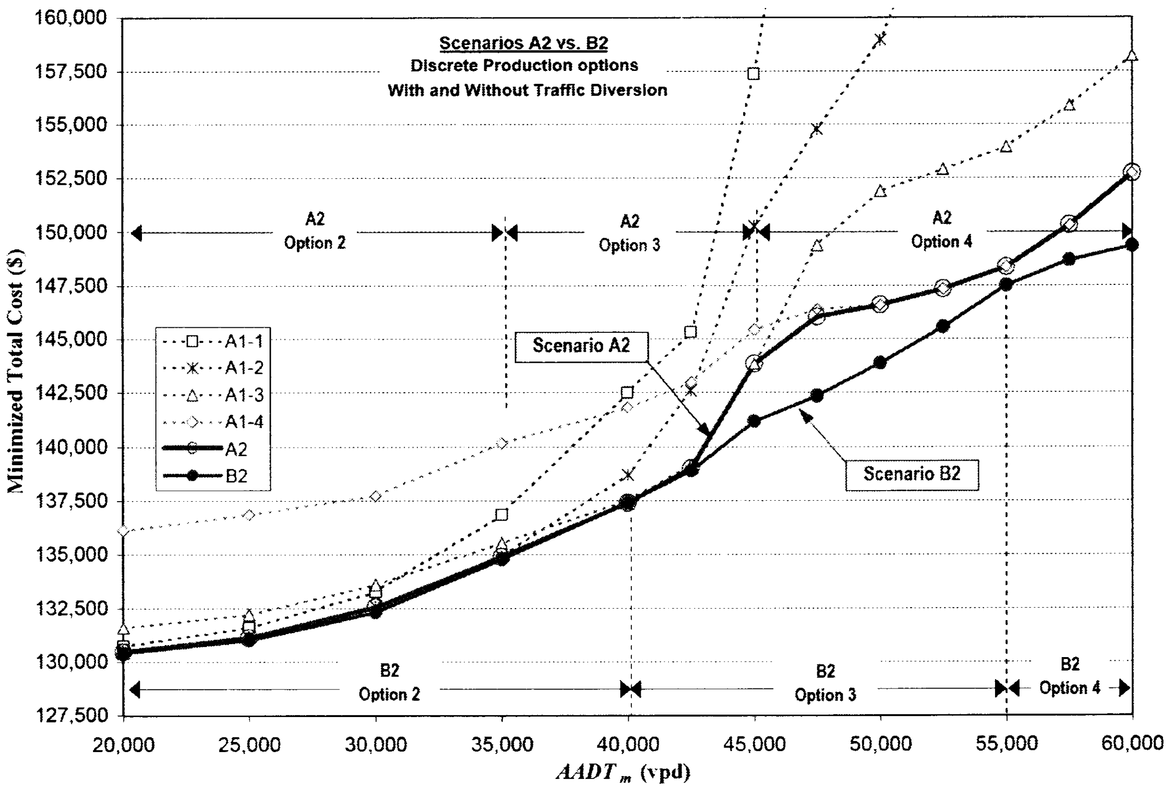


Figure 5.12(c) Scenarios A2 and B2: minimized total costs versus $AADT_m$.

The comparison between Scenarios A2 and B2 is illustrated in Figure 5.12(c), in which the economical ranges of $AADT_m$ corresponding to each production option are also indicated. It was found that utilizing a more productive option may be an effective substitute for traffic diversion, if alternate routes are not available. For example, when $AADT_m$ is within the range of 45,000 vpd ~55,000 vpd, by shifting the work procedure from Option 3 to the more productive Option 4, Scenario A2 (i.e., without traffic diversion) may achieve a minimized total cost comparable to that of Scenario B2 (i.e., with traffic diversion).

The sensitivity analyses provided an overview of the benefits associated with traffic diversion for various traffic volumes on the mainline. The $AADT_m$ threshold would be valuable for transportation agencies in determining whether traffic diversion could bring substantial benefits for minimizing total cost and mitigating the traffic congestion due to work zones. Note that other parameters of the alternate route, such as $AADT_a$, capacity, and detour length, may also affect the thresholds and the outcomes of traffic diversion.

5.3.4 Findings

Section 5.3 optimized work zone schedules with and without a discrete time-cost function while considering time-dependent traffic diversions based on the UE assignment. The findings are:

(1) Given that $AADT_m$ = 45,000 vpd and $AADT_a$ = 25,000 vpd, four optimized schedules (i.e., Schedules "B1-1" through "B1-4") were obtained by the develop GA with respect to the four production options. The minimized total costs, cost components and project durations were summarized in Table 5.19. It was found that Options 3 and 4 outperform Options 1 and 2 in terms of reduced total cost and project duration when $AADT_m$ = 45,000 vpd. The reduced project duration results from less repetitive setups and shorter work breaks.

(2) While considering time-dependent traffic diversions in Scenario B, the approximate linear increase of the minimized total cost is contributed by the increased moving delay cost as $AADT_m$ increases; the significant increase of the minimized total cost in Scenario A1 (i.e., Figure 5.2) does not appear in Scenario B because the cumulative queuing delay was eased by traffic diversion.

(3) Employing a more productive option reduces the road user cost, although the maintenance and idling costs may increase. A cost-effective production option or a

combination of production options can be found by the developed GA. It is worth noting that the best work zone schedule also diverts minor traffic to an alternate route.

(4) With traffic diversion, the $AADT_m$ threshold that justifies an accelerated production option may increase, which means that a production option may be applicable for a wider range of $AADT_m$. The economical range of $AADT_m$ summarized in Table 5.17 may serve as a guideline for planning highway maintenance activities

(5) The optimized work zone schedules in Scenario B (i.e., with traffic diversion) does not necessarily reduce the road user cost on the basis of Scenario A (i.e., without traffic diversion). It was found that the road user costs associated with Schedules "B1-1", "B1-2" and "B1-4" increased with the use of traffic diversion because of the additional moving delay occurring on both the mainline and the alternate route.

(6) Traffic diversion would be highly favorable if employing less productive production options on heavily traveled highways. It was found that utilizing a more productive option may be an effective substitute for traffic diversion if alternate routes are not available.

5.4 Sensitivity Analyses

Previous sections discussed the optimized work zone schedules under various scenarios considering different production options, traffic diversion and various $AADT_m$ while utilizing the baseline values of input parameters shown in Table 5.4. This section focuses on studying the influences of these parameters, such as the constraint of maximum project duration, capacity of alternate route, additional cost for overnight construction, on work zone schedules, project total cost and duration.

5.4.1 Maximum Project Duration ($PD_{\max}$)

As concluded in Section 5.2.1 (i.e., Scenario A1), the project total cost may increase significantly under a tight maximum project duration, especially on heavily traveled highways. Therefore, sensitivity analyses were conducted with respect to the maximum project duration ranging from 40 to 88 hours while $AADT_m$ varies from 20,000 to 52,500 vpd.

Figure 5.13 depicts the results of the sensitivity analyses without traffic diversion (i.e., Scenario A2). It was found that the minimized total cost is not sensitive to $PD_{\max}$ when $AADT_m$ < 30,000 vpd. However, when $AADT_m$ > 30,000 vpd, the minimized total cost generally declines as $PD_{\max}$ increases, specifically between the lower and upper thresholds of T_1 to T_2 indicated in Figure 5.13. A significant cost reduction is observed while increasing $PD_{\max}$ from T_1 to T_2, especially as $AADT_m$ exceeds 47,500 vpd. It is worth noting that the minimized total costs are not sensitive to $PD_{\max}$ beyond the range of T_1 and T_2, because the optimized work zone schedules remain unchanged.

Both thresholds T_1 and T_2 would be very helpful for transportation agencies to determine appropriate project duration and exercising innovative contracting methods, which have incentive and disincentive clauses on project duration (e.g., A+B with I/D contracting method).

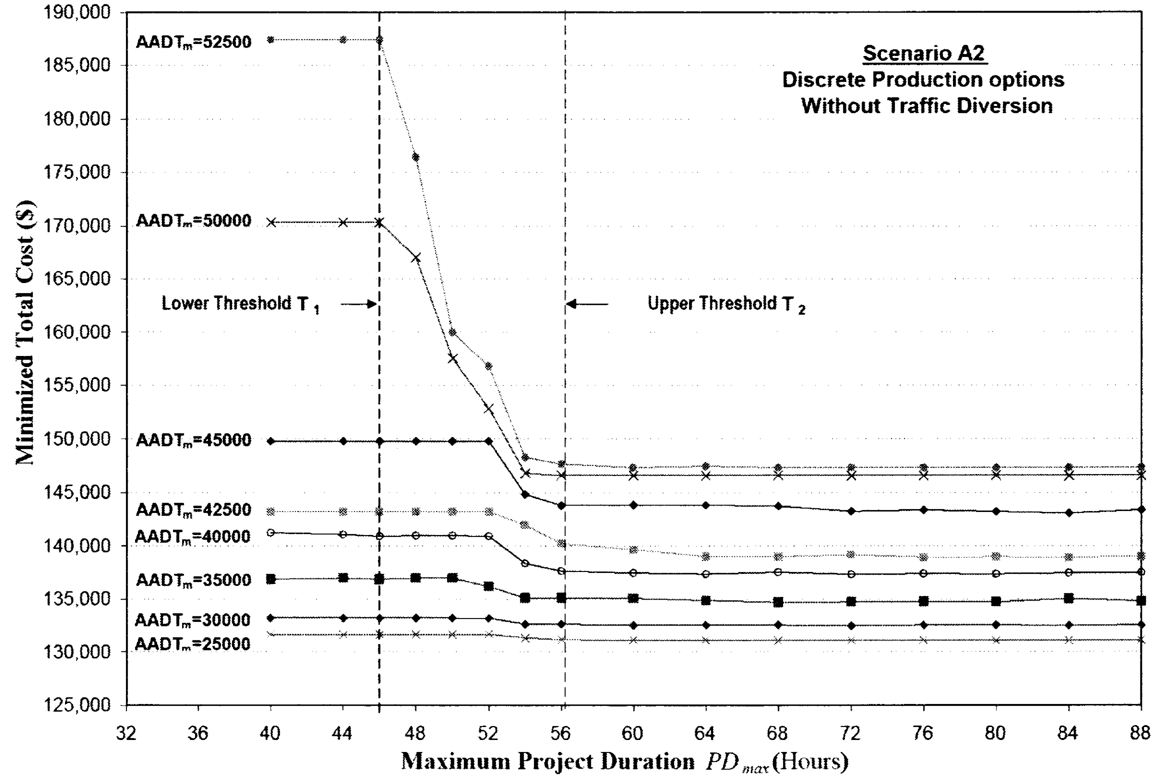


Figure 5.13 Minimized total cost versus $PD_{\max}$ for various $AADT_m$ (Scenario A2).

Figure 5.14 illustrates the results of sensitivity analyses with traffic diversion (i.e., Scenario B2). By comparing the results with those of Scenario A2 in Figure 5.13, the minimized total cost of Scenario B2 is relatively not sensitive to $PD_{\max}$ in Scenario B2, because traffic diversion alleviates the congestion on the mainline and a longer work zone length with less repetitive setups may be used to reduce the overall project duration.

Therefore, the constraint of $PD_{\max}$ becomes less critical in scheduling maintenance work on the mainline. The results also suggest that the project duration may be compressed to accelerate maintenance work without significantly increasing the total cost if traffic diversion is used.

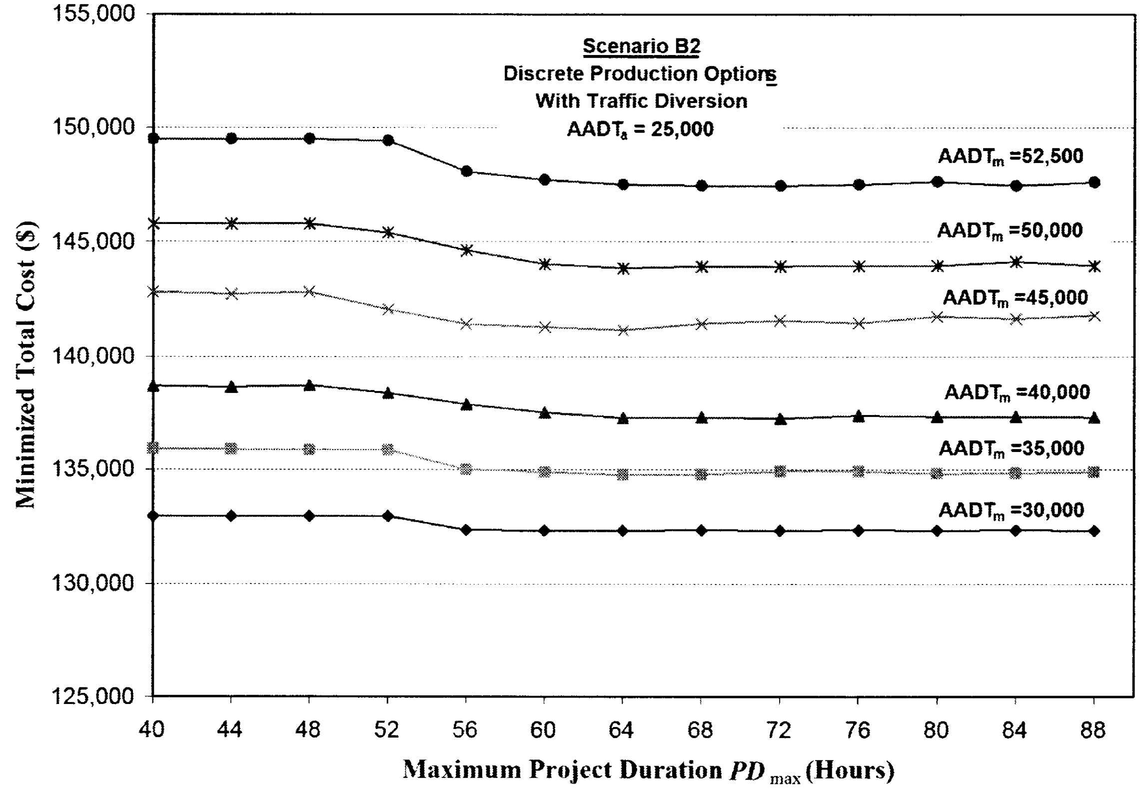


Figure 5.14 Minimized total cost versus $PD_{\max}$ for various $AADT_m$ (Scenario B2).

5.4.2 Capacity of Alternate Route (C_a)

The available capacity of the alternate route is a critical factor that affects not only the travel time and moving delay along the alternate route, but also the time-dependent traffic diversions from the mainline. Sensitivity analyses were conducted to explore the relation between the capacity of the alternate route and the minimized total cost for various $AADT_m$.

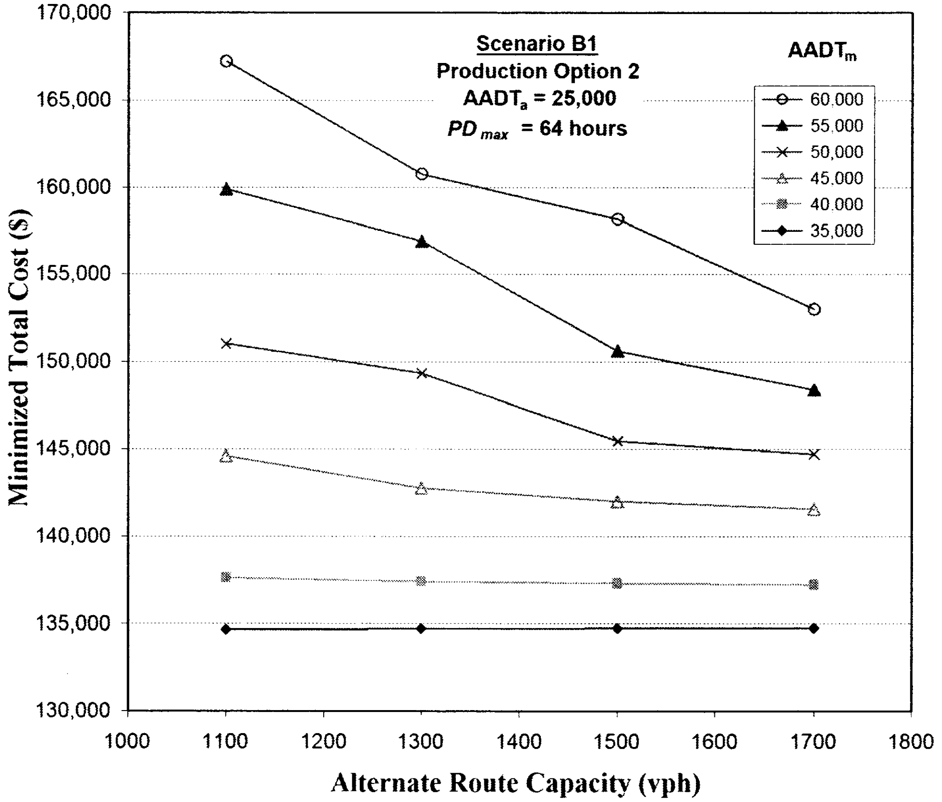


Figure 5.15 Minimized total cost versus alternate route capacity for various $AADT_m$ (Scenario B1).

For a given $AADT_a$ = 25,000 vpd on the alternate route and $PD_{\max}$ =64 hours, the minimized total costs were found under a range of alternate route capacities from 1,100 vph to 1,700 vph. As shown in Figure 5.15, the minimized total cost is not sensitive to the capacity if $AADT_m$ < 40,000 vpd because the capacity of the alternate route is sufficient to accommodate the minor traffic volume diverted from the mainline. However, as $AADT_m > 40{,}000$ vpd, the increase of alternate route capacity will reduce the total cost because the alternate route is able to handle more diverted traffic and reduce the queuing delay on the mainline.

The sensitivity analyses of the alternate route capacity with respect to different production options were also conducted while fixing $AADT_m = 55{,}000$ vpd as shown in Figure 5.16. It was found that the total cost decreases as the capacity increases. Furthermore, significant cost savings may be gained for less productive options by increasing the capacity of the alternate route. This finding is consistent with the results of Scenario B1, in which more traffic is diverted to the alternate route if less productive options are deployed; therefore, a greater reduction in total cost is anticipated.

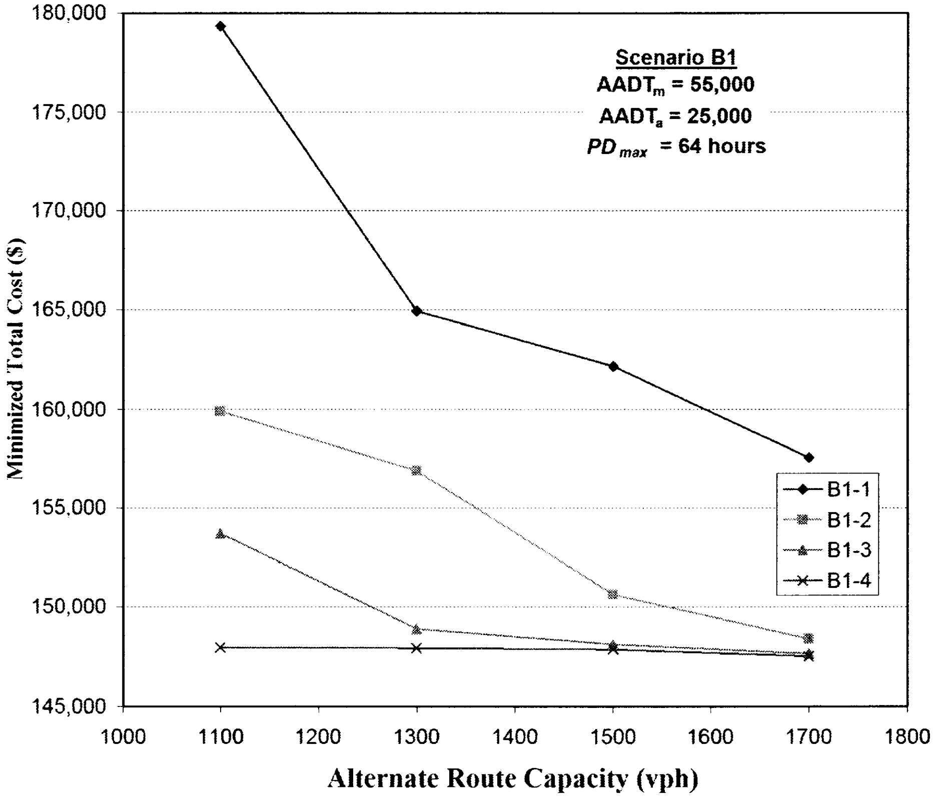


Figure 5.16 Minimized total cost versus alternate route capacity for various production options (Scenario B1).

5.4.3 Nighttime Cost Factor (f_{nc})

Maintenance work during the nighttime off-peak period can reduce the traffic impact and road user cost, especially on heavily traveled highways where off-peak daytime hours are very limited for maintenance work. However, nighttime work is more expensive due to additional traffic control requirement, higher labor cost (e.g., overtime rate), site lighting, etc. To investigate the influence of the additional nighttime maintenance cost, the nighttime cost factor f_{nc} discussed in Section 3.1.1 is applied to a 10-hour period between 8:00PM to 6:00 AM. Note that a nighttime cost factor of 1.0 represents no additional nighttime maintenance cost, and various options of $f_{nc} \geq 1.0$ are considered in this analysis.

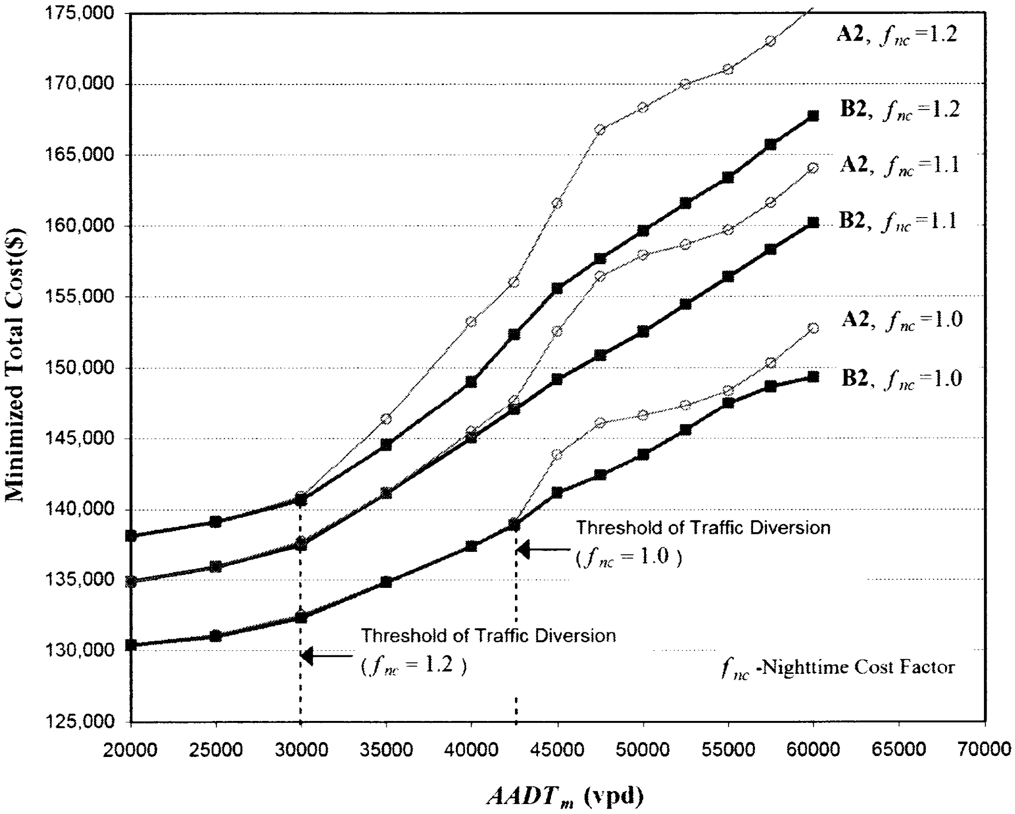


Figure 5.17 Minimized total costs versus $AADT_m$ for various night cost factors (Scenarios A2 and B2).

Figure 5.17 indicates that the minimized total cost increases as the nighttime cost factor increases from 1.0 to 1.2. It was found that the optimized work zone schedule remains unchanged and the increase of the total cost is merely caused by nighttime work.

As shown in Figure 5.17, the different thresholds of $AADT_m$, which justify the implementation of an alternate route, can be found by comparing Scenarios A2(i.e., without traffic diversion) and B2(i.e., with traffic diversion) with respect to different nighttime cost factors. It is worth noting the threshold is reduced as the nighttime maintenance cost factor increases. Subject to high nighttime maintenance cost, traffic diversion would be favorable because it allows more maintenance work to be performed during longer daytime periods, thus the nighttime maintenance cost can be significantly reduced. For instance, the threshold decreases from 42,500 vpd to 30,000 vpd while considering a 20% increase in nighttime maintenance cost.

5.4.4 Findings

This section analyzed the three key factors (i.e., maximum project duration, capacity of alternate route and nighttime cost factor) that play very critical roles in scheduling work zones. The findings of sensitivity analyses are summarized below,

(1) Without traffic diversion, the minimized total cost may be reduced significantly for heavily traveled roadway (i.e., $AADT_m > 30,000$ vpd) by increasing the maximum project duration $PD_{\max}$ from the lower threshold to the upper threshold. The two thresholds of $PD_{\max}$ found in this dissertation may assist transportation agencies to determine appropriate project duration, which are important in exercising the innovative contracting methods, which have incentive and disincentive clauses on project duration.

(2) It was found that the project total cost is relatively not sensitive to $PD_{\max}$ while considering traffic diversion. Thus, the project duration may be compressed to accelerate maintenance work without increasing total cost significantly.

(3) The minimized total cost is sensitive to the capacity of alternate route while the mainline carries heavy traffic. In addition, for less productive options, significant reduction in total cost may be gained while increasing the capacity of alternate route.

(4) The 20% increases of the nighttime maintenance cost will not shift the nighttime work zones to daytime hours because the saving of nighttime maintenance cost cannot offset the excessive road user cost.

(5) The threshold of $AADT_m$ that justifies traffic diversion will decrease as f_{nc} increases, which means traffic diversion would be adopted for lower volume roadways as the nighttime cost increases, because more maintenance work may be conducted during daytime periods to reduce the additional nighttime cost if traffic diversion is applied.

CHAPTER 6

CONCLUSIONS AND FUTURE RESEARCH

Subject to budget constraints, project deadlines, and the resulting traffic impacts, highway work zones should be optimized to mitigate the inconvenience to the public, and to reduce the total project cost. Hence, a scheduling optimization model was developed to minimize the total cost, in which realistic parameters, such as work zone tapers and the nighttime cost factor, were also introduced while formulating the total cost function including agency and road user costs. The framework of jointly optimizing work zone schedules and time-dependent traffic diversions was defined. An iterative algorithm that integrates the powerful searching capability of the GA and the UE assignment was developed and calibrated. Four scenarios, which include a constant or a discrete maintenance time-cost function with or without traffic diversion, were analyzed to evaluate the applicability and benefits of the two strategies, i.e., accelerated constructions and traffic diversion. Guidelines and thresholds of the key factors were discussed and compared through sensitivity analyses.

6.1 Conclusions

Subject to time-dependent traffic conditions of mainline and alternate route(s) as well as various production options, optimized work zone schedules and optimal diverted traffic flow can be obtained by the developed GA. Substantial benefits may be gained on heavily traveled roadways. The major findings and conclusions are follows:

6.1.1 Work Zone Schedules

- Employing a more productive option generally reduces the road user cost; however, the maintenance and idling costs may increase. Without traffic diversion, a significant increase in the total cost is anticipated when deploying less productive options on heavily traveled roadways because of the rapid increase in road user cost. Therefore, when traffic demand exceeds the thresholds found in this study, utilizing an accelerated production option at a higher unit maintenance cost may be justified to reduce the total project cost and duration.

- While considering time-dependent traffic diversion, the increased moving delay cost contributed to the approximate linear increase in the minimized total cost, because the accumulative queuing delay was eased by traffic diversion. The thresholds of employing more productive but expensive production options will increase accordingly.

- A cost-effective production option, which may be applicable to a range of $AADT_m$, was identified for the pavement resurfacing project discussed in this study. With traffic diversion, the cost-effective production option may be applicable to a wider range of $AADT_m$ than without traffic diversion.

- The economical ranges of $AADT_m$ for each production option may serve as a guideline for planning highway maintenance activities. Transportation agencies may identify such a range of $AADT_m$ for various types of maintenance activities, based upon typical traffic conditions in different regions (e.g., different counties) or different classifications of roadways (e.g., arterials or collectors).

- For a heavily traveled roadway (e.g., a four-lane highway carrying $AADT_m >$ 45,000) without alternate route(s), the project total cost is very sensitive to a specific range of $PD_{\max}$ (i.e., maximum project duration). The range is bounded by a lower threshold T_1 and an upper threshold T_2, which may vary with different production options and traffic conditions.

- While considering traffic diversion, the total project cost is relatively not sensitive to $PD_{\max}$. Therefore, the project duration may be compressed to accelerate maintenance work without increasing total cost significantly. Knowing both thresholds T_1 and T_2 would be very helpful for transportation agencies to determine appropriate project duration and exercise the innovative contracting methods that have incentive and disincentive clauses on project duration (e.g., A+B with I/D contracting method).

- Traffic diversion would be highly favorable if employing less productive options on heavily traveled highways. It was found that utilizing a more productive option may be an effective substitute for traffic diversion if alternate routes were not available.

- The threshold of $AADT_m$ for traffic diversion can be identified through the developed methodology. Alternate routes may be established as traffic demand increases over the threshold. This threshold would be valuable for transportation agencies to determine whether traffic diversion is a cost-effective traffic mitigation approach.

- The total cost is sensitive to the capacity of the alternate route for the pavement resurfacing project discussed in this study, while the mainline carries heavy traffic. Especially, for less productive options, significant reduction in total cost may be obtained while increasing the capacity of the alternate route because the alternate route is expected to carry more diverted traffic to reduce the queuing delay on the mainline.

- For the pavement resurfacing project discussed in this study, the 20% cost increase through the nighttime cost factor (f_{nc}) will not justify shifting the nighttime work zones to daytime hours because the saving in nighttime maintenance cost cannot offset the increased road user cost. However, if a higher nighttime cost factor and a lower value of user time are applicable, nighttime work would not be favorable.

- It was found that the threshold $AADT_m$ that justifies traffic diversion will decrease as f_{nc} increases. Thus, applying traffic diversion on a mainline carrying relatively lower traffic demand would be more favorable as the nighttime cost increases, because more maintenance work can be conducted during daytime periods to reduce the additional nighttime cost.

6.1.2 Genetic Algorithm

- The developed GA is suitable for the work zone scheduling optimization problem formulated in this study, which has a nonlinear, integer and discontinuous objective function. The parameters of the GA, such as crossover and mutation ratios as well as population size, were calibrated using the benchmark solution solved by Simulated Annealing (Chen, 2003). The results suggest that utilizing a population size (P) of four times the total number of intervals (N) in a solution (i.e., $P = 4N$) would achieve satisfactorily optimized solutions after multiple iterations.

- The developed iterative algorithm that integrates the GA and the UE assignment was proven to be a feasible method to solve such a multi-dimensional optimization problem. The solution accuracy based on 15-minute intervals adopted in this study is adequate for scheduling short-term maintenance projects. Meanwhile, different interval durations may be used in the GA and UE assignment, respectively. Thus, for a maintenance project that requires a relatively long duration, longer intervals may be utilized by the GA (e.g., one hour) to reduce computation time while the UE assignment uses smaller intervals (e.g., 5 minutes) to approximate the dynamic feature of traffic diversion more precisely.

6.2 Future Research

Future research for the optimization of work zone schedules may be focused on the following aspects:

- This study focused on scheduling single lane closure work zones on a multiple lane highway. The developed model can also handle uniform two-lane closures. However, on the highways with more than three lanes in each direction, employing single lane closure at daytime and two-lane closures during nighttime off-peak periods may be a viable alternative to accelerate construction and reduce total cost. Thus, it is desirable to develop an algorithm for optimizing the work zone schedules of the mixed lane closure alternatives.

- An agency cost component that can reflect environmental impacts due to work zone delays, e.g., emissions, may be supplemented into the developed objective total cost function.

- The vehicle operating cost (VOC) adopted in this study was based upon NCHRP Report No. 133(1972). An updated vehicle-hour based VOC would be desirable to reflect the enhancement in contemporary automobile technologies.

- The assumption of fixed work zone setup cost z_1 and time z_3 associated with each production option may be relaxed if real world data are available for different production options (i.e., crews).

- The objective function in this study minimizes the total project cost. A multi-objective optimization that also minimizes the project duration may be desirable while considering innovative contracting methods that use incentive or disincentive clauses on project duration, e.g., A+B bidding plus I/D method.

- The UE assignment and the link performance functions formulated in this dissertation considered a simplified network including a rural freeway and a service road, and demonstrated the framework of the developed iterative algorithm. The UE assignment may be substituted by a more sophisticated dynamic traffic assignment model to handle complicated roadway networks, and different classes of motorists and their preferences of route choices. In addition, the comparison between the UE assignment and the system-optimal assignment will be a valuable extension of this dissertation.

- The developed GA can reach good solutions that may be very close to the global optimum. The goodness of the optimized solution may be tested statistically (Jong and Schonfeld, 2003). In addition, problem-specific genetic operators may be developed to further improve the quality of the optimized solutions and accelerate the developed GA.

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