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Optimization of Long-Term Highway Work Zone Scheduling

Final Report

by

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DISCLAIMER

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List of Abbreviations

ANN – Artificial Neural Network

BP – Backpropagation

DTA – Dynamic Traffic Assignment

FHWA – Federal Highway Administration

GA – Genetic Algorithm

NCDOT – North Carolina Department of Transportation

NPRM – Notice of Proposed Rulemaking

ODOT – Oregon Department of Transportation

O-D – Origin–Destination

RMSE – Root Mean Square Error

SVM – Support Vector Machine

TTD – Total Travel Delay

TTI – Texas Transportation Institute

UE – User Equilibrium

EXECUTIVE SUMMARY

With the rapid development of the transportation system, an increasing number of work zone projects come with the needs of new constructions and regular maintenance related investments in transportation. However, the negative impacts of the work zone projects on the traffic in the transportation network may be inevitable and can cause many issues socially, economically and environmentally. As such, work zone projects that aim at relieving congestion while expanding capacity of the network is becoming more important. In 2017, the Federal Highway Administration (FHWA) issued a notice of proposed rulemaking (NPRM) for performance-based planning and programming (FHWA, 2017). It requires state departments of transportation and metropolitan planning organizations to measure and report on the performance of infrastructures in the National Highway System within their jurisdictions. A series of enhanced performance measures have been developed and included in this new rule. However, it is still lacking in performance measures for assessing congestion under special events including the presence of work zones. Despite such absence of metrics which can be used for evaluation, attention should also be paid to minimize the impacts of relevant work zone activities.

This research develops and recommends practical optimization model for long-term work zone events management. In such sense, this research analyzes the impacts of the long-term work zone events on the mobility performance of the network in consideration of elastic demand. A bi-level optimization model is built which is later solved by the proposed genetic algorithm (GA). Then, Sioux Falls network is used as a case study to test the proposed GA-based model. The impacts of all work zone combinations are examined and the sensitivity analysis of the elastic demand parameter (Ω_w) is also conducted. Summary and conclusions are made, and further research directions are also given.

Chapter 1. Introduction

1.1 Problem Statement

With the rapid development of transportation system, an increasing number of work zone projects come with the needs of new construction and regular maintenance related investments in transportation. However, the negative impacts of the work zone projects on the traffic in the transportation network may be inevitable and can cause many issues socially, economically and environmentally. As such, work zone projects that aim at relieving congestion while expanding capacity of the network is becoming more important. In 2017, Federal Highway Administration (FHWA) issued a notice of proposed rulemaking (NPRM) for performance-based planning and programming (FHWA, 2017). It requires state departments of transportation and metropolitan planning organizations to measure and report on the performance of infrastructures in the National Highway System within their jurisdictions. A series of enhanced performance measures have been developed and included in this new rule. However, it is still lacking in performance measures for assessing congestion under special events including the presence of work zones (Ramadan and Sisiopiku, 2018). Despite such absence of metrics which can be used for evaluation, attention should also be paid to minimize the impacts of relevant work zone activities.

A preliminary literature review has been conducted to synthesize past and ongoing research related to this research topic. In two publications by FHWA (Jeannotte and Chandra, 2005; Sankar, Jeannotte, Arch, Romero and Bryden, 2006), impacts caused by work zone events can be categorized into following six groups: safety impacts, mobility impacts, economic considerations, environmental concerns, user cost and contractor's maintenance costs.

From the contractor's standpoint, the total maintenance cost of work zone activities might need to be minimized (Meng and Weng, 2013). On the other side, roadway users are also concerned about the interruptions that work zone events cause to their travel mobility and cost. From a high level of planning perspective, local agencies need to comprehensively take at least some of the six aspects into consideration to balance the total impacts. There is no doubt that there are no simple relationships among all those impacts. According to Hardy and Wunderlich (2008), among all six impact types, the impact of mobility is the key for assessing the remaining five aspects associated with work zone events. They further pointed out that after thoroughly evaluating the mobility impacts, all other aspects could be determined as well.

Many research efforts have been carried out to explore the impacts of the work zone events. By striking a balance between work zone project contractors and roadway users, many existing studies focused on minimizing the total costs on both sides (including users' travel delays and the work zone maintenance costs) (Schonfeld and Chien, 1999; Chen et al., 2001). Traditional deterministic queuing theory (Dudek and Richard, 1982; Jiang and Adeli, 2003; Yang et al,, 2009) and shock wave theory (Newell, 1993) can be used to evaluate travel delay and queue length on local roadway segments where road work exists (Gong and Fan, 2016). However, such methods are not able to consider the broader impacts of work zones at a network level (Zhang and Chiu, 2014). Furthermore, most of the research studies are related to short-term work zones within a short time frame. Few studies have focused on modeling the impact of the work zone activities on the transportation network itself over the whole planning horizon before considering other detailed issues. Moreover, when dealing with the behavior change of drivers due to the impacts of work zone activities (such as traffic congestion), traffic diversion is one of the common strategies considered in many literatures (Chen et al, 2005; Zhang and Chiu, 2014; Chien and Tang, 2014). This is useful for short-term work zone events analysis. Since route users are already on roads, it would also be a sufficient way to deal with local roadway segments. However, for the long-term work zone projects planning and management, this practice may not be desirable since it ignores the fact that some of the route users would rather choose other transportation modes to accomplish their trips or daily commutes. Furthermore, it would also be more realistic to consider elastic demand in long-run planning in order to take such user behavior change into consideration for the highway work zone scheduling optimization problem.

1.2 Objectives

The main objective of this research project is to develop and recommend a macroscopic optimization model to evaluate the mobility impacts of long-term work zone events and optimizing the scheduling of starting dates of work zone projects. The objectives of this project are to: (1) conduct a comprehensive review of the state-of-the-art and state-of-the-practice on work zone optimization problem; (2) develop suitable macroscopic optimization model on long-term work zone projects in consideration of elastic demand; (3) develop unique solution framework to solve the long-term highway work zone scheduling; and (4) analyze the performance of the method and provide recommendations on future research directions.

1.3 Expected Contributions

To accomplish these objectives, several tasks have been undertaken. A literature review of the work zone optimization problem has been conducted. According to the literature and the research results from previous studies, optimization models for optimizing long-term highway work zone projects have been developed, associated with approaches to solving the developed optimization models. Based on the results, primary recommendations on the best practice/policy to optimize long-term highway work zone projects will be provided. All products will be integrated into current practices for better managing long-term highway work zone projects, which can greatly help provide method and identify further opportunities to minimize the impacts of long-term highway work zone events in the future planning.

1.4 Report Overview

This report is structured as shown in Figure 1.1. The remainder of this report is organized as follows: Chapter 2 presents a comprehensive review of the current state-of-the-art and state-of-the-practice of highway work zone scheduling optimization problem and related studies nationwide and worldwide, including short-term work zone management, long-term work zone management, etc. Chapter 3 provides a detailed explanation of and formulation for the developed optimization model for long-term work zone projects management by incorporating the elastic demand. Chapter 4 presents model solution methodology utilized to solve the developed optimization in this research. Chapter 5 presents a real-world case study as an example, and comprehensive analyses and detailed numerical results, including sensitivity analysis are provided. Finally, Chapter 6 concludes this report with a summary and a discussion of the directions for future research.

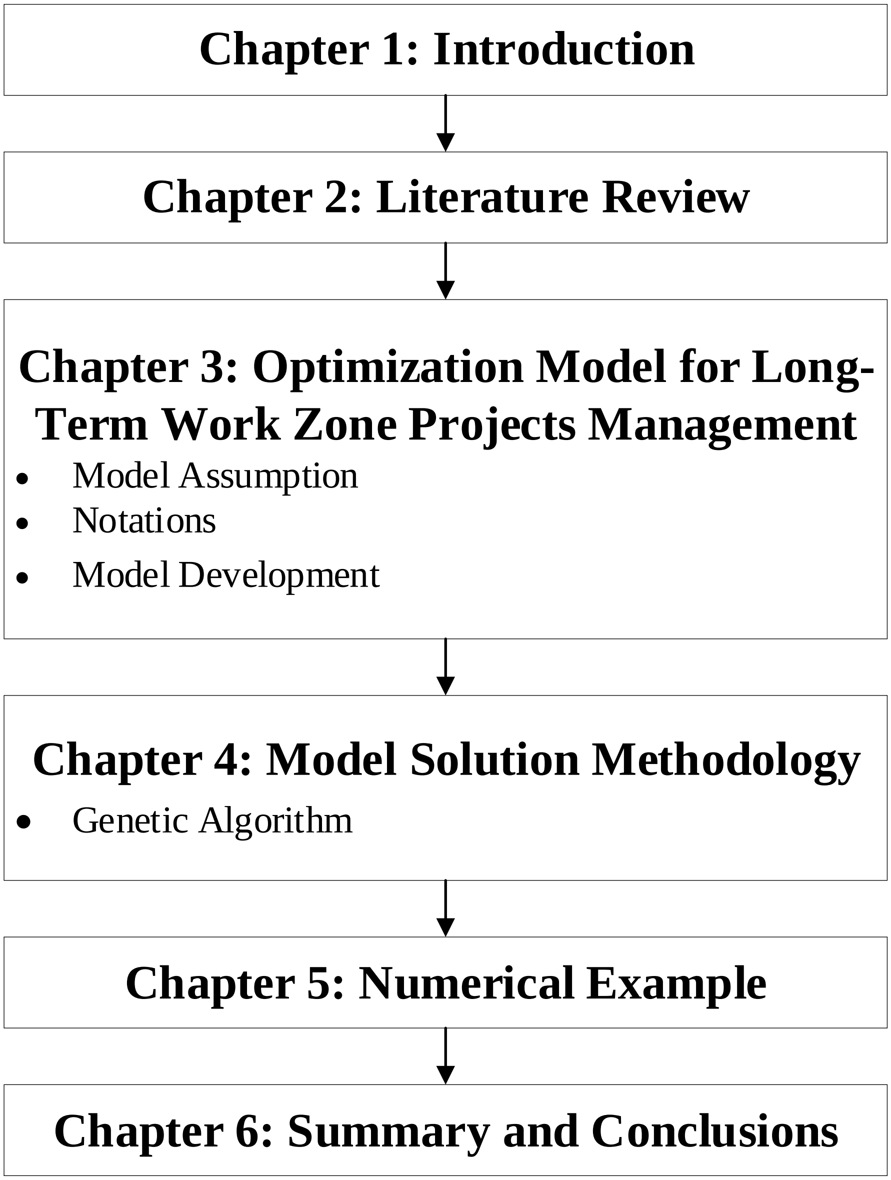


Fig. 1.1. Research Structure

Chapter 2. Literature Review

2.1 Introduction

This chapter provides a comprehensive review of the current state-of-art and state-of-practice of highway work zone scheduling optimization problem and related studies nationwide and worldwide, including short-term work zone management, long-term work zone management, etc. This should give a clear picture of the highway work zone scheduling optimization problem, the methodologies for tackling the problem, and potential applications.

The following sections are organized as follows. Section 1.2 presents an overview of work zone planning in the field of transportation research, including the general information on work zone operation and management, impacts of work zone projects, study objects of work zone planning problem, and methodology for solving the work zone planning related problem. Section 1.3 gives a brief description of previous studies that focused on the work zone optimization problem. Finally, section 1.4 concludes this chapter with a summary.

2.2 Overview of Work Zone Planning in Transportation

With the rapid development of the transportation system, an increasing number of work zone projects come with the needs of new construction and regular maintenance related investments in transportation. The ultimate goal of work zone projects is to provide better mobility and a safer environment to all entities within the whole transportation system. As such, work zone projects that aim at relieving congestion while expanding capacity of the network are becoming more important. However, the negative impacts of the work zone projects on the traffic in the transportation network may be inevitable and can cause many issues socially, economically and environmentally. In 2017, Federal Highway Administration (FHWA) issued a notice of proposed rulemaking (NPRM) for performance-based planning and programming (FHWA, 2017). It requires state departments of transportation and metropolitan planning organizations to measure and report on the performance of infrastructures in the National Highway System within their jurisdictions. A series of enhanced performance measures have been developed and included in this new rule.

2.2.1 Work Zone Operation and Management

In the Highway Capacity Manual, work zone is defined as a segment of a highway where there are maintenance and construction operations which negatively impact the physical capacity (i.e., the number of lanes available to traffic) and affect the traffic flowing through the segment. Factors such as the length of work zone, number of lane closures, duration of lane closures, scheduling of lane closures, posted speed, and the alternative routes are the major components that need to be taken into account while considering a work zone project.

Work zone length is an important issue that has been relatively neglected. In general, longer zones tend to increase the user delays, but the maintenance activities can be performed more efficiently (i.e., with fewer repeated setups) in longer zones (Schonfeld and Chien, 1999). In practice, such lengths have usually been designed to reduce costs to highway agencies rather than users.

The lane closure type is one of the major factors that affect the vehicle capacity in work zones, and it also affects agency costs to a considerable degree. There are three main lane closure types for work zones: partial lane closure, full lane closure and crossover (Pal and Sinha, 1996). In a partial lane closure, one or more lanes are closed in one or both directions, but not all the lanes in one direction are closed simultaneously. Traffic cones, drums, or concrete barriers are used to close the lanes, and maintenance and rehabilitation activities are performed on the closed lanes. During full road closure, traffic is detoured, allowing full access to roadway facilities. Under the appropriate conditions, a full closure can be an effective way to complete projects with shorter duration and less safety risks. Departments of transportation in Oregon, Kentucky, Michigan, Ohio, Washington, and Delaware had experience in using a full closure approach to conducting road rehabilitation/reconstruction projects (Neudorff et al., 2003). In a crossover arrangement, all lanes in one direction are closed and both directions of traffic are brought to one side of a highway. Due to the additional cost of constructing the crossover facility, the fixed set up cost in cases of crossover is always higher than that in cases of partial lane closure at sites. However, in a crossover lane closure strategy, sufficient working spaces are available, which may improve the safety of the workers and increase their productivity and the quality of their work. It is noted that sometimes closed lanes may include not only maintained lanes, but also additional lanes which are used to provide access to and from the work site for maintenance and construction vehicles or provide buffer space to separate traffic and work sites from safety consideration.

Since travel demands are time-varying, work zone scheduling can greatly affect the traffic impact caused by lane closures. Work zones can be categorized into three designations: (1) short-term sites, at which maintenance work lasts less than one day (24 hours) (Jiang, 2003); (2) intermediate sites, at which work lasts over one day but less than four days; (3) long-term sites, at which work lasts more than four days (Rouphail, 1988). Unlike in long-term projects which continuously occupy the road space for several days or months, short term and intermediate work zones are often limited to the time defined in some construction windows, e.g. off-peak daytime, nighttime periods, or weekend periods, in order to avoid the higher volume daytime hours and associated traffic delays.

2.2.2 Impacts of Work Zone Projects

In two publications by FHWA, “Developing and Implementing Transportation Management Plans for Work Zones” and “Work Zone Impact Assessment: An Approach to Assess and Manage Work Zone Safety and Mobility Impacts of Road Projects” (Jeannotte and Chandra, 2005; Sankar et al., 2006), impacts caused by work zone events can be categorized into following six groups: safety impacts, mobility impacts, economic considerations, environmental concerns, user cost and contractor’s maintenance costs.

It is worth mentioning that different interesting subjects basically focused on distinct perspectives of the abovementioned six categories of impacts raised by the work zone project (Gong and Fan, 2016). From the contractor’s standpoint, the total maintenance cost of work zone activities might carry more weight to be minimized (Meng and Weng, 2013). On the other side, roadway users are also concerned about the interruptions that work zone events cause to their travel mobility and cost. While from a high level of planning, local agencies need to comprehensively take at least some of the six aspects into consideration to balance the total impacts. There is no doubt that the there is no simple relationships among all those impacts. According to (Hardy and Wunderlich, 2008), among all six impact types, the impact of mobility is the key for assessing the remaining five aspects associated with work zone events. They further pointed out that after thoroughly evaluating the mobility impacts, all other aspects could be determined as well. Thus, under such circumstance, work zone planning optimization problem is a challenging task and completely different results might arise in the same case when there are different attentions.

Many research efforts have been carried out to explore the impacts of the work zone events. By striking a balance between work zone project contractors and roadway users, many existing studies focused on minimizing the total costs on both sides (users' travel delays and the work zone maintenance costs) (Schonfeld and Chien, 1999; Chien and Schonfeld, 2001; Chen et al., 2001).

2.2.3 Study Objects of Work Zone Planning Problem

Despite focusing on the impacts of the highway work zone events, from a perspective of studied objects, research on optimizing work zone planning can be roughly grouped into three other categories.

The first category includes research that investigates the long-term network rehabilitation planning problem with the objective of maintaining the roads in good condition with least cost in different aspects. For example, Chu and Chen (2012) developed a bi-level hybrid dynamic model in which the upper level problem decides the optimal threshold for each road that triggers maintenance action and the lower level problem solves the user equilibrium problem.

The second category focuses on developing operational strategies for work zone scheduling on a highway segment or a local arterial. Some research in this category has studied the short-term work zone scheduling with time horizons being less than a day. The research in this category focuses on scheduling work zones on single links and has very limited or no consideration of the impact of traffic diversion resulting from multiple link capacity reductions.

The third category consists of research that studied the scheduling of network expansion projects. This research specifically considered the flow pattern changes caused by the increase of link capacities or the addition of new links over the planning time horizon. This research topic is closely related to the network design problem, which selects among a set of candidate links to be added to a network with budget constraints, to achieve lowest total cost at users' equilibrium state or system optimum. It is an extension of the network design problem since the addition of the chosen links needs to be scheduled, and possible traffic flow pattern changes need to be evaluated after the addition of each link.

2.2.4 Methodology for Solving Work Zone Planning Problem

The aforementioned classification methods of work zone planning problem mainly consider how the problem could be formed. From the perspective of solving problem or based on the methodology utilized in the related research, three major groups could be summarized: 1) parametric, 2) simulation, and 3) nonparametric approaches.

There are two subcategories within the parametric method, including the traditional deterministic models and traffic assignment models. For traditional deterministic models, commonly the deterministic queuing theory is employed for predicting work zone delay (Dudek and Richard, 1982; Chien and Schonfeld, 2001; Jiang and Adeli, 2003). Another well-known parametric approach for delay prediction is shockwave theory, first introduced by Lighthill and Whitham (1955), and Richards (1956). Deterministic queuing models are suitable for predicting delay for planning purposes. The shockwave theory assumes that the traffic flow is analogous to fluid flow and employs a flow-speed-density relationship to analyze the transition of traffic flow over space and time.

These two methods can be used to evaluate travel delay and queue length on local roadway segments where road work exists. However, such methods are not able to consider the broader impacts of work zones at a network level (Zhang and Chiu, 2014). Thus, scholars try to deploy the traffic assignment models, which are both static and dynamic traffic assignment, to resolve this problem (Pesti et al., 2010; Chiu et al., 2011; Gong and Wei, 2016). The widely recognized advantages of traffic assignment models include the ability to solve largescale problems, to converge to precise equilibriums and to provide consistent solutions (if a proper algorithm is used with an enough iterations). Due to these features, they have been widely used by planning agencies and traffic management centers for decades (Chiu et al., 2011).

Recently, researchers applied microscopic traffic simulation to quantify work zone delay (Chien et al., 2002; Meng and Weng, 2010; Chung et al., 2012). Well-calibrated simulation models can generate high fidelity traffic measures under various work zone configurations. CORSIM and VISSIM are among the most widely used models. However, the simulation approach for delay prediction suffers from high computational time and the results only represent the traffic measures for a specific work zone on a specific segment of a highway.

To overcome the limitations of parametric and simulation approaches, nonparametric models were developed. Many studies have successfully applied Artificial Neural Networks (ANNs) to predict various traffic measures, such as traffic flow (Jiang and Adeli, 2005; Kumar et al., 2015), freeway work zone capacity (Neubert et al., 2000; Karim and Adeli, 2003), and work zone delay (Ghosh-Dastidar and Adeli, 2006; Du and Chien, 2014; Du, 2017). With technological advancements, a wide variety of massive traffic data from infrastructure sensors and probe vehicles have become increasingly available. This new and rich data has made ways for big data analytics as an emerging method for predicting freeway spatiotemporal work zone delay.

2.3 Previous Studies on Work Zone Planning

Section 1.2 discuss the general information on work zone planning problem in transportation research area and different perspective on classifying the research focusing on work zone planning problem were also provided. Based on the given classification method, this section will present the reviewed literatures based on different methodologies.

2.3.1 Deterministic Queuing Theory and Shockwave Theory

2.3.1.1 Work of Wirasinghe (1978)

Wirasinghe (1978) used shock wave theory to develop formulas for calculating individual and total delays upstream of incidents. The formulas were based on areas and densities of regions representing different traffic conditions (mainly congested and capacity regions) that are formed by shock waves in the time-space plot.

2.3.1.2 Work of Dudek and Richard (1982)

By applying the deterministic queuing theory, Texas Transportation Institute presented detailed information based on field data analysis for estimating road capacity during maintenance work. They considered lane closure strategies and obtained cumulative distributions of observed work zone capacities. Findings of capacity studies conducted at 28 maintenance and construction work zones on freeways in Houston and Dallas were summarized. Studies were conducted on five-, four-, and three-lane freeway sections. The results indicated that the per-lane capacities are affected by the number of lanes open during the roadwork.

2.3.1.3 Work of Newell (1992)

Newell implicitly proposed a merge queuing model in his original theory. Unlike what is commonly believed, the model assumed full priority for ramp traffic so that it always bypasses any queue at a merge and experiences no delay. Though unrealistic to a certain extent, this model did make the simplified theory easy and elegant. Newell’s simplified theory of kinematic wave was particularly efficient to assist these efforts in terms of implementation and application. Unfortunately, the simplified theory dealt only with freeway mainline.

2.3.1.4 Work of Schonfeld and Chien (1999), Chien and Schonfeld (2001)

In this study, Schonfeld and Chien developed a mathematical model by combining the deterministic queuing theory to optimize work zone lengths and traffic control on two-lane highways where one lane at a time was closed. By considering the aggregate effects of various work zone lengths and combined flow rates, their method provided a practical approach for reducing both traffic delays and maintenance costs. Traffic control and work zone lengths were jointly optimized, while unbalanced traffic flows in both directions were considered. However, accidents were not considered in both studies.

In a later work (Chien and Schonfeld, 2001), similar mathematical model was developed to optimize work zone lengths on four-lane highways where one lane in one direction at a time was closed. The objective was to minimize the total cost, including the agency cost, the accident cost, and the user delay cost. The optimized variable (e.g., work zone length) and the sensitivity results generated from a numerical example were presented in this study. With user-specified input parameters, this model can be used to optimize work zones on four-lane highways for a wide variety of circumstances.

2.3.1.5 Work of Jiang and Adeli (2003)

Jiang and Adeli (2003) used deterministic queuing theory to present a new freeway work zone traffic delay and cost optimization model in terms of two variables: the length of the work zone segment and the starting time of the work zone using average hourly traffic data. The total work zone cost defined as the sum of user delay, accident, and maintenance costs was minimized. Number of lane closures, darkness factor, and seasonal variation in travel demand normally ignored in prior research were included. To find the global optimum solution, a Boltzmann-simulated annealing neural network was developed to solve the resulting mixed real variable-integer cost optimization problem for short-term work zones. In addition, the potential benefits of applying this model were also discussed. For example, they argued that, by using their model, traffic engineers would be able to systematically and quickly find the best decisions on the cost impact factors such as lane closure numbers and project starting times. This study was based on a research project sponsored by Oregon Department of Transportation (ODOT) and FHWA. North Carolina Department of Transportation (NCDOT) provided data for their numerical tests.

2.3.1.6 Work of Du and Chien (2014)

Based on the deterministic queuing theory, Du and Chien (2014) developed an analytical model with formulating the work zone delay by considering time-varying traffic pattern, work zone capacity adjustment factors (e.g., light condition, heavy-vehicle percentage, and lane width), and shoulder usage. The objective aimed at optimizing the length of work zones. The results can be used to evaluate the work zone impact (i.e., delay and cost) and assist engineers/planners to prepare and develop a cost-effective highway maintenance plan. A case study for a highway work zone in New Jersey was conducted, in which the optimized solution was found. A guideline of using road shoulder under various circumstances was developed.

2.3.1.7 Work of Abdelmohsen and El-Rayes (2018)

Abdelmohsen and El-Rayes (2018) developed an optimization tool for work zone management planning. Providing the tool with the necessary data on the highway characteristics, work zone layout and characteristics, etc., the developed program used a four-stage optimization process to provide the user with an optimal work zone traffic control plan based on the acceptable traffic delay and crash index. It also provided a means to analyze the impact of different traffic control measures on traffic delays and crash index at work zones. As mentioned previously, these deterministic models were inappropriate for prediction of incident delay in real-time situation where the incident duration was unknown.

2.3.2 Traffic Assignment Models

2.3.2.1 Work of Tang and Chien (2009)

In this study, the time-varying traffic diversion due to work zones was developed and incorporated with a work zone schedule optimization model. The developed model optimized work zone schedules jointly considering the time-varying traffic diversion, variable maintenance cost and production rate of different maintenance crews, which minimizes the total cost including agency cost and user's cost. The numerical example compared various combinations of the mitigation plans in a generalized two-link network, consisting of a freeway and an alternate route. The results of sensitivity analysis indicated that implementing traffic diversion is desirable as the freeway volume exceeds the threshold found in this study. This study also demonstrated a feasible approach to planning maintenance activities cost-effectively for a real-world highway resurfacing project.

2.3.2.2 Work of Pesti et al. (2010)

Pesti et al. (2010) from Texas Transportation Institute (TTI), deployed a dynamic traffic assignment (DTA) tool to quantify and evaluate how traffic patterns change in response to various construction scenarios in the El Paso region, Texas. Although DTA models can perform detailed modeling of traffic dynamics of congestion formulation, spillovers, etc., a number of input data and parameter need to be specified prior to model development and calibration.

2.3.2.3 Work of Ng (2012)

In this study, Ng (2012) relaxed the assumption of determinism, and model vehicle arrivals as being stochastic. While previous work showed that this relaxation is important in the quantification of user delay at work zones, no model exists that explicitly accounts for stochasticity in the optimization of work zones. Second, unlike previous work in which idealized traffic flow modeling techniques were used, the proposed model employed the traffic flow theory–based cell transmission model, yielding a more accurate and realistic representation of traffic flow dynamics. The focus in this paper was on two-lane two-way highways. A case study was presented to illustrate the proposed model.

2.3.2.4 Work of Zheng et al. (2014)

In this paper, Zheng et al. (2014) developed a mathematical decision model associated with traffic assignment. A solution algorithm was also developed to prioritize and schedule work zones in the planning process. The model was designed to measure the mutually interacting traffic impact and delay as a result of work-zone disruptions in the network. Several construction strategies that interest stakeholders were discussed, including daytime and nighttime construction modes, sequencing precedence, and the seasonal variation effect of demand. The method evaluated networkwide traffic delay through a k-shortest path algorithm to analyze drivers' behavior of alternative-route selection. A numerical example was analyzed on a real-world network to demonstrate the applicability of the model for a road construction scheduling problem.

2.3.2.5 Work of Gong and Fan (2016)

In this study, the impacts of scheduling long-term work zone activities were analyzed from the perspective of traffic agencies and jurisdictions. A bi-level genetic algorithm (GA)-based optimization model was formulated to determine the optimal starting date of each work zone project. The upper-level subprogram minimized the total travel time over the entire planning horizon, while the lower-level subprogram was a user equilibrium (UE) problem where all users try to find the route that minimizes their own travel time. The demand, and the number of work zones as well as their durations were assumed to be fixed and given a priori. The proposed GA model was applied to the Sioux Falls network, which has 76 links and 24 origin–destination (O–D) pairs.

2.3.3 Simulation Methods

2.3.3.1 Work of Chien et al. (2002)

To improve computational efficiency, one unique method is to integrate the concept of deterministic queuing theory and the microscopic simulation software to estimate work zone traffic delay. In this study, a method was developed to approximate delays by integrating limited simulation data, obtained from CORSIM and the concept of deterministic queuing model, while various geometric conditions and time-varying traffic distribution were considered. A calibrated and validated simulation model that can reflect work zone traffic operations on a segment of Interstate I-80 in New Jersey was used to generate data for developing the proposed model. The comparison of delays estimated by the deterministic queuing model and the proposed model was conducted, while factors affecting the accuracy of the delay estimates were also discussed. The developed models jointly optimized work-zone lengths and the scheduling of work-zone activities associated with traffic control on two-way two-lane and multiple-lane highway work zones considering both steady and time-varying flows without any detour.

2.3.3.2 Work of Yang et al. (2008)

Yang et al. (2008) proposed such a hybrid approach that integrates a macroscopic analytical model with a microscopic simulation tool to calculate work zone delays. In unsaturated traffic conditions, the CORSIM was used to estimate traffic delay while the deterministic queuing model was employed for the saturated and oversaturated conditions. Nevertheless, microscopic traffic simulation tools (e.g., CORSIM) may not accurately represent driver behavior when drivers are approaching to a work zone. This is because some software simulates a work zone as a prolonged incident blockage. When modeling a lane blockage in CORSIM, the tool assumes that drivers have no knowledge of the approaching blockage and that there is no transition taper. Although other software packages (e.g., INTEGRATION) do a better job of capturing appropriate lane changing behavior in work zones, they do not allow users to modify work zone configurations. In other words, the estimated traffic delays from this software do not vary with different work zone configurations.

2.3.3.3 Work of Meng and Weng (2010)

Meng and Weng (2010) presented a cellular automata model incorporating work zone configuration to model work zone traffic. The randomization probability parameter of the proposed model can characterize driver acceleration–deceleration behavior. Authors consider the randomization probability as a function of traffic flow and work zone configuration that comprises the activity length and transition length other than just a value. They also calibrated the randomization probability from field data. A polynomial regression method was employed to formulate the randomization probability functions in and outside the work zone. A case study was performed to test the proposed model dependent on work zone configuration. Comparison of field data and the proposed model for travel time and traffic delay showed a very close agreement.

2.3.3.4 Work of Chung et al. (2012)

Chung et al. (2012) presented a methodology based on accurate traffic data measures for the estimation of delays. This paper suggested that to accurately estimate congestion impact due to work zones, a dedicated estimation for each work zone is inevitably required. In this paper, a microsimulation model accurately calibrated with a dedicated local traffic survey campaign was presented. The research could be interesting also for practitioners as it was not possible to find any other recent paper in the literature depicting a microsimulation model developed specifically for highways work zones. The objective of this study was to develop a method to quantify nonrecurrent traffic congestion caused by freeway work zones based on traffic flow data and spatial-temporal work zone information. In addition, to demonstrate the efficacy of the developed method, a case study was performed using 1-year historical traffic data and work zone data on major freeways in Korea.

2.3.3.5 Work of Astarita et al. (2014)

Astarita et al. (2014) presented a state-of-the-art on issues relating to the evaluation of delays in highway re-construction sites and an experimental analysis of highway speeds in the presence of work zones. Moreover, a methodology based on traffic simulation was applied for the estimation of the delay suffered by users in motorway sections affected by rebuilding works. This methodology allows one to evaluate traffic conditions for road users. From the first experimental results, it was showed that the best solution for the highway works is the fragmentation, where possible, of the road, so that the average delay suffered by users was lower than the delay suffered in case of more extended work zones. This result based on detailed experimental data confirmed the results of previous scientific works.

2.3.4 Nonparametric Approaches

2.3.4.1 Work of Ghosh-Dastidar and Adeli (2006)

Based on their previous study, in which a new mesoscopic-wavelet model for simulating freeway traffic flow patterns and extracting congestion characteristics was developed, Ghosh-Dastidar and Adeli (2006) presented a multilayer feedforward neural network model (i.e., Levenberg-Marquardt neural network model) for delay and queue length prediction at freeway work zones. The model incorporated the dynamics of a single vehicle in changing traffic flow conditions. The extracted congestion characteristics obtained from the mesoscopic-wavelet model were used in a Levenberg–Marquardt backpropagation (BP) neural network for classifying the traffic flow as free flow, transitional flow, and congested flow with stationary queue. The ANN model was trained using simulated data instead of real data collected from the fields. In the paper, authors demonstrated that the microsimulation model is more accurate than macroscopic models and substantially more efficient than microscopic models.

2.3.4.2 Work of Du et al. (2016, 2017)

Du et al. (2016) developed a multilayer feedforward ANN model to predict work zone delay using the probe-vehicle data (i.e., speeds under normal and work zone conditions) subject to the condition when traffic volume and capacity information are missing. Based on the prediction results of three examples, it was found that the ANN model outperformed analytical models in terms of the accuracy in predicting delays caused by reconstruction projects.

However, the accuracy of that ANN model can be improved if the relationship of approaching traffic volume and work zone capacity can be captured. Hence, Du et al. (2017) developed a new hybrid machine-learning model, integrating an ANN and a Support Vector Machine (SVM) model to predict spatiotemporal delays, subject to road geometry, number of lane closures, and work zone duration in different periods of a day and in the days of a week. The proposed methodology required less data inputs. With that, the delays caused by a work zone on any location within the whole network can be predicted. To this end, tremendous amounts of data from different sources were collected to establish the relationship between the model inputs and outputs. A comparative analysis was conducted, and results indicated that the proposed model outperforms others in terms of the least root mean square error (RMSE). The proposed hybrid model can be used to calculate contractor penalty in terms of cost overruns as well as incentive reward schedule in case of early work competition. Additionally, it can assist work zone planners in determining the best start and end times of a work zone for developing and evaluating traffic mitigation and management plans.

2.4 Summary

A comprehensive review and synthesis of the general information on work zone project in transportation research area and the current and historical research related to work zone optimization problem were presented in this chapter. This is intended to provide a solid reference for and assistance in formulating work zone optimization problem and developing effective improvement strategies for future tasks.

Chapter 3. Optimization Model for Long-Term Work Zone Projects Management

3.1 Introduction

This chapter mainly focuses on developing the optimization model for minimizing the total impacts of work zone projects by optimizing relevant schedules in consideration of elastic demand.

The following sections are organized as follows. Section 3.2 provides a general overview of the basic idea of developing the optimization model for minimizing the total impacts of work zone projects by optimizing relevant schedules. Brief descriptions of several major assumptions are introduced in Section 3.3. Section 3.4 presents the associated notations used in the developed model. Then Section 3.5 shows the model development of the optimization model for minimizing the total impacts of work zone projects by optimizing relevant schedules in consideration of elastic demand. Finally, Section 3.6 concludes this chapter with a summary.

3.2 Overview

In this project, the objective is to minimize the total impacts (i.e., total travel delay [TTD]) induced by long-term work zone activities. In other words, the impacts of scheduling long-term work zone activities are analyzed. A bi-level optimization model is developed, which aims at determining the optimal scheduling of the starting dates of each work zone project. The objective of the upper level sub model is to minimize the TTD induced by long-term work zone projects over the entire planning horizon. On the other hand, the objective lower-level sub model is a traffic assignment problem under user equilibrium (UE) condition in consideration of elastic demand. Moreover, the number of work zones and their durations are assumed to be fixed and given a priori.

3.3 Assumptions for Model development

As introduced, the main purpose of this project is to evaluate the mobility impacts (i.e., TTD) of long-term work zone events and optimize the scheduling of starting dates of work zone projects from the perspective of decision-makers. The major assumptions of the model development can be described as follows: (1) The O–D matrix and the topological information of the transportation network are given (based on which the user equilibrium with elastic demand model can be built); (2) The number of work zones and the project duration of each work zone are also given; (3) Drivers have perfect information on and knowledge of the network (including the status of the network), and they are all homogeneous and rational decision makers (i.e., user equilibrium (UE) assumption).

3.4 Notations Used in the Model

The problem solved by the developed model in this study is basically a network design problem. Generally, the network design problem can be described in terms of ‘nodes’, ‘links’, and ‘route’. The transportation network utilized in this project could be considered as a connected network with N nodes and A links, *G* (*N, A*), which consists of a finite set of N nodes and A links. Note that link $a \in K$, which connects pairs of nodes. To formulate the model, the following notations are used:

- a = arc, or link index, $a = 1,2,\ldots,A$;
- w = OD pair index, $w \in W$;
- B = the subset of A, a set of selected work zone projects on link a, $a \in B \subseteq A$;
- P_w = a set of paths of OD pair w;
- f_p^w = the flow on the p-path of OD pair w $(p \in P_w)$;
- C_a = the basic capacity of link a;
- T_a = the estimated duration of the work zone project (on link a, $a \in B$);
- γ_a = the capacity reduction factor of work zone (on link a), $0 \le \gamma_a \le 1$;
- $\delta_{ap}^w = 1$ if link a is used in path p which connects OD pair w; otherwise $= 0$;
- d_{0w} = a priori demand of OD pair w;
- $t_a(x_a)$ = the travel time on link a given link volume x_a;
- q_a = the project starting date of the work zone;
- T_{max} = the maximum project deadline for all work zone activities.

3.5 Model Development

3.5.1 Model Formation

As mentioned previously, this study proposes a bi-level programming model for determining the starting dates of each work zone project with the consideration of elastic traffic demand. Generally speaking, in the bi-level model, there are two players: the leader and the follower. Hence, there are two sets of decision variables and objectives that correspond to these two levels; and two players try to optimize their own objectives in sequence (Fan and Gurmu, 2014). The bi-level programming has been successfully applied by many research efforts during the past years for various network design problems (Constantin and Florian, 1995; Yang, 1996; Yang and Bell, 1998; Clegg et al, 2001; Zhang and Yang, 2004; Fan and Machemehl, 2011). In this project, the upper-level sub-model is to minimize the total travel delay (in terms of *veh*time*) caused by work zone projects over the entire planning horizon, and the lower-level sub-model is a network user equilibrium with an elastic traffic demand model in terms of generalized travel cost.

The upper-level sub-model that minimizes the total travel delay (TTD) is written as follows in Equations 1-3:

$$\min_{q_a,\, a\in B} \sum_{s=1}^{2^{|B|}} \sum_{a\in A} m_s(q_a)\cdot[t_{sa}(x_{sa}) - t_{0a}]\cdot x_{sa} \qquad (1)$$

Subject to:

$$1 \le q_a \le T_{max} - T_a, a \in B \tag{2}$$

$$\textstyle\sum_{s=1}^{2^{|B|}} m_s(q_a) = T_{max}, a \in B \tag{3}$$

where m_s is the number of days when the network is under status s (s = 1, 2, …, $2^{|B|}$), and s here is supply status of the network corresponding to possible combination of the starting date of each work zone project. t_{0a} is the free flow travel time on link a (a = 1, 2, …, A), and x_{sa} is the solution to the following lower-level sub-model, which represents the UE with elastic O-D demand, as shown in Equations 4-7:

$$\min\left(\textstyle\sum_{a\in A}\int_0^{x_a} C_a(\omega)\, d\omega - \sum_{w\in W}\int_0^{d_w} D_w^{-1}(\omega) d\omega\right) \tag{4}$$

Subject to:

$$x_a = \textstyle\sum_{w\in W}\sum_{p\in P_w} f_p^w \times \delta_{ap}^w\,, a \in A \tag{5}$$

$$\textstyle\sum_{p\in P_w} f_p^w = d_w, w \in W \tag{6}$$

$$f_p^w \ge 0, p \in P_w, w \in W \tag{7}$$

where the $C_a(\omega)$ is the generalized link cost function and employs the most widely used Bureau of Public Roads (BPR) link performance function, as shown in Equation 8:

$$C_a(\omega) = t_{0a}\left[1 + \alpha\left(\frac{\omega}{\gamma_a \times \mathrm{Cap}_a}\right)^{\beta}\right]\ (\gamma_a = 1, \text{if } a \in A\backslash B; = 0.5, \text{if } a \in B) \tag{8}$$

where α and β are empirical coefficients with common values of 0.15 and 0.4, respectively. d_w is the demand function, which can be expressed as below in Equation 9:

$$d_w = d_{0w} \cdot e^{-\Omega_w \times \mu_w}, w \in W \tag{9}$$

where d_{0w} is the fixed demand between O-D pair w that was first proposed by Bar-Gera (2010), μ_w is the minimum generalized travel time between O-D pair w, and Ω_w denotes the demand parameter measuring the impact of the travel time on elastic demand. Note that this relationship used here is adopted from (Chen and Yang, 2004; Recker et al., 2005).

3.5.2 A Simple Example Illustration for *s*

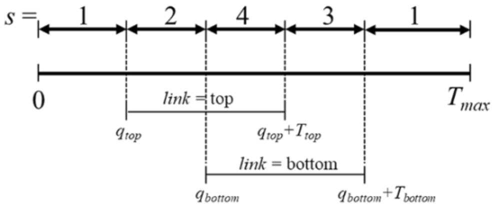
As shown in the Figure 3.1, this simple network contains 4 nodes and 8 links. Links with bold arrows are chosen to be maintained, denoted as the *top link* and *bottom link*. It is assumed that they have the same project duration (i.e., $T_{top} = T_{bottom}$) with corresponding starting dates q_{top} and q_{bottom}. Thus, there will be potentially four different network supply statuses during the entire planning horizon [0, T_{max}], including the basic status without any work zone activities, which are shown in the Figure 1. a to d. Scenario 1, as shown in Figure 1. e, can be explained as follows: (1) periods [0, q_{top}] and [q_{bottom}+T_{bottom}, T_{max}] are basic statuses when s = 1, without any work zone activities; (2) when s = 2, only *top link* (i.e., top work zone in Figure 1) is under maintenance with capacity reduction of *top link* from C_{top} to $C_{top} \cdot \gamma_{top}$ $(0 \leq \gamma_{top} \leq 1)$, and the corresponding period is [q_{top}, q_{bottom}]; (3) when s = 4, both links are work zones of which both link capacities are reduced from C_{top} and C_{bottom} to $C_{top} \cdot \gamma_{top}$ and $C_{bottom} \cdot \gamma_{bottom}$ $(0 \leq \gamma \leq 1)$, and the corresponding period is [$q_{bottom,}$ q_{top}+T_{top}]; (4) when s = 3, it is similar to s = 2, however, only *bottom link* (i.e., bottom work zone in Figure 1) is under maintenance with capacity reduction of link above from C_{bottom} to $C_{bottom} \cdot \gamma_{bottom}$ $(0 \leq \gamma_{bottom} \leq 1)$, and the corresponding period is [q_{top}+T_{top}, $q_{bottom,}$ q_{bottom}+T_{bottom}]. In Scenario 2, as displayed in Figure 3.1. f, both work zone events start at the same date, and as such, only two different network supply status exist (i.e., s = 1 and s = 4).

a. s = 1, no work zone

b. s = 2, only 1 (top) work zone

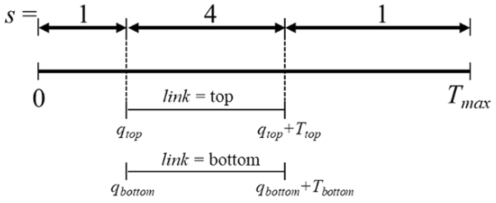
c. s = 3, only 1 (bottom) work zone

d. s = 4, both work zones



e. Scenario 1: a – b – d – c – a

(1) starting with basic status (s=1);
(2) top work zone starts (s=2);
(3) bottom work zone starts and top work zone is unfinished (s=4);
(4) top work zone is finished and bottom work zone continues (s=3);
(5) bottom work zone is finished, system returns to basic status (s=1)



f. Scenario 2: a – d – a

(1) starting with basic status (s=1);
(2) both work zones start at the same time (s=4);
(3) both work zones are finished, system returns to basic status (s=1)

Fig. 3.1. Different Combination of Network Supply Status

In a more complicated and general scenario with $|B|$ work zones, the number of link work zone (s) could possibly be any integer number that falls into the range of $[0, |B|]$ for each single day during $[0, T_{max}]$. Such a situation will yield a total number of $2^{|B|}$ potential network supply status.

3.6 Summary

The idea of developing optimization models for minimizing the total impacts of work zone projects by optimizing relevant schedules in consideration of elastic demand. Major assumptions for developing the bi-level optimization model are briefly introduced. The bi-level optimization model is further developed with detailed explanations about its objectives and the associating constraints.

Chapter 4. Model Solution Methodology

4.1 Introduction

The chapter presents model solution methodology used to solve the developed optimization model in this study, which is the genetic algorithm (GA).

The following sections are organized as follows. Section 4.2 describes GA with the associating procedure. Section 4.3 provides the key parameter setup in GA for the numerical study. Then Section 4.4 concludes this chapter with a summary.

4.2 Genetic Algorithm (GA)

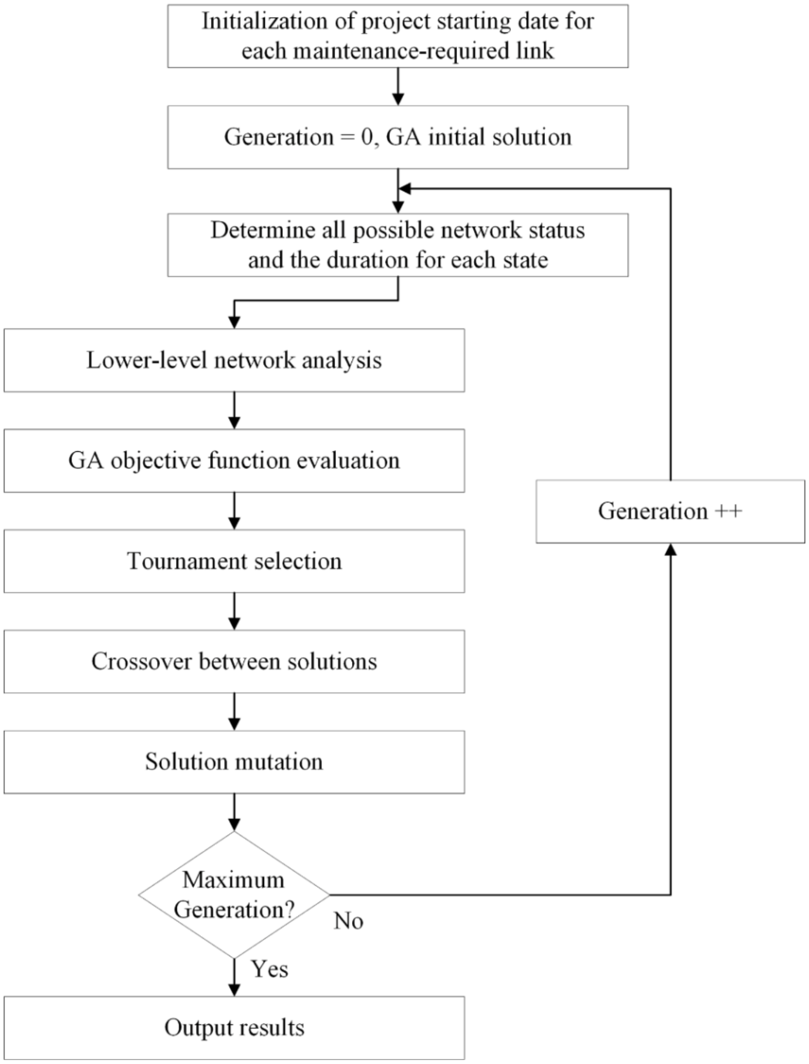


Fig. 4.1. Flow Chart of the GA-based Solution Framework

The Figure 4.1 shows the flow chart of the whole GA process for the stated problem. It is important to note that the time for finding the optimal long-term highway work zone scheduling (i.e., the combination of starting date for each work zone project) will increase remarkably when $|B|$ increases. Hence it is worthwhile to design an efficient solution method for solving the bi-level optimization model that has been built for the long-term highway work zone scheduling problem. Inspired by the evolutionary ideas of natural selection and genetics (Holland, 1975; Goldberg, 1989; Michalewicz, 1999), the genetic algorithm (GA) has already been a well-known type of adaptive heuristic search algorithm. Many research efforts have proven that GA can provide a robust and near-optimal solution within a reasonable amount of time. There are several intermediate steps within the GA process as well. For instance, the lower level network analysis involves the determination of the link flows and O-D demands which will be used as input to the upper level sub-model, by applying the Frank-Wolfe (FW) algorithm.

4.3 Parameter Setup in GA

Parameters inherent in the GA algorithms need to be selected carefully; otherwise they might have some effects on the optimal solution. Some research work has been done to determine the inherent parameters in the GA algorithm. Based on (Chen and Yang, 2004; Recker, et al., 2005), the following parameters are chosen in this study for numerical analysis: population size, 64; maximum number of generations, 200, crossover probability, 0.7; mutation probability, 0.05; and elastic demand parameter (Ω_w), 0.02.

4.4 Summary

This chapter presents the detail information about solution methodology for the developed model in this research, which is the genetic algorithm (GA). Meanwhile, the key parameters for implementing the GA are also provided.

Chapter 5. Numerical Example

5.1 Introduction

As described in both Chapters 3 and 4, one model has been developed aiming at minimizing the total impacts of work zone projects by optimizing relevant schedules in consideration of elastic demand, along with the proposed GA solution methodology. This chapter focuses on the numerical results of the developed model. Numerical results of the case study based on the Sioux Fall example network are analyzed and presented in detail.

The remainder of this chapter is organized as follows: Section 5.2 provides the description of the Sioux Fall example network in the case study. Section 5.3 give detailed results and analysis of the model. Then, Section 5.4 presents the sensitivity analysis for the elastic demand parameter. Finally, a summary concludes this chapter in Section 5.5.

5.2 Description of Example Network

As shown in Figure 5.1, the Sioux Falls network is considered as the example network in this study, which consists of 24 travel demand zones, 76 links and 576 O-D pairs. Network data used in this study are adopted from (LeBlanc, Morlok and Pierskalla, 1975). The data could be accessed from the repository of the Transportation Networks for Research Core Team. It should be worth mentioning that the input data for the model only include the files of “SiouxFalls_net” and “SiouxFalls_trips”, which show the ease of use of the proposed model. Meanwhile, (Bar-Gera, 2010) found the Sioux Falls user equilibrium solution by applying the quadratic BPR cost functions, which could be used for cross-checking results. This solution corresponds to the minimum generalized travel time between O-D pair w (i.e., μ_w).

Adopted form (Gong and Fan, 2016), 5 links in the example network are selected to be maintained as the work zone projects, which are displayed in red lines in Figure 5.1 (i.e., $B = \{12, 36, 41, 56, 68\}$). The corresponding durations for these five selected work zones are $T_a = [90, 180, 270, 360, 450]$. For convenience, the capacity reduction factor for all the selected work zones is assumed to be 0.5, which means the capacity of the road will be reduced by a half due to work zone events (i.e., $\gamma_a = 0.5$).

Based on all the assumptions above, the proposed GA procedure is performed via MATLAB software package.

Table 5.1 O-D Demand Table for Sioux Falls Network

OD/Flow	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
1	0	100	100	500	200	300	500	800	500	1300	500	200	500	300	500	500	400	100	300	300	100	400	300	100
2	100	0	100	200	100	400	200	400	200	600	200	100	300	100	100	400	200	0	100	100	0	100	0	0
3	100	100	0	200	100	300	100	200	100	300	300	200	100	100	100	200	100	0	0	0	0	100	100	0
4	500	200	200	0	500	400	400	700	700	1200	1400	600	600	500	500	800	500	100	200	300	200	400	500	200
5	200	100	100	500	0	200	200	500	800	1000	500	200	200	100	200	500	200	0	100	100	100	200	100	0
6	300	400	300	400	200	0	400	800	400	800	400	200	200	100	200	900	500	100	200	300	100	200	100	100
7	500	200	100	400	200	400	0	1000	600	1900	500	700	400	200	500	1400	1000	200	400	500	200	500	200	100
8	800	400	200	700	500	800	1000	0	800	1600	800	600	600	400	600	2200	1400	300	700	900	400	500	300	200
9	500	200	100	700	800	400	600	800	0	2800	1400	600	600	600	900	1400	900	200	400	600	300	700	500	200
10	1300	600	300	1200	1000	800	1900	1600	2800	0	4000	2000	1900	2100	4000	4400	3900	700	1800	2500	1200	2600	1800	800
11	500	200	300	1500	500	400	500	800	1400	3900	0	1400	1000	1600	1400	1400	1000	100	400	600	400	1100	1300	600
12	200	100	200	600	200	200	700	600	600	2000	1400	0	1300	700	700	700	600	200	300	400	300	700	700	500
13	500	300	100	600	200	200	400	600	600	1900	1000	1300	0	600	700	600	500	100	300	600	600	1300	800	800
14	300	100	100	500	100	100	200	400	600	2100	1600	700	600	0	1300	700	700	100	300	500	400	1200	1100	400
15	500	100	100	500	200	200	500	600	1000	4000	1400	700	700	1300	0	1200	1500	200	800	1100	800	2600	1000	400
16	500	400	200	800	500	900	1400	2200	1400	4400	1400	700	600	700	1200	0	2800	500	1300	1600	600	1200	500	300
17	400	200	100	500	200	500	1000	1400	900	3900	1000	600	500	700	1500	2800	0	600	1700	1700	600	1700	600	300
18	100	0	0	100	0	100	200	300	200	700	200	200	100	100	200	500	600	0	300	400	100	300	100	0
19	300	100	0	200	100	200	400	700	400	1800	400	300	300	300	800	1300	1700	300	0	1200	400	1200	300	100
20	300	100	0	300	100	300	500	900	600	2500	600	500	600	500	1100	1600	1700	400	1200	0	1200	2400	700	400
21	100	0	0	200	100	100	200	400	300	1200	400	300	600	400	800	600	600	100	400	1200	0	1800	700	500
22	400	100	100	400	200	200	500	500	700	2600	1100	700	1300	1200	2600	1200	1700	300	1200	2400	1800	0	2100	1100
23	300	0	100	500	100	100	200	300	500	1800	1300	700	800	1100	1000	500	600	100	300	700	700	2100	0	700
24	100	0	0	200	0	100	100	200	200	800	600	500	700	400	400	300	300	0	100	400	500	1100	700	0

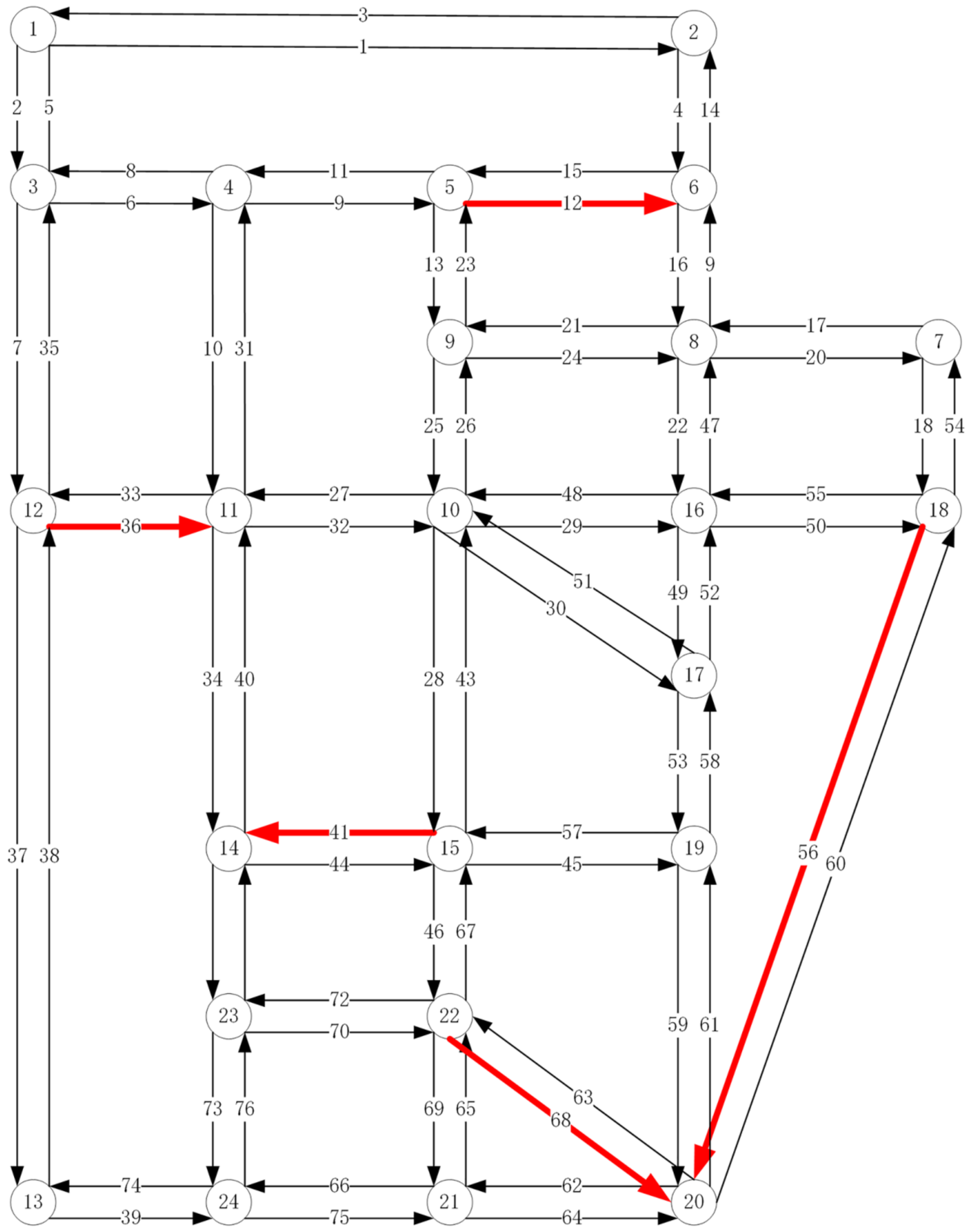


Fig. 5.1. Sioux Falls Test Network (Links in Red Denote Presumed Work Zones)

5.3 Numerical Results of the Developed Bi-level Model

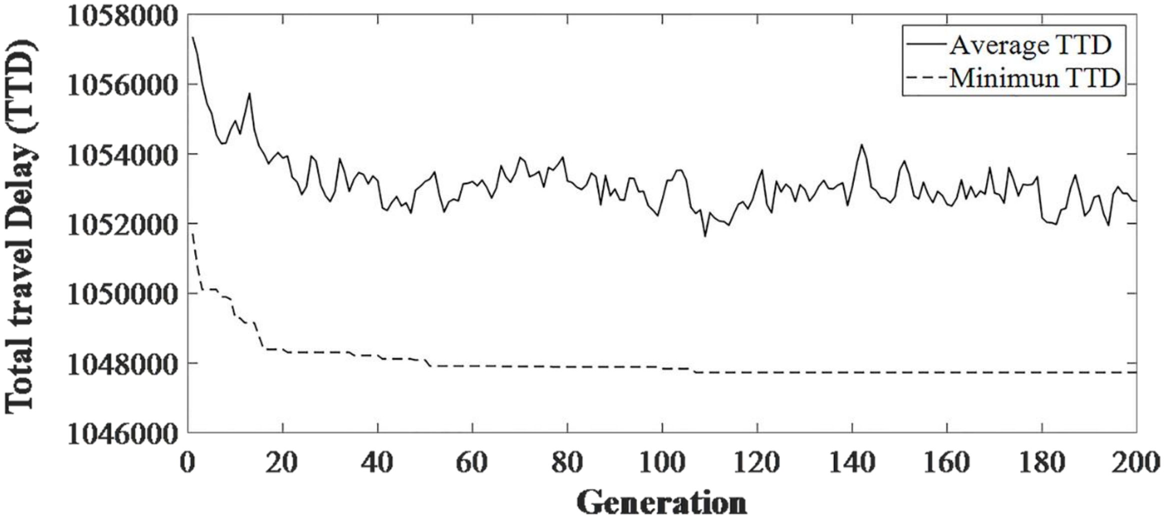


Fig. 5.2. Total Travel Delays over Generations

Figure 5.2 shows the average and minimum total travel delays (TTDs) over generations of the proposed GA algorithm. It can be seen that both TTDs decrease very rapidly during the first 20 generations of the GA algorithm; after the 20th generation, the solutions gradually level off with a certain level of variations in the average TTD. Such variations could be explained as results of the mutation operations in the GA algorithm. This illustrates that the proposed GA-based framework is capable of solving the multiple work zone starting date optimization problem with elastic demand and can provide efficient and stable solutions.

Table 5.2 Analysis of the TTD for Each Network Status and Examples of Optimal Solution

Status ID	**Combination of maintenance required roads**					**# of roads maintained**	**TTD**	**% change with respect to the uninterrupted network**	**Rank**	**Example of one optimal solution**	
										Duration of each network status	**Starting date of each work zone**
1	0	0	0	0	0	0	1011160	0.00%	32	31	
2	12	0	0	0	0	1	1029438	1.81%	29	24	**23**
3	0	36	0	0	0	1	1036381	2.49%	28	0	**167**
4	0	0	41	0	0	1	1043886	3.24%	25	0	**47**
5	0	0	0	56	0	1	1022402	1.11%	31	0	**77**
6	0	0	0	0	68	1	1028757	1.74%	30	274	**261**
7	12	36	0	0	0	2	1057240	4.56%	19	0	
8	12	0	41	0	0	2	1059970	4.83%	16	30	
9	12	0	0	56	0	2	1040812	2.93%	26	0	
10	12	0	0	0	68	2	1047571	3.60%	23	0	
11	0	36	41	0	0	2	1057192	4.55%	20	0	
12	0	36	0	56	0	2	1046221	3.47%	24	0	
13	0	36	0	0	68	2	1055943	4.43%	22	0	
14	0	0	41	56	0	2	1056942	4.53%	21	53	

Status ID	**Combination of maintenance required roads**					**# of roads maintained**	**TTD**	**% change with respect to the uninterrupted network**	**Rank**	**Example of one optimal solution**	
										Duration of each network status	**Starting date of each work zone**
15	0	0	41	0	68	2	1059945	4.82%	17	0	
16	0	0	0	56	68	2	1040733	2.92%	27	90	
17	12	36	41	0	0	3	1077947	6.61%	7	0	
18	12	36	0	56	0	3	1066219	5.45%	14	0	
19	12	36	0	0	68	3	1075379	6.35%	9	0	
20	12	0	41	56	0	3	1072375	6.05%	11	37	
21	12	0	41	0	68	3	1076019	6.41%	8	0	
22	12	0	0	56	68	3	1059684	4.80%	18	0	
23	0	36	41	56	0	3	1067563	5.58%	13	94	
24	0	36	41	0	68	3	1075364	6.35%	10	0	
25	0	36	0	56	68	3	1064987	5.32%	15	30	
26	0	0	41	56	68	3	1071220	5.94%	12	0	
27	12	36	41	56	0	4	1090138	7.81%	3	0	
28	12	36	41	0	68	4	1097155	8.50%	2	0	
29	12	36	0	56	68	4	1087261	7.53%	4	0	
30	12	0	41	56	68	4	1086747	7.48%	6	0	
31	0	36	41	56	68	4	1086851	7.49%	5	57	
32	12	36	41	56	68	5	1108368	9.61%	1	0	
										q_a = [23, 167, 47, 77, 261] ***TTD* = 753343866** **Average *TTD* = 1046310**	

Table 5.1 exhibits all the specific combinations of work zone links corresponding to each network status associated with the TTD values. The "Rank" column shows the rankings of TTD for each network status. The impacts of each work zone combination are also examined and displayed as the percentage changes compared to the uninterrupted network status. It is noticeable that the combinations "4" and "15" have highest impacts compared to other combinations within their sub-groups, respectively (i.e., one work zone combination and two work zone combination, respectively). Moreover, "4" even has a higher impact than combinations "9" and "16", and a similar result is obtained with "15" when it compares to combination "22". Also, compared to (Gong and Fan, 2016), the results of TTDs are less, and this might be the reason that the reduction in traffic volumes in the whole network due to the consideration of elastic demand.

One example of the optimal solutions is also given in Table 5.1. It should be pointed out that in the proposed GA, the duration of each network status is actually determined by the relative gap between the starting dates of different work zone events, other than the absolute starting date of each project within the whole planning horizon (discussions can be referred to (Gong and Fan, 2016)). Thus, the proposed GA-based algorithm could find the near optimal solution very quickly.

5.4 Effect of Elastic Demand Parameter (Ω_w)

As discussed previously, the demand function used in this study is shown in Equation 9 in the Section 3.5. It is hypothesized that how much TTD are generated might greatly depend upon how traffic flows change in the elastic demand scenario. Since the elastic demand parameter (Ω_w) is the key to connect the traffic demand with travel time, it would be worthwhile to conduct the sensitivity analysis and evaluate the impacts of this parameter.

Table 5.3 Demand Parameter Sensitivity Analysis

Demand parameter value (Ω_w)	TTD (optimal solution)	Uninterrupted network total traffic volume
0.001	2837300479	854592
0.002	2545944476	834460
0.005	1938199211	784795
0.01	1368616643	720700
0.02	753343866	632193
0.05	250892088	462084
0.1	49520431	293889
0.2	7205951	139073
0.5	10440	26130

Table 5.2 shows the results of the sensitivity analysis of the demand parameter. As the elastic demand parameter increases, the TTD in the optimal solution also decreases. Since as the elastic demand parameter increases, travelers become more sensitive to the generalized travel time, and therefore, it is likely that more travelers may forego their trips or switch to alternative modes. As a result, less demand is produced. As shown in the Table 5.2, such phenomenon is also supported by the total traffic volume under the status of uninterrupted network (corresponding to “status 1” in Table 5.1). Note that changes under other work zone combinations are examined and the same trends are also obtained. This clearly highlights the importance of considering the impact of elastic demand parameter when planning for the starting date of each work zone event to minimize the total travel delay due to the long-term work zone activities.

5.5 Summary

This chapter presents detailed numerical results of the optimization model aiming at minimizing the total impacts of work zone projects by optimizing relevant schedules in consideration of elastic demand that are developed and applied in the case study of the Sioux Fall example network. In addition to the numerical results, the sensitivity analysis of the elastic demand parameter in the model is also provided to demonstrate the capacity of the proposed model.

Chapter 6. Summary and Conclusions

6.1 Introduction

With the rapid development of the transportation system, an increasing number of work zone projects come with the needs of new construction and regular maintenance related investments. Therefore, the negative impacts of the work zone projects on the traffic in the transportation network may be inevitable and can cause many issues socially, economically and environmentally. In this context, many studies had been done to explore such impacts. However, it is still lacking in performance measures for assessing congestion under special events including the presence of work zones. Despite such absence of metrics which can be used for evaluation, attention should also be paid to minimize the impacts of relevant work zone activities.

In the meantime, few studies have focused on modeling the impact of the work zone activities on the transportation network itself over the whole planning horizon before considering other detailed issues. Furthermore, it would also be more realistic to consider elastic demand in long-run planning in order to take such user behavior changes into consideration for the highway work zone scheduling optimization problem.

The primary objective of this research is to develop and recommend a macroscopic optimization model to evaluate the mobility impacts of long-term work zone events and optimize the scheduling of starting dates of work zone projects. A bi-level optimization model is built which is later solved by the proposed GA algorithm. Then, Sioux Falls network is used as case study to test the proposed GA-based model. The impacts of all work zone combinations are examined and the sensitivity analysis of the elastic demand parameter (Ω_w) is also conducted.

The rest of this chapter is organized as follows. In section 6.2, major works of this report are reviewed and the capability of the model is discussed. Section 6.3 presents a brief discussion of the limitations of the current approaches and possible directions for further research are also given.

6.2 Summary and Conclusions

As presented throughout the research, this report has discussed the development of the optimization model for long-term work zone events management to minimize the overall impacts of such events. A comprehensive review has been conducted on the current state-of-art and state-of-practice of the highway work zone scheduling optimization problem and related studies nationwide and worldwide, including short-term work zone management, long-term work zone management, etc. In this study, a bi-level optimization model is built which is later solved by the proposed GA algorithm. Sioux Falls network is then used as case study to test the proposed GA-based model. The impacts of all work zone combinations are examined and the sensitivity analysis of the elastic demand parameter (Ω_w) is also conducted.

The objective is to minimize the total impacts (i.e., total travel delay [TTD]) induced by long-term work zone activities with the consideration of elastic traffic demand. In other words, the impacts of scheduling long-term work zone activities are analyzed. A bi-level optimization model is developed, which aims at determining the optimal scheduling of the starting dates of each work zone project. The objective of the upper level sub model is to minimize the TTD induced by long-term work zone projects over the entire planning horizon. On the other hand, the objective lower-level sub model is a traffic assignment problem under user equilibrium (UE) condition with the consideration of elastic demand. Three major assumptions were made and could be described as follows: (1) The O–D matrix and the topological information on the transportation network are given (based on which the user equilibrium with elastic demand model can be built); (2) The number of work zones and the project duration of each work zone are also given; (3) Drivers have perfect information on and knowledge of the network (including the status of the network), and they are all homogeneous and rational decision makers (i.e., user equilibrium (UE) assumption). The proposed model is programmed and solved by using MATLAB.

Additionally, a case study has been conducted by using the Sioux Falls network. Five routes were selected to be maintained as the work zone projects with thirty-two different scenarios. The proposed bi-level optimization model was applied to the example network and solved by the proposed GA. Optimal results on TTDs and the starting dates of each potential work zone event were obtained for all work zone combinations. Additionally, the sensitivity analysis of the elastic demand parameter (Ω_w) was also conducted to explore its impacts on TTD and traffic demands.

Numerical results implied that the proposed model and algorithm is capable of providing near-optimal solutions for the long-term work zone scheduling problem with elastic demand at a network level during the entire planning horizon. The result of sensitivity analysis indicated that it is important to consider the impact of elastic demand parameter, since the fact that some of the route users would rather switch to alternative transportation modes to complete their trips or daily commutes since a larger Ω_w indicates more sensitivity to the generalized travel time of the travelers.

6.3 Directions for Future Research

In this section, some of the limitations of the proposed optimization model in this research are presented and directions for further research are also discussed.

Since this research mainly focuses on the impacts of work zone from the perspective of traffic agencies and jurisdictions, concerns about other aspects (such as the maintenance cost to contractors) are not considered in this study. Meanwhile, the proposed method is not able to capture the characteristics of how traffic flow evolves with time (i.e., short periods); rather it intends to solve the long-term work zone scheduling problem during the planning stage. Thus, future research may consider bringing other benefits into the model and combining both long-term and short-term scheduling planning together. Finally, future research can also be directed toward examining the heterogeneity across drivers and applying the dynamic traffic assignment (DTA) to solve the highway work zone scheduling optimization problem.

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