ABSTRACT

OPTIMIZING WORK ZONE SCHEDULES CONSIDERING TRAFFIC DIVERSION WITH ARTIFICIAL BEE COLONY ALGORITHM

by
Celina Semaan

Highway maintenance activities often decrease roadway capacity and intrude traffic movements. The need to finish the project on time and under a specific budget while minimizing the traffic congestion and complying with the emission standards requires an appropriate work zone schedule optimization. The objective of this research is to improve the efficiency of work zone activities and minimize the total project cost including maintenance, user, and emission cost.

While previous studies investigated the work zone optimization problem, they did not consider the implementation of emission standards nor applied a green diversion strategy. This dissertation analyzes the optimization of work zone schedule considering a discrete time-cost relation and a time-dependent traffic flow. The objective function is to minimize the total cost including the emission cost under various realistic constraints. Moreover, the effect of traffic diversion as a congestion mitigation strategy is evaluated under the User Equilibrium (UE) and System Optimum (SO) strategies.

In the developed model many variables interrelate to create a combinatorial optimization problem that is difficult to solve analytically (e.g., the length and duration of work zones, the productivity of the crew, etc.). Consequently, an Artificial Bee Colony (ABC) algorithm is used as a tool to optimize the work zone schedule and minimize the total cost under multiple constraints such as maximum project duration and budget constraint. Traffic diversion is optimized by finding the best diversion rate into the alternative route while considering the delay cost and emission cost on the mainline and alternative route. The emission rates caused by work zone activities and

diverted traffic are estimated using the state-of-the-art Motor Vehicle Emission Simulator (MOVES3) developed by the Environmental Protection Agency (EPA). Consequently, two projects are created that illustrate the conditions of the roadways without and during the work zone activities.

Two case studies are presented in this research: Case A and Case B. The purpose of Case A is to validate the applicability of the model whereas Case B proves the ability to optimize real-life work zone projects using different databases under Tier 3 federal emission standards. Sensitivity analyses are conducted to explore the relationships between the model parameters and the decision variables. The results prove the efficiency of ABC in solving the work zone optimization problem and the importance of considering the vehicle emissions during work zone activities.

The developed model can assist transportation agencies in alleviating the congestion and minimizing the total cost considering vehicle emissions and two different traffic diversion strategies. Additionally, the model offers flexibility to investigate the effect of various strategies on the optimal work zone schedule. Hence, the developed model can be applied to evaluate and optimize the work zone schedule in case of a tight schedule or the need to finish the work before a certain event. The model can also suggest a work zone schedule that complies with the federal emission standards.

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Two Roads Diverged in a Wood and I- I Took the One Less Traveled by, and that Made All the Difference - '*Robert Frost'*

إلى عائلتي الحبيبة سمير، سميرة، وسامر سمعان

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LIST OF SYMBOLS

$AADT$	Average Annual Daily Traffic (vpd)
A_i	Random Number from 1 to m Associated with Work Zone *i*
B	Maintenance Budget ($)
C'_{EM}	Emission Cost under Normal Conditions ($/project)
C'_{EMi}	Emission Cost under Normal Conditions of Work Zone *i* ($/work zone)
c_0	Road Capacity without Work Zone (veh/hr)
C_A	Accident Cost ($/project)
c_a	Capacity of Alternative Route (veh/hr)
C_{Ai}	Accident Cost ($/work zone)
C_D	User Delay Cost ($/project)
C_{Di}	User Delay Cost of Work Zone *i* ($/work zone)
C_E	Emission Cost Caused by Work Zone ($/project)
C_{Ei}	Emission Cost Caused by Work Zone *i* ($/work zone)
C_{EM}	Emission Cost under Work Zone Conditions ($/project)
C_{EMi}	Emission Cost under Work Zone Conditions of Work Zone *i* ($/work zone)
C_I	Idling Cost ($/project)
C_{Ii}	Idling Cost of Work Zone *i* ($/work zone)
C_M	Maintenance Cost ($/project)
C_{Mi}	Maintenance Cost of Work Zone *i* ($/work zone)
C_T	Total Cost ($)
C_U	Road User Cost ($/project)
C_{Ui}	Road User Cost of Work Zone *i* ($/work zone)
C_V	Vehicle Operating Cost ($/project)
C_{Vi}	Vehicle Operating Cost of Work Zone *i* ($/work zone)
c_w	Road Capacity with Work Zone (veh/hr)
D_B	Minimum Duration of Work Break (hr)
d_i	Duration of Work Zone *i* other than Minimum Duration (hr)

D_i	Duration of Work Zone *i* (hr)
D_m	Minimum Duration of Work zone or Work Break (hr)
D_M	Moving Delay (veh-hr)
D_Q	Queuing Delay (veh-hr)
e	Index of Vehicle Emission Types
E_i	End Time of Work Zone *i* (hr)
j	Index of Time Interval (15 minutes)
k	Index of Production Options for Different Crews
L	Summation of all work zone length (km)
l_a	Length of entrance ramp (km)
l_e	Length of exit ramp (km)
l_i^k	Length of Work Zone *i* under Production Option *k*
l_m	Minimum Length of Work Zone (km)
l_T	Total Length of Tapers and Buffers of a Work Zone (km)
l_v, u_v	Lower and Upper Bounds of ABC decision variable *v*
m	Number of Work Zones
n	Number of Intervals
p	Weight Factor of the User Delay Cost
P_i	Probability of Work Zone *i* used in Random Generation Method
PL	Total Project Length (km)
q_1^j	Queue Length at the Start of Interval *j* (veh)
q_2^j	Queue Length at the End of Interval *j* (veh)
r	Number of Emission Types
r_a	Accident Rate
R_b	Number of Work Breaks (work breaks)
R_{ei}	Rate of Emission Type e of Work Zone *i*
S_i	Start Time of Work Zone *i* (hr)
SL	Solution List
T	Duration of a Time Interval
t_1, t_4	Time at which the Queue Starts (Figure 3.5)
t_2, t_5	Time at which the Queue Starts to Dissipate Initially (Figure 3.5)

$t_{3,}R$	Time of which the Queue Discharges (Figure 3.5)
T_m	Minimum Duration of the Project (hr)
T_M	Maximum Project Duration (hr)
v	Value of Road User's Time ($/veh-hr)
v_a	Average Cost per Accident ($/accident)
V_a	Average Traffic Speed without Work Zone (km/hr)
V_A	Average Speed on Alternative Route (km/hr)
V_{ei}	Average Cost for Emission Type *e* in Work Zone *i* ($/ton)
V_d	Average Idling Cost per Hour ($/hr)
V_{fv}	Neighbor Food Source (new possible solution)
v_o	Average Vehicle Operating Cost ($/veh-hr)
V_r	Average Speed on Ramps (km/hr)
V_w	Average Traffic Speed within Work Zone (km/hr)
X_{fv}	A food Source (a possible solution to the problem)
z_1	Work Zone Setup Cost ($/zone)
z_2	Unit Maintenance Cost per lane kilometer ($/lane-km)
z_3	Fixed Total Time of Setting and Removing a Work Zone ($/zone)
z_4	Unit Production Time per Lane Kilometer (hr/lane-km)

CHAPTER 1

INTRODUCTION

1.1 Background

In general, an efficient roadway network improves the overall accessibility and economic development in a country. Statistics show that around $14 trillion in services and goods are carried from the U.S. to internal or international destinations and 87% of them are transported using various levels of U.S. highways (Geddes and Madison, 2017). In 2014, $165 billion were invested on state and local U.S. highways for operation and maintenance purposes (Geddes and Madison, 2017). Funds invested to upgrade the quality of the U.S. public roads allow industries to ship their goods at a cheaper cost and a more reliable delivery schedule. Collectively, this leads to fewer stationary inventories, less storage costs, and higher service efficiency. Investment in highway networks also creates new job opportunities for managers, laborers, manufacturers and other supplier companies (Geddes and Madison, 2017). Therefore, the transportation network is a critical factor of the U.S. economic growth (Ivanova and Masarova, 2013).

Traffic demand has increased over the years resulting in a reduction of highway efficiency and an increase in the maintenance needs. During maintenance projects, lane closures instigate traffic delays leading to additional vehicle operating cost and user costs. As a solution, the FHWA report (FHWA, 2010) used tools to estimate work zone delays and user costs to elude the increasing effect of maintenance projects on private and communal entities. Rescheduling work zone activities to off-peak periods can also help eliminate the effect of work zone projects on traffic flow. However, this could expand the maintenance project duration due to periodical changes in the projects' schedule.

In addition to increased motorists' delays, greenhouse gases emissions and fuel consumption in the U.S. have increased by 84% and 86% on multi-lane highways and freeways, respectively (Wang and Michael, 2018). Statistics show that 14% of CO_2 emissions per year and 24% of global CO_2 emissions are caused by transportation (Wang and Ge, 2020). In relation to greenhouse gases, the transportation emissions exceed industrial emissions which makes the U.S. rank the highest in transportation emissions (Wang and Ge, 2020).

To reduce the impact on traffic, work zone projects may be scheduled over short-term activities. Many factors interrelate to affect the overall optimization of short-term projects such as the productivity of maintenance crew, the traffic volume, and the schedule time. Moreover, most work activities are subject to project deadlines and specific budget limitations. Therefore, the optimization of the work zone schedule is highly recommended to mitigate the effect of the work zone on users and reduce the total cost of the project.

Traffic diversion helps with mitigating the congestion by diverting the traffic demand into alternative routes. Consequently, the delay cost imposed on users on the mainline may decrease. While traffic diversion generally decreases the travel time, the User Equilibrium (UE) diversion strategy aims at minimizing the individual travel time per individual. The System Optimum (SO) strategy, on the other hand, aims at decreasing the total impedance in the system, hence considerably reducing the total travel time of the studied highway system (Jahn et al., 2005).

The objective of this dissertation is to develop a model that can jointly evaluate the time-dependent traffic diversion and minimize the total cost of the maintenance projects including agency, user, and emission costs. Due to the complicated combinatorial nature of the work zone optimization problem, an efficient algorithm that is able to find a near optimal solution of the decision variables is highly required. The Artificial Bee Colony (ABC) is a global optimization algorithm proposed to solve numerical problems under constrained conditions in a flexible, simple, and robust. Its performance is inspired by the intelligent foraging behavior of honeybee swarms and limited to only a few control parameters compared to other metaheuristics. Each artificial bee of the swarm has a specific mission to find an optimal solution.

In this dissertation, the ABC is utilized as a solution algorithm to the work zone optimization problem due to its efficient performance and capability to outpace other metaheuristic algorithms in finding optimal solutions (Karaboga and Basturk, 2007; Kalayci and Gupta, 2013; Panda and Swamy, 2018; Sharma et al., 2019). Hence, ABC provides higher accuracy with better solutions to the same problem. Moreover, ABC offers near optimal solutions with less time, cost, and solution space (Wahib et al., 2015). With that, the ABC is expected to be used effectively to solve work zone optimization problems resulting in less total cost and higher efficiency.

1.2 Problem Statement

In order to reduce the maintenance cost and commuters' delays, it is required to optimize the time window and duration at which each work zone is performed. Normally, scheduling maintenance projects during nighttime, off-peak periods, and weekends minimizes the impact of work zones on motorists. However, during nighttime the cost of the work zones might be higher due to higher labor cost, proper site lighting and traffic control management (Tang, 2008). In addition to the increased delays, the additional vehicle operation time during work zones leads to an increase in fuel consumption; hence, an increase in vehicle emissions and air pollution (Zarin and Ardekani, 2015).

Typically, the major goal of transportation agencies is to minimize the maintenance cost of work zones. Other goals resemble the decrease in construction time and the ease of the impact of work zones on users. However, a compressed schedule requires more laborers and equipment, which increases the project cost.

When properly executed, traffic diversion could be an efficient management plan to decrease the traffic flow into the work zone. Two diversion techniques can be used to optimize the traffic diversion rates: (1) The UE strategy which aims at reducing the individual travel time; (2) The SO strategy which aims at decreasing the total travel time in the system (Jahn et al., 2005).

In addition, the transportation sector being the highest emitter of greenhouse gases, air pollutants contribute to the formation of ground level ozone which is the source of serious health problems such as asthma and cardiovascular damage (Baghestani et al., 2020). Moreover, studies have linked the fine particulate matters ($PM_{2.5}$) caused by the vehicles' exhaust to 361,000 and 385,000 death cases worldwide in 2010 and 2015, respectively. It is worth mentioning that the main precursor to both $PM_{2.5}$ and ozone levels is the nitrogen oxide (NO_x). For this reason, federal standards such as Tier 3 target the reduction of NO_x emissions through a plan that extends to the year 2025 (Vijayaraghavan et al., 2016).

Many parameters interrelate during the work zone optimization process such the total number of activities with their starting times, ending times, and lengths, the efficiency of the working crew, the impact on the traffic, and the impact on the vehicle emissions. Due to the abovementioned interests, the optimization process should thoroughly investigate the different components of the total cost, including users, agency, and environmental costs. Therefore, an efficient model that optimizes the work zone length and schedule, taking into consideration agencies, users, and environmental benefits is greatly desirable.

1.3 Objectives and Work Scope

Taking into account the above-mentioned concerns, the objective of this research is to improve the efficiency of work zone activities by minimizing the total cost taking into consideration the traffic diversion. The developed model uses Artificial Bee Colony algorithm to optimize work zone length and schedule and minimize the total cost including agency, user, and environmental costs. Moreover, the scope of work of this research involves the development of an optimization model taking into consideration a discrete time-cost relationship and evaluating a time-varying traffic demand and diversion. The work scope of this research includes:

- Generate an Artificial Bee Colony algorithm that optimizes the work zone schedules including the work zone numbers, lengths, and productivity of the crew,

- Incorporate the emission cost component into the total cost function. Consequently, the objective function of the model is to minimize the total cost of the project including agency, user, and environmental costs,

- Integrate MOVES3 emission model results to generate emission rates with and without work zone conditions into the ABC algorithm to optimize the work zone schedules accordingly, and

- Implement the User Equilibrium (UE) and evaluate the System Optimum (SO) strategies to perform a time-dependent traffic diversion and redirect the traffic from mainline to alternative routes.

1.4 Dissertation Organization

This dissertation is organized into six chapters. Chapter 1 includes the background and problem statement. It highlights the need to develop a model that optimizes work zone schedule under minimized total cost conditions. Chapter 1 also discusses the objective and the work scope of the research. Chapter 2 represents a thorough literature review of previous efforts in work zone optimization and all associated parameters. Chapter 3 covers the cost factors affecting the work zone activities and includes a formulation of the objective function with a traffic diversion methodology. In Chapter 4, an Artificial Bee Colony (ABC) algorithm is generated to optimize the work zone activities. Chapter 5 represents two case studies with a detailed application of the model: Case A and Case B. Finally, Chapter 6 includes conclusions along with suggestions for future studies.

CHAPTER 2

LITERATURE REVIEW

Many studies have been conducted in order to ease the effect of work maintenance on traffic flow. A thorough literature review analyzing the previous studies on optimizing work zone length and schedule as well as available solution algorithms has been performed and the results are presented herein. The previous emission models are also summarized to enumerate the possible ways of calculating the vehicle emission rates. This literature review covers three major parts: Work Zone Optimization, Traffic Management and Operations, and Optimization Algorithms.

2.1 Work Zone Optimization

In the past two decades, many studies have been performed in order to optimize work zone length and schedule. Their objective functions were to minimize the total work zone cost (e.g., user cost, agency cost, vehicle operating cost, etc.) and/or to minimize the total delay incurred by the work zone.

2.1.1 Work Zone Optimization Models

Several studies have suggested dividing the total length of the project into smaller segments to be executed separately. This allows for breaks to be incorporated into the work plan. The objective function of the work zone optimization is usually to minimize the effect of work zone maintenance projects on user delay; hence, decreases the associated delay cost. In addition, the optimization serves at minimizing the total costs associated with the projects.

McCoy et al. (1980) used data collected in Nebraska from 1979 to develop a model that optimizes work zone length in construction and maintenance zones for a four-lane highway. The objective function of this model was to minimize total cost including delay cost caused by speed reduction, vehicle operating cost, accident cost and traffic management costs. Accident costs were estimated using a fixed accident rate in the corresponding work zone. However, due to the considerable change in the cost factors, the optimal lengths of work zones were found to be 60% larger than the ones used in Nebraska (McCoy & Peterson, 1987). Janson et al. (1987) reviewed the efforts of optimizing work zone traffic control practices and parameters such as optimal lane closure design and work zone length design. Zhou (1996) developed a model to optimize work zone length of a four-lane highway by minimizing the total cost. User and highway maintenance costs were the main functions of the total cost and were both formulated as linear functions.

McCoy's model has been modified later to include queuing delay cost (Martinelli and Xu, 1996). The objective function of the modified model was to minimize the total cost including congestion delay cost. The study concluded that the queuing delay in long-term work zones did not affect the optimal work zone length. McCoy and Mennenga (1998) worked on enhancing the mode of McCoy et al. (1980) by including work zone installation and relocation costs, as well as maintenance costs of work zone traffic control devices. The objective function is to optimize work zone length with partial lane closure while minimizing the total cost.

Work zone lengths and traffic control cycles were both optimized by a model developed by Schonfeld and Chien (1999). This model minimized the total cost of a two-lane, two-way highway only taking into consideration static traffic flow. However, the moving delay was neglected in this study, which eased the effect of speed reduction on traffic flow. Additionally, a sensitivity analysis was conducted in order to determine the effect of work zone length on traffic. The results showed that as traffic flow increases, the decrease of work zone length helps in the discharge rate of the traffic, hence decreasing the user delay cost. However, this had a negative effect on the maintenance cost. In a later study, Chien and Schonfeld (2001) analytically optimized the work zone length for a four-lane highway. The objective function was to decrease the total cost including agency cost, accident cost, and user delay cost. The demand used in this study was hourly distributed. The results showed that work zone length under heavy traffic demand highly affects the total cost of the project.

In order to account for the maintenance work breaks, Chien et al. (2002) added an additional component to the objective function developed by Schonfeld and Chien (1999). This component included the idling cost of labor and equipment. Idling cost, also called the stopping maintenance cost, is the cost of labor and equipment during a break. The model developed by Chien, et al. (2002) for a two-lane, two-way highway was enhanced to be applied in real life. Furthermore, work breaks were scheduled during off-peak periods in order to ease the effect of maintenance project activities on roadway users. Furthermore, time-dependent traffic demand was used for the work zone starting time optimization, as well as the projects' schedule and length optimization based on a sequential search method.

Two years later, Jiang and Adeli (2003) used Chien and Schonfeld's model (2001) to optimize work zone length for a multi-lane freeway based on minimum delay and minimum total agency cost. Additionally, the effect of nighttime and traffic variation due to seasonal maintenance were taken into consideration. The agency cost of this model included user delay cost, accident cost, and maintenance cost. It is worth noting that Jiang and Adeli (2003) included factors in their model in order to account for lane closures, nighttime work projects, and seasonal variations of traffic demand.

Chen (2003) developed a model to optimize work zone scheduling, taking into account traffic diversion. The study was conducted on two-lane, two-way highways as well as four-lane, two-way highways. Chen (2003) addressed four different scenarios for each work zone project and evaluated the best one to minimize the total project cost. This study evaluated the effect of lane-closure (full or partial closure) and traffic diversion options (single or multiple detour) on the total project cost. Chen and Schonfeld (2004) proposed a model for optimizing work zone length, schedule, and traffic management for two-lane work zone projects. The objective function of the model was to minimize the total cost of the project, including user delay cost, accident cost, maintenance cost, and stopping maintenance cost, taking into consideration the variation of traffic demand over time.

El-Rayes and Hyari (2005) studied the optimal light arrangement for nighttime construction projects and concluded that daytime work zones increased safety aspects but had an impact on traffic mobility, whereas nighttime work zones had higher safety risks and less impact on mobility. Chen and Schonfeld (2005) optimized work zone length for a four-lane highway taking into consideration traffic diversion on one alternative route. In 2006, Schonfeld and Chen analyzed a simple hyperbolic time-cost relation by optimizing a single work zone length. This study assumed a static traffic demand and a fixed work zone traffic diversion ratio, which may not be feasible in the real world. Schonfeld et al. (2006) developed a tool for work zone evaluation based on minimized total cost. The model was formulated based on three different approaches: analytical approach for steady traffic demand, analytical approach for time-dependent traffic flow, and a simulation approach to evaluate the different conditions of a work zone.

In 2008, Chien and Tang optimized work zone length and schedule using Genetic Algorithm (GA) in order to minimize the total cost. The production efficiency of the laborers was incorporated in this study by a continuous or discrete function highlighting the effect of unit production time on unit maintenance cost. The unit production option was incorporated in this study to evaluate the relationship between unit production time and the unit maintenance cost. The other decision variables included in this study were work zone lengths, starting time and ending time. A sensitivity analysis was conducted to test the relationship between total cost, maximum project duration, and Average Annual Daily Traffic (AADT). The results indicated that a compressed schedule may increase the total cost of the project while traffic diversion may decrease it.

Yang et al. (2009) minimized the total cost including agency cost, road user delay cost, and accident cost using a hybrid objective function evaluation approach (H2SA) in two stages. For the first stage, the decision variables were pre-optimized analytically, while in the second stage the optimization was based on microscopic simulation models. Additionally, the analytical approach was based on previous studies (Chien & Schonfeld, 2001) (Chien et al., 2002). Corridor Simulator (CORSIM) was used to evaluate traffic work zone delay as a microscopic simulation model. Lee (2009) optimized the work zone project schedule considering the impact of traffic diversion. The objective function of the study was to minimize the total delay resulting from work zone projects. Furthermore, this model utilized VISSIM microscopic simulation to analyze the interaction between drivers and work zones. Additionally, an ant colony algorithm was utilized in order to search for the optimized work zone schedule. Compared to the project planner's schedule, this study presented a schedule that induces 11.1% less traffic delay. Nevertheless, this study does not reflect on real life where traffic delay is not the only concern in work zone scheduling.

Tang and Chien (2010) developed an analytical approach to consider time-varying traffic diversion. This approach was incorporated into their previous optimization model (2008). The resulting model optimized work zones considering three different factors: (1) time-varying traffic diversion, (2) the cost of varying maintenance, and (3) the production option of laborers. The objective function of the model was to minimize the total cost of the project including both agency (maintenance cost and stopping maintenance cost) and user cost (delay cost, vehicle operating cost, and accident cost). Moreover, Yang (2010) developed a systematic methodology based on both analytical and simulation approaches in order to develop a work zone management plan. Which addressed the effect of short-term work zones on road users and long-term work zones on pavement serviceability.

Ng (2012) proposed a model that deals with two main limitations of the previous studies. First, the developed model considered stochastic traffic demand with respect to time after relaxing the deterministic random gene of work zone arrivals. Second, the developed model employed a cell transmission model (CTM) to accurately represent traffic flow conditions through a work zone. The CTM model was introduced by Daganzo (1994, 1995) as a powerful tool that accurately represented real-world traffic flow conditions such as bottlenecks and shockwaves. Meng and Weng (2013) studied the agencies' perspective and developed a model to minimize the total work zone cost based on queue length, travel delay constraints and hourly traffic demand. The model findings showed that the optimal work zone length and work zone starting time depended on user travel delay and queue length formation.

Goa and Zhang (2013) developed a Markov-based optimization model to minimize both user cost and maintenance cost, taking into consideration vehicle operating cost and user delay cost. The developed model was tested and compared with the periodic project maintenance plan; the results showed that the model produced cheaper and more practical maintenance plans. This study highlighted the trend between the user and the maintenance cost and concluded that the contrary trend between these two costs is initiated by the contribution of vehicle operating cost in user delay cost.

Du and Chien (2014) suggested the use of shoulder lanes during short-term construction work to increase the road capacity and reduce the effect of work zones on moving traffic. The analytical model optimizes work zone length on a multi-lane highway under time-varying demand. The factors that came into play in this model are the lighting conditions, the lane width, and the percentage of heavy vehicles. The results of the model showed that for short-term work zones, the use of the shoulder as a lane for travel increased roadway capacity which in turn decreased user delay cost. However, for a long-term work zone, increasing the capacity may be accomplished by the use of the shoulder lane, providing good lighting conditions, and reducing the percentage of heavy vehicles through providing alternative routes. Chien and Tang (2014) used GA to optimize highway work zone length and schedule. The objective function was to minimize the total cost taking into consideration the effect of traffic diversion.

Chien and Mouskos (2015) developed a model to optimize work zone length and schedule using Floating Car Data (FCD) also called vehicle-probe data. The FCD data for location and speed were collected using GNSS (Global Navigation Satellite System), either from the vehicle itself or the driver's phones. Another FCD technology used in this study was the Bluetooth Technology (BT), which allows the collection of vehicle location and travel speed data from Bluetooth devices deployed on the freeways. The objective function of the study was to develop a model that (1) estimated the traffic demand in work zones using FCD data, (2) minimized the effect of construction projects on traffic flow, and (3) minimized the total work zone cost including maintenance cost, idling cost, and user cost. Gong and Fan (2016) optimized the schedule of long-term work zone projects from agencies' perspectives. This study did not consider the dynamic flow assignment and the optimization of work zones form users' point of view. Zhao et al. (2018) used GA to optimize work zone length and schedule taking into consideration the diversion of traffic as well as the shoulder use using floating car data. Nevertheless, this study did not consider the emission cost into the objective function.

2.1.2 Optimization Constraints

Including practical consideration in the work zone optimization process is necessary to obtain realistic work zone length and schedule results. Jiang and Adeli (2003) addressed a minimum work zone length constraint to be larger than a fixed value, however, this did not consider work breaks in the optimization process. This study also considered the total user delay time constraint to be larger than or equal to zero. Nevertheless, this can be considered in the mathematical formulation of the model and does not have to be part of the constraints. Chen and Schonfeld (2004) only considered the project length constraint which resulted in the summation of the work zones to be equal to the total project length. Schonfeld et al. (2006) addressed many constraints from the agencies' perspective. An allowed time constraint for the work activities was considered along with a minimum required work zone length that is necessary to job completion. The maximum project length constraint was also considered to make sure that the summation of the optimized work zone lengths did not exceed the total project length. In addition to that, this study introduced a constraint on the diverted traffic into the alternative route by setting a maximum allowable diverted traffic fraction.

Tang and Chien (2008) integrated three different constraints in order to find the optimal schedule. The first constraint was the minimum activity duration constraint that differed between work zone and work break depending on the minimum amount of time needed for each. The maximum project duration was another constraint taken into consideration by Tang and Chien (2008) to schedule the optimized work zone within an appropriate duration set by the user. This last constraint is one that has been used previously in the literature: the total work zone length.

Yang (2010) addressed three constraints, one of which was directly related to user delays. These constraints were the total amount of work zones, the total duration of the project, and the maximum queue length allowed. The implementation of the queue length constraint can efficiently decrease the work zone impact of traffic; however, this might affect the duration of the project in high demand cases. Ng (2012) introduced realistic constraints on the traffic diverting from the work zone area into the other open lane of the mainline. These constraints limited the number of vehicles diverted to be within the capacity of the opposite lane. Meng and Weng (2013) addressed two constraints directly related to the users. These two constraints are in favor of the user, neglecting the agency's needs to finish the project within a specific amount of time. Abdelmohsen and El-Rayes

(2016) identified some practical constraints set by the user such as the boundaries of work zone length, the lane width, the lateral clearance, the shoulder use, and the work zone starting time. Zhao et al. (2018) addressed three realistic constraints, the minimum activity duration, the total work zone length and maximum work zone duration.

None of the above-mentioned studies considered the budget constraint. Transportation agencies often run on a tight budget allocated to every work zone. Including a budget constraint to the objective function insured the work completion within a specific budget. The optimized schedule will then be adjusted in order to take into consideration a budget constraint on the maintenance cost component of the objective function.

This dissertation will address the budget constraint along with three other realistic constraints: the maximum project duration, the minimum activity duration, and the total project length. These constraints are defined in Chapter 3. Furthermore, Chapter 4 will include methods to handle the four different constraints.

2.1.2 Vehicle Emission

During work zone activities, lane closure instigated excessive delays causing on-road vehicles to decelerate. Many vehicle emission standards have been defined over the years to regulate the vehicle emissions and gasoline impurities. Tier 1 and Tier 2 have been defined for light-duty vehicles in the Clean Air Act Amendments (CAAA) in 1991 and 1999, respectively. Tier 1 was phased-in progressively from 1994 to 1997 and considered all new light-duty vehicles. Tier 2 however, was phased-in between 2004 and 2009 and extended the standards to include medium-duty passenger vehicles. Finally, Tier 3 standards were finalized in 2014 to be phased-in between 2017 and 2025 and include standards for heavy vehicles. During the phase-in periods, the manufacturers are required to certify a percentage of their new vehicles to meet the standards.

Besides emission standards, many studies in the literatures analyzed the effect of various parameters on the vehicle emissions. Rouphail et al. (2000) evaluated traffic emissions during vehicle's acceleration, deceleration, idle and cruising. The results showed that vehicle emissions doubled with traffic delays and were highest during acceleration modes. Stevanovic et al. (2009) studied the effect of reduced speed, increased delay, and increased number of stops on vehicle emissions. The study showed that these factors are the main contributors to traffic-induced emissions. Pandian et al. (2009) evaluated the effect of intersections on air quality. A positive correlation between the speed reduction and vehicle emissions was proven.

Different models can be used to estimate vehicle emissions which can be classified into static and dynamic models. Static models, such as Mobile 6.2 (EPA, 2003) and EMission FACtors Model (EMFAC) (Nesamani et al., 2007) are macroscopic models that can estimate vehicle emission rates based on vehicle's type and speed. These models, however, were not able to determine vehicle emissions on a microscopic level nor were they able to estimate the emissions during the time the work zone was scheduled. Nevertheless, dynamic models such as the Comprehensive Model Emission Model (CMEM) (Barth et al., 2008), accounted for speed changes and acceleration profiles to measure the emissions at detailed levels. A dynamic model for estimating vehicle's emissions based on microscopic evaluation of the vehicles' acceleration, deceleration was developed by Panis et al. (2006). The model used a non-linear multiple regression approach and traffic simulator (e.g., DRACULA), which proved the efficiency of microsimulation models when dealing with vehicle emissions. The corresponding model validation, however, was persistently challenging. Saedi et al. (2018) developed a macroscopic model for vehicle emissions estimation taking into account the properties of microlevel models. The calibration of the model required an intensive process which was performed using linear regression.

Following the Clean Air Act, the Environmental Protection Agency (EPA) developed MOtor Vehicle Emission Simulator (MOVES) (EPA, 2010) subsequent to the MOBILE macroscale emission estimator (EPA, 2003). MOVES is a multi-scale dynamic model capable of estimating vehicle emission at aggregate level as well as macroscale level of on-road and nonroad vehicles. MOVES takes into consideration the day, the temperature, the humidity, and the volume distribution within a project. The model's outputs are flexible, allowing the user to choose the detailed level of the results as they range from annual to hourly emissions (EPA, 2010). In December 2020, EPA released the latest version: MOVES3. This version incorporated the latest data on vehicle population, travel activities, fuel information, and emission rates (FHWA, 2020). The new MOVES3 also adjusted the vehicle on-road hoteling data, as well as the nonroad idling data, such as the idling of construction vehicles on site (FHWA, 2020). In addition to that, new vehicle rules and standards have been incorporated into MOVES3, such as the Heavy-Duty Greenhouse Gas Phase 2 rule that sets emission standards for heavy vehicles, and the Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule that sets carbon dioxide and fuel economy standards from year 2021 to 2026 (Wang and Miao, 2021).

Based the previously mentioned emission simulators, studies in the literature developed dynamic traffic assignment and route choice models based on an environmental approach. Ahn and Rakha (2008) studied the total emission of a travel system and minimized the emissions of particular pollutants for highways and arterial roads. The study used various estimation models such as CMEM. Aziz and Ukkusuri (2012) assigned the traffic in a way to minimize the total system CO emissions and travel time cost. The study used a speed-based model estimated from MOBILE 6.2 emission rates. In 2013, a study by Ahn and Rakha minimized the user's fuel consumption using microscopic simulation and dynamic emission models. Guo et al. (2013) used MOVES and a microscopic traffic simulator to assign the traffic in a way to minimize the user's emission of a particular pollutant, as well as minimize the fuel consumption. Long et al. (2016) studied the traffic assignment with an objective function to minimize the total system CO emission and travel time using macroscopic simulation and an emission model from data estimated from MOBILE 6.2. Detailed information about the dynamic traffic assignment models based on environmental consideration can be found at Wang et al. (2018).

Even though minimizing vehicle emission has been the focus of researchers in the past, none of these studies have used vehicle emission as a base for work zone optimization. This study optimizes the work zone schedule and the traffic diversion during maintenance projects, based on a minimized total cost and vehicle emissions.

MOVES3 is used for the first time in this dissertation to estimate vehicle emissions due to work zones by creating two projects that illustrate the conditions under normal and work zone conditions. MOVES3 is used due to its simplicity, user-friendliness, and capability of estimating emissions on national, county, and project levels.

2.2 Traffic Management and Operations

Traffic management during highway maintenance projects has been an important parameter to mitigate the adverse effect of work zones on traffic. This section discusses the history related to traffic operation and management in work zones, including traffic delay estimation and mitigation techniques.

2.2.1 Traffic Delay and Capacity Estimation

The estimation of freeway queuing delay has been analyzed using two well-developed models for decades, the deterministic queuing theory model and the shockwave queuing theory model (Abraham and Wang, 1981; Dudek and Richards, 1982). The usual inputs of the deterministic queuing delay theory are the demand over the construction time period, the road capacity, the work zone capacity, and the duration of the maintenance work (Morales, 1986; Schonfeld and Chien, 1999). The shock wave theory, however, estimates the delay by studying the linear propagation of shockwave speed with respect to flow (Richards, 1956; Wirasinghe, 1978).

The estimation of queuing delay and capacity reduction during work zones have been studied by many researchers. Chien et al. (2002) highlighted the importance of estimating work zone related delays using a computer simulation approach instead of a deterministic approach. The model developed in this study integrated limited simulation data extracted from CORSIM taking into consideration road geometric conditions and traffic distribution. The generated simulation-based model was able to accurately estimate total delay including queuing and moving delays.

Ramezani and Benekohal (2011) analyzed the formation and dissipation of the queue in a work zone. This study considered two locations in the work zone area as bottleneck areas: (1) the area in which the work is in process, (2) the transition area due to lane closure. Additionally, this study investigated the relation between these two bottlenecks as well as the propagation and dissipation of the queue. The results were compared with field data collected during work zone, which showed that this model could be effectively used for calculating the delay and queue length propagated during a work zone.

Weng and Meng (2014) analyzed the issues related to work zone operation such as capacity reduction and travel delay estimation. The study represented three categories for work zone capacity estimation: parametric, non-parametric, and simulation approach. It also represented user delay estimation for the three categories. Under the same objective, Astarita et al. (2014) evaluated the delay suffered by user in a two-lane highway under construction. Different demand flow levels were studied under different work zone construction lengths. The results showed that dividing work zones into smaller segments to be conducted separately, decreased the effect of construction work on user delays.

Zhu (2015) studied the effect of closing one lane in a two-lane highway and proposed strategies for effectively using one lane for traffic flow. The study represented a mathematical model that calculated the capacity reduction and vehicular delays incurred by construction work. VISSIM was used as a simulation model to validate the mathematical model using field data. As a result, the study proposed a model to optimize work zone two-way highway lane closure. The objective function of the study was to reduce the total user delay cost through pre-timed signal control optimization and to maintain an acceptable roadway capacity. Sensitivity analysis was conducted, and the results showed that roadway capacity might increase with the reduction of work zone length, increasing the allowable travel speed within a work zone, and using traffic signal that are adaptable to the actual traffic demand. In 2016, Fei et al. analyzed the effect of work zone projects on traffic flow. They divided the roadway area into normal, merging, and work zone areas, and recommended appropriate merging lengths and speed limits during two-lane work zone projects.

Abdelmohsen and El-Rayes (2016) studied the trade-off between reducing work zone delay and decreasing work zone maintenance cost. They developed a multi-objective optimization model that is able to generate this trade-off between delay and maintenance cost. The decision variables considered in this study were the work zone length, the work zone starting time, the availability of shoulder use, and the lateral clearance, which is the distance between the construction area and the barrier provided to isolate the work zone from traffic flow. The model concluded that, in order to minimize traffic delay, it is desirable to minimize work zone length, start the work zone during nighttime, use a flagger to control the traffic flow around a work zone, provide a maximum lateral clearance, and utilize the shoulder as a lane for traffic flow. However, in order to minimize the maintenance cost, it is desirable to maximize the work zone length (less set-up cost), start the work during daytime hours, avoid the use of shoulder or provide any lateral clearance. Additionally, the model was able to provide a trade-off between these two opposite conclusions for the agencies to utilize the optimal trade-off that fulfills their objectives.

Zhu et al. (2017) studied the effect of work zone in a two-lane highway after one lane closure. Closing one lane in a two-lane highway led to bidirectional traffic flow, which makes it important for traffic control management techniques to be implemented. Zhu et al. (2017) proposed two models to analyze the traffic control management problem. The first model was a mathematical model that estimated the delay and capacity during work zone activities basing the strategy on signalized intersections' concept. The second model was a micro-simulation model that estimated the delay and capacity reduction based on observed and collected real time data. After estimating the delays with minimal errors, these two models were used for work zone optimization for a two-lane highway with one lane closure. The objective function of the optimization study was to analyze the effect or pre-timed signal control and dynamic signal control on user delays during work zone activities. The results showed that dynamic traffic control management techniques assisted in reducing the delay incurred due to work zone projects.

On a separate note, Yang et al. (2017) studied the effect of Variable Speed Limit (VSL) in a work zone area on traffic delay. VSL is a flexible speed rate at which motorists are obliged to travel in order to increase their safety. Yang et al. (2017) model used the model developed by Papageorgiou et al. (1989) in order to predict the flow variation over time and predict the speed limit at which motorists should safely travel during work zone. This study also proposed a methodology to ease the difference between speed transitions on highways in order to avoid shockwave formation. After integrating the model in VISSIM, the results showed that the VSL model is efficient at reducing the speed variance in freeway work zone sections.

Du et al. (2017) developed a hybrid machine-learning model to estimate the work zone delays and the associated costs. The factors associated in work zone delays are the road geometry, the number of lanes closed, and the time and period at which the work zone is being accomplished. Data were collected and compared with the model results, showing the least root mean square error (RMSE). The model developed by Du et al. (2017) can be used as a planning tool for the agency to study the effect of their work zone projects beforehand, thus determining the best start and end time of the project, minimizing the delay effect on users.

In a recent study, Abdelmohsen and El-Rayes (2017) considered the trade-off between traffic safety and traffic mobility in a multi-objective function to minimize work zone probability of crashes as a first phase and to minimize traffic delay as a second phase using multi-objective Genetic Algorithm. The decision variables included work zone speed limit, work zone start time, shoulder use, lateral clearance, work zone segment length, and temporary traffic control measures TTC. In this study, Shoulder use fraction and lateral clearance determined the number of available lanes through work zone length, which is related to safety and mobility. A Crash Modification Factor (CMF) measured the probability of crash occurrence for each decision variable. However, this study did not take the equivalent cost of mobility and safety into consideration, but rather optimized both safety and mobility in two separate stages. Furthermore, this study along with others, evaluated the effect of posted speed limit on safety and vehicular delays and concluded that posted speed limit enhanced safety (Sommers & McAvoy, 2013), but decreased traffic mobility (Aghdashi et al., 2015).

2.2.2 Traffic Diversion

Due to advanced technologies, commuters are now able to estimate their travel time from origin to destination and pick the route with the least travel time. By that, drivers avoid additional travel delays caused by work zones. Thus, considering traffic diversion is a crucial parameter that affects work zone schedules.

Many researchers studied the effect of traffic diversion on work zones. Ullman (1996) conducted a research study highlighting the effect of natural traffic diversion on travel configuration upstream a short-term work zone on urban freeways in Texas. Thus, the objective function of this work was to specifically study the effect of natural traffic diversion at the exit and entrance ramp upstream of one-lane closure maintenance projects, taking into consideration the amount of diverted traffic and the interrelationship between the mainline and the alternative routes. Ullman observed the queue formation upstream a work zone using the shock wave theory and was able to observe the changes in the ramp volumes and the resulting effect on the studied freeway.

Tong and Wong (2000) developed a dynamic model/simulator predicting the traffic assignment in congested capacity-constrained networks. The dynamic traffic simulator is used to periodically load traffic demand into the model and update the traffic condition. A time-dependent shortest-path model was used to link the demand from origin to destination based on the minimum travel time path. Added together, the dynamic traffic simulator and the path algorithm were combined in one model of successive averages to provide a dynamic equilibrium in the system. Kuwahara and Akamatsu (2001) developed a dynamic model to optimize the user assignment based on physical queues. Traffic origin-destination volume data were used, and a kinematic wave theory was proposed to reach the optimal equilibrium conditions.

Horowitz et al. (2003) studied the effect of implementing a variable message sign in a work zone on the alternative route selection. The diversion of the traffic was estimated through carefully counting the traffic flow on mainline and alternative routes before and after applying the variable message sign system. Flow data were analyzed, and the study concluded that around 10% of the freeway traffic was diverted depending on the day of travel and the location of the car on the freeway.

Ullman and Dudek (2003) developed a model to predict the propagation of the queue due to short-term work zones considering the impact of traffic diversion. The model was developed based on the permeable theory of fluid-flow in a pipe. The developed model was based on a permeability factor that is related to the corresponding work zone site and needs massive amount of data to be calibrated, thus cannot be effectively used for work zone scheduling problems.

As for the studies concerning work zone optimization, Chen (2003, 2006) developed an optimization model to schedule four-lane, two-way and two-lane, two-way highways undertaking different scenarios and considering the impact of traffic diversion. The objective function of this study was to minimize the total cost consisting of agency and user cost. The optimization model was generated to optimize work zone lengths, schedules, and the ratios of traffic diversion. System optimum (SO) was used for the optimization of the traffic diversion ratios. However, Chen's model (2003) was based on the assumption of constant traffic diversion ratios during work zone, which is not considered realistic considering time-dependent traffic volume. Ma et al. (2004) developed a simulation model to estimate delays taking into consideration traffic diversion. However, the simulation model requires a huge amount of time, which makes it infeasible for work zone optimization problems. Chen et al. (2005) developed a work zone optimization model considering the impact of traffic diversion through possible mixed alternative routes using

Simulated Annealing (SA) algorithm. Zhang et al. (2008) proposed a model to estimate time-dependent demand and traffic diversion flow due to work zone delay. The model was based on regression analysis and was applied on a case study, which the results proved the efficiency of the model. Song and Yin (2008) were able to estimate the diversion rate through developing a binary logit model. The model results showed that many factors influence the driver's choice for alternative routes, such as the weather, the travel time, and the location of the work zone.

However, the above-mentioned studies used a fixed traffic diversion ratio during the entire maintenance project. In order to take into consideration, the special and temporal variation of the diversion demand with respect to traffic conditions, a time-varying traffic diversion should be implemented. Tang and Chien (2010) developed a cost-effective work zone scheduling model taking into consideration the impact of time-varying traffic diversion. User Equilibrium (UE) was used for traffic assignment. The resultant model can be used for planning work zone project with limited set of data.

Chen et al. (2010) developed a logistic regression model based on observed data to imitate commuters' diversion behavior upstream of a work zone. The model was tested and compared with the field data, the results showed the efficiency and accuracy of the logistic regression model. Yang and Schonfeld (2011) studied the drivers' diversion behavior during work zone by applying three different models for predicting the diversion rates: User Equilibrium (UE), System Optimum (SO), and Logit-based Route Choice Model (RC). Hence, this model can effectively account different drivers' behavior under different conditions. Chien and Tang (2014) developed an analytical model to optimize work zone length and to schedule reflecting the effect of traffic diversion. The objective function of the model was to minimize total cost, taking into consideration multiple scenarios that imitate the relationship between the minimized total cost and the travel time saving threshold.

In an effort to improve safety and communication around a work zone, Genders and Razavi (2015) studied the effect of deploying a connected vehicle system on the corresponding traffic during a work zone. The proposed connected vehicle system used vehicle-to-vehicle (VTV) communication in order to share data about travel times around work zones. After receiving information from other connected vehicles, drivers' behavior was modified by increasing awareness and attentiveness. Once the information about the work zone and travel time are shared between the connected vehicle, connected vehicles would be diverted to their destination based on the minimum travel time in order to bypass the work zone. Different market penetration values are studied along with different behavior models to study the corresponding changes in work zone safety. Furthermore, the study found an optimal market penetration for a safer work zone to be 40%.

Chien and Zhao (2016) conducted a study to optimize work zone schedule and evaluate the effectiveness of traffic diversion during work zone using Genetic Algorithm (GA). To cope with the previous findings, Zhao et al. (2018) conducted a study using Chien and Zhao's model (2016) with floating car data, while accounting for traffic diversion using both System Optimum (SO) and User Equilibrium (UE). However, assumptions were made regarding the application of the SO and UE models. As for the UE, this study assumed that users have accurate information about the network and hence are able to adjust their route choice to achieve minimal travel time. Additionally, for achieving SO conditions, the study assumed the application of a proper traffic diversion strategy with 100% compliance rate.

Floating car data were integrated into the model to achieve optimal conditions of work zone schedules. This study concluded that traffic diversion helps reduce the congestion on the mainline. It also concluded that UE-based traffic assignment optimization returned a schedule with slightly higher user cost and total cost while UE-based traffic assignment returned a higher maintenance cost due to the use of crew with higher production option.

2.3 Optimization Algorithms

Work zone optimization is a complicated combinatorial problem where many decision variables come into play, e.g., starting and ending time of work zone projects, duration of work breaks, crew assignment, length of the project, and length of each section into which the project could be divided. In order to reach a near optimal solution, a powerful optimization algorithm is required. Metaheuristic optimization algorithms such as Artificial Bee Colony (ABC) and Genetic Algorithm (GA) are highly desirable to find near optimal solution due to their problem-independent nature, which allows them to adapt to any problem (Glover, 1997; Back et al., 1997; Glover and Kochenberger, 2002; Parejo et al., 2003). Optimization algorithms can be classified as either complete or approximate. Using complete optimization algorithms, the search for an optimal solution is guaranteed; however, exponential computation time might be needed to reach an optimal solution, which makes it hard to implement in real life projects (Nemhauser and Wolsey, 1988). Thus, in recent years, approximate methods have gained popularity as algorithms for solving optimization problems. By using approximate methods, researchers might sacrifice the finding of optimal solution for getting a near optimal solution (good solution) in a considerably reduced amount of time. The basic approximate methods also called heuristic algorithms are usually divided into two sections: constructive and local algorithms. Constructive algorithms generate solutions from scratch without the need for an initial solution space. They construct the solution space by adding components to the initial empty space until returning good solutions, which are less optimal than the ones generated by local search algorithms. The latter starts from an initial solution and try to formulate a better solution by iteration. The next best solution or the neighbor solution is one-step closer to the near optimal result (Blum and Roli, 2003). Additionally, heuristic algorithms consist of comprehensive tools that are able to solve complex problems and find good solutions relatively close to the desired optimal ones. However, heuristics are problem dependent as they are based on characteristics related to the specific problem, which makes their development more complicated (Glover, 1997).

In the past decade, advanced research methods have emerged in the purpose of effectively enhancing the search space engine and efficiently improving the basic heuristic methods. These algorithms are commonly known as metaheuristic algorithms. In an effort to improve the results obtained from heuristic algorithms, metaheuristics have been introduced as algorithms that are able to adapt to the problem. They range from very simple local search to the most complex problem (Blum and Roli, 2003). The term metaheuristic was first introduced by Glover (1986) and later on used as modern heuristics by Reeves (1993). The term metaheuristic refers to Greek origins where Metaheuristic means to find a solution in an upper level (Glover, 1986).

This section of the literature review describes the characteristics of the metaheuristic algorithms that include, but are not restricted to:

- Ant Colony Optimization (ACO)

- Simulated Annealing (SA)
- Genetic Algorithm (GA)
- Artificial Bee Colony Algorithm (ABC)

2.3.1 Ant Colony Optimization Algorithm

Ant Colony Optimization (ACO) algorithm was first proposed and discussed by Dorigo (1992, 1996, 1999) for solving complicated combinatorial optimization problems. The algorithm was inspired by the behavior of ants which enables them to find the shortest possible path between the nest and the food sources. On their way from the food source to the nest or vice versa, the ants place a substance called pheromone. The concentration of the pheromone on the path is an indication of the closeness of the food source to the nest: the higher the pheromone concentration, the higher the probability of other ants to take this path. This represents the corporative interaction of all ants for finding the shortest path (Dorigo, 1996).

ACO has been used in many optimization problems over the years. Bauer et al. (2000) used ACO to solve the problem of job sequencing in order to minimize the total delay of sets of jobs. Compared with other metaheuristics, the results showed that ACO is efficient for solving job-scheduling problems. Merkle et al. (2000) used ACO for solving a resource-constrained scheduling problem in which the ACO was tested on different benchmark problems, the results prove the capability of ACO of finding new optimal solutions compared to other metaheuristics. Sun and Pang (2017) used ACO for solving vehicle routing optimization problems in agriculture. The proposed model showed efficiency in reducing the fuel consumption in agriculture products distribution.

Few studies have considered ACO algorithm in work zone optimization. Lee (2009) used Ant Colony Algorithm to develop a model that is able to optimize work zone schedule taking into consideration the impact of traffic. This study was the first to considered Team Ant Colony Optimization (TACO) in scheduling by grouping the ants into teams forming a working crew. However, the computational time of such a solution algorithm is high, resulting in unpredicted computational time in complicated case studies. Lukas et al. (2010) used ACO to optimize the schedule of infrastructure work zones in order to minimize the maintenance cost and the impact on traffic.

Based on the literature, ACO algorithm showed outstanding performance in solving optimization problems in different engineering fields. Lakshminarayanan et al. (2010) used ACO for time, risk, and cost optimization of construction projects. The multi-objective optimization problem was efficiently solved by ACO compared to other solution algorithms.

Ant colony algorithm was effectively applied to solve many combinatorial optimization problems in the literature. However, the ACO algorithm is difficult to analyze theoretically. That is due to the random decision's sequences taken by the aunts in which the probability distribution differs from iteration to another (Castillo et al., 2008). Moreover, the convergence time of ACO is uncertain specially for more complicated case studies.

2.3.2 Simulated Annealing Algorithm

The simulated annealing algorithm (SA) is developed from statistical mechanics by Kirkpatrick et al. (1983). It is grounded upon a strong correlation between the physical annealing mechanism of solids and the solving process of large combinatorial problems.

The state of solid is a virtual representation of the feasible solution of an optimization problem, meaning that the energy of each physical state represents the value of the objective function of this solution. Hence, the optimal solution corresponds to the minimum energy of solid crystal state. The simulated annealing problem usually includes four essential parts: the representation of the solution, the objective function, the neighboring solutions, and the cooling schedule.

Previous studies have shown the efficiency of simulated annealing in adjusting local optimal search. SA has been used in many transportation related projects to solve optimization problems such as work zone optimization (Chen, 2003; Jiang and Adeli, 2003). Chen and Schonfeld (2004) optimized work zone lengths, durations, starting times, and breaks using SA algorithm and Powell's method. The SA was found to be an efficient algorithm to solve the problem with less computation time than the Powell's method. Chen et al. (2005) used SA in order to consider traffic diversion within work zones. The model focused on evaluating several alternative routes and choosing the one alternative route that serves the traffic best. In addition, SA was used to find a mix of best alternative routes within the two-lane highway resurfacing project. SA was found to be a reliable solution algorithm for the resurfacing project optimization problem. In transportation, Fan and Machemehl (2006) used SA the optimal bus routing problem at the distribution node level. The SA results were compared with a GA benchmark model showing the outstanding outperformance of the SA.

SA was fond to be a reliable efficient optimization algorithm to find a near optimal solution of work zone problems. However, one aspect the literature neglected was that the SA optimization process begins with initial random population, then focuses on generating multiple iterations for the regions of the population that have highest fitness value. Hence, when the optimal solution is surrounded by a low fitness value region, neglection of the optimal solution will occur (Busetti, 2003). The quality of the optimal solution proposed by the SA is then greatly related to the computational time.

2.3.3 Genetic Algorithm

Genetic algorithm (GA) is an algorithm inspired by the Darwinian strife for survival and the genetic inheritance (Michalewicz, 2013). GA is a stochastic algorithm whose components include genetic representation of solution, objective function, and reproduction function to generate new solutions.

In previous studies, genetic algorithm showed good performance in finding near optimal solutions for transportation optimization problems. Park et al. (1999) optimized the traffic signals using genetic algorithm. Fwa et al. (1998, 2000) used Genetic Algorithm for scheduling problem of pavement maintenance activities. Chien and Schonfeld, (2001) as well as Ngamchai and Lovel (2003) used GA for planning and designing of transit routes. Chien et al. (2001) used GA in order to determine an optimal feeder bus route. The objective function of this model was to minimize the total cost under geometric, capacity, and budget constraints. The results demonstrated the efficiency of the developed model, which was compared with other exhaustive search methods. Jong and Schonfeld (2003) used GA for designing the highway geometry. All the above studies used genetic algorithm to find the best sequence of decision variables in order to maximize or minimize the objective function.

Tang and Chien (2008) used GA for work zone optimization schedule. The proposed model aimed at minimizing the total cost of the project under maximum project duration, minimum activity duration, and total project length constraints. In 2014, Chien and Tang (2014) used GA to optimize work zone schedule while considering the impact of traffic diversion using user equilibrium model. Thereafter, Zhao et al. (2018) used GA for optimizing work zone schedule while accounting for traffic diversion and feasibility of shoulder use, using both system optimum and user equilibrium.

GA has shown good performance in optimization problems. However, there are some limitations of the GA usage compared to other optimization algorithms, such as the inefficiency of the model with complexity. For example, when the number of elements under mutation is large, the searching space size increases exponentially. Another drawback of the GA would be its tendency to converge towards local optima instead of global optimum solution. Which means, the GA might return a solution that is optimal among set of neighbor solutions, however, not the global optimal solution of the problem. This is due to its allocation of more trials within the region of high fitness value, neglecting the region with less fitness. This is a disadvantage when the optimal solution is surrounded by low fitness value regions. Increasing the mutation rates might help eliminate this problem, which will increase the computation time of the algorithm and add another drawback to the algorithm.

2.3.4 Artificial Bee Colony Algorithm

Artificial Bee Colony (ABC) is an optimization algorithm based on the swarm behavior. It was first proposed by Karaboga (2005) as a solution algorithm to find the optimal solution of mathematical problems. The algorithm was inspired by the intelligent foraging behavior of honeybee swarm and it illustrates three groups of bees: employed bees, onlooker bees, and scout bees. Employed bees are the ones busy exploiting a specific food source. They hold information about the source, its location and direction from the nest. They also carry information about the profitability of the source, or its richness. They may share information about the nectar amount of the food source with the onlooker bees by dancing in the dance area, a common area in the hive. They share the information with a probability that is related to the profitability of the food source through a waggle dance. The duration of the dance is related to the amount of nectar in the food source, the longer the dance the higher amount of nectar the food source contains (Kalayaci and Gupta, 2013). Onlooker bees are the ones waiting in the hive and making decisions on which food source to choose. They watch numerous dances performed on the dance floor and tend to choose a food source to exploit based on its corresponding quality (Karaboga et al., 2014). Therefore, the good food sources tend to attract higher number of bees than the bad ones. The bees that are randomly looking for new food sources are called scout bees. They are basically exploring the hive for potential food sources (Kalayaci and Gupta, 2013).

ABC was efficiently used in previous studies to solve many optimization problems. After it was proposed to solve unconstraint problems, Karaboga and Basturk (2007) proved that ABC could be used for solving constraint problems as well. A constraint problem is one that has two domains to be evaluated, the objective function and its constraints.

Artificial Bee Colony was efficiently used to solve optimization problems in various engineering fields. Yao et al. (2010) used ABC to optimize subway routes in order to maximize the amount of population served by the service. Ravi and Duraiswamy (2011) used ABC to improve the stability and efficiency of the power system. Later that year, ABC was used by Baijal et al. (2011) to solve the problem of economic load dispatch. Gozde and Taplamacioglu (2011) proposed ABC for the optimization of an automatic voltage regulator (AVR) problem, this study concluded that ABC could be successfully used for enhancing the performance of AVR. Sonmez (2011) explored the use of ABC for truss structures optimization. Rao and Patel (2011a) proposed the use of ABC for optimization design problems of rotary regenerator. Pan and Duan (2016) used ABC for solving a hybrid flow ship problem. Additionally, Ghaleini et al. (2018) created an optimization algorithm that combines both ABC and Artificial Neural Networks (ANN) for safety factors optimization of retaining walls.

In the Transportation field, Wang and Leong (2018) found ABC to be the most efficient optimization algorithm for solving the travelling salesman problem in light rail. Panda and Swamy (2018) proposed ABC for pavement resurfacing optimization in order to find the best frequency and resurfacing intensity. A previous study (Sharma et al., 2019) tackled the use of ABC in cost optimization problems of work zone schedules in construction, taking into consideration the predecessor and successor in context of direct cost, indirect cost, bonus and penalty. The results proved the efficacy of ABC in construction planning; however, this study did not consider the different components of the total cost, nor did it tackle the optimizing work zone length and the efficiency of the crew.

ABC was chosen to be the solution algorithm for the work zone optimization problem of this dissertation as it can be effectively used to solve a wide range of optimization problems, including constraints and unconstraint problems. Since the work zone optimization problem is a realistic combinatorial and complicated problem subject to many real-life constraints, ABC would be a good fit to consider all corresponding constraints. In addition, ABC engages fewer control parameters as opposed to other metaheuristics. ABC consists of only three control parameters: the population size, maximum cycle number, and the limit. Making it easier to calibrate compared to other metaheuristic algorithms such as the GA and SA which both contain five control parameters, and the ACO which contains six control paraments that need to be calibrated. Moreover, ABC is flexible and robust as it can adapt to different variations to the same problem.

2.4 Summary of the Findings

The findings of the literature review can be summarized as follows:

1. Many studies in the literature aimed at optimizing work length and schedule (Schonfeld and Chien, 1999; Chien et al., 2002; Jiang and Adeli, 2003; Schonfeld et al., 2006; Tang and Chien, 2008 and 2010; Zhao et al., 2018; etc.). The objective of these studies was to minimize the total cost including maintenance and user costs. However, none of these studies considered the emission cost component of the total cost function, nor have they studied the effect of the optimized schedule on the environment. This dissertation analyzes the additional vehicle emission due to work zone delays and implement an emission cost component into the total cost function in order to create an environmentally friendly optimization model.

2. Previous studies considered the total project length constraint (Chen and Schonfeld, 2004; Schonfeld et al., 2006; Tang and Chien, 2008; etc.), the maximum project duration and the minimum activity duration constraints (Tang and Chien, 2008; Zhao et al., 2018; etc.). Other studies considered user related constraints such as the maximum queue formation allowed (Yang, 2010) and limitation on the amount of vehicle diverted due to work zone (Ng, 2012). However, these studies neglected one realistic constraint which is the budget constraint. This dissertation will tackle four main constraints: the total project length, the maximum project duration, the minimum activity duration, and the budget constraints. Other constraints in the literature that focus solely on users will be considered in this dissertation by implementing the user cost component in the total cost function and utilizing traffic diversion models that favor the user.

3. Dynamic and static models have been used in the literature in order to estimate vehicle emissions. The dynamic model MOVES3 will be used in this dissertation for its simplicity and user-friendliness; it is a state-of-the-science emission model that estimates emissions for both, macro and microscale levels.

4. Several studies researched the effect of traffic diversion due to work zones on the mainline and alternative route. This dissertation will implement both the User Equilibrium and System Optimum as traffic assignment models under the consideration of vehicle emissions, which was never studied in the literature.

5. Artificial Bee Colony is used as a solution algorithm as it can be utilized to solve a wide range of constraint and unconstraint optimization problems, it engages less control parameters as opposed to other metaheuristics, and it is flexible and adapts to any given problem. This is the first attempt in the literature to utilize the ABC for the work zone optimization combinatorial problem under corresponding constraints and time-varying traffic demand.

CHAPTER 3

METHODOLOGY

The increase in traffic demand has accelerated the deterioration of the roadways and the needs of maintenance projects for mobility and safety purposes. With that, the optimization of the work zone schedule is very critical to minimize the total cost such as agency, user, and emission cost. However, many factors come into play when optimizing the work zone maintenance projects. These factors include budget limitations, roadway capacity, minimum and maximum duration of work zones, and the projects' deadline.

This dissertation aims at formulating a model that optimizes the work zone schedule by minimizing the total cost considering a discrete time-cost relation and traffic diversion. The objective total cost function is discussed in this chapter with all corresponding components and constraints. The framework of the proposed optimization is illustrated in Figure 3.1

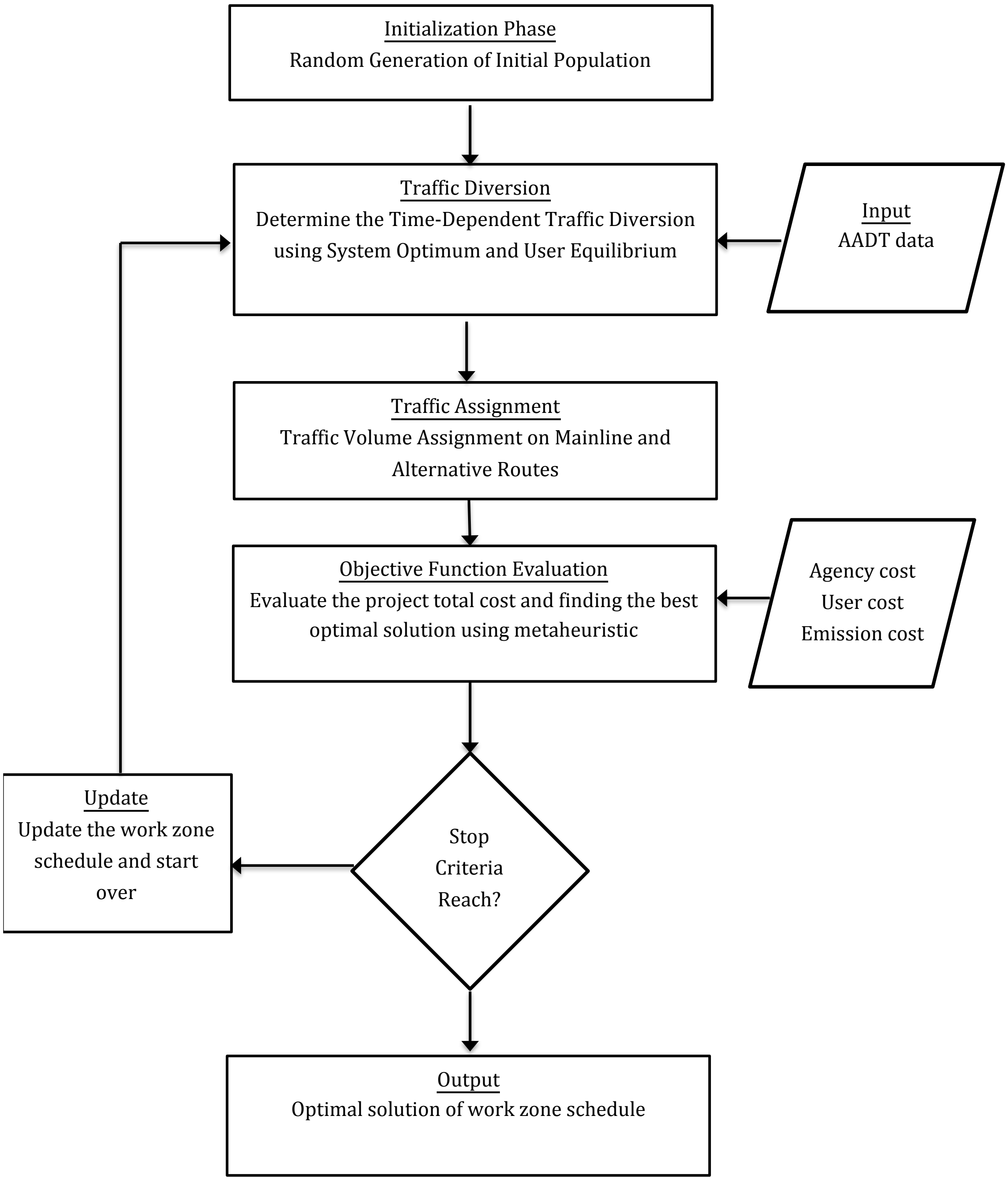

Figure 3.1 Optimization framework.

3.1 Assumptions

The formulation of the total cost function in this dissertation is based on the following assumptions. These statements are made in favor of finding a near optimal solution of the work zone problem based on various constraints:

1. The traffic volume used in this dissertation is a given time-varying demand obtained from the "Road User Cost Manual" developed by the New Jersey Department of Transportation and the New Jersey Congestion Management System (NJCMS).

2. The time and cost to step up and remove a work zone are given.

3. The average idling cost per hour is given.

4. The maximum working hours per day is not limited to 8 hours.

5. Parameters of the BRP equation $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ fit the calibration of Jeihani et al. (2006). When this is not the case, $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ has to be calibrated to fit the studied highway.

6. The traffic may be diverted into one alternative route. Many alternative routes are not considered in this study

7. Any delays on the exit and entrance ramps are not considered.

8. The user compliance rate with the traffic diversion decision is 100%

3.2 Cost Minimization Model

This section discusses the formulation of the objective total cost function to minimize the total cost and its associated constraints. The components of the total cost (C_T) are shown in Figure 3.2, which consists of the agency cost $(C_M + C_I)$, the user cost (C_U), and the environmental cost (C_E).

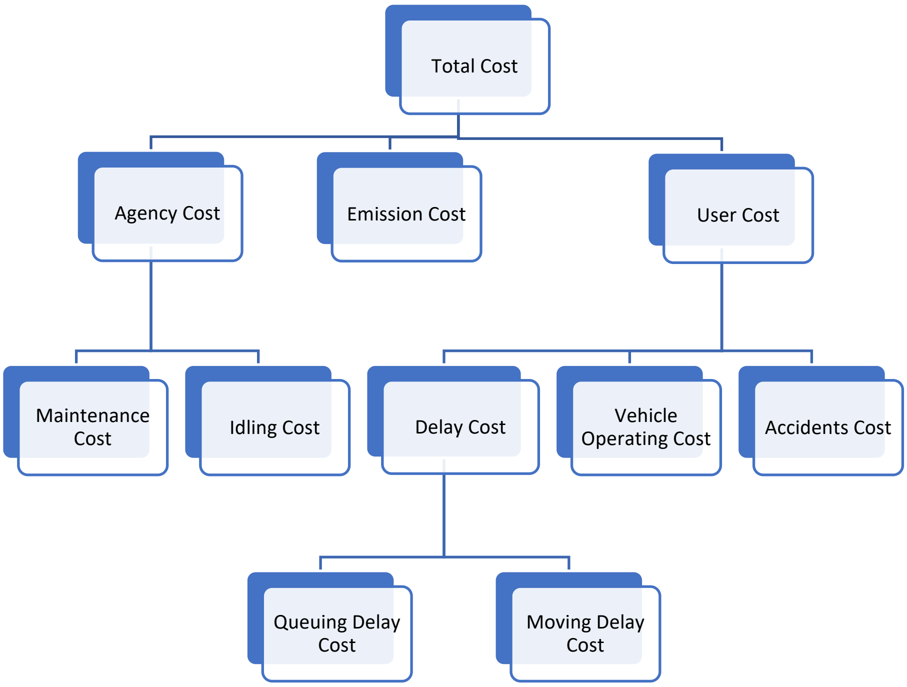

Figure 3.2 Configuration of the objective total cost function.

The agency cost includes maintenance cost (C_M) and idling cost (C_I), also known as cost for stopping maintenance because of idling labor and/or equipment. The user cost (C_U) includes delay cost (C_D), vehicle operating cost (C_V), and accidents cost (C_A), in which the delay cost consists of queuing delay cost and moving delay cost. The user delay cost is associated to a weight factor p for the value of time. The total cost is then the summation of the costs of all work zones (i).

Thus, the objective function is:

$$\text{Minimize } C_T = C_M + C_I + C_U + C_E = C_M + C_I + (p\,C_D + C_A + C_V) + C_E \quad (3.1)$$

$$= \sum_{i=1}^{m} (C_{Mi} + C_{Ii}) + \sum_{i=1}^{m} (p\,C_{Di} + C_{Ai} + C_{Vi}) + \sum_{i=1}^{m} C_{Ei}$$

3.2.1 Maintenance Cost

For work zone i, the maintenance cost ($C_{M_i}^{k}$) is associated with the crew k, the work zone length l_i^k, and the unit maintenance cost z_{2i}^{k} ($/lane-km). The maintenance cost can then be calculated using the following equation:

$$C_{Mi} = z_1 + z_{2i}^{k}\, l_i^k \quad (3.2a)$$

where:

- z_1 is a fixed cost for setting and removing the work zone;
- k is the crew index of production option; and
- z_{2i}^{k} is the unit maintenance cost for each lane-km corresponding to production option k.

The work zone length l_i^k is related to the start (S_i) and end (E_i) times of work zone i, Thus:

$$l_i^k = \frac{E_i - S_i - z_3}{z_{4i}^{k}} \quad (3.2b)$$

where:

- z_{4i}^{k} is the production time (hours/lane-km) corresponding to each crew production option k;
- E_i is the work zone ending time;
- S_i is the work zone starting time; and
- z_3 is the work zone setup time.

Due to lane closure, merging taper is used to merge the traffic into the work zone area. The length of the merging taper is critical to offer the traffic enough warning in advance of a transition into a reduced number of lanes. Hence, the length of the merging taper is calculated based on the mainline speed such as:

- Speed of 45 mph or more:

$$l_T = WS \tag{3.2c}$$

- Speed of 45 mph or less:

$$l_T = \frac{WS^2}{60} \tag{3.2d}$$

where:

- l_T is the base taper length;
- W is the width of offset in feet (lane width); and

- S is the posted speed.

The maintenance cost can then be written as

$$C_{Mi} = z_1 + \frac{z_{2i}^k}{z_{4i}^k} \ (E_i - S_i - z_3) \qquad (3.2e)$$

With the decrease of unit production time z_{4i}^k (e.g., higher crew production rate) the unit maintenance cost z_{2i}^k increases since more equipment and skillful crew are employed. This normally leads to higher total cost of the project, thus z_{4i}^k and z_{2i}^k are inversely related (Adeli and Karim, 1997). Thus, the production option k is a critical variable to be optimized.

The z_{4i}^k and z_{2i}^k combinations for each production option *k* are illustrated in Figure 3.3 based on a discrete time-cost function (RS Means, 2006). In the figure, k=1 represents the point with the highest production time but lower maintenance cost. K=4, on the other hand, represents the point with the highest unit maintenance cost yet lowest unit production time. When previous data on the unit maintenance cost and the unit production time are available, the values of z_{4i}^k and z_{2i}^k can be computed to illustrate the specific project location.

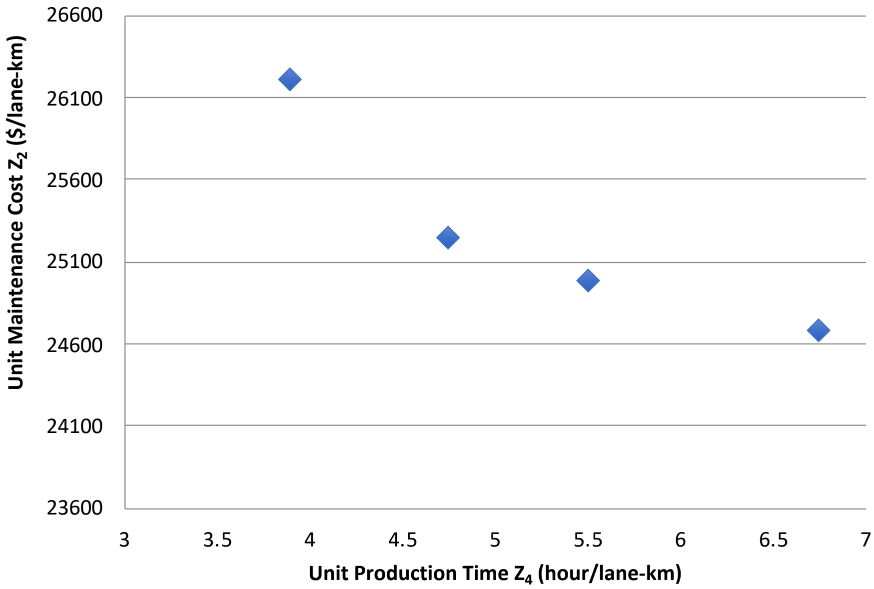

Figure 3.3 Unit production time and unit maintenance cost based on a discrete function.
Source: Tang and Chien, 2008

3.2.2 Idling Cost

The idling cost or cost for stopping maintenance is the cost incurred during work breaks if the crew and equipment are not being used in another work zone or assigned to other tasks. Work breaks are considered dummy links in the project where no activities are being performed. The corresponding length of a work break is equal to zero with a variable duration. Consequently, the idling cost is the production of the duration of work break and the average cost of idling. Hence the stopping maintenance work is calculated using the following equation (Chien et al., 2002).

$$C_{Ii} = v_d D_i \; = \; v_d \, (E_i - S_i) \qquad \forall i \tag{3.3}$$

where:

- v_d is the average idling cost per hour; and
- D_i is the duration of work zone i.

3.2.3 Road User Cost

The user cost is the cost incurred by drivers while passing through the work zone area. It consists of three major components: vehicle operating cost C_V, accident cost C_A, and user delay cost C_D. A weight factor p is assigned to the user delay cost to account for the magnitude of the user time value cost component as compared to the hard cash cost components. In this dissertation, p is considered equal to 1 unless mentioned otherwise. The user cost may then be calculated using the following equation:

$$C_U = \sum_{i=1}^{m} C_{Ui} = \sum_{i=1}^{m} (p\, C_{Di} + C_{Ai} + C_{Vi}) \qquad \forall i \qquad (3.4a)$$

Vehicle Operating Cost

The vehicle operating cost is the cost of operating the vehicle in the work zone area due to queuing conditions. It is considered as the additional cost to the one incurred without the occurrence of maintenance activities. It can be calculated by multiplying the queuing delay D_{Qi}^{j} by the vehicle operating cost v_o as illustrated in the equation below.

$$C_{Vi} = D_{Qi}\, v_o \qquad \forall i \qquad (3.4b)$$

where:

- D_{Qi} is the queuing delay associated with work zone i; and
- v_o is the vehicle operating cost. Chien and Tang (2014) calculated the additional vehicle operating cost to be \$0.91, \$1.01, and \$1.08 for cars, trucks with single units, and multiple-unit trucks, respectively.

When the percentage of heavy vehicles is known (Case B), the queuing delay D_{Qi} must be analyzed for heavy vehicles and passenger cars separately. This can be done by integrating the percentage of heavy vehicles into Equation (3.4b) through multiplying D_{Qi} by the corresponding percentage and the operating cost of heavy vehicles.

Accidents Cost

The accident cost takes into consideration the accident occurring in and adjacent to a work zone area.

$$C_{Ai} = \left(D_{Qi} + D_{Mi}\right) v_a\, r_a \qquad \forall i \qquad (3.4c)$$

where:

- D_{Qi} and D_{Mi} are the queuing and moving delays, respectively, of work zone i;
- r_a is the accident rate or the number of work zone accident per 100 million vehicle hours (McCoy and Peterson, 1987; Chien and Schonfeld, 2001); and
- v_a is the average cost per accident

Delay Cost

The delays caused by a work zone on a roadway are divided into the queuing delays and the moving delays.

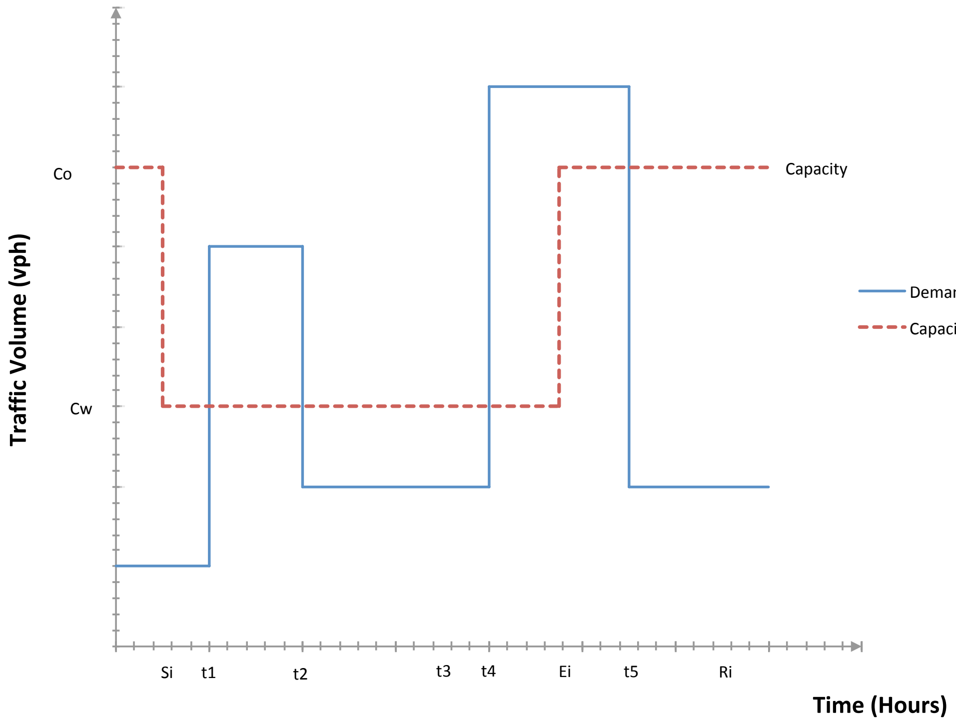

Figure 3.4 Traffic demand and capacity over time.

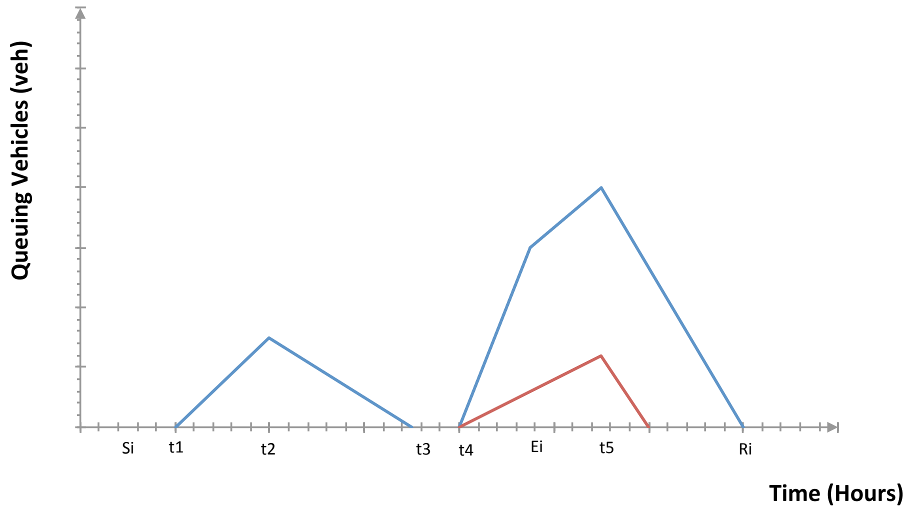

Figure 3.5 Queue formation and dissipation based on demand and capacity diagram over time.

Queuing Delay

The determination of queuing delay on highways is based on a time-dependent relationship between demand and capacity as shown in Figure 3.4 in which the capacity is represented by an orange line and the demand by a blue line.

The figure indicates that during a work zone and between the start S_i, and the end E_i ($[S_i, E_i]$) the capacity of a roadway drops from c_0 to c_w. Figure 3.5 represents the queue formation with time. The times at which the queue starts are represented by t_1 and t_4, where the demand exceeds the capacity of the roadway. The queue starts to dissipate at t_2 and t_5 when the demand drops below capacity. The queue is all cleared at times t_3 and R_i after the demand is below capacity.

The area below the orange line in Figure 3.5 is the existing queuing delay D_R, which starts at t_4 when the demand Q_4 is greater than the roadway capacity c_0. The total queuing delay however is the overall area below the blue lines in Figure 3.5. The demand Q is assumed to be uniform over a small interval of time j (e.g., 15 minutes). Hence, the queuing delay of work zone i within interval j is denoted by D_{Qi}^{j} and can be determined by multiplying the average number of vehicles in queue at the beginning and the end of interval j with the interval duration T. the number of vehicles at the beginning and the end of interval j are denoted by q_1 and q_2, respectively and can be calculated using the equation below:

$$q_2^j = \begin{cases} q_1^j + \left(Q^j - c\right) T & if \quad q_2^j > 0 \\ 0 & if \quad q_2^j \leq 0 \end{cases} \qquad \forall j \qquad (3.4d)$$

where:

- Q^j and c are the demand within interval j and the capacity, respectively;
- q_1^j and q_2^j are the number of vehicles at the beginning and the end of interval j; and
- T is the duration of interval j.

The queuing delay can then be calculated using the following formula:

$$D_{Qi}^j = \frac{q_1^j + q_2^j}{2} T \qquad \forall i, j \tag{3.4e}$$

The total queuing delay incurred between time t_1 and t_3, and t_4 and R_i can be derived as:

$$D_{Qi} = \sum_{j=Si}^{Ri} D_{Qi}^j = \sum_{j=Si}^{Ri} \left(\frac{q_1^j + q_2^j}{2} \right) T \qquad \forall i, j \tag{3.4f}$$

R_i is the time at which all queued vehicles are discharges and can be determined by calculating q_2^j iteratively until the queue is cleared.

Moving Delay

Moving delay due to work zone i (D_{Mi}) is the extra travel time incurred by the commuters caused by speed reduction within a work zone.

$$D_{Mi} = \sum_{j=Si}^{Ei} D_{Mi}^{j} = \left(\frac{E_i - S_i - z_3}{z_{4i}^{k}} + l_T\right)\left(\frac{1}{V_w} - \frac{1}{V_a}\right)\sum_{j=Si}^{Ei} min\ (Q^j, c_w)\ \ T \qquad \forall i, k \qquad (3.4g)$$

The delay cost can then be estimated as:

$$C_{Di} = (D_{Qi} + D_{Mi})\ v \qquad \forall i \qquad (3.4h)$$

where:

- D_{Qi} is the queuing delay due to work zone i;
- D_{Mi} is the moving delay due to work zone i; and
- v is the value of user time.

When the percentage of heavy vehicles is known, the queuing delay D_{Qi} and the moving delay D_{Mi} must be analyzed for heavy vehicles and passenger cars separately. This can be done by integrating the percentage of heavy vehicles into Equation (3.4h) through multiplying the delays by the corresponding percentage and value of user time for passenger cars and heavy vehicles. This will be analyzed in Case B.

Hence, the road user cost can be determined by:

$$C_{Ui} = \sum_{i=1}^{m} (p\, C_{Di} + C_{Ai} + C_{Vi})$$

$$= p\,(D_{Qi} + D_{Mi})\, v + D_{Qi} v_0 + (D_{Qi} + D_{Mi})\, r_a\, v_a \qquad \forall i$$

$$= D_{Qi}\,(p\, v + v_0 + r_a\, v_a) + D_{Mi}\,(p\, v + r_a\, v_a) \qquad (3.4i)$$

Finally, the total cost function can be calculated by integrating the maintenance cost, the idling cost, and the user delay cost in one equation (Equation 3.4i).

3.2.4 Emission Cost

Based on the "Work Zone Road User Costs" manual by FHWA (2011), vehicle emissions can be classified into two categories: air pollutant emissions and greenhouse gases. Reduced speed and queues due to work zone activities result in additional vehicle emissions causing adverse effects on the environment. The increase in vehicle emissions by emission type (R_e) due to work zones is affected by different factors, such as the type of the commuter's vehicle, the reduced speed in work zone areas, and the congestion due to queuing and detour.

In order to determine the emission rates at detailed level MOtor Vehicle Emission Simulator (MOVES3) is used. This is a state-of-the-art emission simulator developed by the U.S. Environmental Protection Agency (EPA) for estimating the emissions from highway vehicles. MOVES3 is used to accurately estimate the emissions from on-road vehicles with and without work zone conditions under user-defined project conditions. These conditions are the model's specifications, such as the time periods of the project, the on-road vehicle types, the pollutant types, and road types.

The monetary value of emission type (V_e) is determined based on the Highway Economic Requirements System State Version (HERS-ST) report (FHWA, 2005). HERS-ST provides dollar cost estimates per vehicle mile as a function of vehicle speed, vehicle type, and roadway functional class. The emission types that are mainly investigated are carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2), volatile organic compound (VOC), and fine particulate matter ($PM_{2.5}$). The monetary value of these emission types given from HERS-ST report (FHWA, 2005) are converted into 2021-dollar value through an inflation factor calculated from the website of Bureau of Labor and Statistics.

For different types of vehicles, once the emission rates are estimated, the emission cost is identified as a function of unit cost by emission type ($/ton) and vehicles miles traveled (VMT) such as:

$$C_{EMi} = VMT_i \times \sum_{e=1}^{r} (R_{ei} \times V_{ei}) \qquad \forall i \qquad (3.5a)$$

where:

- C_{EMi} = emission cost of work zone *i;*
- V_{ei} = cost per ton ($/ton) for emission type *e* in work zone *i;*
- R_{ei} = emission rate for emission type *e* in work zone *i* (ton/mile);
- VMT_i = vehicles miles traveled of work zone *i;* and
- r = the total number of emission types.

Thus, the emission cost (C_{Ei}) of work zone i is then obtained by subtracting the emission costs under work zone conditions from the recurrent emission cost, denoted by C_{EMi} and C'_{EMi}, respectively. Thus:

$$C_{Ei} = C_{EMi} - C'_{EMi} \qquad \forall i \qquad (3.5b)$$

Thus, the total cost function can be formulated by substituting Equations [3.2e, 3.3, 3.4h, and 3.5b] in Equation (3.1a).

3.3 Traffic Diversion

Due to work zone conditions, motorists may choose to avoid the congested segment on the mainline by taking an alternative route. In this study, two traffic diversion strategies are analyzed: The User Equilibrium (UE) and the System Optimum (SO).

Figure 3.6 represents the mainline, the alternative route, and the corresponding entrance and exit ramps. Link AD is the mainline route which can be divided into three segments during a work zone: the upstream work zone segment AB, the work zone segment BC, and the downstream work zone segment CD. The exit and entrance ramps of the mainline are AE and FD, respectively.

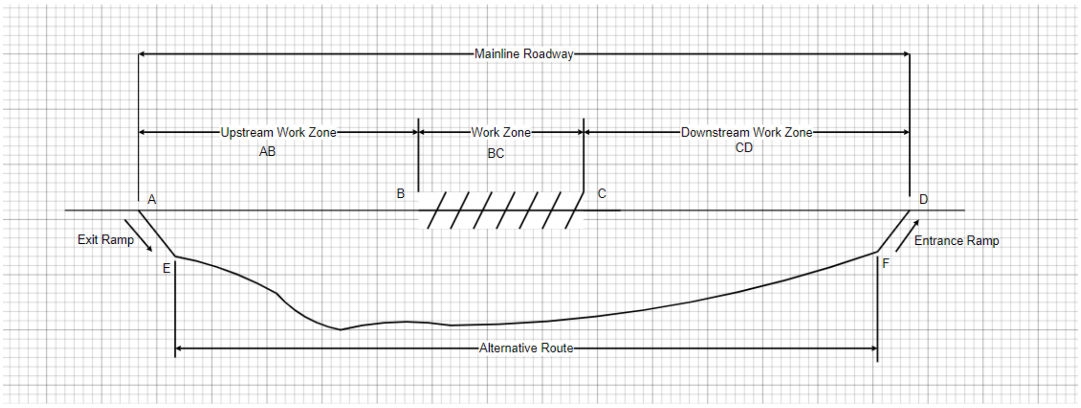

Figure 3.6 Work zone layout.

3.3.1 Travel Time on Mainline

The travel time of the mainline during an interval j (t_m^j) is the summation of the travel time on the three segments t_{AB}^j, t_{BC}^j, and t_{CD}^j

Travel time on link AB

The travel time on link AB can be calculated using the Bureau of Public Road (BPR) function:

$$t_{AB}^j = t_{AB}^0\left(1 + \alpha\left(\frac{Q_m^j - Q_d^j}{c_0}\right)^\beta\right) + t_q^j \qquad \forall j \tag{3.6a}$$

where:

- t_{AB}^0 and c_0 are the free-flow travel time on link AB and the capacity of the mainline, respectively;
- α and β are model parameters. Their typical values are $\boldsymbol{\alpha}$ = 0.15 and $\boldsymbol{\beta}$ = 4.0;
- Q_m^j is the existing flow on the mainline;
- Q_d^j is the diverted flow; and

- t_q^j is the average individual queuing delay within interval j, which represents the average waiting time in queue and can be derived as:

$$t_q^j = \frac{D_{Qi}^j}{(Q_m^j - Q_d^j)T} \qquad \forall j \tag{3.6b}$$

where:

- D_{Qi}^j is the total queuing delay (e.g., vehicle-hour) occurred during interval j due to work zone i; and
- T is the duration of interval j.

Calibration of $\boldsymbol{\alpha}$ *and* $\boldsymbol{\beta}$

Previous studies calibrate $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ based on the road classification. $\boldsymbol{\beta}$ (often set to 4) is the percentage increase of link travel time when demand is increased by one percent, and $\boldsymbol{\alpha}$ (often set to 0.15) is the ratio of travel time per unit distance at practical capacity to that at free flow. The standard values of $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$**,** or 0.15 and 4, respectively, will be used for Case A for model calibration purposes. Calibration statistics verify that the model is better calibrated using dynamic intersection delay (Jeihani et al., 2006).

Table 3.1 Parameters of the BRP Function

Road Type	Link Delay		Static Intersection Delay		Dynamic Intersection Delay	
	α	ß	α	ß	α	ß
Interstate	1.65	4	1.65	4	0.99	4
Limited Access Highway	0.33	3.9	0.33	3.9	0.2	3.9
Principal Arterial	1.1	3.9	1.1	3.9	0.66	3.9
Minor Arterial	0.39	3.9	0.39	3.9	0.23	3.9
Major Collector	0.28	3.9	0.28	3.9	0.17	3.9
Urban Local	606	3.9	6.6	3.9	3.96	3.9
Rural Major Collector	0.75	3.9	0.75	3.9	0.45	3.9
Ramps	0.33	3.9	0.33	3.9	0.2	3.9
Internal Dummy Load Link	0.66	5.3	0.66	5.3	0.4	5.3
External Dummy Load Link	0.66	5.2	0.66	5.2	0.4	5.2
Coordinated Signal	1.65	2	1.65	2	0.99	2

Source: Jeihani et al., 2006

Based on Assumption 6 in Section 3.1, the parameters of the BPR function will be based on the calibration of Jeihani et al., 2006. The case studies evaluated in this dissertation are considered under limited access highways with dynamic intersection delays. Thus, the values of $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ used in Case B are 0.2 and 3.9, respectively.

Travel time on link BC

The travel time within the work zone, t_{BC}^{j} is calculated using the following formula:

$$t_{BC}^{j} = \frac{l_i}{V_W^j} \qquad \forall i, j \tag{3.7}$$

where:

- l_i is the length of work zone i; and

- V_W^j is the work zone travel speed during interval j.

Travel time on link CD

The travel time on link CD can be calculated using the BPR function below:

$$\begin{cases} t_{CD}^j = t_{CD}^0 \left(1 + \alpha \left(\frac{Q_m^j - Q_d^j}{c_0} \right)^{\beta} \right) & if\ Q_m^j - Q_d^j \leq c_w \\ t_{CD}^j = t_{CD}^0 \left(1 + \alpha \left(\frac{c_w}{c_0} \right)^{\beta} \right) & if\ Q_m^j - Q_d^j > c_w \end{cases} \quad \forall j \tag{3.8}$$

where:

- t_{CD}^0 is the free flow speed on link CD; and
- c_w is the reduced capacity of the roadway due to work zone conditions.

Thus, the total travel time on the mainline (t_m^j) is derived as a function of the diverted flow such as:

$$t_m^j = t_{AB}^j + t_{BC}^j + t_{CD}^j \qquad \forall i \tag{3.9}$$

3.3.2 Travel Time on Alternative Route

The alternate route 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 the three links AE, EF and FD.

Travel time on link EF

The travel time on the link EF (t_{EF}^{j}) is a function of the diverted traffic from the mainline Q_d^j and can be calculated from the BPR function as:

$$t_{EF}^{j} = t_{EF}^{0}\left(1 + \alpha\left(\frac{Q_a^j + Q_d^j}{c_a}\right)^{\beta}\right) \qquad \forall j \tag{3.10}$$

where:

- t_{EF}^{0} and c_a are the free-flow travel time and capacity on link EF, respectively; and
- Q_a^j is the existing flow on link EF during interval j.

Travel time on ramps AE and FD

Travel time on exit ramp AE and entrance ramp FD (t_{ramp}) can be calculated as follows:

$$t_{ramp}^{j} = \frac{l_{AE} + l_{FD}}{V_T^j} \qquad \forall j \tag{3.11}$$

where:

- l_{AE} and l_{FD} are the lengths of the AE and FD ramps, respectively; and
- V_T^j is the average speed of the ramps during interval j.

$$t_a^j = t_{EF}^{j} + t_{ramp}^{j} \qquad \forall j \tag{3.12}$$

User Equilibrium Assignment

Upon including the traffic diversion into the optimization model, the objective function considering the US and the SO strategies remains to minimize the total cost with additional variations to the total cost components. Section 3.3 shows the delay cost component upon the integration of traffic diversion.

The UE strategy is applicable only when the travel time on the mainline exceeds the one on the alternative route due to the work zone. The state of equilibrium is reached when the travel time on the mainline is the same as on the alternative route within interval j after diverting the traffic. Such as:

$$t_m^j - t_a^j = 0 \qquad \forall j \tag{3.13}$$

Since both the travel time on mainline and alternative route are in function of the diverted traffic and since the demand within interval j is uniform, the diverted traffic Q_d^j can be optimized by solving Equation (3.13). The UE mechanism is shown in Figure 3.7.

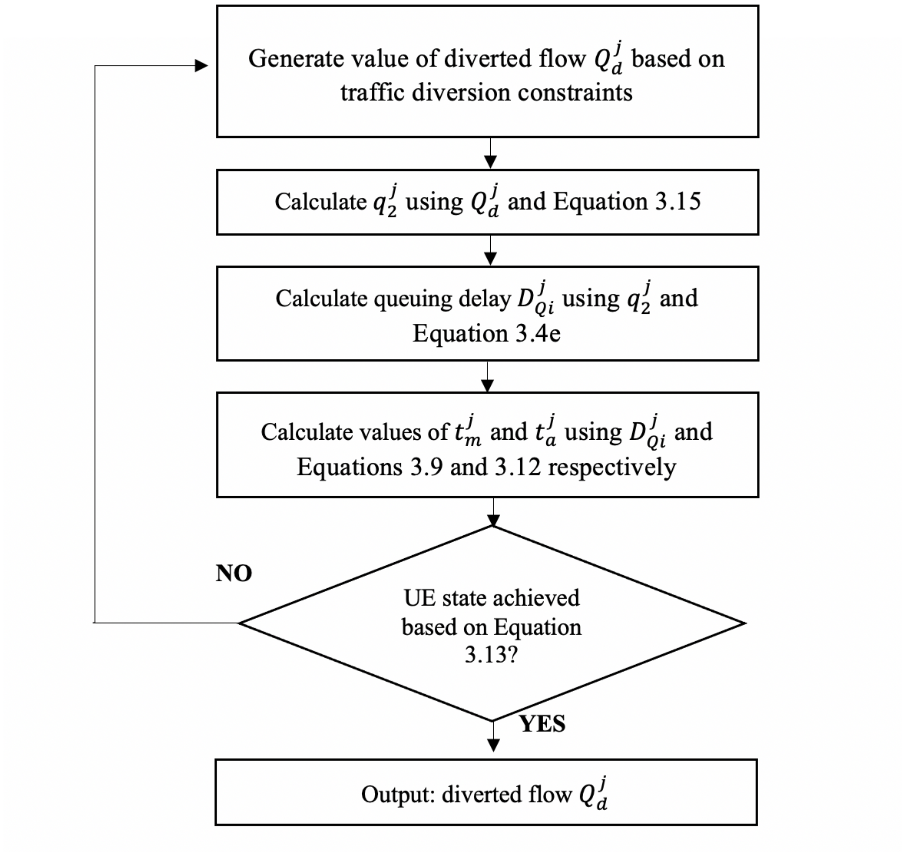

Figure 3.7 User equilibrium traffic assignment.

The travel time on both the mainline and the alternative route are affected by the diverted traffic Q_d^j. The optimized Q_d^j from Equation (3.13) will be used in Equations [3.6a, 3.6b, 3.8, 3.10, 3.15, 3.16, and 3.19] in order to determine the total cost components.

System Optimum Assignment

Assuming 100% compliance rate, based on the System Optimum (SO) approach, the traffic will be assigned in a way to minimize the total network travel time. Thus, the diverted traffic can be optimized by solving the below function:

$$\min t^j = t_m^j + t_a^j \qquad \forall j \tag{3.14}$$

where:

- t^j is the total travel time of the network during interval j;
- t_m^j is the travel time on the mainline during interval j; and
- t_a^j is the travel time on the alternative route during interval j.

The optimized Q_d^j from Equation (3.14) will also be used in Equations [3.6a, 3.6b, 3.8, 3.10, 3.15, 3.16, and 3.19] in order to determine the total cost components. The diagram below shows SO mechanism.

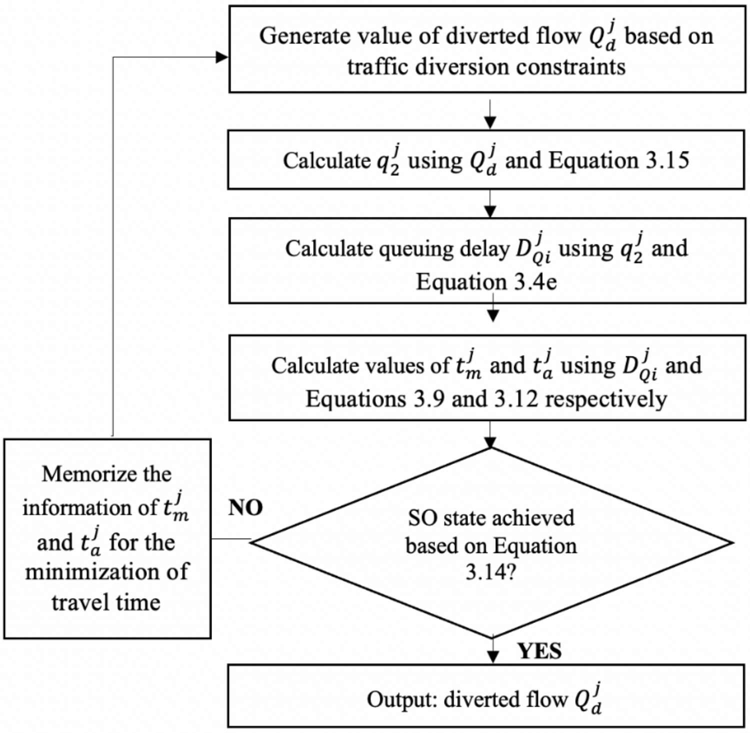

Figure 3.8 System optimum traffic assignment.

3.3.3 Queuing and Moving Delays Considering Traffic Diversion

After optimizing the diverted traffic flow Q_d^j, the queuing and moving delay in the system could be calculated as follows:

Queuing Delay with Traffic Diversion

Queuing delay can be calculated by integrating Q_d^j in the queuing delay equation (Equation 3.4e) by substituting q_2^j by:

$$q_2^j = \begin{cases} q_1^j + \left(Q_m^j - Q_d^j - c_w\right) T & q_2^j > 0 \\ 0 & q_2^j \leq 0 \end{cases} \qquad \forall j \tag{3.15}$$

Moving Delay with Traffic Diversion

The total moving delay on the mainline and alternative route can be obtained by comparing the travel time difference in between the two routes with and without a work zone. The total moving delay on mainline can be calculated as follows:

$$D_M^j = (Q_m^j - Q_d^j)(t_m^j - t_m^{j'}) \quad \forall j \tag{3.16}$$

where:

- t_m^j and $t_m^{j'}$ are the travel time on the mainline with and without a work zone, respectively; and
- $t_m^{j'}$ can be calculated using the BPR function:

$$t_m^{j'} = t_{AD}^0 \left(1 + \alpha \left(\frac{Q_m^j}{c_0} \right)^{\beta} \right) \qquad \forall j \tag{3.17}$$

The total moving delay on the alternative route D_A^j takes into consideration the moving delay caused by the existing flow Q_a^j on link EF and the diverted traffic flow Q_d^j.

The moving delay of the existing flow can be calculated as follows:

$$D_{EF}^{j} = Q_{a}^{j}\left(t_{EF}^{j} - t_{EF}^{j'}\right) \qquad \forall j \tag{3.18a}$$

where:

- t_{EF}^{j} and $t_{EF}^{j'}$ are the travel time on EF with and without considering the diverted flow Q_{d}^{j};
- $t_{EF}^{j'}$ can be obtained from the BPR function below:

$$t_{EF}^{j\prime} = t_{EF}^{0}\left(1 + \alpha\left(\frac{Q_{a}^{j}}{c_{a}}\right)^{\beta}\right) \qquad \forall j \tag{3.18b}$$

The moving delay of the diverted traffic can be calculated as follows

$$D_{d}^{j} = Q_{d}^{j}\left(t_{a}^{j} - t_{m}^{j'}\right) \qquad \forall j \tag{3.19}$$

The total moving delay on alternative route D_{A}^{j} is then:

$$D_{A}^{j} = D_{EF}^{j} + D_{a}^{j} \qquad \forall j \tag{3.20}$$

Thus, the delay cost of a work zone *i* can be calculated as:

$$C_{Di} = \left(D_{Qi} + D_{Mi} + D_{Ai}\right) v \qquad \forall i \tag{3.21}$$

where:

- v is the value of user time ($/veh-hr)

The objective function of the model while considering traffic diversion is to minimize the total cost including user, agency, and emission cost under the UE and the SO traffic assignment strategies.

3.4 Constraints

The objective function defined in Section 3.2 is subject to realistic constraints which set different conditions and boundaries for the optimized decision variables. When the decision variables satisfy the constraints, the solution suggested by the model is considered feasible. Four major constraints are used in this dissertation to comply with the realistic circumstances during work zone projects. Thus, the objective function defined in Equation (3.1) is subject to:

Maximum project duration: $$\sum_{i=1}^{m} D_i \leq D_x \quad (3.22)$$

Minimum activity duration: $$D_i \geq D_m \quad (3.23)$$

Project length specified by the user: $$\sum_{i=1}^{m} l_i^k = PL \quad (3.24)$$

Budget Constraint: $$\sum_{i=1}^{m} C_{Mi} + C_{Ii} \leq B \tag{3.25}$$

Where the maximum project duration, denoted by D_x, is determined by either the deadline of the project or contract terms. D_m is the minimum duration per activity and it differs between work zone activities and work breaks. The minimum work zone duration D_w is based on the fundamental work required in each work zone, such as the set-up time and the minimum work production. Whereas the minimum work break duration D_b may be identified by the duration of peak hours or the duration at which the crew may need to accomplish other activities. The number of work zone activities m is a variable to be optimized by the model. The length of each work zone is denoted by l_i^k . In addition, PL represents the total length of the project obtained by the summation of all work zone activities lengths. The approach of incorporating the constraints into the solution algorithm will be discussed in Chapter 4 Section 4.6.

Two case studies will be analyzed in Chapter 5 to validate the objective function and the corresponding constraints: Case A and Case B. The constraints used in each case study are based on the purpose of that study. Case A will only include three constraints: minimum activity duration, maximum project duration, and total project length. While Case B will also include the budget constraint. The purpose of Case A is to validate the model, while Case B will analyze a more complicated optimization problem with a bigger data set and budget limitation.

3.5 Summary

This chapter includes the formulation of the total cost objective function as well as the constraints. This total cost (C_T) consists of the maintenance cost (C_M), the idling cost (C_I), the user cost (C_U), and the emission cost (C_E). Each of the four major elements of the total cost function is the sum of costs of each maintenance work and stopped maintenance work, which are derived in Section 3.2. The user cost includes the delay cost, vehicle operating cost, and the accident cost. While the emission cost covers the additional emission due to work zone delays.

Section 3.3 covers the traffic diversion mechanism and the implementation of the BRP equation into the objective function as well as the total moving delay on the alternative route and the mainline. The diverted flow into the alternative route (Q_d^j) is estimated using the User Equilibrium and System Optimum traffic diversion strategies.

The objective function constraints are considered in Section 3.4 due to realistic limitations. These constraints are the total project length, the minimum activity duration, the maximum project duration and the budget constraint. The budget constraint is a limitation on the maintenance cost and the idling cost and will be implemented in Case B along with the vehicle emission standards.

The combinatorial work zone scheduling problem can be solved by employing the Artificial Bee Colony in order to find the optimized schedule of work zones with and without traffic diversion and emission cost. A metaheuristic algorithm such as the ABC is necessary due to the combinatorial interdependent relationship between the decision variable of the optimized problem. These variables are the starting time (S_i), the ending time (E_i), the productivity of the working crew (k_i), and the total number of work zones (m).

CHAPTER 4

SOLUTION ALGORITHM

The objective of this research is to minimize the total cost of work zone maintenance projects taking into consideration different decision variables such as the work zone starting time (S_i), ending time (E_i), production option of the crew (k_i) and total number of work zone activities (m). Due to the interdependency between the decision variables and the number of combinations they form, it is important to develop a solution algorithm that is able to find a near optimal solution.

In this study, the Artificial Bee Colony (ABC) algorithm is utilized as a solution algorithm to search for the optimal schedule of work zones in a maintenance project. ABC was first introduced by Karaboga (2005) as a global optimization algorithm able to deal with global optimization issues. The mechanism of the ABC is based on finding a parameter vector that optimizes the problem's objective function. ABC was based on a model proposed by Tereshko and Loengarov (2005) that studies the foraging behavior of honeybee colonies. The colony of the artificial bees consists of three types: (1) employed, (2) onlooker, and (3) scout. Furthermore, those artificial bees are intelligent enough to divide the work among each other by assigning appropriate tasks to each bee such as sharing information about the food source and looking for nectar.

The job of the artificial bee can be summarized by discovering the best solution vector that minimizes the objective function (e.g., S_i, E_i, k_i, m). The process begins by generating an initial population of solution vectors and iteratively ameliorates them through the policy of moving to a better solution by neighbor search mechanism while leaving the poor solutions behind (Karaboga, 2005). Additionally, the elements of the parameter vector in this dissertation consist of the total number of work zones (m), the starting (S_i) and ending time (E_i) of each work zone, the length of each work zone (l_i), and the parameter of crew production option (k_i).

A food source (X_f) is a possible solution to the problem under optimization. The employed bees' job is to exploit the food source. They hold information about this food source, its quality, location and direction from the nest. The employed bees communicate this information with the onlooker bees that are waiting in the hive through a waggle dance. The duration of the dance is related to the amount of nectar in the food source, the longer the dance the higher amount of nectar the food source has (Kalayaci and Gupta, 2013). In the ABC algorithm, the nectar amount depicts the quality of the solution.

The onlooker bees waiting in the hive watch the dances of the employed bees and make decisions on which food source to choose depending on the quality and quantity of the nectar. Hence, onlooker bees choose the more profitable food source to exploit and attract food sources with higher quality (Karaboga et al., 2014). Therefore, as the information circulation about the food sources increases, the probability of the onlooker bees choosing the more profitable food source increases. Afterwards, the onlooker bees become employed bees.

The scout bees are responsible for the exploration of new food sources. They are unemployed bees that randomly choose their food by exploring the hive for potential food sources (Kalayaci and Gupta, 2013). When a scout bee discovers a rich food source, it becomes an employed bee to this specific food source. There is only a single employed bee for each food source. If the selected food source is not improved after a predetermined number of trials (the limit), the food source is abandoned, and the employed bee becomes a scout bee that randomly explores food sources. This predetermined number of trials is called "limit" which is one of the three control parameters of the ABC. The other control parameters are the population size (number of employed and unemployed bees) and the maximum cycle number (stopping criterion of ABC). With that, ABC is characterized by very few parameters.

In every iteration, the employed bee searches the neighborhood for a nearby food source and evaluates its nectar amount. If the nectar amount of the adjacent food source is higher than the current one, the employed bee aims at the new food source and forgets the location of the current one. Otherwise, it remains in the same location and communicates the information to the onlooker bees.

The phases below represent the mechanisms of the bees in finding the optimal food source, which is in this dissertation the optimal work zone schedule.

4.1 Phases of ABC

In ABC, the position of a food source signifies a probable solution to the problem and the nectar amount of the food source represents the quality or fitness value of the corresponding solution. Additionally, the ABC algorithm is developed based on the following mechanisms and equations:

4.1.1 Initialization

The vectors of food sources population X_f's (f= $1 \ldots SN$, where SN is the population size) are initialized by scout bees. Each food source vector X_f represents n decision variables

($v = 1 \dots n$) to be optimized in order to return the least objective function. The representation of the solution vector of the developed ABC is presented in Section 4.3. In general, the initialization phase of each food source in ABC can then be executed using the following expression:

$$X_{fv} = l_v + rand\ (0,1)\ (u_v - l_v) \tag{4.1}$$

where:

- X_{fv} is the initial food source;
- l_v and u_v consists the lower and upper boundaries of the decision variables, respectively; and
- rand (0, 1) is a random number in the range [0, 1].

Those food sources are randomly assigned to the employed bees to evaluate their nectar quantity or fitness value.

The applicability of the initialization phase in the developed ABC to solve the work zone optimization problem is explained in Section 4.4.

4.1.2 Employed Bee

The employed bee's role is to find a new food source V_{fv} within the neighborhood of the food source assigned in the initialization phase X_{fv}. The determination of the new food source can be done using:

$$V_{fv} = X_{fv} + \text{Ø}_{fv}\ (X_{fv} - X_{Rv}) \tag{4.2}$$

where:

- X_{fv} is the initial food source;
- V_{fv} is a neighbor food source;
- X_{Rv} is a food source selected randomly; and
- $\emptyset_{fv}$ is a random number within the range [-1,1]

The employed bee calculates the fitness value of the initial X_{fv} and the neighbor food sources V_{fv} and performs a greedy selection where the food with best fitness value is chosen. This is the general interpretation of the neighbor search of the ABC. Problem specific interpretations are presented in Section 4.5 of this chapter.

4.1.3 Onlooker Bee

The exploration process of the ABC is further enhanced by the onlooker bees. The onlookers collect information about the food sources from the employed bees and choose one food source X_{fv} based on Equation (4.3). In this phase, the quantity of nectar of the food source is evaluated by its profitability compared to the profitability of other food sources. Consequently, onlooker bees choose a specific food source relying on probability values calculated after receiving information about the fitness values on employed bees. Hence, the roulette wheel selection method is used as a fitness selection technique using the following expression:

$$P_f = \frac{f(X_{fv})}{\sum_{f=1}^{SN} f(X_{fv})} \tag{4.3}$$

where:

- P_f is the profitability of the food source;
- SN is the number of initial generated population; and
- $f(X_{fv})$ is the fitness function value of X_{fv}.

After probabilistically choosing a food source X_{fv}, the onlooker bee modifies the food source and by generating a neighbor food source V_{fv} using Equation (4.2). Then again, a greedy selection is held between X_{fv} and V_{fv} and like in the previous phase, the food source with the best fitness value is chosen.

4.1.4 Scout Bee

The scout bee searches for random solutions using Equation (4.1) of the initialization phase. Employed bees become scout bees when their solution cannot be improved after a number of trials that have been predetermined. In this case, the abandoned food source is given negative feedback.

4.2 Mechanism of ABC

The mechanism of the ABC algorithm can be summarized as follows

1) Begin the optimization process by initializing the initial population vector of food sources X_{fv} (possible solution to the problem) using Equation (4.1)
2) Evaluate the initial population by employed bees by determining the amount of nectar (quality of the possible solution) and set the number of cycles g of running the ABC, g=1 (initially);

3) Find new food sources in the neighborhood by the employed bees (neighbor solutions) V_{fv} , using Equation (4.2);

4) Determine the amount of nectar in the neighbor solution V_{fv};

5) Greedy selection between initial X_{fv} and neighbor V_{fv} food source and choosing the one with the best fitness value;

6) Calculate the probability of the food source at which they are preferred by the onlooker bees and send the rest of the onlookers to the most profitable food source, using Equation (4.3);

7) Evaluate and keep the best food sources determined by the onlooker bee;

8) Stop the process of exploiting the food sources that are already abandoned by the bees after reaching the limit and replace them by new food source found randomly by the scout bee, using Equation (4.1);

9) Memorize the best food source (best solution to the problem);

10) Update cycle number, g = g +1; and

11) REPEAT until conditions are met, until g = maximum cycle number.

Below is a flow chart detailing the mechanism of the ABC algorithm

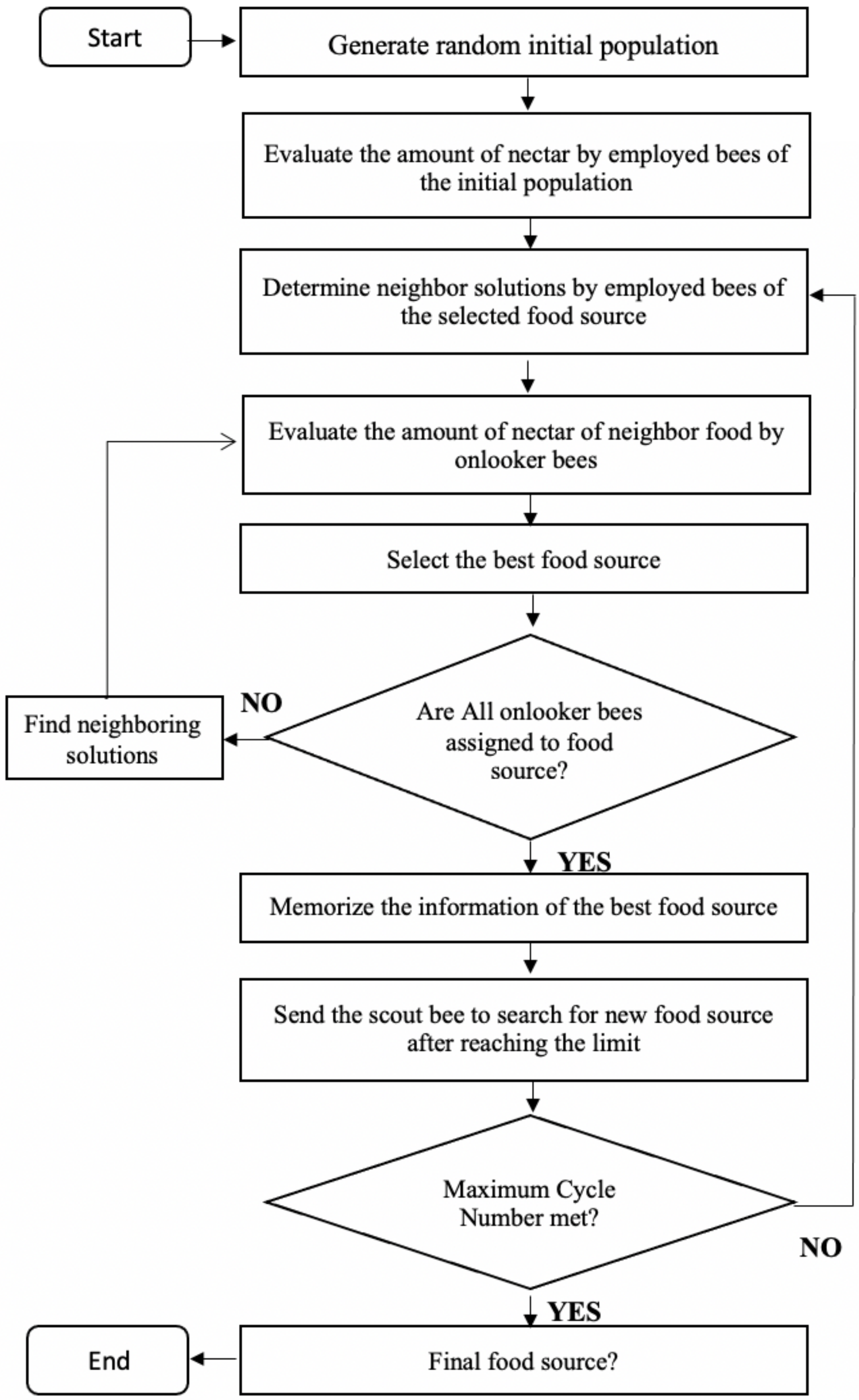

Figure 4.1 Flow chart of ABC algorithm.

4.3 Solution Representation

The work zone schedule solution of the developed ABC may be represented by a list of optimal solutions denoted by SL.

$$SL = \{(D_1, K_1), \dots, (D_i, K_i), \dots, (D_m, K_m)\} \tag{4.4}$$

Where D_i and K_i are the duration and the index of the production option of work zone i, respectively (i = 1 to m).

The starting time of the first work zone represented by S_1 is optimized based on the least total cost value of the project. The ending time of the work zone denoted by E_i can then be calculated using the following equation:

$$E_i = S_i + D_i \tag{4.5}$$

The list of optimal solutions SL can then be represented as follows:

$$SL = \{(S_1, E_1, K_1), \dots, (S_i, E_i, K_i), \dots, (S_m, E_m, K_m) \tag{4.6}$$

Where S_i and E_i are the start and end of work zone *i,* respectively. K_i is the production option index associated with each work zone *i* with K_i=0 representing a work break.

Each node in the SL represents a work zone with the total number of work zones m is equal to the number of the nodes in the SL.

4.4 Random Generation Method

As a first step, the above SL is generated randomly in the ABC algorithm, where the random generation method creates the initial space for the unemployed bee to search. After finding a good solution, a neighboring method is used in order to generate the most optimal solution within the objective function’s constraints. Hence, the random generation method is a random representation of the solution list where the decision variables follow a random generation.

A minimum duration of each work zone is required by construction practices. The total minimum duration of all work zone activities is generated randomly based on the user specified minimum duration as follows:

$$D_t = D_B \, R_B + (m - R) \, D_W \tag{4.7}$$

where:

- D_t is the total minimum duration of the project;
- R_B is the total number of work breaks in the SL;
- D_B is the minimum duration of work break;
- m is the total number of project activities (work zones and work breaks); and
- D_W is the minimum work zone duration.

Each work zone duration D_i is represented in 15 minutes duration block T. The total number of blocks can be calculated by subtracting the total minimum durations value D_t from the maximum duration of the project D_X such as:

$$n = D_X - D_t \tag{4.8}$$

Where n is the total number of 15 minutes blocks, D_X is the maximum duration of the project, and D_t is the total minimum duration calculated, in Equation (4.7).

The probability of each work zone is calculated as follows:

$$P_i = \frac{A_i}{\sum A} \tag{4.9}$$

where:

A_i is a random number from 1 to m corresponding to work zone *i* such as A_i= rand (1, m)

The duration of work zone activity i, other than the minimum duration, is represented by d_i such as:

$$d_i = n\, P_i \tag{4.10}$$

The total duration of each work zone D_i can then be calculated as follows:

$$D_i = d_i + D_{mi} \tag{4.11}$$

Where D_{mi} is the minimum duration of work zone *i* the value of D_{mi} changes depending on the type of the work zone. Such as, the minimum duration of a work zone D_W is different than the minimum duration of work break D_B .

4.5 Neighboring Method

As stated in Section 4.1, onlookers wait in the hive for information received from employed bees about the quality and location of the food source. After collecting the corresponding information through waggle dance, the onlookers choose a food source to exploit based on the richness of the source. The onlooker bees become employed bees. Their job is not only to exploit the corresponding food source, but also to search in the neighborhood of the food source for a new food source. Jason et al. (2018) defined the neighborhood of a solution as a set of solutions connected to the original solution.

In the developed model, the neighborhood of a solution is one in which the parameters of the solution vector change. The production option of the crew is an important control parameter of the work zone optimization problem. Employed bees that are exploiting a food source, try to look in the neighborhood for neighboring solutions by randomly modifying the production option k to another value between 1 and 4 different from the current value. Thereafter, the duration of the work zone and the corresponding length are modified based on the neighbor value of production option. The objective function's constraints are checked to avoid any violation using the constraint handling methods discussed in Section 4.6. In case of violation, the value of the production option is disregarded and a new search for another production option begins. In the case where all the possible production options are tested (k = 1 to 4) and the solution does not return a better fitness value, the solution is then abandoned, the location of the initial solution is memorized, and the employed bees become scouts; this is called the "limit" which is one important parameter of the ABC.

4.6 Constraint Handling Method

The objective function of the developed model is bounded by four constraints: (1) minimum duration of work activities D_m, (2) maximum project duration D_X, (3) total length of the project, and (4) budget constraint.

4.6.1 Minimum Work Activity Duration Constraint

The first constraint depicts the importance of keeping the duration of each work zone higher than a minimum value. The minimum duration of work break D_B is a parameter that may be specified based on the peak period duration or the time needed in case the work crew is scheduled to be reassigned to another work activity. The minimum work zone duration D_m however can be calculated using the following expression that is based on Equation (3.2b):

$$D_m = z_3 + z_{4i}^k l_m \tag{4.12}$$

where:

- D_m is the minimum work zone duration;
- z_3 is the time need to set and remove a work zone;
- z_{4i}^k is a production time associated with production option; and
- l_m is the minimum length of a work zone.

The neighbor function discussed in Section 4.5 might generate solutions with short durations that violate the minimum duration constraint. To fix this violation, the node could be added to its preceding or subsequent node.

If the node i is a work activity and its duration is less than the fixed time to setting and removing a work zone z_3, then this node should be removed, and its duration is added to the node $i-1$ or $i+1$. Therefore, the start and end time of the nodes should be updated. However, if the duration of the node i is greater than z_3. but less than D_m., node i might be repaired by taking additional duration from node $i-1$ or $i+1$. The start and end duration of work zones should also be updated. Additionally, if the node i is a work break and D_i. < D_B., then the node i is added to $i-1$ or $i+1$ and the start and ending time of the nodes is updated.

4.6.2 Maximum Project Duration Constraint

The maximum project duration constraint ensures that all project activities are completed within the required time period. For that, a maximum number of nodes N is implemented into the model as:

$$N = \frac{T_m}{T} \tag{4.13}$$

where:

- T_m is the maximum project duration
- T is the duration of time interval (15 minutes)

4.6.3 Total Project Length Constraint

The total project length constraint ensures that the optimized total sum of optimized work zone lengths (L) is equal to the project length (PL). If L > PL, the duration of the node at which PL > L is reduced, and its ending time is updated with Eq. 14 below.

$$E_i = E_i - (PL - L)\frac{z_4^k}{T} \tag{4.14}$$

where:

- PL = Actual total project length; and
- L = Total optimized work zone lengths such as $L = \sum p_i^k$ where p_i^k is the optimized length of work zone i.

The remaining nodes after E_i are merged in one node with k=0 (work break).

In case when $PL < L$, the shortage in project length may be compensated by increasing the work zone duration and decreasing the duration of work break, taking into consideration the maximum project duration. The first step would be to check if this repair is possible by converting all work breaks to working hours. If the total activity length PL is still less than the optimized project length L, then this solution is infeasible and may be discarded. Otherwise, the shortage in length may be distributed proportionally to work zones according to the length of each work zone segment. Consequently, the working hours of each work zone segment will then be extended to cover the additional working length.

4.6.4 Budget Constraint

When a budget limitation is applied, the budget constraint ensures that the maintenance cost and idling cost of the optimized schedule are below a certain amount. This amount is usually set by transportation agencies and it represents the out-of-pocket money they are willing to spend on the maintenance project.

If the maintenance and idling costs of the optimized schedule are above the budget, $\sum_{i=1}^{m} C_{M_i}^k + C_{I_i}^k \geq B$, the most expensive crew in the project is substituted with a less expensive crew. The maintenance cost is computed again and checked against the value of the budget. This process repeats until finding a feasible solution where $\sum_{i=1}^{m} C_{M_i}^{k} + C_{I_i}^{k} \leq B$ and the project duration is still below the maximum project duration value.

4.7 Control Parameters

It is very critical to find the set of control parameters that return the optimal solution for the ABC algorithm. These control parameters are the maximum cycle number, the population size, and the limit.

Previous studies have analyzed the behavior of ABC under different control parameter values. In 2007, Karaboga conducted a study on the performance of ABC and concluded that as the population size increases, the algorithm produces better results. Nevertheless, after an adequate value of population size, any increment in the value does not improve the performance of the ABC algorithm significantly. The same conclusion goes to the maximum cycle number. Additional analysis on the control parameters of the developed ABC are presented in Chapter 5.

4.8 Summary

In summary, this chapter includes detailed information about the development of the ABC algorithm. In comparison to other metaheuristic algorithms, ABC shows outstanding performance in finding optimal solutions to given problems for many reasons summarized below:

1) ABC is an algorithm inspired by the foraging behavior of honeybees. This behavior is characterized by a collective knowledge and intelligence of foraging bees, especially through exchanging essential information related to the food quality. Making the process of exploiting the good/rich food sources more efficient.

2) ABC is a global optimization algorithm, defined by evaluating a set of parameters (e.g., start time and end time of work zone, crew productivity, etc.) that optimizes the objective function, which minimizes the total cost of the project.

3) ABC is an algorithm proposed for the optimization of numerical problems (Karaboga, 2005), which makes it well suitable for the numerical optimization problem of work zone scheduling for minimizing the total cost.

4) ABC can be effectively used for solving both constrained and unconstrained optimization problems (Karaboga and Akay, 2009; Dominguez, 2009). The ability of ABC to flexibly deal with the problem constraints makes it a feasible solution algorithm for work zone optimization problems.

5) ABC engages only three control parameters: the limit, the maximum cycle number, and the population size (Karaboga, 2005).

6) Simplicity, flexibility and robustness. ABC is a simple and flexible algorithm that can be adjusted to adapt to a specific problem. It is also robust as the exploration and the exploitation are carried out together. While onlookers and employed bees exploit the food sources, the scouts are exploring the hive for other possible rich sources.

CHAPTER 5

CASE STUDIES

In order to study the effectiveness of the developed model, two numerical case studies are presented in this chapter. Case A validates the effectiveness and applicability of the model; and Case B proves the model's ability to handle more complicated optimization problems. The User Equilibrium and the System Optimum are used to study the effect of traffic diversion on work zone optimization. In addition, the implementation of the emission cost into the total cost function is evaluated. For this purpose, six scenarios are presented under Case A and four scenarios under Case B. Furthermore, sensitivity analyses are conducted to demonstrate the feasibility of real-life circumstances such as budget constraint, project duration limitations, and vehicle emission standards.

5.1 Case A

Case A represents the optimized work zone schedules associated with variable production options, time-dependent traffic diversions and emission cost. The six scenarios developed in Case A are presented in Table 5.1 such as:

- Scenario A.1: No traffic diversion and emission cost.
- Scenario A.2: With emission cost no traffic diversion.
- Scenario A.3: UE traffic diversion without emission cost.
- Scenario A.4: UE traffic diversion with emission cost.
- Scenario A.5: SO traffic diversion without emission cost.
- Scenario A.6: SO traffic diversion with emission cost.

Table 5.1 Case A Scenarios

Scenarios	Maintenance Cost	Idling Cost	User Cost	Emission Cost	Traffic Diversion	
					UE	SO
A.1	x	x	x			
A.2	x	x	x	x		
A.3	x	x	x		x	
A.4	x	x	x	x	x	
A.5	x	x	x			x
A.6	x	x	x	x		x

5.1.1 Input Parameters

The maintenance project consists of resurfacing a 5-km highway section with 2-inch asphalt concrete in Middlesex County. The work is conducted on a principal arterial road with 2 travel lanes per direction; one of them will be closed during maintenance work. While the results represent the optimized maintenance schedule on one travel lane, the optimized schedule of the other lane can be conducted following the same manner.

Table 5.2 summarizes the hourly volume distribution on the mainline and the alternative route in the work zone travel direction obtained from the Road User Cost Manual developed by the New Jersey Department of Transportation (2015). With that, the Average Annual Daily Traffic is 45,000 vehicles per day (vpd) on the mainline ($AADT_m$) and 25,000 vpd on the alternative route ($AADT_a$).

The capacity of the highway drops from 4,500 vehicles per hour (vph) to 1,200 vph upon one lane closure. Additionally, the posted work zone speed limit is 50 km/hour, the design speed is 80 km/hour, and the total length of buffer and taper is 0.4 km.

The fixed time to set and remove a work zone (z_3) is 2 hours and the related cost (z_1) is $1,000 per zone. The values of unit maintenance cost (z_2^k) and unit production time (z_4^k) for various production option values are presented in Table 5.4. These values are obtained from the Means Heavy Construction Cost Data 2006 (RS Means, 2006). The higher the production option, the more skillful the crew and the equipment are. Thus, a high maintenance cost is associated with a high production rate. Furthermore, the work breaks scheduled in between work zones incur an idling cost of $800 per hour. All input parameters are summarized in Table 5.3. It is worth noting that those values are adopted to validate the developed model without signifying any specific site.

Table 5.2 Hourly Traffic Demand for Case A

Hour	$AADT_m$ = 45,000	$AADT_a$ = 25,000
00:00-01:00	259	84
01:00-02:00	173	72
02:00-03:00	122	45
03:00-04:00	143	53
04:00-05:00	215	80
05:00-06:00	429	212
06:00-07:00	1077	627
07:00-08:00	1701	810
08:00-09:00	1915	742
09:00-10:00	1436	714
10:00-11:00	1102	663
11:00-12:00	1170	727
12:00-13:00	1283	788
13:00-14:00	1264	845
14:00-15:00	1308	816
15:00-16:00	1550	822
16:00-17:00	1588	760
17:00-18:00	1629	740
18:00-19:00	1311	764
19:00-20:00	994	705
20:00-21:00	725	529
21:00-22:00	670	456
22:00-23:00	497	348
23:00-24:00	367	276

Table 5.3 Input Parameters for Case A

Parameters	Descriptions	Values
$AADT_a$	The AADT on the alternative route	25,000 vpd
$AADT_m$	The AADT on the mainline	45,000 vpd
c_0	Capacity of mainline	4,500 vph
c_a	Capacity of the alternative route	1,700 vph
c_W	Capacity of mainline with work zone	1,200 vph
D_m	Minimum duration of work zone and work break	3 hr and 2 hr
T_M	Maximum project duration	64 hr
l_T	Total length of tapers and buffers	0.4 km
PL	Total project length	5 km
r_a	Crash rate average per 100 million veh-hr (100 mvh)	40 crashes/100 mvh
T	Duration of a time interval	15 mins
v	Value of user time	15 $/veh-hr
V_a	Design speed on the alternative route	55 km/hr
v_a	Average cost per crash accident	40,000 $/accident
v_d	Average idling cost per hour	800 $/hr
V_F	Design speed of mainline	80 km/hr
v_o	Additional vehicle operating cost	0.91 $/veh-hr
V_W	Average work zone speed	50 km/hr
z_1	Fixed setup cost	1,000 $/zone
z_2	Maintenance cost per lane-kilometer	$/lane-km (Table 5.4)
z_3	Fixed total time of setting and removing a work zone	2 hr/zone
z_4	Production time per lane-kilometer	hr/lane-km (Table 5.4)

Table 5.4 Unit Maintenance Cost and Time for Various Production Options

k	Daily Production 8 hr (yd^2)	Material Cost ($/$yd^2$)	Labor and Equipment ($/$yd^2$)	Total Cost ($/$yd^2$)	z_2^k ($/lane-km)	z_4^k (h/lane-km)
1	5,200	4.18	0.8	5.68	24,860	6.75
2	6,345	4.18	0.83	5.71	24,983	5.5
3	7,400	4.18	0.85	5.85	25,243	4.75
4	9,000	4.18	1.07	5.98	26,211	3.89

*Note: k is the production option, z_2^k is the unit maintenance cost, and z_4^k is the unit production time
Source: Means Heavy Construction Cost Data 2006 (RS Means, 2006)

5.1.2 ABC Control Parameters

It is very critical to find a set of control parameters that return an optimal solution of the developed model. The parameters of the developed ABC are the maximum cycle number, the population size, and the limit.

Maximum Number of Cycles

The maximum cycle number defines the maximum number of cycle searches in which the mechanism of employed bee, onlooker bee, and scout bee is repeated. Karaboga and Bastruk (2006) suggested a good value of the maximum cycle number to be 500. The study concluded that, depending on the function being optimized; the maximum cycle number varies with higher cycle number returns a better solution.

To determine the appropriate maximum cycle number in this study, a sensitivity analysis was conducted with a range of maximum cycle numbers from 10 to 2000 in increments of 10. The analysis concluded that a maximum cycle number of 500 is enough to reach a near optimal solution. This leaves the computation time of ABC to be 5 minutes.

Population Size

In justification of Karaboga (2007) findings, sensitivity analyses were conducted to determine the best population size to be applied. A range of population sizes from 10 to 200 with increments of 10 are tested. The results show that a population size of 100 is enough to return the least total cost value.

Limit

The “limit” defines a predetermined number of trials after which a solution, otherwise improved, is abandoned by the employed bee. After that, the employed bee is transformed into a scout bee.

In the developed work zone optimization model, the improvement of a current solution is made through a neighbor function that searches for a better production option for each work zone. Then a possible solution is not abandoned until all possible production options, for each work zone, are tested.

Numbers of Different Artificial Bees

Karaboga and Basturk (2006, 2007) defines the number of onlooker bees to be 50% of the population size and equal to the number of onlooker bees. While the number of the scout bee is sufficient to be 1 for each cycle. Hence, for the developed model, the designed initial population size is 100 with 50 employed bees, 50 onlooker bees, and 1 scout bee.

With 500 cycle runs and 64 hours of maximum project duration, a feasible solution comprehends 256 intervals of 15 minutes duration. The 500 runs take approximately 5 minutes on a 2.5 GHz Intel Core i5 with 4 GB 1600 MHz.

5.1.3 Scenario-based Analyses

Based on the above-mentioned input and control parameters, the scenarios of Case A are analyzed and presented herein. Each scenario presents a unique analysis under specific conditions.

Scenario A.1: No Traffic Diversion and no Emission Cost

In Scenario A.1 the traffic diversion from the mainline to the alternative route and the emission cost are not considered for optimizing the work zone schedule. Additionally, for comparison purposes the crash rate in Scenario A.1 is considered 0 crashes/100mvh; while the crash rate used in other scenarios is presented in Table 5.3.

The project under Scenario A.1 is suggested to finish in 36.25 hours, during which two work zones and one work break will be conducted. The schedule is optimized to avoid the periods with high traffic demand due to the absence of any congestion mitigation technique. Consequently, two work zones are scheduled during nighttime, while the break is assigned during daytime.

The optimal starting time is calculated by checking the total cost of each starting time, in 15 minutes intervals, and choosing the time that returns the least total cost. Table 5.5 shows that the optimal starting time is 6:45 pm, which is directly at the end of the afternoon peak period.

In accordance with the lack of congestion mitigation strategies, high production crews help expedite the work and reduce the potential traffic delays. Hence, high production option crews are assigned to the work zones (e.g., k_1=4 and k_2=3). Nonetheless, an over compressed project is not necessary in this case, which explains the utilization of crew 3 in the last work zone. It is worth noting that in this scenario, the work zone schedule is not optimized to minimize the emission cost. Nevertheless, under the current schedule, an emission cost of $101 is estimated based on the additional vehicle emissions due to different vehicle operation modes (e.g., idling, acceleration, deceleration) in the work zone.

Table 5.5 Optimized Results Under Scenario A.1

i	S_i - E_i	D_i (h)	l_i^k (km)	k	C_M (\$)	C_I (\$)	C_U (\$)	C_E (\$)	C_T (\$)
1	18:45-7:00	12.25	2.65	4	70,065	0	2,094	47	72,211
2	7:00 -18:00	11	0	0	0	8,800	0	0	8,800
3	18:00 - 7:00	13	2.35	3	59,457	0	2,766	54	62,321
Total		36.25	5.00	-	129,522	8,800	4,861	101	143,332

*Note: i is the work zone index, S_i and E_i are the starting and ending times, D_i is the duration, p_i is the length, k is production option, C_M is maintenance cost, C_I is idling cost, C_U is user delay cost, C_E is the emission cost, and C_T is total cost.

A comparison between GA and ABC is analyzed by Semaan et al. (2020) showing the efficiency of ABC in solving the work zone optimization problem.

Scenario A.2: No Traffic Diversion with Emission Cost

Scenario A.2 investigates the optimization of work zone schedule while considering the vehicle emission cost. For comparison purposes, the crash rate in Scenario A.2 is considered 0 crashes/100mvh; while the crash rate used in other scenarios is presented in Table 5.3.

In this scenario, the vehicle emission rates under normal and work zone conditions are estimated using the vehicle emission simulator MOVES3 and integrated into the developed model. As a result, the schedule is optimized to minimize multiple costs including the emission cost.

Table 5.6 Optimized Results under Scenario A.2

i	*Si - Ei*	*Di* (h)	l_i^k (km)	*k*	C_M ($)	C_I ($)	C_U ($)	C_E ($)	C_T ($)
1	19:30-07:00	11.5	2.44	4	65011	0	1,624	49.62	66,685
2	07:00-10:00	3	0	0	0	2400	0	0	2,400
3	10:00-13:00	3	0.21	3	6,314	0	881	1.14	7,197
4	13:00-19:00	6	0	0	0	4800	19	0	4,819
5	19:00-06:00	11	2.35	4	61,642	0	1,375	44.97	63,063
Total		34.5	5.00	-	132,968	7,200	3,900	95.72	144,164

*Note: *i* is the work zone index, S_i and E_i are the starting and ending times, D_i is the duration, p_i is the length, k is production option, C_M is maintenance cost, C_I is idling cost, C_U is user delay cost, C_E is the emission cost, and C_T is total cost.

Due to the absence of traffic diversion strategies in this scenario, the highest crews are implemented, and the project is recommended to finish as soon as possible to avoid potential delays and vehicle emissions. With that, crew 4 is assigned on the first and the last work zones, while crew 3 is assigned on the remaining work zone. Hence, the total project duration drops to 34.5 hours. A later start time (7:30 pm) is suggested here to avoid the periods with higher traffic demand.

When the emission cost is applied, a midday work zone period offers the flexibility to schedule the work during off-peak hours in general. This reduces the user cost without the need to extend the duration of the project. However, a queue is formed between 12 and 1 pm, where the second work zone extends, leading to $639 of queuing delay cost. Whereas all in all, we still encounter a reduction in queuing, moving, and vehicle operation cost. The latter is underlined by a 33% reduction of additional fuel consumption due to a decrease in the project duration, hence a decrease in the additional vehicle operation time.

Amongst the reduction of fuel consumption, the evaluation of the emission of CO, NO_x, SO_2, $PM_{2.5}$ and VOC show a saving of 5.3%. Even though this seems to be minor compared to other savings, the reduction of both fuel consumption and vehicle emission during the work zone is a saving of pollutants, smog, and greenhouse gases that cause health and global warming effects.

It is worth mentioning that the minimum duration of work zone activities in this study is considered to be 3 hours. This number may differ depending on the type of the project performed and the efficiency of the crew. Additionally, historical data of similar projects can be used to determine the value of the minimum activity duration. Consequently, this number can be updated to fit a specific project.

Scenario A.3: With UE Traffic Diversion and no Emission Cost

This scenario presents the optimization of the work zone schedule considering traffic diversion using the User Equilibrium (UE) strategy without the integration of the emission cost component into the objective function.

The optimized schedule of Scenario A.3 is presented in Table 5.7. The project is scheduled to start at 6 pm and last for 36.5 hours. A total of three work zones and two work breaks are scheduled upon the implementation of UE. Consequently, the suggested schedule, including one mid-day work zone, eliminates the need for extended idling hours hence significantly decreases the idling cost ($4,200).

It was found that production options 2 and 3 are sufficient to execute the work when traffic diversion using the UE strategy is in place. Accordingly, the implementation of traffic diversion eliminates the need of employing the highest productive crew to accomplish the work within a shorter time period.

In total, 805 vehicles are diverted from the mainline to the alternative route, which represents 9.89% of the mainline volume during the diversion periods. Those vehicles incur a moving delay cost on the alternative route of $655.58. While on the mainline, the values of queueing and moving delay costs caused by lane reduction and diversion of traffic are $552.09 and $3828.33 with a vehicle operating cost and crash cost of $52.18. It is worth mentioning that the diversion of the traffic onto the alternative route often causes an increase in the user delay cost due to the additional moving delays on both the mainline and the alternative route.

Table 5.7 Optimized Results Under Scenario A.3

i	S_i - E_i	D_i (h)	l_i^k (km)	k	C_M ($)	C_I ($)	C_U ($)	C_E ($)	C_T ($)
1	18:00-07:15	13.25	2.37	3	60,786	0	1515.73	51.43	62,121
2	07:15-9:15	2	0	0	0	1,600	47.92	0	1,648
3	09:15-14:30	5.25	0.68	3	18,272	0	1692.19	3.61	19,964
4	14:30-17:45	3.25	0	0	0	2,600	0	0	2,600
5	17:45-06:30	12.75	1.95	2	50,012	0	1832.33	41.92	51,844
Total		36.50	5.00	-	129,070	4,200	5088.18	96.96	138,358

*Note: i is the work zone index, S_i and E_i are the starting and ending times, D_i is the duration, p_i is the length, k is production option, C_M is maintenance cost, C_I is idling cost, C_U is user delay cost, C_E is the emission cost, and C_T is total cost.

Scenario A.4: With UE Traffic Diversion and with Emission Cost

Traffic diversion is usually based on the minimized travel time, either for the individuals or the entire system. This can be reflected by traveling on routes that are lengthier but quicker. However, taking the longer/faster route to reach a destination might result in higher energy consumption and increased vehicle emissions transmission into the atmosphere. Scenario A.4 investigates the optimization of work zone schedules taking into consideration traffic diversion based on the UE strategy and the emission cost. The results are shown in Table 5.8.

The model suggests a delayed starting time of the project following the implementation of emission cost to bypass a higher traffic demand period between 6 pm and 7 pm. The majority of the work, except 5 hours, are assigned to crew 3 which helps with the accomplishments of the tasks, hence decreases the total project duration.

A total of 570 vehicles were diverted from the mainline to the alternative route in order to minimize the delays on the mainline. Those vehicles are diverted in a way to minimize the individual vehicle's travel time while minimizing the total cost. The emission cost on the other hand, is being minimized by generating a schedule that returns the least cost, taking into consideration the additional emissions of the diverted traffic on the alternative route.

Table 5.8 Optimized Results Under Scenario A.4

i	***S_i - E_i***	***D_i* (h)**	**l_i^k (km)**	***k***	**C_M ($)**	**C_I ($)**	**C_U ($)**	**C_E ($)**	**C_T ($)**
1	19:00-07:00	12	2.10	3	54,143	0	801.03	41.84	54,986
2	07:00-9:30	2.5	0	0	0	2,000	0	0	2,000
3	09:30-14:30	5	0.55	2	14,627	0	1,412.58	2.65	16,042
4	14:30-17:45	3.25	0	0	0	2,600	0	0	2,600
5	17:45-06:45	13	2.35	3	60,255	0	1,602.97	49.32	61,907
Total		35.75	5.00	-	129,025	4,600	3,816.58	93.82	137,535

*Note: *i* is the work zone index, S_i and E_i are the starting and ending times, D_i is the duration, p_i is the length, k is production option, C_M is maintenance cost, C_I is idling cost, C_U is user delay cost, C_E is the emission cost, and C_T is total cost.

Scenario A.5: With SO Traffic Diversion and Without Emission Cost

This scenario optimizes the work zone schedule considering time-dependent traffic diversion using the System Optimum (SO) strategy discussed in Chapter 3. Herein, the emission cost is not considered in the optimization.

The optimized schedule shown in Table 5.9 indicates that the best starting time of the project is 6:15 pm. The total project duration is 35.75 hours, and the total number of work zones is three with two work breaks. While the three work zones occur during off-peak periods, SO traffic diversion strategy allows for one mid-day work zone (9 am-3:30 pm), which offers flexibility in scheduling the work especially when night-time cost factor is implemented. The other two work zones are scheduled during off-peak periods (6:15 pm-7:00 am and 6pm-6am) to avoid excessive delays on the mainline and the alternative route.

Table 5.9 Optimized Results Under Scenario A.5

i	S_i - E_i	D_i (h)	l_i^k (km)	k	C_M ($)	C_I ($)	C_U ($)	C_E ($)	C_T ($)
1	18:15-07:00	12.75	1.95	2	49,603	0	1,514.17	42.10	51,160
2	07:00-9:00	2	0	0	0	1,600	0	0	1,600
3	09:00-15:30	6.5	0.95	3	24,914	0	2,081.32	4.41	27,000
4	15:30-18:00	2.5	0	0	0	2,000	0	0	2,000
5	18:00-06:00	12	2.10	3	54,143	0	906.21	43.21	55,093
Total		35.75	5.00	-	128,661	3,600	4,501.70	89.72	136,852

*Note: i is the work zone index, S_i and E_i are the starting and ending times, D_i is the duration, p_i is the length, k is production option, C_M is maintenance cost, C_I is idling cost, C_U is user delay cost, C_E is the emission cost, and C_T is total cost.

In total 824 vehicles are diverted into the alternative route which accounts for 10.10% of the mainline volume during the diversion times. This causes a total of $324.38

and $3,471.72 of queuing and moving delays on the mainline, respectively. As for the alternative route, the diversion of traffic causes an additional cost of $669.72 of moving delays.

In this scenario, the emission cost that is generated by the proposed schedule is estimated to be $89.72. However, the schedule is not optimized to minimize the vehicle emissions and costs herein.

Scenario A.6: With SO Traffic Diversion and Emission Cost

The System Optimum (SO) traffic diversion approach aims to minimize the total system travel time hence guide the detour. When the emission cost is integrated into the objective function the diversion is guided in a way to minimize the total emission cost, hence decreasing the vehicle emission into the atmosphere. This scenario presents the optimization of the work zone schedule considering the time-dependent traffic diversion using System Optimum (SO) while considering the emission cost.

The optimal starting time of the schedule shown in Table 5.10 is still 6:15 pm. The crews 2 and 3 are also still suggested, with crew 3 assigned for the majority of the work. The work is scheduled to finish in 35.5 hours with a total cost of $136,197.

A change in the optimized project schedule in this scenario has shifted to work into the times with less traffic emission, with that 10.38% of the traffic during diversion periods is redirected to the alternative route. Those vehicles are enough to eliminate the queuing delay on the mainline, leaving $2,513.08 of moving delay cost only. On the alternative route however, the moving delay cost is accounted for $602.17. The total vehicle operating cost and crash cost are minimal compared to other costs ($10.38)

Table 5.10 Optimized Results Under Scenario A.6

i	S_i - E_i	D_i (h)	l_i^k (km)	k	C_M ($)	C_I ($)	C_U ($)	C_E ($)	C_T ($)
1	18:15-07:00	12.75	2.26	3	58,129	0	841.87	47.60	59,018
2	07:00-9:00	2	0	0	0	1600	0	0	1,600
3	09:00-15:00	6	0.73	2	19,169	0	1455.59	4.44	20,629
4	15:00-18:15	3.25	0	0	0	2600	54.82	0	2,655
5	18:15-04:45	11.5	2.01	3	51,486	0	773.69	34.49	52,294
Total		35.50	5.00	-	128,784	4200	3125.97	86.53	136,197

*Note: i is the work zone index, S_i and E_i are the starting and ending times, D_i is the duration, p_i is the length, k is production option, C_M is maintenance cost, C_I is idling cost, C_U is user delay cost, C_E is the emission cost, and C_T is total cost.

Table 5.11 Optimized Results for Various Scenarios of Case A

Scenario	$S_i - E_i$	D_i (h)	l_i^k (km)	k	C_M (\$)	C_I (\$)	C_U (\$)	C_E (\$)	C_T (\$)
A.1	18:45-7:00	12.25	2.65	4	70,065	0	2,094	47	72,211
	7:00 -18:00	11	0	0	0	8,800	0	0	8,800
	18:00 - 7:00	13	2.35	3	59,457	0	2,766	54	62,321
	Total	36.25	5.00	-	129,522	8,800	4,861	101	143,332
A.2	19:30-07:00	11.5	2.44	4	65011	0	1,624	49.62	66,685
	07:00-10:00	3	0	0	0	2400	0	0	2,400
	10:00-13:00	3	0.21	3	6,314	0	881	1.14	7,197
	13:00-19:00	6	0	0	0	4800	19	0	4,819
	19:00-06:00	11	2.35	4	61,642	0	1,375	44.97	63,063
	Total	34.5	5.00	-	132,968	7,200	3,900	95.72	144,164
A.3	18:00-07:15	13.25	2.37	3	60,786	0	1515.73	51.43	62,121
	07:15-9:15	2	0	0	0	1,600	47.92	0	1,648
	09:15-14:30	5.25	0.68	3	18,272	0	1692.19	3.61	19,964
	14:30-17:45	3.25	0	0	0	2,600	0	0	2,600
	17:45-06:30	12.75	1.95	2	50,012	0	1832.33	41.92	51,844
	Total	36.50	5.00	-	129,070	4,200	5088.18	96.96	138,358
A.4	19:00-07:00	12	2.10	3	54,143	0	801.03	41.84	54,986
	07:00-9:30	2.5	0	0	0	2,000	0	0	2,000
	09:30-14:30	5	0.55	2	14,627	0	1,412.58	2.65	16,042
	14:30-17:45	3.25	0	0	0	2,600	0	0	2,600
	17:45-06:45	13	2.35	3	60,255	0	1,602.97	49.32	61,907
	Total	35.75	5.00	-	129,025	4,600	3,816.58	93.82	137,535
A.5	18:15-07:00	12.75	1.95	2	49,603	0	1,514.17	42.10	51,160
	07:00-9:00	2	0	0	0	1,600	0	0	1,600
	09:00-15:30	6.5	0.95	3	24,914	0	2,081.32	4.41	27,000
	15:30-18:00	2.5	0	0	0	2,000	0	0	2,000
	18:00-06:00	12	2.10	3	54,143	0	906.21	43.21	55,093
	Total	35.75	5.00	-	128,661	3,600	4,501.70	89.72	136,852
A.6	18:15-07:00	12.75	2.26	3	58,129	0	841.87	47.60	59,018
	07:00-9:00	2	0	0	0	1600	0	0	1,600
	09:00-15:00	6	0.73	2	19,169	0	1455.59	4.44	20,629
	15:00-18:15	3.25	0	0	0	2600	54.82	0	2,655
	18:15-04:45	11.5	2.01	3	51,486	0	773.69	34.49	52,294
	Total	35.50	5.00	-	128,784	4200	3125.97	86.53	136,197

- Due to lack of all mitigation strategies, reducing the emission cost in Scenario A.1 would require assigning the highest efficiency crew (e.g., k=3 and 4) to both work zones. Scenario A.2 suggests dividing the project into five work zones and mixing between crews 3 and 4 to finish the project as soon as possible. Consequently, smaller work zones durations along off-peak periods are recommended. A saving of 5.3% in the emission cost 33% in the vehicle operating cost and 20% in the user cost are observed in Scenario A.2 by integrating the emission cost. With that, the schedule is optimized to avoid periods with high traffic delays and vehicles emissions.

- As compared to Scenario A.1, the UE strategy in Scenario A.3 allows for a mid-day work zone activity and eliminates the need for long work breaks which consequently decreases the idling cost. The less productive crews (e.g., k=2, k=3) are found to be efficient when diversion is in place leading to lower maintenance cost as compared to Scenarios A.1. However, higher user cost is observed due to the additional moving delays on both the mainline and the alternative route. Nevertheless, this increase in user cost is compensated by a significant decrease in the idling and maintenance cost, resulting in lower total cost.

- The results of Scenario A.4 highlight the efficiency of integrating the emission cost when traffic diversion is in place. Using the UE strategy, the results of Scenario A.4 represent savings on the emission cost, user cost, and total cost through a reduction in the number of the diverted vehicles. Hence, the traffic herein is diverted to the path that returns the least individual travel time yet also accounts for vehicle emissions.

- By comparing the results of the SO strategy in Scenario A.5 to the UE strategy in Scenario A.3, a conclusion can be drawn: the similar travel time between the mainline and the alternative route suggested by the UE strategy does not certainly reflect the least total cost and optimized schedule. The total project duration suggested by the SO strategy is smaller, leading to a reduction in maintenance and idling costs. More vehicles are diverted into the alternative route using the SO strategy to minimize the total system travel time. The increase in the moving delays on the alternative route is compensated by a decrease in both queuing and moving delays on the mainline. Hence, the SO strategy suggests a schedule with less duration and total cost than the UE strategy.

- In Scenario A.6, the implementation of the emission cost and the SO strategy simultaneously has resulted in a decreased user cost, emission cost, and total cost. The diverted traffic in Scenario A.6 is less than Scenario A.5, which highlights the possibility of increased emissions with the diversion, especially when the alternative route's length is similar to the mainline with a speed greater than the work zone speed.

5.1.4 Sensitivity Analyses

Sensitivity analyses were conducted to investigate the relationship among decision variables and model parameters. The analyses delivered in this study provide helpful guidelines for transportation agencies to account for while optimizing the work zone schedules.

Maximum Project Duration

Different values of AADT are investigated as the maximum project duration varies in between 40 and 92 hours. The results shown in Figure 5.1 evaluates a range of AADT from 40,000 vpd to 50,000 vpd. The analysis shows that as the MPD increases from 40 hours to 92 hours, the minimum total cost generally decreases. The figure illustrates the threshold boundaries in which the minimum total cost is exposed to major decrease. This threshold is defined in between MPD 48 and 58 hours. Therefore, especially on roadways with higher AADT, an increase in the MPD from 48 to 58 hours can cause a significant decrease in the minimum project total cost since more time is offered to schedule the work zones. Any change in the MPD below 48 hours and above 58 hours does not have a considerable effect of the minimized total cost. These two boundaries can help transportation agencies in making the appropriate judgments corresponding to the MPD that leads to the best total cost. This analysis is excluding the traffic diversion and using Scenario A.2.

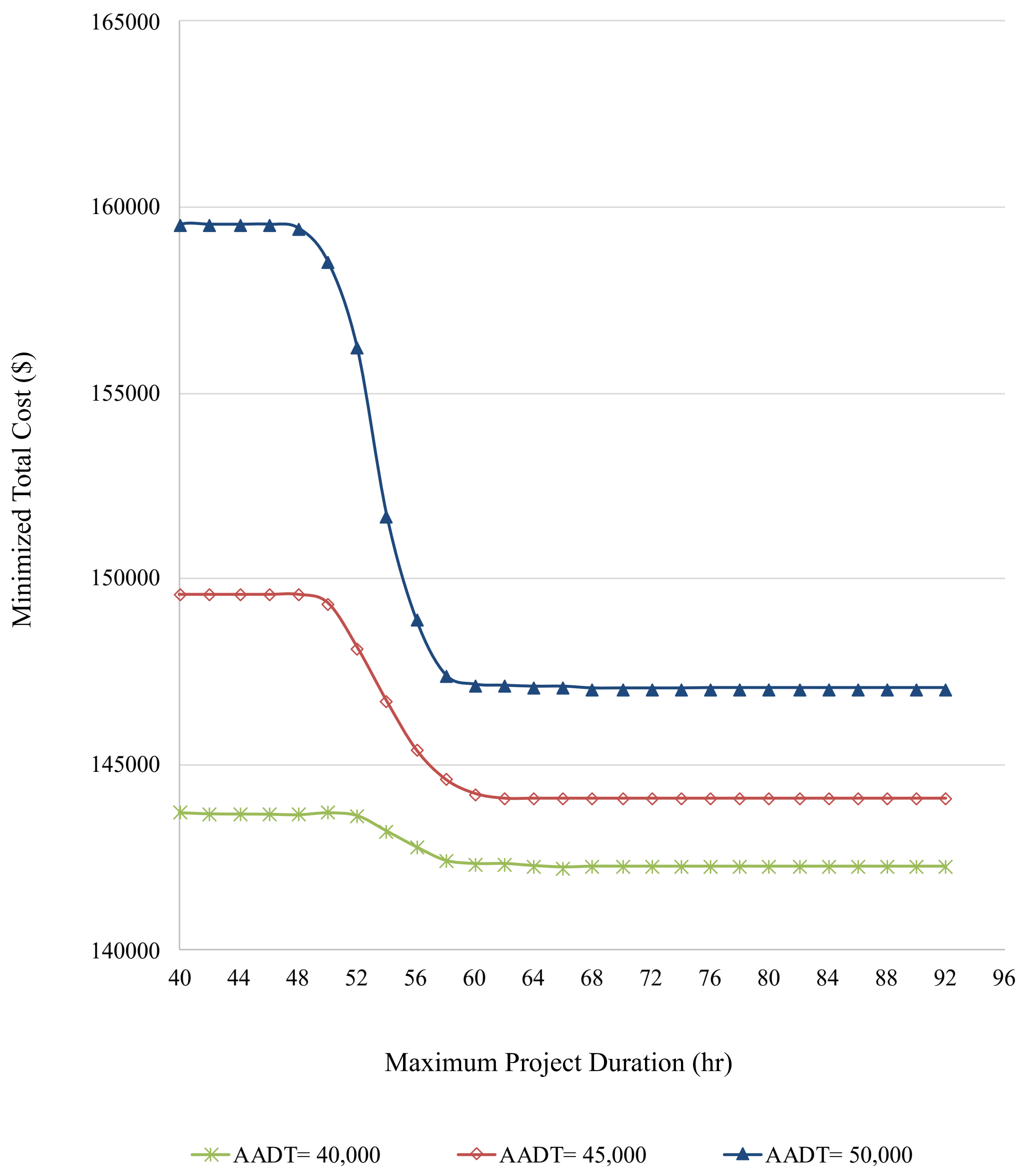

Figure 5.1 Minimized total cost vs maximum project duration for various AADT.

Cost of Vehicle Emission

The cost of vehicle emission can be referred to as the monetary value of the damage caused by vehicle emissions to human health and environment. Sensitivity analysis was conducted by evaluating the increase of emission cost by 5% and 10% while fixing the AADT to be 45,000 vpd.

The results shown in Figure 5.2 indicates that the total cost of the project tends to increase with the upsurge of the vehicle emission cost. While the MPD varies between 40 and 92 hours, the thresholds that determine the boundaries of the minimized total cost change are almost the same. Any change in the maximum project duration below 48 hours and above 58 hours will not significantly change the minimized total cost as the optimized schedule has already been reached.

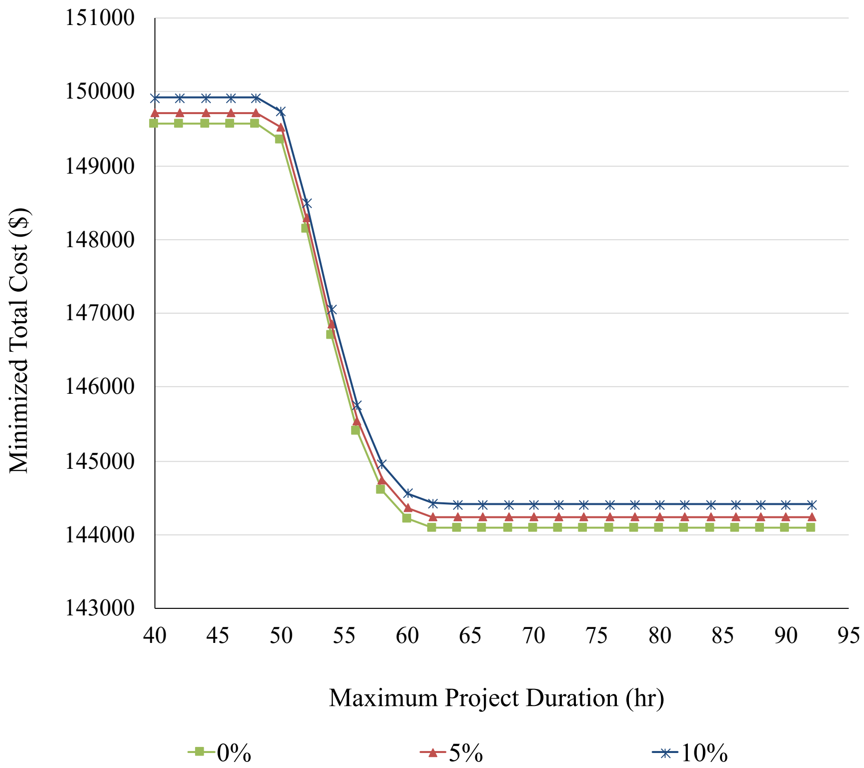

Figure 5.2 Minimized total cost vs maximum project duration under various emission cost increase.

5.2 Case B

The applicability of the model to a real case study is evaluated in Case B. The purpose of this section is to present a more complicated case study than the one evaluated in the previous section in which the work zone data are provided by the New Jersey Congestion Management System (NJCMS) and integrated into the model. Work zone schedules are developed based on emission cost analysis while integrating the traffic diversion using both the UE and the SO strategies.

Below is a list of potential work zone data provided by the NJCMS and the New Jersey Department of Transportation (NJDOT):

Table 5.12 Sample Pavement Rehabilitation Projects

Site	Location	Description
I-78	MP 48 to 52 EB/WB	Closing 1 lane,11pm-6am, 06/07/18-06/09/18
I-78	MP 26.5 to 31.4 WB	Closing 1 lane,8pm-6am, 4/9/18-4/10/18
I-80	MP 53.6 to 54.7 EB/WB	Shoulder/right lane closure, 9pm -5am, 06/20/18 06/22/18
I-80	MP 27.5 to 28.8 EB	1 lane closure, 9pm- 5am, 04/09/2018 -04/12/2018
I-80	MP 53.2 to 53.8 EB/WB	1 lane closure, 9pm -6am, 06/22/2018-06/25/2018
I-80	MP 45.3 to 52.5 EB	1 lane closure, 9pm- 5am, 07/ 20/2018-07/22/ 2018
I-80	MP 40 to 43 EB	1 lane closure, 9pm-5am, 04/30/2018-05/12/2018
Route 40	MP 5.73 to 8.1 EB/WB	1 lane closure 9pm-5am, 07/24/2012- 08/13/2012

Source: CoVal Systems. Introduction to OpenReach: http://www.covalsystems.com/latest/openreach/openreach.html. Retrieved September 2020.
State of New Jersey Department of Transportation. https://www.nj.gov/transportation/. Retrieved August 2020

The list of possible options is evaluated against a set of criteria to choose the most appropriate case study for this section. Below is the list of criteria for choosing the case study:

- A short-term pavement rehabilitation project which can be divided into smaller work zones with lane closure.
- An alternative route available for diverted traffic from the mainline if needed.
- The work zone data shall be accessible through NJCMS and NJSLD.

Based on the above-mentioned criteria, one work zone is found to meet the acceptable standards in this section: I-80: MP 45.3 to 52.5 EB. Consequently, Case B is conducted based on a work zone project on I-80 Eastbound in New Jersey. The work zone is illustrated in Figure 5.3 and located between mileposts 45.3 and 52.5. In addition, the project consists of rehabilitating a 11.6 km-long segment between the 20th (Wednesday) and 22nd (Friday) of July 2018. From the available data, the work was scheduled over a nighttime period between 9 pm and 5 am to avoid excess traffic demand during daytime hours by closing one lane out of three.

When needed, a percentage of the mainline traffic can be diverted into an alternative route located on US-46 from milepost 48.3 to 56.3 via an exit ramp (Exit 45 on I-80 shown in Figure 5.4) and then back to I-80 via an entrance ramp shown in Figure 5.5.

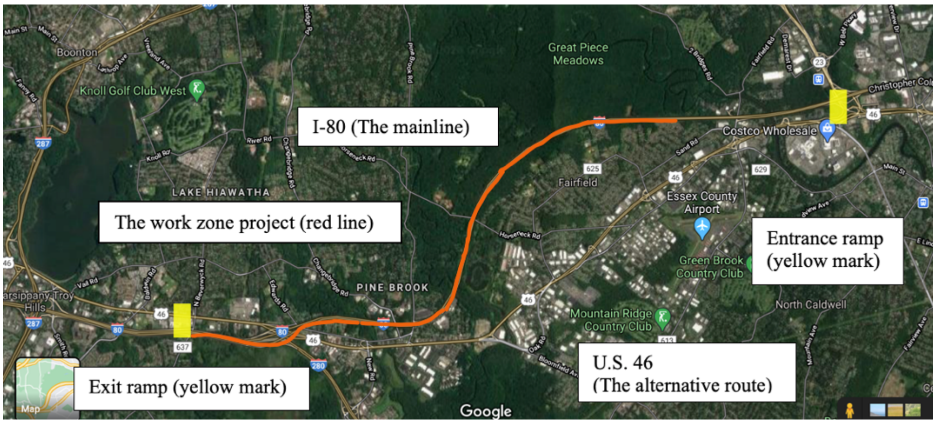

Figure 5.3 Location of the work zone on I-80.
Source: Google. (2020). I-80. Retrieved from [https://www.google.com/maps on December 2020](https://www.google.com/maps)

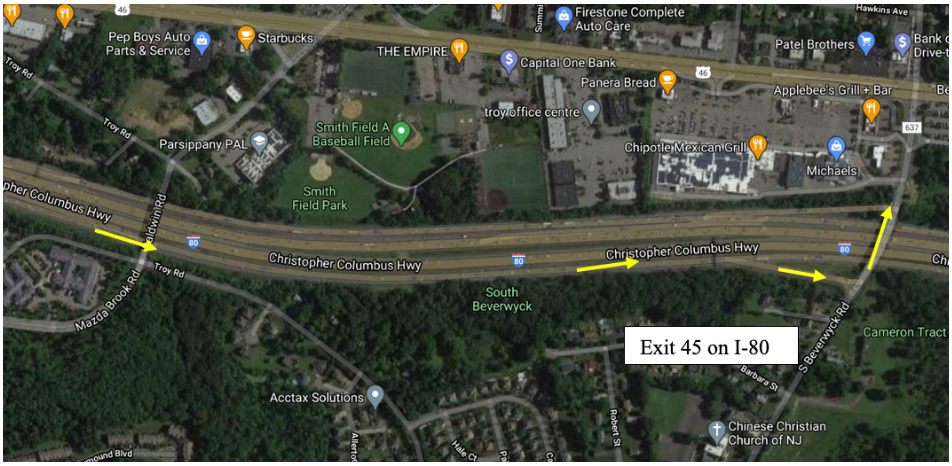

Figure 5.4 Exit route from I-80 to the U.S. 46.
Source: Google. (2020). I-80. Retrieved from [https://www.google.com/maps on December 2020](https://www.google.com/maps)

Figure 5.5 Return route to I-80 from U.S. 46.
Source: Google. (2020). U.S. 46. Retrieved from https://www.google.com/maps on December 2020

The length of the exit ramp, measured from the point the vehicles exit I-80 to the point they enter U.S. 46, is 0.33623 km and the speed limit on the ramp is 40 mph. The entrance route shown in Figure 5.5 is through NJ-23 from milepost 5 to 5.5 where the speed is 40 km/hr.

5.2.1 Data Collection and Input Parameters

In order to optimize the work zone schedule for Case B, data from various sources are needed to formulate the model's input parameters. Three major databases are used:

1. New Jersey Congestion Management System (NJCMS): used to develop effective database of the hourly traffic volume on the mainline (I-80) and the alternative route (U.S.46), as well as the corresponding amount of passenger cars and trucks;

2. New Jersey Straight Line Diagram (NJSLD): used to retrieve information about the road type, geometry, and configuration in between the corresponding mainline and alternative route's mileposts.

3. OpenReach: Used to find information on the work zone type, location, starting/ending time, duration, number of lanes closed, and length.

The traffic on the mainline and the alternative route per approach (all lanes) for passenger cars and trucks are presented in Table 5.13. A passenger car equivalent factor for trucks (E_t) is needed in order to convert the number of trucks into passenger cars under prevailing roadway conditions. Consequently, the number of trucks will be adjusted to an equivalent number of passenger cars that occupy the same capacity on the highway. The value of E_t for a level terrain is 2.0 (HCM, 2016).

Table 5.13 Hourly Traffic Demand on Mainline (I-80 EB) and Alternative Route (U.S. 46 EB)

Hour	I-80 EB			U.S. 46 EB		
	Passenger cars	**Trucks**	**Hourly Traffic Demand (veh/hr)**	**Passenger cars**	**Trucks**	**Hourly Traffic Demand (veh/hr)**
00:00-01:00	499	37	482	116	8	112
01:00-02:00	339	25	328	61	4	59
02:00-03:00	315	23	304	37	3	36
03:00-04:00	333	24	321	40	3	39
04:00-05:00	428	31	413	63	4	60
05:00-06:00	310	23	300	113	8	109
06:00-07:00	1031	76	996	557	40	537
07:00-08:00	3287	242	3176	1372	98	1323
08:00-09:00	3595	265	3474	1750	125	1688
09:00-10:00	2309	170	2231	1183	84	1140
10:00-11:00	1244	120	1228	931	78	908
11:00-12:00	1343	123	1319	1048	84	1019
12:00-13:00	1690	150	1656	1367	94	1315
13:00-14:00	1679	152	1648	1305	112	1275
14:00-15:00	1498	133	1468	1236	104	1206
15:00-16:00	1740	123	1677	1301	100	1261
16:00-17:00	3343	177	3168	1468	84	1397
17:00-18:00	3610	177	3408	1650	90	1566
18:00-19:00	2387	176	2307	1383	99	1334
19:00-20:00	1191	88	1151	1035	74	998
20:00-21:00	945	70	914	744	53	717
21:00-22:00	1026	76	992	588	42	567
22:00-23:00	890	66	860	409	29	394
23:00-24:00	673	50	651	238	17	230
Sum	35705	2597	34472	19995	1437	19289

Source: New Jersey Department of Transportation. New Jersey Congestion Management Systems. 2015. https://www.state.nj.us/transportation/refdata/sldiag/. Retrieved September 2020.

As mentioned earlier, the hourly traffic demand of the mainline and the alternative route of the eastbound travel direction in vehicles per hour are represented in Table 5.13.

The demand is calculated by multiplying the flow rate (pc/hr) by the factor of heavy vehicle and the driver adjustment factor (HCM, 2016).

The capacity values are obtained from the NJCMS data such as the capacity on the mainline (I-80) is 5,236 veh/hr and the capacity the alternative route (U.S. 46) is 2,465 veh/hr. The reduced capacity of the mainline after lane closure can be calculated by finding the baseline capacity value per lane of a work zone. The values of baseline work zone capacities are found in the Highway Capacity Manual (HCM, 2016) and shown in Table 5.1. This table represents the reduced capacity of the roadways due to lane closure in vehicles per hour per lane. The capacity values are based on the original number of lanes without a work zone (before the work zone) and the number of lanes available for traffic after implementing the work zone. The capacity under work zone conditions is then 2,900 veh/hr

Table 5.14 Work Zone Capacities under Various Configurations (in veh/hr/ln)

Capacity (veh/hr/ln)	1-Lane Closure	2-Lane Closure	3-Lane Closure
2 Lanes Road	1,400	NA	NA
3 Lanes Road	1,450	1,450	NA
4 Lanes Road	1,350	1,450	1,500
Average	1,400	1,450	1,500

Source: Highway Capacity Manual (2016). TRB, National Research Council, Washington, D.C.

The speed limit on I-80 and U.S. 46 (unrestricted speed) is 65 mph and 50 mph, respectively. Based on the guidelines of the Federal Highway Administration, the regulatory reduction of the work zone speed limit, for short-term work zones that are longer than 0.5 miles, is 10 mph. Thus, the reduced mainline speed due to the work zone is 55 mph (FHWA, 2010). Since the posted speed (S) on I-80 is 104.6 km/hr (65 mph) and the standard lane width of the interstate highway in the U.S. is 3.65 m, the taper length based on Equation (3.2c) is 0.25 km. Consequently, the total taper length 0.5 km.

The average operating cost is estimated to be $0.1819/ veh-hr for cars, $0.2017/veh-hr for single unit trucks and $0.2166/veh-hr for combination trucks (FHWA, 2017). These values are converted into a current dollar value (2021-dollar value) based on inflation factor calculation from the Bureau of Labor Statistics. The estimated additional operating cost is then $1.25/veh-hr for cars, $1.39/veh-hr for single unit trucks, $1.49/veh-hr for combination trucks, and $1.44/veh-hr as an average for all trucks. The additional vehicle operating cost for trucks and passenger cars as well as the queuing and moving delay costs are estimated based on the hourly proportion of heavy vehicles.

The idling cost, on the other hand, is estimated based on the expenses of the project, the time required to finish the tasks, and whether the crew and equipment can be used at another working site during the break. For this matter, the idling cost in Case B is estimated to be 800 $/hour during a break and negligible when the work is in progress.

The maximum project duration is then assumed to be 72 hours. Additionally, the rate of accidents occurring in and around the work zone is assumed to be 40 crashes per 100 million vehicle hours, and the average accident cost is assumed to be $40,000/accident. Moreover, the fixed cost of setting and removing a work zone is assumed to be $1000/zone and the fixed time required for that is 2 hr/zone.

The values of unit production time (z_4^k) are adjusted to fit the rehabilitation project in Case B. The values of the production time (z_4^k) and unit maintenance cost (z_2^k) used are presented in Table 5.15. All input parameters of Case B are summarized in Table 5.16 below.

Table 5.15 Unit Maintenance Cost and Time for Various Production Options

k	**z_2^k (\$/ln-km)**	**z_4^k (hr/ln-km)**
1	24,860	2.71
2	24,983	2.21
3	25,243	1.91
4	26,211	1.55

It is worth noting that Case B considers different values of user time with respect to passenger cars and trucks and different additional vehicle operating cost. The emission cost is being considered on the mainline as well as the alternative route using Equations [3.5a and 3.5b]. The emission rate on the mainline is estimated using MOVES3, before and during the work zone by creating two projects. Those projects illustrate the roadway conditions before and during the maintenance project. While the emission rate on the alternative route is estimated with and without diversion. Hence, the total emission cost resulting from the work zone is the summation of the additional emission cost on the mainline and the alternative route.

Table 5.16 Input Parameters of Case B

Descriptions	**Values**
Road capacity of the mainline (c_0)	5,236 vph
Reduced mainline capacity due to work zone (c_W)	2,900 vph
Road capacity of the alternative route (c_a)	2,465 vph
Total length of tapers and buffers (l_T)	0.5 km
Length of entrance ramp (l_a)	0.8 km
Length of exit ramp (l_e)	0.33623 km
Total project length (PL)	11.6 km
Duration of a time interval (T)	15 mins
Average speed without work zone (V_a)	104.6 km/hr
Average speed in a work zone (V_W)	88.5 km/hr
Average speed on alternative route (V_A)	80.5 km/hr
Average speed on ramps (V_r)	64.4 km/hr
Value of user's time for cars (v_c)	$20.12/veh-hr
Value of user's time for trucks (v_t)	$33.54/ veh-hr
Idling cost per hour (v_d)	800 $/hr
Vehicle operating cost for cars (v_{oc})	$1.25/veh-hr
Vehicle operating cost for trucks (v_{ot})	$1.44/ veh-hr for trucks
Fixed setup cost (z_1)	1,000 $/zone
Fixed time of setting and removing a work zone (z_3)	2 hr/zone
Minimum duration of a work zone and a work break (D_m)	3 hr and 2hr
Maximum project duration (T_M)	72 hrs
Accident rate (r_a)	40 crash/100mvh
Average accident cost (v_a)	$40,000/accident

5.2.2 Scenario-based Analyses

In this section, the cost of the schedule by the NJDOT is estimated and compared to the optimized schedules suggested by the developed model under the UE and the SO strategies. Thus, four scenarios are presented herein:

- Scenario B.1: NJDOT schedule without traffic diversion;
- Scenario B.2: Optimized schedule without traffic diversion;
- Scenario B.3: Optimized schedule with UE traffic diversion;
- Scenario B.4: Optimized schedule with SO traffic diversion.

Scenario B.1: NJDOT Schedule without Traffic Diversion

The NJCMS data shows that the work on I-80 was performed from Wednesday July 20 to Friday July 22, from 9pm to 5am. The corresponding schedule is analyzed based on the input parameters provided in Section 5.2.1 and the results are shown in Table 5.17.

Table 5.17 Schedule Under Scenario B.1 Based on NJCMS Data

i	***S_i* - *E_i***	***D_i* (h)**	**l_i^k (km)**	***k***	**C_M ($)**	**C_I ($)**	**C_U ($)**	**C_E ($)**	**C_T ($)**
1	21:00-05:00	8	3.87	4	10,2462	0	491	165.85	103,119
2	05:00-21:00	16	0	0	0	12,800	0	0	12,800
3	21:00-05:00	8	3.87	4	10,2462	0	491	165.85	103,119
4	05:00-21:00	16	0	0	0	12,800	0	0	12,800
5	21:00-05:00	8	3.87	4	10,2462	0	491	165.85	103,119
Total		56	11.6	-	307,386	25,600	1,474	497.54	334,958

*Note: *i* is the work zone index, S_i and E_i are the starting and ending times, D_i is the duration, p_i is the length, k is production option, C_M is maintenance cost, C_I is idling cost, C_U is user delay cost, C_E is the emission cost, and C_T is total cost.

The work was executed over 8 hours during nighttime to avoid potential traffic delays. While this is a good strategy to mitigate congestion, the most efficient crew 4 is employed to expedite the work and finish the project by working 8 hours per day only. This explains the high amount of maintenance cost compared to other cost components. The idling duration in the NJDOT schedule is double the working duration, which is leading to a high idling expense.

The idling cost is modeled to be the product of the idling duration and the average cost of idling equipment and crew. When data is available regarding the utilization of crew and equipment during a work break, the more accurate idling cost can be estimated. The user and emission cost are considerably less than the maintenance and idling cost. Which is reflected by a nighttime schedule where the traffic delays are significantly mitigated.

Scenario B.2: Optimized Schedule without Traffic Diversion

Scenario B.2 utilizes the developed ABC algorithm to optimize the work zone project on I-80 without the implementation of traffic mitigation strategies. This scenario is analyzed for the purpose of comparison with the executed NJDOT schedule shown in Scenario B.1.

The optimized schedule B.2 in Table 5.18 highlights the significance of optimizing the work zone schedules instead of solely assigning the work to the nighttime periods. By comparing schedule B.2 and B.1, it was found that two off-peak daytime work zones are suggested to be adopted in addition to one off-peak night work zone, instead of assigning three nighttime work zones. This allows for a considerable decrease in the total project duration, offering the transportation agencies the opportunity to move on to the next maintenance project.

Crew 3 is suggested to be implemented on the second work zone of scenario B.2, instead of the more productive crew 4. Even though scenario B.2 is adopting high crew rates (e.g., Crew 3 and 4) due to lack of traffic mitigation strategies, the selection of crew 3 for the second work zone allows for a significant decrease in the maintenance cost as compared to scenario B.1.

Subsequently, while the work is assigned during off-peak daytime the need for a long idling duration is eliminated which is reflected by a substantial decrease in the idling cost. However, this allows for a slight increase in the user cost and emission cost as compared to scenario B.1. This slight increase is mitigated by a considerable decrease in other cost components, leading to a noteworthy decrease in the total project cost.

Table 5.18 Optimized Results Under Scenario B.2 without Traffic Diversion

i	S_i - E_i	D_i (h)	l_i^k (km)	k	C_M ($)	C_I ($)	C_U ($)	C_E ($)	C_T ($)
1	9:30-15:45	6.25	2.74	4	72,869	0	1,231.50	87.60	74,061
2	15:45-18:15	2.5	0	0	0	2,000	0	0	2,000
3	18:15-7:00	12.75	5.63	3	143,074	0	1,068.11	345.41	144,488
4	7:00-9:15	2.25	0	0	0	1,800	0	0	1,800
5	9:15-16:15	7.00	3.23	4	85,552	0	2,024.90	116.29	87,693
Total		30.75	11.60	-	301,495	3,800	4,324.51	549.30	310,042

*Note: i is the work zone index, S_i and E_i are the starting and ending times, D_i is the duration, p_i is the length, k is production option, C_M is maintenance cost, C_I is idling cost, C_U is user delay cost, C_E is the emission cost, and C_T is total cost.

Scenario B.3: Optimized schedule with UE traffic diversion

Scenario B.3 utilizes the UE assignment technique to emphasize the significance of traffic mitigation strategy during work zone projects. By comparing scenario B.3 to B.2, it was found that crew 2 is suggested to be assigned to the first work zone, instead of crew 4. Thus, scenario B.3 outperforms scenario B.2 in terms of lower maintenance and total cost. The implementation of different crews in scenario B.3 may offer elasticity in scheduling the work when significant cost exists among different crews.

The implementation of UE traffic diversion allows for longer work periods; hence less idling cost as compared to scenario B.2. However, the increase in moving delays on the mainline and alternative route may cause a surge in user delay cost as compared to scenario B.2. The assignment of traffic causes a slight increase in the emission cost on the alternative route as compared to scenario B.2 where no mitigation strategies are adopted since the traffic is diverted to a slightly longer route.

Table 5.19 Optimized Results Under Scenario B.3 with UE Traffic Diversion

i	S_i - E_i	D_i (h)	l_i^k (km)	k	C_M (\$)	C_I (\$)	C_U (\$)	C_E (\$)	C_T (\$)
1	9:00-16:30	7.5	2.50	2	72,869	0	1,810.27	96.65	65,082
2	16:30-18:45	2.25	0	0	0	1,800	20.82	0	1,821
3	18:45-7:00	12.25	5.38	3	143,074	0	936.78	329.03	137,732
4	7:00-9:00	2	0	0	0	1,600	0	0	1,600
5	9:00-16:45	7.75	3.72	4	85,552	0	2,856.63	163.71	101,255
Total		31.75	11.60	-	297,876	3,400	5,624.51	589.39	307,490

*Note: i is the work zone index, S_i and E_i are the starting and ending times, D_i is the duration, p_i is the length, k is production option, C_M is maintenance cost, C_I is idling cost, C_U is user delay cost, C_E is the emission cost, and C_T is total cost.

Scenario B.4: Optimized schedule with SO traffic diversion

Scenario B.4 adopts the SO traffic diversion as a mitigation strategy. As compared to scenario B.3, crew 3 is assigned to the first work zone instead of crew 2. However, crews with lower production rates are adopted in scenarios B.3 and B.4, as compared to B.2

resulting in a reduced maintenance cost and idling cost. The user cost and total cost in scenario B.4 are less than scenario B.3, which is mainly associated with the fact that SO aims at minimizing the total system travel time, and not just the individuals. The emission cost is also slightly less in scenario B.4.

Table 5.20 Optimized Results Under Scenario B.4 with SO Traffic Diversion

i	S_i - E_i	D_i (h)	l_i^k (km)	k	C_M (\$)	C_I (\$)	C_U (\$)	C_E (\$)	C_T (\$)
1	9:30-16:30	7	2.62	3	67,081	0	1,497.81	93.97	68,673
2	16:30-18:30	2	0	0	0	1,600	2.76	0	1,603
3	18:30-7:00	12.5	5.50	3	139,770	0	1,002.44	329.66	141,103
4	7:00-9:00	2	0	0	0	1,600	0	0	1,600
5	9:00-16:30	7.5	3.48	4	92,316	0	1,624.70	144.81	94,085
Total		31	11.60	-	299,167	3,200	4,127.72	568.44	307,063

*Note: i is the work zone index, S_i and E_i are the starting and ending times, D_i is the duration, p_i is the length, k is production option, C_M is maintenance cost, C_I is idling cost, C_U is user delay cost, C_E is the emission cost, and C_T is total cost.

Comparison between Case B Scenarios and Summary of the Results

Table 5.21 Optimized Results of Case B under Various Scenarios

Scenario	S_i - E_i	D_i **(h)**	l_i^k **(km)**	k	C_M **($)**	C_I **($)**	C_U **($)**	C_E **($)**	C_T **($)**
B.1	21:00-05:00	8	3.87	4	10,2462	0	491	165.85	103,119
	05:00-21:00	16	0	0	0	12,800	0	0	12,800
	21:00-05:00	8	3.87	4	10,2462	0	491	165.85	103,119
	05:00-21:00	16	0	0	0	12,800	0	0	12,800
	21:00-05:00	8	3.87	4	10,2462	0	491	165.85	103,119
	Total	56	11.60	-	307,386	25,600	1,474	497.54	334,958
B.2	9:30-15:45	6.25	2.74	4	72,869	0	1,231.50	87.60	74,061
	15:45-18:15	2.5	0	0	0	2,000	0	0	2,000
	18:15-7:00	12.75	5.63	3	143,074	0	1,068.11	345.41	144,488
	7:00-9:15	2.25	0	0	0	1,800	0	0	1,800
	9:15-16:15	7.00	3.23	4	85,552	0	2,024.90	116.29	87,693
	Total	30.75	11.60	-	301,495	3,800	4,324.51	549.30	310,042
B.3	9:00-16:30	7.5	2.50	2	72,869	0	1,810.27	96.65	65,082
	16:30-18:45	2.25	0	0	0	1,800	20.82	0	1,821
	18:45-7:00	12.25	5.38	3	143,074	0	936.78	329.03	137,732
	7:00-9:00	2	0	0	0	1,600	0	0	1,600
	9:00-16:45	7.75	3.72	4	85,552	0	2,856.63	163.71	101,255
	Total	31.75	11.60	-	297,876	3,400	5,624.51	589.39	307,490
B.4	9:30-16:30	7	2.62	3	67,081	0	1,497.81	93.97	68,673
	16:30-18:30	2	0.00	0	0	1,600	2.76	0	1,603
	18:30-7:00	12.5	5.50	3	139,770	0	1,002.44	329.66	141,103
	7:00-9:00	2	0.00	0	0	1,600	0	0	1,600
	9:00-16:30	7.5	3.48	4	92,316	0	1,624.70	144.81	94,085
	Total	31	11.60	-	299,167	3,200	4,127.72	568.44	307,063

- Scenario B.2 highlights the importance of implementing an efficient optimization schedule to eliminate the unnecessary long work zone projects and significantly minimize the idling cost. The schedule suggested in Scenario B.2 also returns a cheaper maintenance cost due to the implementation of crew 3 in the second work zone. However, since the schedule in Scenario B.1 avoids all high demand periods, it returns the lowest emission cost and user cost among all scenarios.

- The utilization of UE traffic diversion in Scenario B.3 offers flexibility in the assignment of working crew. With that, crews 2,3, and 4 are assigned each to a specific work zone. The implementation of traffic diversion in Scenario B.3 allows for the reduction of work zone breaks and consequently decreases the idling cost. The diversion using UE, however, does not necessarily decrease the user delay due to the additional moving delay costs on both the mainline and alternative route.

- The diversion of traffic into the alternative route in Scenario B.3 instigates additional traffic emissions after applying the UE strategy. The identical travel time strategy adopted by the UE would divert the traffic onto alternative routes to minimize the individual vehicle travel time. In Case B the alternative route is longer than the mainline, which causes additional vehicle emissions on the alternative route even when the travel time is the same.

- The SO strategy used in Scenario B.4 suggests the utilization of a higher productive crew than Scenario B.3. With that, the maintenance cost increases, and the project duration slightly decreases. Less vehicles are diverted into the alternative route in Scenario B.4, which is highlighted by a reduced user and emission cost.

- Consequently, the identical travel time between routes suggested by the UE strategy does not necessarily lead to minimum travel time for the whole network. The SO strategy, however, aims at minimizing the total network travel thus guides the detour. With that, the SO strategy is more efficient than the UE in traffic diversion while considering the emission cost.

5.2.3 Sensitivity Analyses

The previous sections discussed the optimized schedule under various scenarios considering the traffic diversion and the emission cost. In this section, Scenario B.4 will be utilized as a base scenario to study the effect of various factors such as maximum project duration, budget limitation, emission standards, and weight factor on travel time value.

Maximum Project Duration

Under different circumstances, transportation agencies might be forced to expedite the project and complete the work within a specific period of time. In this section, the effect of the reduction in maximum project duration is analyzed after a drop from 72 hours to 48 hours.

The results in Table 5.22 shows that a compressed schedule may increase the minimized total cost due to a limitation in schedule flexibility caused by the reduced MPD by 24 hours. The highest productive crew (e.g., k=4) is assigned for the two work zones and the least break duration is suggested (e.g., 2 hours). With that, the project can be accomplished in one day as compared to 31 hours in Scenario B.4. However, the total cost increases by $5,850, including a $7,219 increase in maintenance cost. Nevertheless, the reduction in idling periods causes savings of $1,600 in idling cost.

The implementation of traffic diversion has proved to be efficient under reduced maximum project duration. The schedule shown in Table 5.22 hits a peak period between 4 pm and 6 pm which would lead to significantly higher user delay cost in case where traffic diversion is not used. A diversion of 780 vehicles from the mainline has helped reduce the queuing delay cost. In addition, an over compressed schedule has proved to cause additional emissions ($123) due to reduced schedule flexibility.

Table 5.22 Case B Schedule under Reduced Maximum Project Duration from 72 hours to 48 hours

i	S_i - E_i	D_i (h)	l_i^k (km)	k	C_M ($)	C_I ($)	C_U ($)	C_E ($)	C_T ($)
1	18:00-7:00	13	7.10	4	187,014	0	1,133.77	444.59	188,592
2	7:00-9:00	2	0	0	0	1600	0	0	1,600
3	9:00 - 18:00	9	4.50	4	119,372	0	3,101.61	246.85	122,721
Total		24.00	11.60	-	306,386	1600	4,235.38	691.44	312,913

*Note: i is the work zone index, S_i and E_i are the starting and ending times, D_i is the duration, p_i is the length, k is production option, C_M is maintenance cost, C_I is idling cost, C_U is user delay cost, C_E is the emission cost, and C_T is total cost.

A sensitivity analysis was performed to further investigate the effect of MPD on the project total cost when traffic diversion is in place and the results are shown in Figure 5.6. The effect of traffic demand is also analyzed by changing its value by 15%. The results show that the total cost decreases as the traffic demand decreases. However, the minimized total cost does not seem to vary considerably with the change of MPD when traffic diversion is applied. Hence, traffic diversion can minimize the congestion on the mainline as the MPD decreases, which is similar to the effect of implementing the work zone in areas with reduced traffic. Consequently, the implementation of traffic diversion allows for the project to be compressed without a major change in the total cost.

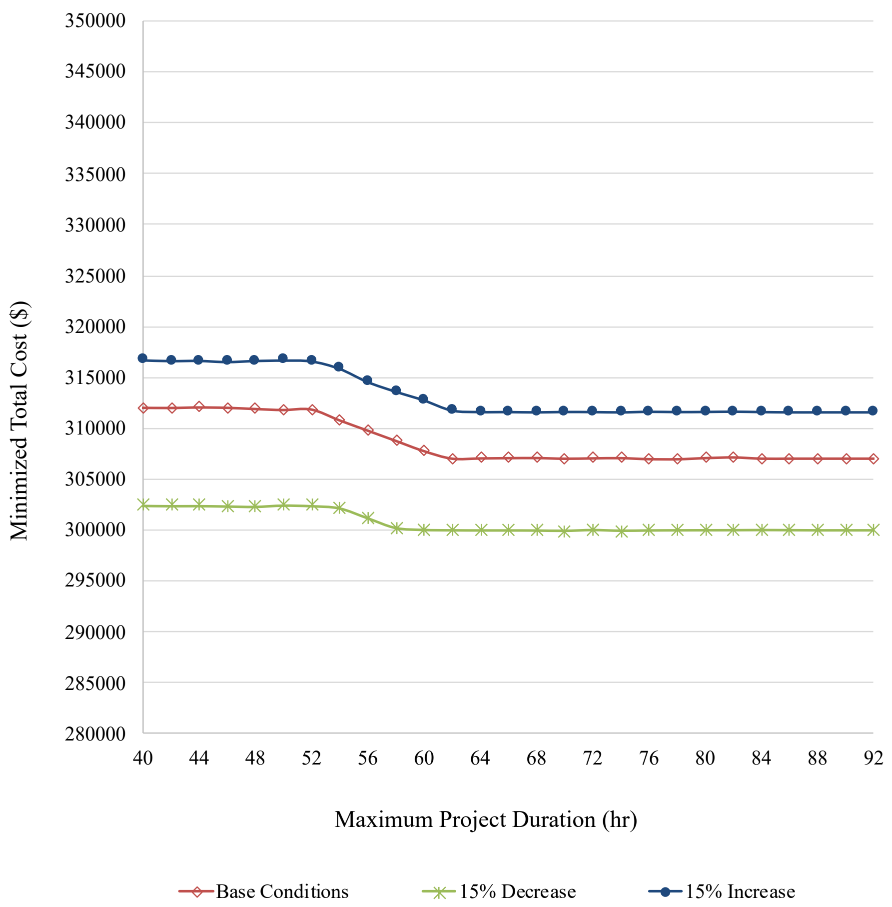

Figure 5.6 Minimized total cost vs. MPD under various traffic demand.

Budget Constraint on Maintenance Cost and Idling Cost

In addition to tight schedules, transportation agencies often limit the amount they are willing to spend on a certain maintenance project due to restrictions and limitations in their annual budget. When a budget constraint is in place, limitations on the maintenance cost and the idling cost components of the total cost function should be implemented. However, budget limitation affects other parameters such as the project duration. Sensitivity analysis is conducted in this section in order to study the effect of the budget constraint on the project duration.

The purpose of this analysis is to highlight the trend between the budget and the time to complete a project. Figure 5.7 shows a negative relationship between the budget and the project duration. For example, when the work budget is $302,367 the project can be completed in 31 hours. While a tighter budget of $295,065 would require 39 hours to finish the work. This could be related to the fact that higher budget offers the flexibility to assign a more productive crew which leads to a reduction in the project duration.

In addition, Figure 5.7 can help estimate the minimum budget needed for a certain maximum project duration value. For example, in case where the maximum project duration is 35 hours, transportation agencies need to have a minimum budget of $296,600 otherwise the project cannot be completed. Consequently, Figure 5.7 can help estimate the time needed to finish a project under a certain budget.

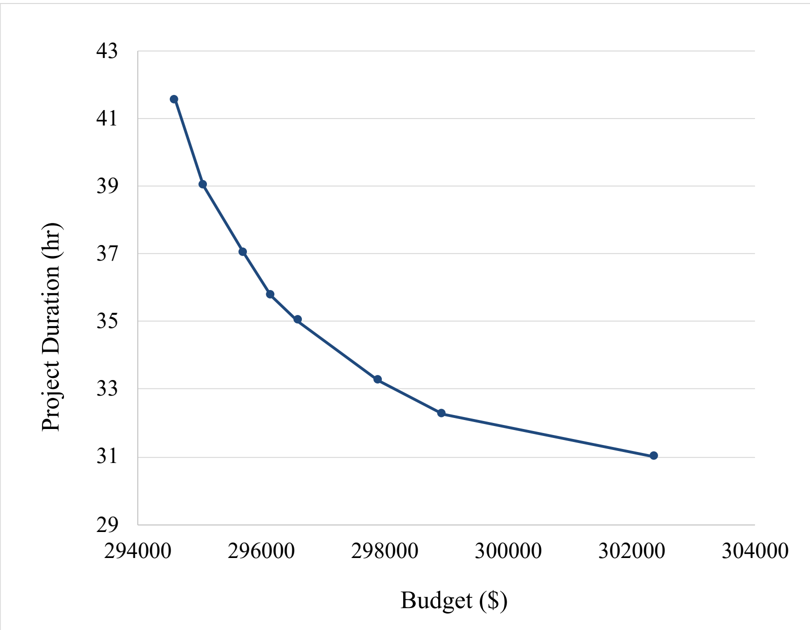

Figure 5.7 Project duration vs. maintenance budget constraint.

Vehicle Emissions Policy

Additionally, other realistic parameters may come into play while optimizing the work zone schedules. One of those parameters is the standards limit on the emission cost if applicable. Tier 3 emission standards set by the EPA tightens the fleet average limit of NO_x pollutants over the years, as shown in Table 5.23, to reach 58 mg/mi in 2021 and 30 mg/mi in 2025 for light-duty vehicles and trucks (Vijayaraghavan et al., 2016). This section provides an analysis to reduce the emission of NO_x due to a work zone below the 2021 standards of 58 mg/mi. Consequently, this highlights the capability of the model to adjust to different emission standards when in place.

Table 5.23 Tier 3 Fleet Average NO_x Standards

Year	2017	2018	2019	2020	2021	2022	2023	2024	2025
NO_x Standards (mg/mi)	86	79	72	65	58	51	44	37	30

Source: Vijayaraghavan et al., 2016

Table 5.24 represents the optimized work zone schedule results considering the Tier 3 policy. To minimize the NO_x emissions below 58 mg/mi the schedule is suggested to be completed within three work zones generally between 9 pm and 6 am, except for the last one that ends at 3 am. With that, the total project duration is extended to a total of 54 hours. The highest productive crew (e.g., k=4) is used to expedite the work and avoid working in peak periods. Vehicle diversion in this scenario is also avoided to exclude the additional emissions on the alternative route.

As compared to Scenario B.4, the fleet average NO_x emission rate drops from 112 mg/mi to 43.5 mg/mi upon complying with the Tier 3 standards. Moreover, a significant reduction in the user cost is observed as the emission cost decreases. This can be explained by the elimination of the moving delays on the alternative route and restricting the work to off-peak periods. The idling cost, however, encounters an increase as the periods with high traffic are avoided. Under the current vehicle and emission data, the Tier 3 standards set for 2025 do not return a feasible solution as NO_x emissions at any time during the work zone are higher than 30 mg/mi.

Hence, implementing the Tier 3 standards in the work zone optimization model is essential to lower the fleet average NO_x emission rates to meet with the Tier 3 federal standards. This section emphasizes on the flexibility of the model to take into consideration the vehicle emission standards when enforced. The model can also ensure whether a specific schedule complies with the emission standards set locally or internationally by comparing the projects' emission rates to the standards values.

Table 5.24 Optimized Results under Tier 3 NO_x Standards

i	***S_i* - *E_i***	***D_i* (h)**	**l_i^k (km)**	***k***	**C_M (\$)**	**C_I (\$)**	**C_U (\$)**	**C_E (\$)**	**C_T (\$)**
1	21:00 -6:00	9	4.52	4	119,372	0	525.28	215.86	120,113
2	6:00-21:00	15	0.00	0	0	12,000	0	0	12,000
3	21:00-6:00	9	4.52	4	119,372	0	525.28	215.86	120,113
4	6:00-21:00	15	0.00	0	0	12,000	0	0	12,000
5	21:00-3:00	6	2.57	4	68,303	0	408.56	77.91	68,790
Total		54	11.60	-	307,048	24,000	1,459.12	509.62	333,016

*Note: *i* is the work zone index, *S_i* and *E_i* are the starting and ending times, *D_i* is the duration, *p_i* is the length, k is production option, C_M is maintenance cost, C_I is idling cost, C_U is user delay cost, C_E is the emission cost, and C_T is total cost.

Weight Factor on Time Value

The user value of time is an estimate related to the wages of drivers and the type of their vehicles. It varies as a function of the way the time is used. For example, the user value of time is higher when the driver fails to arrive to work on time or misses a train however this value is lower when nothing is changing at the destination. Hence, the value of time differs with the travel motivation: drivers have a bigger value of time when traveling to work rather than the shopping center.

This dissertation does not tackle the estimation of user value of time. However, the value of time can be estimated by developing a disaggregate demand model that serves as a forecasting tool where the demand and the cost are independent variables. Furthermore, different time variables can be implemented such as the running time and waiting time. The purpose of the demand model is to estimate the value of each variable. For example, the weight of waiting time as compared to running time.

Under various time of the day and different travel motivations, the weight factor considered in the developed work zone optimization model has to be adjusted accordingly. In this dissertation, a weight factor p is associated with the user delay cost to account for its weight as compared to the other hard cash cost components. In the previous sections no special consideration was given to the value of time with respect to the hard cash ($p = 1$). The analysis herein compares the work zone schedule when reducing the value of time by 50% to Scenario B.4. Hence, this section demonstrates the ability of the model to deal with the implementation of weight factors to the objective function cost components with different p values.

Table 5.25 illustrates the results of the work zone schedule considering a weight factor $p = 0.5$. The model suggests assigning the low productive crew (e.g., k=2) on three separate work zones. With that, the total duration of the project is 35.75 hours. Which is higher than the duration in Scenario B.4 when $p = 1$. All costs associated with the schedule in Table 5.25 are generally lower than the costs of Scenario B.4, except for the emission cost. Thus, the utilization of low productive crew in this section and the increase of the project duration result in an upsurge in the emission costs. Especially that the reduction in user value of time offers the flexibility to schedule the work during a peak period (4 pm – 6 pm) without the increase in user costs.

5.25 Optimized Results with 50% Reduction in Value of Time

i	S_i - E_i	D_i (h)	l_i^k (km)	k	C_M (\$)	C_I (\$)	C_U (\$)	C_E (\$)	C_T (\$)
1	9:30-16:30	7.5	2.49	2	63,175	0	800.54	96.65	64,072
2	16:30-18:30	2	0.00	0	0	1,600	32.83	0.00	1,633
3	18:30-7:00	12.75	4.86	2	122,524	0	534.05	297.86	123,356
4	7:00-9:00	2	0.00	0	0	1,600	0.00	0.00	1,600
5	9:00-20:30	11.5	4.25	2	107,149	0	1772.73	272.26	110,438
Total		35.75	11.60	-	292,848	3,200	3140.15	666.77	301,098

*Note: i is the work zone index, S_i and E_i are the starting and ending times, D_i is the duration, p_i is the length, k is production option, C_M is maintenance cost, C_I is idling cost, C_U is user delay cost, C_E is the emission cost, and C_T is total cost.

CHAPTER 6

CONCLUSIONS AND FUTURE RESEARCH

Highway maintenance projects are necessary for infrastructure rehabilitation. However, lane closures during maintenance activities cause considerable traffic delays which could lead to additional vehicle emissions and delays. The optimization of work zone schedules is essential to mitigate the effect of highway capacity reduction on the traffic. Due to the existence of variant decision variables and the interdependency among them, a metaheuristic algorithm is needed to find an optimal schedule. A model was developed using ABC algorithm to minimize the total cost of the maintenance projects including agency cost, user cost, and emission cost. Besides work zone scheduling, traffic diversion using both the UE and the SO strategies is analyzed. In addition, this study is the first that considers vehicle emission for the optimization of work zone schedules.

The developed model is able to determine a cost-effective work zone schedule by considering the productivity of the crew and other realistic constraints such as the budget limitations and maximum project duration. When applied, the developed model is a useful tool for the transportation agencies to determine the reduction in greenhouse gases and vehicle pollutants for the specific project site. Additionally, upon the availability of work zone data, the overall reduction in emitted vehicle pollutants can be determined as a performance index of the projects. All input parameters in this study are specific to the case studies presented herein and may be adjusted to fit different types of roadways. Hence, the model may be transferable to other states than New Jersey, however, the input parameters need to be tuned for that specific location. The findings and conclusions can be summarized below:

- Employing a higher efficiency crew might increase the maintenance yet decrease the user cost. Hence, employing a less productive crew with no traffic diversion will increase the total cost of the project exponentially due to the increase in the road user cost and the increase in project duration. Therefore, when traffic flow is heavy, employing a more productive crew, resulting in a higher maintenance cost, is justifiable in order to reduce the total project cost as well as duration.

- It was found that when traffic diversion is not implemented, the integration of emission cost might increase the total cost of the project. This could be related to the implementation of a more productive crew to expedite the work process. However, when traffic diversion is utilized, considering the emission cost could help decrease the total cost due to the diversion of vehicles into the alternative route in a way to minimize vehicle emissions and delays.

- Traffic diversion using the UE strategy helps decrease the total cost of the project. With that, the traffic diversion using the SO strategy suggests the utilization of a more productive crew as compared to UE or assign the productive crew for longer periods. Furthermore, the SO strategy allows for an early start of the project and a shortened total duration.

- The application of the emission cost while using UE and SO traffic diversion increases the number of vehicles diverted onto the alternative route. Consequently, it eliminates the need of considerable increase in the total project duration and allows for shorter breaks. Nonetheless, the decrease in the idling and maintenance cost are sufficient to compensate for the increase in alternative route delay cost.

- The application of a budget constraint helps optimize the work zone schedule under a preset amount of maintenance and idling cost. When the budget is tight, the agency might have to compromise on the duration of the project as less efficient and cheaper crew is required.

- The implementation of a reduced value of time factor is important to have a site-specific work zone schedule. In a certain location, when the work has to be done during peak periods, the value of time might increase. Incorporating the change of the weight factor into the model results in a more efficient and optimal work zone schedule as it depicts the current project conditions.

- When vehicle emission standards are enforced, the model is flexible to take on those limitations and suggest the best work zone schedule under specific pollutants and greenhouse gases standards. The restrictions on the NO_x emission are important to minimize the adverse effect of vehicle emissions on human health.

Although the System Optimum (SO) outperforms the User Equilibrium (UE) in this study, it is not considered a realistic option for traffic guidance in real situations. Following the SO patterns, some users might end up traveling longer to permit the system to achieve an optimum global efficiency. Not all drivers, however, end up accepting suggested routes that contradicts their optimal shortest paths. The System Optimum strategy shows transportation planners how to use the road system for their global advantage. However, additional considerations may be applied to deal with the unfairness of this strategy.

Future extensions of the present work may consider multiple diversion routes with the corresponding optimized traffic assignment. Moreover, while this study assumes a 100% user compliance with the traffic assignment, future studies can analyze different user obedience rates and discuss their effect on the work zone optimization schedule. Future studies may also focus on the economic impact of diversion on the alternative route. This can be analyzed when data about the economic impact of traffic diversion is available. Additionally, the emission cost estimation may be enhanced by considering the non-road emission from construction vehicles while on site or being transported to the site. Another way to enhance the model is to consider additional variables when estimating the roadway capacity such as an indicator factor for daytime and nighttime work.

APPENDIX A

DELAY COST TABLES

Parameters of the delays cost estimation of Case A

Table A.1 Delay Costs on Mainline and Alternative Route under Scenario A.3

Hour	Diverted Traffic (veh/hr)	Queuing Delay Cost on Mainline ($)	Moving Delay Cost on Mainline ($)	Delay Cost on Alternative Route ($)
00:00-01:00	0	0	87.9	0
01:00-02:00	0	0	60.75	0
02:00-03:00	0	0	41.4	0
03:00-04:00	0	0	37.2	0
04:00-05:00	0	0	50.25	0
05:00-06:00	0	0	90.45	0
06:00-07:00	0	0	136.05	0
07:00-08:00	105	75.94	151.5	95.17
08:00-09:00	0	0	120.75	0
09:00-10:00	155	123.75	376.95	122.75
10:00-11:00	0	41.24	237.45	0
11:00-12:00	0	0	164.55	0
12:00-13:00	100	0	166.35	79.29
13:00-14:00	80	0	164.67	65.07
14:00-15:00	60	0	83.4	48.57
15:00-16:00	0	0	0	0
16:00-17:00	0	0	0	0
17:00-18:00	90	32.34	109.05	75.42
18:00-19:00	215	163.12	495.9	82.82
19:00-20:00	0	100.88	523.2	0
20:00-21:00	0	1.875	245.4	0
21:00-22:00	0	0	196.2	0
22:00-23:00	0	0	163.8	0
23:00-24:00	0	0	121.5	0
Sum	805	552.09	3828.33	655.58

Table A.2 Delay Costs on Mainline and Alternative Route under Scenario A.4

Hour	Diverted Traffic (veh/hr)	Queuing Delay Cost on Mainline ($)	Moving Delay Cost on Mainline ($)	Delay Cost on Alternative Route ($)
00:00-01:00	0	0	48.66	0
01:00-02:00	0	0	34.3	0
02:00-03:00	0	0	40.22	0
03:00-04:00	0	0	60.46	0
04:00-05:00	0	0	120.66	0
05:00-06:00	0	0	265.18	0
06:00-07:00	0	0	0	0
07:00-08:00	0	0	0	0
08:00-09:00	0	0	221.84	78.46
09:00-10:00	100	67.5	222.55	0
10:00-11:00	0	33.75	164.64	0
11:00-12:00	0	0	166.37	79.29
12:00-13:00	100	0	166.53	65.08
13:00-14:00	80	0	82.81	52.8
14:00-15:00	65	0	126.19	0
15:00-16:00	0	0	381.93	0
16:00-17:00	0	0	152.01	92.8
17:00-18:00	110	13.6	101.96	90.46
18:00-19:00	115	106.32	234.05	0
19:00-20:00	0	6.09	203.96	0
20:00-21:00	0	0	188.44	0
21:00-22:00	0	0	139.78	0
22:00-23:00	0	0	103.22	0
23:00-24:00	0	0	72.8	0
Sum	880	227.25	3102.44	458.9

Table A.3 Delay Costs on Mainline and Alternative Route under Scenario A.5

Hour	Diverted Traffic (veh/hr)	Queuing Delay Cost on Mainline ($)	Moving Delay Cost on Mainline ($)	Delay Cost on Alternative Route ($)
00:00-01:00	0	0	72.84	0
01:00-02:00	0	0	48.66	0
02:00-03:00	0	0	34.3	0
03:00-04:00	0	0	40.22	0
04:00-05:00	0	0	60.46	0
05:00-06:00	0	0	120.66	0
06:00-07:00	0	0	151.53	0
07:00-08:00	0	0	0	0
08:00-09:00	0	0	0	0
09:00-10:00	220	120	410.83	173.56
10:00-11:00	0	30	215.05	0
11:00-12:00	0	0	164.65	0
12:00-13:00	84	0	168.64	66.32
13:00-14:00	64	0	168.81	51.81
14:00-15:00	108	0	168.75	87.12
15:00-16:00	176	0	84.03	156.11
16:00-17:00	0	0	0	0
17:00-18:00	0	0	0	0
18:00-19:00	112	130.78	560.03	88.02
19:00-20:00	0	43.59	366.85	0
20:00-21:00	0	0	101.96	0
21:00-22:00	0	0	188.44	0
22:00-23:00	0	0	139.8	0
23:00-24:00	0	0	103.22	0
Sum	824	324.38	3471.72	669.72

Table A.4 Delay Costs on Mainline and Alternative Route under Scenario A.5

Hour	Diverted Traffic (veh/hr)	Queuing Delay Cost on Mainline ($)	Moving Delay Cost on Mainline ($)	Delay Cost on Alternative Route ($)
00:00-01:00	0	0	72.84	0
01:00-02:00	0	0	48.66	0
02:00-03:00	0	0	34.31	0
03:00-04:00	0	0	40.22	0
04:00-05:00	0	0	52.91	0
05:00-06:00	0	0	60.33	0
06:00-07:00	0	0	51.57	0
07:00-08:00	0	0	0	0
08:00-09:00	0	0	0	0
09:00-10:00	180	0	166.00	190
10:00-11:00	60	0	155.05	0
11:00-12:00	0	0	164.64	0
12:00-13:00	80	22.3	214.21	64
13:00-14:00	20	5.47	52.88	15.81
14:00-15:00	0	0	0	0
15:00-16:00	0	0	0	0
16:00-17:00	0	0	0	0
17:00-18:00	0	0	0	0
18:00-19:00	141	12.65	277.80	134.45
19:00-20:00	30	4.21	238.53	0
20:00-21:00	0	0	203.93	0
21:00-22:00	0	0	188.45	0
22:00-23:00	0	0	139.78	0
23:00-24:00	0	0	103.22	0
Sum	511	44.63	2265.34	404.26

Table A.5 Delay Costs on Mainline and Alternative Route under Scenario A.6

Hour	Diverted Traffic (veh/hr)	Queuing Delay Cost on Mainline ($)	Moving Delay Cost on Mainline ($)	Delay Cost on Alternative Route ($)
00:00-01:00	0	0	72.84	0
01:00-02:00	0	0	48.66	0
02:00-03:00	0	0	34.3	0
03:00-04:00	0	0	40.22	0
04:00-05:00	0	0	52.9	0
05:00-06:00	0	0	60.33	0
06:00-07:00	0	0	151.53	0
07:00-08:00	0	0	0	0
08:00-09:00	0	0	0	0
09:00-10:00	260	0	165.16	207.53
10:00-11:00	0	0	155.05	0
11:00-12:00	0	0	164.64	0
12:00-13:00	100	0	166.37	79.29
13:00-14:00	105	0	162.99	86.16
14:00-15:00	120	0	167.05	97.15
15:00-16:00	0	0	54.58	0
16:00-17:00	0	0	0	0
17:00-18:00	0	0	0	0
18:00-19:00	84	0	252.92	66.02
19:00-20:00	0	0	279.66	0
20:00-21:00	0	0	203.92	0
21:00-22:00	0	0	188.44	0
22:00-23:00	0	0	139.78	0
23:00-24:00	0	0	103.22	0
Sum	753	0.00	2513.08	602.17

Table A.6 Delay Costs on Mainline and Alternative Route under Scenario B.3

Hour	Diverted Traffic (veh/hr)	Queuing Delay Cost on Mainline ($)	Moving Delay Cost on Mainline ($)	Delay Cost on Alternative Route ($)
00:00-01:00	0	0	51.21	0
01:00-02:00	0	0	34.78	0
02:00-03:00	0	0	32.27	0
03:00-04:00	0	0	34.06	0
04:00-05:00	0	0	43.82	0
05:00-06:00	0	0	31.81	0
06:00-07:00	0	0	105.79	0
07:00-08:00	0	0	0	0
08:00-09:00	0	0	0	0
09:00-10:00	0	0	477.06	0
10:00-11:00	0	0	263.96	0
11:00-12:00	0	0	283.04	0
12:00-13:00	0	0	355.28	00
13:00-14:00	0	0	353.74	0
14:00-15:00	0	0	314.66	0
15:00-16:00	0	0	356.12	0
16:00-17:00	320	335.25	995.05	398.73
17:00-18:00	0	0	0	0
18:00-19:00	0	0	61.71	0
19:00-20:00	0	0	122.25	0
20:00-21:00	0	0	96.99	0
21:00-22:00	0	0	105.31	0
22:00-23:00	0	0	91.35	0
23:00-24:00	0	0	69.08	0
Sum	320	335.25	4280.29	398.73

Table A.7 Delay Costs on Mainline and Alternative Route under Scenario B.4

Hour	Diverted Traffic (veh/hr)	Queuing Delay Cost on Mainline ($)	Moving Delay Cost on Mainline ($)	Delay Cost on Alternative Route ($)
00:00-01:00	0	0	51.21	0
01:00-02:00	0	0	34.77	0
02:00-03:00	0	0	32.27	0
03:00-04:00	0	0	34.06	0
04:00-05:00	0	0	43.82	0
05:00-06:00	0	0	31.81	0
06:00-07:00	0	0	105.78	0
07:00-08:00	0	0	0	0
08:00-09:00	0	0	0	0
09:00-10:00	0	0	357.8	0
10:00-11:00	0	0	263.96	0
11:00-12:00	0	0	283.04	0
12:00-13:00	0	0	355.28	0
13:00-14:00	0	0	353.74	0
14:00-15:00	0	0	314.66	0
15:00-16:00	0	0	356.12	0
16:00-17:00	266	18.19	323.22	331.2
17:00-18:00	0	0	0	0
18:00-19:00	0	0	123.43	0
19:00-20:00	0	0	122.25	0
20:00-21:00	0	0	96.99	0
21:00-22:00	0	0	105.31	0
22:00-23:00	0	0	91.35	0
23:00-24:00	0	0	69.08	0
Sum	266	18.19	3549.96	331.2

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