Travel Time Reliability Based Work Zone Scheduling

by

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Abstract

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The continued deterioration of highway infrastructure in the US has resulted in increased number, duration, and scope of work zone projects. Transportation agencies are facing great challenges to schedule and manage work zones efficiently and economically. To improve the decision making process, in the past decades, several models have been developed to determine an optimal single work zone project schedule and operational strategy. Existing work zone scheduling models usually assume fixed average traffic impact given a designed work zone schedule. Recently, the incorporation of travel time reliability (TTR) in evaluating highway facility and traffic improvement projects has drawn increased attention. In comparison to traditional average travel time based methods, it considers the full distribution of travel time under a large number of traffic scenarios such as demand fluctuations, incidents, weather, etc. rather than an average value thus provide more comprehensive insights on the potential traffic impact of a highway improvement plan and new transportation facilities. However, the existing Highway Capacity Manual (HCM) toolbox of evaluating travel time reliability is complex and inefficient to be integrated into the optimization framework of work zone scheduling problem. In this study, we develop simplified methods that identify and model the work zone impact on travel time and travel time reliability to provide evaluation input for the work zone scheduling problem. Combined with the work zone cost such as maintenance cost, the user cost, and additional accident cost, a new work zone schedule model is proposed that incorporates travel time reliability measures. A genetic algorithm is used to solve this combinational optimization problem. Numeric examples are carried out to demonstrate the applicability and effectiveness of the developed model. Sensitivity analysis about maximum project duration and value of reliability is also conducted. The results indicate that this TTR based work zone scheduling is effective and promising.

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1. Introduction

1.1 Background

The economy of a nation depends heavily on an efficient and reliable transportation system which provides mobility and accessibility to travelers and that promotes the safety and efficiency of people and good movement. However, total vehicle miles traveled on U.S. highways is growing at a much more rapid rate than the increase in total highway capacity. To keep up with the growing demand and to provide a good level of service to motorists, the work zone has become an unavoidable commonplace of the highway system. Hereafter, a work zone is referred to as a segment of road in which maintenance or construction operations impinge on one or more lanes available to traffic, or affect the operational characteristics of traffic flow through the segment (HCM2010).

The appearance of work zone may cause both mobility issues such as capacity drop, traffic breakdown, and increase of total delay, and safety issues e.g. rear-end and sideswiping crashes. According to Highway Statistic 2008 (FHWA, 2008), among the 8 million miles of public roads, more than 4% on average have lane closures related to work zones each year due to the growing demand of vehicle miles traveled, aging infrastructure, and highway improvement projects. It is reported that the work zone leads to nearly 24% of all non-recurring delays and over 10% of overall delays in the

United States (FHWA 2004). In addition, inappropriately planned and managed work zones can become active bottlenecks resulting in severe congestion, significant delay and lower driver satisfaction, which also have negative impacts on the economy and the environment.

The safety issues of work zones also pose serious concerns. The US had 87,606 crashes in work zones in 2010, approximately 1.6% of the total number of roadway crashes (Work Zone Mobility and Safety Program, 2012). Among those work zone related crashes, 0.6% were fatal crashes, 30% were injury crashes, and 69% were property damage only crashes. This equates to one work zone injury every 14 minutes and one work zone fatality every 15 hours.

Therefore, there is a need to mitigate the impact of work zone as well as improve safety in work zones on both the planning level and the operation level. Transportation professionals have proposed a variety of work zone control devices and operation strategies over the past two decades. Those efforts have been focused not only on traffic safety by implementing speed reduction and smooth merging operations, but also on delay minimization or throughput maximization in the weaving section. With the application of well-designed merge controls such as dynamic early merge, traffic efficiency and safety could be improved, to a certain extent. Other operational applications include restriction of construction operation to off-peak or night hours, use of alternative routes, temporary widening of the roadway to increase capacity. In recent years, transportation engineers have employed new technologies for increasing safety and providing information, such as dynamic message signs and portable information boards.

On the other hand, a few researchers have focused on the optimal work zone scheduling or sub-work zone strategy to mitigate the flow disruption, and to reduce total maintenance and user cost. Therefore, freeway work zone delay and cost have been mathematically modeled and evaluated in terms of some decision variables including the length of the work zone segment, the starting time of the work zone, and the maintenance production rate. By optimizing the total cost of the work zone, optimum work zone segment length and optimum starting time could be found and used to schedule work zone activities. According to these models, the optimal length and schedule of work zones are determined by the work production rate, traffic demand pattern, operation time windows, and budget constraints in terms of time and capital investment. However, these models only reveal the impact of work zone based on average condition, and do not take into account the various sources that influence travel time. Moreover, due to the complexity of spatial-temporal scheduling, and the lack of a mathematical relationship established between work zones, multiple work zones management and scheduling has not been tackled.

In the existing studies, the data source is a key limitation since it requires both detailed work zone characteristics data and traffic flow data during the work zone operation period. Intelligent Transportation System (ITS) technologies apply and integrate a broad range of advanced information and communication technologies into the transportation infrastructure and vehicles for the purpose of improving the safety and mobility of the transportation system and enhancing road users' productivity. To encourage the retention and reuse of ITS-generated data, the archived data user service element of the National ITS Architecture requires that data from ITS systems be collected and archived for historical, secondary and non-real-time uses and that these data be made readily available to users (ADUS Program, 1998). The archived real-time and historical ITS / traffic operations data are then used to support various aspects of transportation systems, from traffic monitoring, to traffic control, vehicle routing, crash avoidance, vehicle emission control, etc. Common achieved data includes traffic detector data, lane closure data, traffic incident data, historical crash reports, historical travel time data, and weather data.

A relatively new concept, called travel time reliability, attracts more attention in the field of traffic operations and transportation planning. It is the distribution of travel time of trips using a facility over an extended period of time, and leads to a set of reliability performance measures that capture the nature of the travel time variability (HCM 2000). Those performance measures could be used as a basis for developing agency performance standards for congested facilities, for quantifying the degree of severity of LOS F conditions, for quantifying the impacts of physical and operational measures designed to improve travel time reliability, and for finding and analyzing the sources of variability that leads to travel time unreliability.

Figure 1.1 Average Travel Time vs. Travelers' Experience

Different from traditional averaging based performance measures, TTR indexes identify characteristics of travel time distributions. TTR is essentially a user based evaluation index describing the majority of travelers’ experiences on a highway rather than an “average” traveler, which may not be representative, when the distribution of travel times among users fluctuates significantly (Figure 1.1). TTR also has the benefits of directly being interpreted into social benefit (money) values combined with corresponding time values. Therefore, TTR indexes are suitable performance measures that can be used to quantify the work zone impact and schedule work zones.

1.2 Problem Statement

A work zone scheduling problem can be defined as: a set of work zone projects on a freeway corridor are required to be performed within specific time period. An optimal work zone schedule in terms of the operational strategy, the order and the starting times of the work zones needs to be optimized based on necessary project data, facility geometric data, historical traffic and incident data to minimize the impact of work zones or the total cost.

Transportation agencies are facing great challenges to solve such a scheduling problem efficiently and economically. Although the analytical comparison of several competing alternatives based on subjective engineering experience and judgment is widely used in practice, it becomes an inefficient approach when the scale and complexity increase. Scheduling work zone activities during off-periods, nighttime, and weekends, or providing alternative diversion route are also commonly used to ease the impact of congestion within peak-period. However, nighttime operations may increase safety concern and productivity resulting higher cost and longer completion time.

To improve the decision making process, in the past decades, several models (Jiang and Adeli, 2003; Yang et.al 2008; Tang and Chien, 2008) have been developed to determine an optimal single work zone project schedule and operational strategy. Some models solely focused on identifying the optimum work zone length without considering the project start time. However, it is not practical in real case since different start times may result in different work zone impact and cost. Recent studies therefore took into account the start time choice of a work zone project and built a constrained total work zone cost minimization models to simultaneously identify the optimum work zone length and the best project start time. Some other studies enhanced those models to focus on sub-work-zone operational strategy. One major deficiency of dividing a work zone project into sub-group of work zones is the repetitive setup and removal of work zones as well as interrupted working process may slow down the project progress and increase the overall project cost.

Despite the fact that these proposed models are only able to schedule short-term (a day-long at most) single work zone project, these models should still be improved or reformulated in view of the following issues. First, although time of day variation are considered by using average hour traffic, it cannot reveal the nature of real traffic variation since traffic varies by day of week and time of day. In addition, the one-hour time interval as analysis period is still too large for work zone impact and capacity estimation especially during the peak-hour period. Second, the previous models only capture the average impact of work zone, which cannot indicate the potential variability in travel times due to various sources such as severe weather or incidents. The result therefore is not helpful for trip planning purpose due to traffic condition varies day to day. Third, the queuing delay may be overestimated because they neglect a fact that a queue may completely disappear before the end of time interval. In addition, assuming a constant work zone capacity may result in in accurate queue length estimation.

Travel time reliability measures (TTR) how consistent travel conditions are from day to day, and can be used to measure work zone impact no matter under average condition or near worst condition. Recently, the incorporation of TTR in evaluating highway facility and traffic improvement projects has drawn increased attention. Compare with traditional average travel time based methods, it can help develop highway improvement plan and evaluate facility performance under a large number of traffic scenarios such as demand fluctuations, incidents, weather, etc. rather than an assumed average traffic condition. Some simulation tools, like FREEVAL-RL and VISSIM, offers the functionality of evaluate the TTR indexes for highway facilities under work zone conditions. However, using them in practice to evaluate the large set of planning scenarios in work zone scheduling is quite computationally inefficient. For example, if three work zones are required to be scheduled in one week, considering different start times for each work zone, there would be at most $C_{96\times 7}^{3}$ (96 15-min time intervals a day, 7 days a week) work zone combinations to be implemented and run in FREEVAL. The average running time for one combination is 20 minutes, and the total time needed to find the optimal work zone schedule would be an astronomical number.

To address the aforementioned research gaps on work zone scheduling, there is pressing need to conduct additional research that focus on:

1. Given the large number of potential work zone scheduling scenarios, how to develop efficient intelligent optimization framework and algorithms with consideration of travel time reliability?
2. What are the impacts of work zone on TTR considering different start time and day and work zone types?
3. How to simplify the impact analysis procedure and methodologies without the significant loss of accuracy and performance for work zone scheduling?
4. What are the parameters and how to effectively calibrate them in TTR based work zone scheduling model?
5. How to evaluate the performance of work zone optimization model?
6. How is the sensitivity of model parameters?

1.3 Objectives and Scopes

Given the current research about work zone mobility impact and work zone scheduling methods, the research of this study are to:

1. Explore the reliability impact due to work zone appearance considering different starting time, starting day, work zone duration, and length of work activity.

2. Propose dynamic traffic flow model based TTR impact evaluation methods consistent with but more efficient than FREEVAL-RL.
3. Develop a genetic optimization model for identifying reasonably optimal solution within a large scheduling scenario set.
4. Develop a spatial-temporal correlation method to automate the historical recurrent and work zone traffic data processing.
5. Analyze the effectiveness of the proposed work zone scheduling model with real work zone configurations and field data

6. Provide some recommendations and guideline for deployment of such work zone scheduling method in both data rich and data poor condition.

The scope of this research will be restricted as follow:

- Focus on offline work zone scheduling applications, however, the computational time and resources should still be reasonable for traffic operations department at a state DOT (Department of Transportation).
- Focus on urban freeway work zone, and urban arterial work zone impact and scheduling are not covered.
- Focus on freeway mainline closure, work zone or lane closure on ramp is not covered.
- As one source of traffic data, loop detector data are used in this study for field

data collection.

- The data quality issues are covered by utilizing a series of quality check algorithms.
- The work zone scheduling strategies considered include isolated work zones. The research can be extended to concurrent work zone scenarios.
- Different driver composition and driver behavior are not considered in this study.

1.4 Expected Contribution

The expected contributions through this study include:

1. Extend the application of TTR by developing a work zone delay estimation model for work zone scheduling.
2. Propose an offline work zone scheduling model that has better performance than other widely used methods.
3. Improve the analytic model to estimate work zone impacts.
4. Develop an iterative procedure that integrates with genetic algorithm to search for the optimal solution.
5. Propose a data integration method for historical traffic operation data and work zone data.
6. Propose an efficient calibration procedure for thresholds and model

parameters.

1.5 Organization

The rest of the dissertation is organized as the flowchart shown in Figure 1.2. Chapters of the dissertation follow the procedures of this dissertation research. Chapter 2 first delivers an introduction about work zone, and its configuration. The existing work zone capacity estimation models and delay models are then summarized and discussed. The existing studies related to work zone scheduling are listed and discussed. Also, the current research effort on TTR and its application are reviewed. The proposed methodology includes two parts: 1) TTR based work zone delay estimation model; and 2) the formulation of the objective total cost function for freeway work zone scheduling, which are described in details in Chapter 3. Chapter 4 covers the data sources and data processing. Since quality data is essential for this research, the data sources, data quality, and data integration method are presented and discussed in this chapter. In Chapter 5, the experimental design is presented, which includes model calibration, model validation, and numerical examples along with sensitivity analysis. And finally, conclusion and suggestions for future study are presented in Chapter 6.

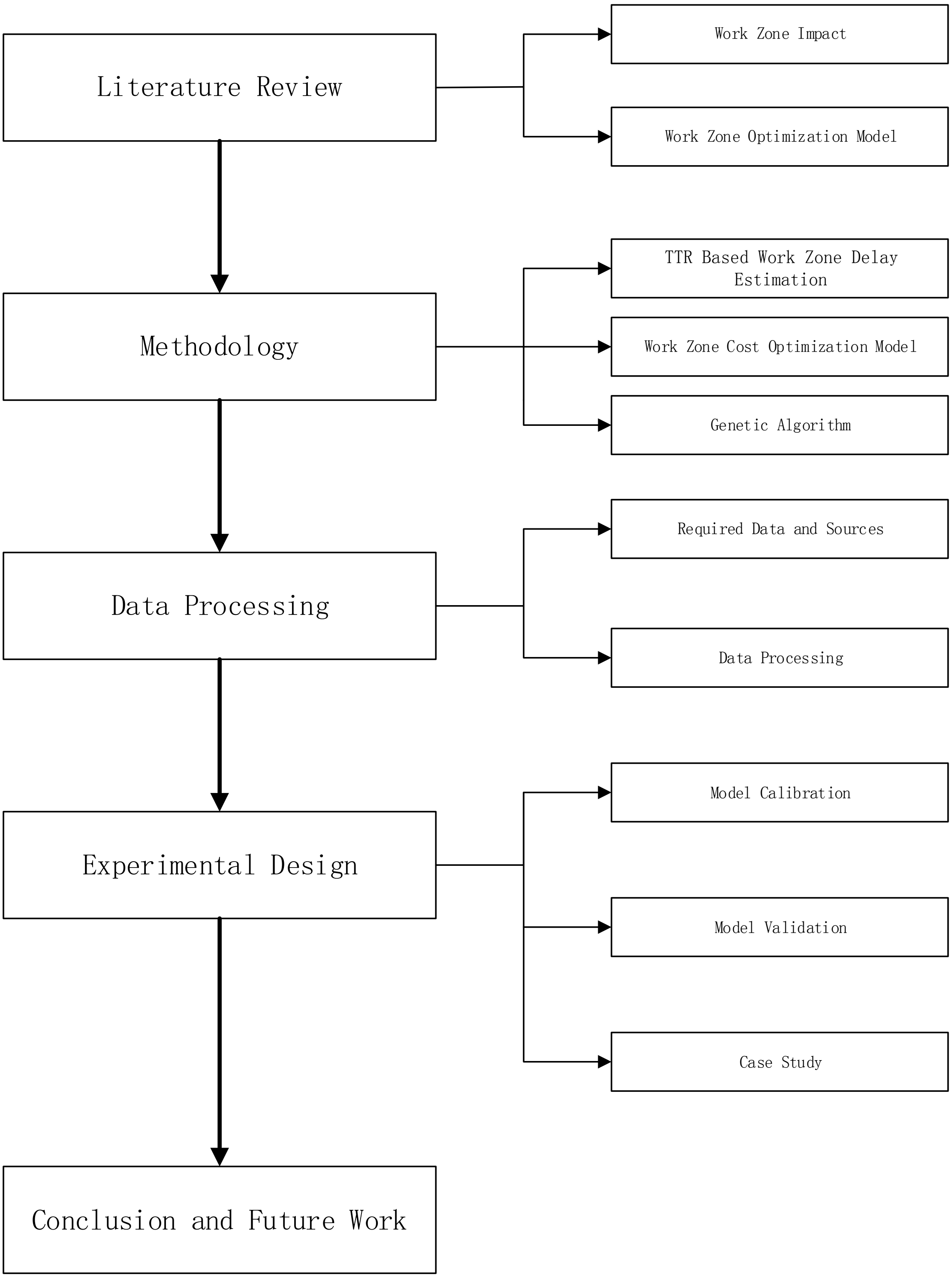


Figure 1.2 The Flowchart of Dissertation Research

2. Literature Review

In the past two decades, a large amount of study effort has been made by federal, state and local transportation engineers, consultants and researchers to mitigate mobility impact and reduce delays due to work zones. A comprehensive literature review has been conducted using a computerized literature search method, and the review results are summarized herein. Review and discussion on work zone mobility impacts including work zone capacity and delay estimation method, and construction scheduling methods along with a work zone optimization model and travel time reliability methods are presented. Some relevant definitions are presented in advance to aid understanding and clarify commonly used terminology.

2.1 Work Zone Definition and Layouts

The freeway work zone has been defined as " a segment of highway in which maintenance and construction operations reduce the number of lanes available to traffic or affect the operational characteristics of traffic flowing through the segment'' (HCM 2010).

As Figure 2.1 shows, there are four major components in a work zone (MUTCD 2003):

1. Advance Warning Area. The section where road users are informed about the upcoming work zone and response to adjust their driving behavior correspondingly.

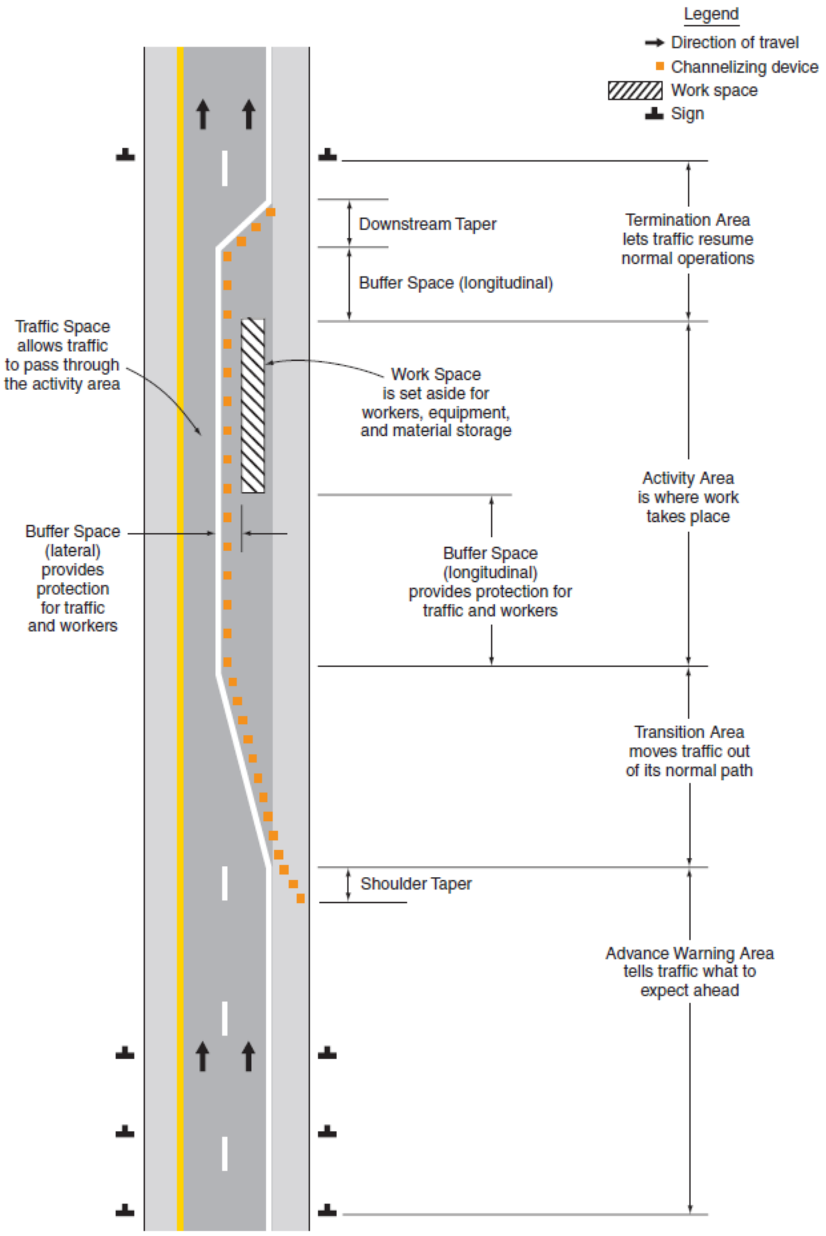


Figure 2.1 Work Zone Configuration and Major Components

2. Transition Area. The section where road users are redirected of their normal path. It also works as merging area.
3. Activity Area. The section where the work activity take place and roader users are routed through.
4. Termination Area. The section where road users are returned to their normal driving

path.

2.2 Work Zone Capacity

Road capacity at the work zone is a key variable in estimating work zone mobility impact and scheduling work activity. In other words, understanding the effect of capacity reduction will result in better planning and scheduling of lane closure since the value of the capacity is key input for most work zone user-cost models or software. In the literature, the work zone capacity value can be obtained using the HCM capacity definition of the maximum 15-min sustainable flow rate. Other studies (Edara et.al 2012) demonstrated that the queue discharge flow rate observed by means of rescaled cumulative flow curves (Cassidy and Bertini, 1999;), or the 85th percentile of the traffic flow can be used as the work zone capacity Sarasua et.al, 2006).

2.2.1 Factors Affecting Work Zone Capacity

It has been found that there are many factors affecting the value of the work zone capacity. Weng and Meng (2010) concluded there were 16 factors that significantly impact on work zone capacity and grouped them into 5 categories: 1) work zone configurations; 2) roadway conditions; 3) work activity characteristics; 4) Environmental condition; and 5) vehicle and driver compositions.

Work zone configuration

Work zone configuration refers to the number of lane closure, and the effects on the shoulder usage. Measurements based on freeway work zones data collected from Texas (Krammes and Lopez, 1994) and North Carolina (Dixon et al., 1996) showed clearly that work zone capacity varies significantly with the number of lane closures and the lane closure location. Closure of the rightmost lanes resulted in capacities 6% higher than those resulting from closure of the leftmost lanes (AL-Kaisy and Hall, 2003). The length of work zone might reasonably be expected to be a significant impact factor for work zone capacity, as well as work time. Normally, longer work zone might result in conservative driver behavior since it involves more driver workload, work activity, and visual distractions. Kim et al. (2001) found that the presence of grades may reasonably to be expected to exacerbate the flow constriction in work zones, particularly in the presence of heavy vehicles. In addition, a few other work zone configuration factors such as lateral clearances, lane taper characteristics and merge control provisions (e.g., signs, cones), could also affect the work zone capacity.

Table 2. 1 Demonstration of Work Intensity

Intensity Level	Qualitative description	Work type examples
1	Lightest	Median barrier installation
2	Light	Pavement repair
3	Moderate	Resurfacing

4	Heavy	Stripping
5	Very Heavy	Pavement making
6	Heaviest	Bridge repair

Roadway conditions

Work zone capacity on an urban freeway is usually 20–30% higher than that on a rural road (Dixon et al. 1996). According to the HCM (2010), the presence of ramps, distance from ramps, especially the entrance ramps inside the work zone activity area, can create traffic turbulence, which results in a reduction of the work zone capacity. In addition, the width of the lanes and the distance to lateral obstructions will both affect capacity. In HCM (2010), an adjustment factor of up to 14% is suggested to account for the effect of lane width on work zone capacity.

Work activity characteristics

Generally, work activity characteristics refers to work intensity, work time (time of day or day of the week) and work zone duration (short-term or long-term). Researchers have confirmed that work zone capacity decrease as the work intensity increases from the lightest (e.g., guardrail installation) to the heaviest (e.g., bridge repair) and demonstrated a consistent relationship between capacity and the number of open lanes. Work zone intensity has been classified into three levels (low, medium, or high) by Karim and Adeli (2003), while being classified into six levels in California and Texas ().

The work time, as another work activity characteristic, also affects work zone capacity. According to the work of Al-Kaisy and Hall (2001), night construction or maintenance could decrease the work zone capacity because of the reduced traveler’s attention. In terms of day of the week, Dixon et al. (1996) found that weekend peak work zone capacity was 5% higher than weekdays after morning peak flow. Another feature of work activities is Work zone duration. Generally, the average capacity in long-term work zones might logically be assumed to be greater than that in short-term work zones because commuters and frequent travelers become familiar with the work zone configuration and road condition.

Environmental conditions

A variety of weather conditions (e.g., snowy, rainy, sunny, etc) usually has a significant impact on work zone capacity. A recent study by Venugopal (22) on the capacity of short-term maintenance sites reported that a moderately rainy condition might result in a capacity reduction of about 10%. The HCM (2010) generally suggests 10–20% capacity reductions by reason of bad weather conditions. More hazardous and extreme conditions would have more noticeable effect on capacity

Vehicle Composition

Heavy vehicles such as trucks, besides their presence making other drivers apprehensive, occupy more space on the roadway and move more slowly than passenger cars resulting in reduction of work zone capacity (Krammers 1994). Moreover, Al-Kaisy and Hall (2003) observed that the effect of heavy vehicles is greater in queue discharge (capacity) flow than free-flow. Driver composition (commuters/non-commuters) is another factor affecting work zone capacity since driver behavior varies with time of day. The percentage of non-commuters trends to reduce work zone capacity.

2.2.2 Work Zone Capacity Estimation Approaches

As listed above, many factors are found to affect work zone capacity and are applied to estimate work zone capacity. Since work zone capacity estimation is complex and there is no general guideline for calculation, a number of approaches have been proposed in the literature and can be generally categorized into three groups: parametric approaches, non-parametric approaches, and simulation approaches

Parametric approaches

A number of work zone capacity studies have concentrated on estimating work zone capacity with parametric approaches. Upon the traffic flow data and work zone data collected from the field sites, the coefficients of each predictor can be determined.

Krammes and Lopez (1994) developed a model, which is recommended in the Highway Capacity Manual (HCM) (2010), to estimate the capacity of short-term freeway work zone using the data collected in 33 work zones in Texas between 1987 and 1991 for the short term work zones:

$$c = (1600 + I - R) \times f_{HV} \times N$$

The proposed model is based on a simple linear regression that takes into account four variables: c is the estimated work zone capacity (vphpl) of a cross-section; I is the adjustment factor for work zone intensity, which is suggested that 160 for low intensity, 0 for medium intensity and -160 for heavy intensity; R is the adjustment factor for the presence of ramps, which 0 for no ramp is present, and 160 if entrance ramp is present. f_{HV} is the adjustment factor for heavy factor (function of heavy vehicle proportion and passenger car equivalent). N is the number of open lanes in work zone. 1600 is the capacity of a single lane under ideal condition.

Later on, Kim et al. (2008) proposed an enhanced model with a more complicated linear regression approach to estimate short-term work zone capacity using data collected from 12 work zone sites with lane closure on four normal lanes in one direction, shown below:

$$c = 1857 - 168.1 NUMCL - 37.0 LOCCL - 9.0 HV - 92.7 LD - 34.3 WL - 2.3 WG \times HV$$

where *NUMCl* is the number of closed lane, *LOCCL* is the lane closure location(right, otherwise). *HV* is the heavy vehicle percentage. *LD* is the lateral distance to the lane closure. *WL* is the work zone length. *WI* is the work intensity, and *WG* is the work zone grade.

Al-Kaisy et.al (2001) examined queue discharge flow as a measurement and result showed significant variation in long term work zone capacity. He developed a generic long-term work zone capacity estimation model with a multiplicative form instead of an additive form, which can produce better estimates for the effect of heavy vehicles:

$$c = c_b \times f_{HV} \times f_d \times f_w \times f_s \times f_r \times f_l \times f_i$$

where c_b is based work zone capacity, $f_{HV}, f_d, f_w, f_s, f_r, f_l, f_i$ represent the adjustment factor for heavy vehicles, driver population, work activity, side of lane closure, rain, light condition, and non-additive interactive factor respectively.

Table 2.2 Parameter Concerned in Reviewed Papers

Models	Abrams (1981)	Memmott (1984)	Krammes (1991)	Kim (2000)	Hall (2003)	Adeli (2003)	Benekohal (2004)	Sarasua (2005)	Weng (2012)	Adeli (2003)
Heavy Vehicle	X		X	X	X	X		X	X	X
Lane Width	X					X	X		X	X
Lateral Clearance	X			X			X			X
Work Intensity	X		X	X		X	X		X	X
Capacity Risk		X								
Ramp			X						X	X
Lane Configuration			X	X		X			X	X
Work Zone Length				X	X				X	X
Driver Population					X				X	X
Weather					X				X	X
Lane Location				X	X				X	X
Work Zone Grade				X	X				X	X
Urban/Rural						X		X		

In general, the model accuracy for both the additive form and the multiplicative form were formulated based on the measured work zone capacity data, which means the model accuracy may rely highly on the accuracy of the measured work zone data from the field sites. Therefore, some researchers adopted an alternative method that derived the capacity from speed-flow curves. Benekohal et al. (2004) provided a step-by-step approach based on the speed-flow information to estimate work zone capacity for a two-to-one lane closure configuration. Sarasua et al. (2006) depicted the speed-flow curves for two-to-one, three-to-two and three-to-one lane closure configurations of interstate highway work zones. Avrenli et al. (2011) developed two non-linear speed-flow models for work zones with no lane closure under uncongested and congested conditions, respectively. Based on these two nonlinear models, a work zone capacity model was derived to estimate the work zone capacity.

Although many mathematical models were proposed, each method is only available for a specific work zone type or work zone duration (short-term or long-term). Clearly, the capacities of long-term work zones are higher than that of short-term work zones. In this regard, the current HCM (2010) provides the following two distinct work zone capacity estimation guidelines for short-term work zones and long-term work zones, respectively:

For short term work zones:

$$c = \{(1600 + I) \times f_{HV} \times N\} - R$$

where c = the estimated work zone capacity; I = adjustment factor for work zone intensity; R = adjustment factor for the presence of ramps; f_{HV} = adjustment factor for heavy factor; N = the number of open lanes in work zone. 1600 is the capacity of a single lane under ideal condition.

For long term work zone, HCM recommends an average capacity of 1750 vphpl for a two-to-one lane closure and 1860 vphpl for a three-to-two lane closure. It may require manual adjustment for those impact factors.

Non-parametric approaches

In addition to parametric approaches, non-parametric approaches for work zone capacity analysis aims to describe the complicated effects of influencing factors since there might exist nonlinear relationships and high-order interactions between influencing factors. Since parametric approaches may not provide high accuracy on value prediction, many researchers employed non-parametric methods for the work zone capacity estimation. In general, the non-parametric approaches refer to an artificial intelligence technique in which the structure of the model is not assumed to be fixed. Typically, the corresponding model is adaptive and grows in size to accommodate the complexity of the data.

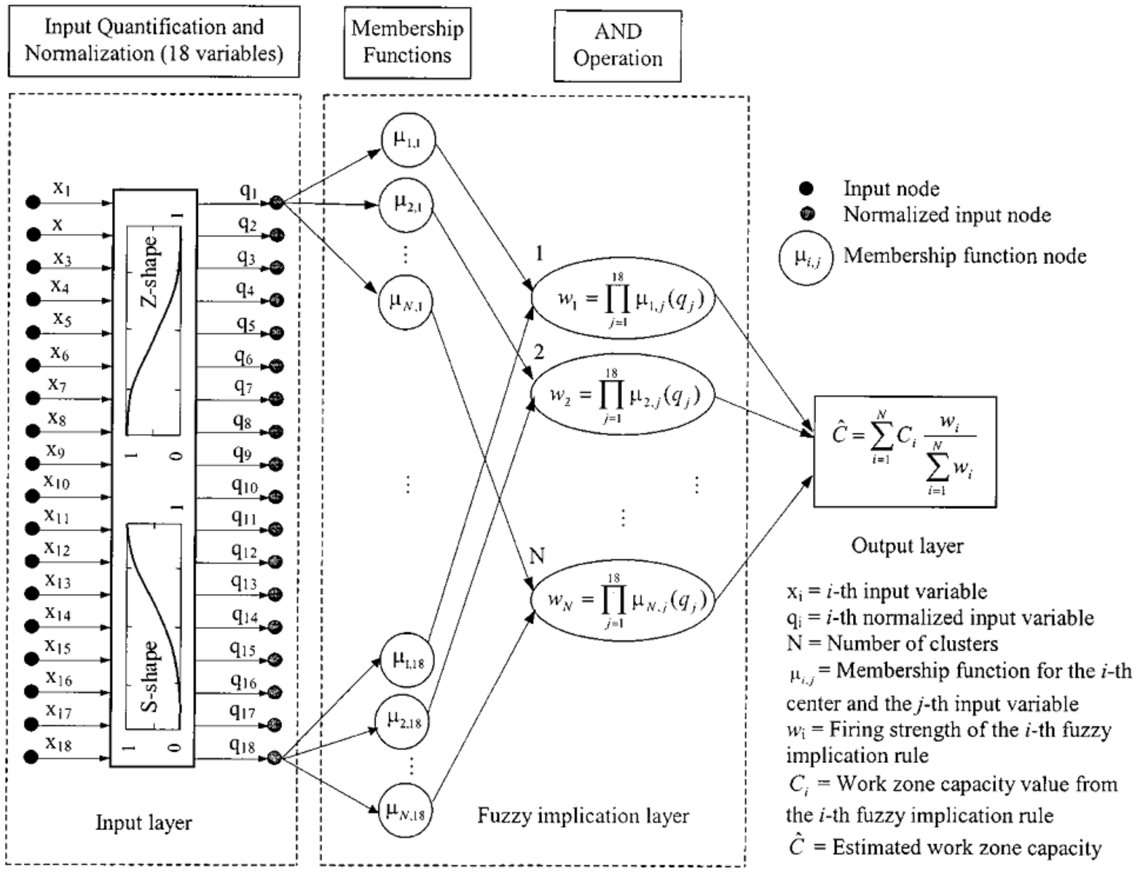
Adeli and Jiang (2003) introduced their capacity estimation model, namely a neural-fuzzy logic approach to estimating work zone capacity, which is the first well-known model applied non-parametric approach. A total of seventeen different factors effecting work zone capacity are included in the model. A neural network is then employed to estimate the parameters associated with the bell-shaped Gaussian membership functions used in the fuzzy inference mechanism. After quantification and normalization of input variables, implication rules are generated using a fuzzy logic algorithm. The capacity from an implication rule can be calculated by:

$$C_i = \sum_{j=1}^{M} \exp(-\frac{(q_i - c_{ij})^2}{2\sigma_{ij}})q_j$$

where c_i is the work zone capacity from the implication rule i, q_j is the input value for the variable j, c_{ij} and σ_{ij} are the parameter of membership function for variable j for rule i. Therefore, the estimated work zone capacity, c , is finally obtained from the fuzzy inference mechanism as the aggregation (weighted summation) of the outputs of N fuzzy implication rules as follows:

$$C = \sum_{i=1}^{N} C_i \frac{w_i}{\sum_{i=1}^{N} w_i}$$

where $w_i$is weighted value for the implication rule i.



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The Figure 2.2 shows the topology of the reviewed neural-fuzzy inference model. It consists of an input layer, a fuzzy implication layer, and an output layer. The input layer has 18 nodes representing the 17 variables impacting work zone capacity and an 18th node to indicate the data collection locality. By applying the S-shape and Z-shape spline-based nonlinear functions, the values of the variables in the input layer are quantified and normalized to values between 0 and 1.

Weng and Meng (2011) employed a decision tree approach to estimating work zone capacity. The work zone capacity can be estimated by tracing a path down the tree to a terminal node according to the characteristics of work zone. Weng and Meng (2012) continue improving the model by applying an ensemble tree approach to make the tree structure more stable. However, although the neural-fuzzy logic approach or decision tree approach could provide higher prediction accuracy compare with other parametric approaches (Zheng et al., 2011), they have poor applicability for users due to the complexity of implementation. In addition, some detailed relationship between work zone capacity and its influencing factors could not be revealed or understood.

Simulation approaches.

A drawback of previous reviewed data-driven approaches is they are highly rely on the quantity or quality of work zone configuration data and traffic flow data collected from field sites. The poor data quality or lack of available data may reduce accuracy and reliability of estimation values.

Moreover, field data cannot be used scenario creation or scheduled plan evaluation, as well as individual factor analysis. In this aspect, to better evaluate of these factors, simulation approaches are considered as a good alternative choice. There are several advanced simulation software in the market, some are specific for work zone: QUEWZ (Memmott and Ducek, 1984), Construction Analysis for Pavement Rehabilitation Strategies (CA4PRS), QuickZone (Mitretek System, 2000), CORSIM, and VISSIM. Different simulation software might be appropriate for different situations depending on the size and scope of the project. In past studies, the simulation approaches have been successfully applied to estimate the capacity value of the work zone under different work zone configuration (Arguea, 2006; Chatterjee et al., 2009) and different network (Ping and Zhu, 2006).

Since each well-structured microscopic simulation models or tools requires comprehensive calibration process to make them match the field conditions to improve the prediction accuracy, some researchers have discovered hybrid approaches to estimating work zone capacity by integrating mathematical approaches and simulation approaches.

Table 2. 3 List of Reviewed Paper for Work Zone Capacity Estimation

Approaches	References	Detailed approaches/tools
Parametric approaches	Al-Kaisy et al. (2000)	Multi-regression approach
	Al-Kaisy and Hall (2003)	A generic multiplicative approach
	Avrenli et al. (2011)	Derived from speed-flow relationship
	Benekohal et al. (2004)	A step-by-step approach based on the speed-flow
	HCM (2010)	Two distinct guildlines
	Kim et al. (2001)	A multiple regression approach
	Krammes and Lopez (1994)	A multiple regression approach
	Racha et al. (2008)	Derived from speed-flow relationship
	Sarasua et al. (2006)	Derived from speed-flow relationship
Non-parametric approaches	Adeli and Jiang (2003)	A neural-fuzzy logic approach
	Karim and Adeli (2003)	Radial basis function neural network
	Weng and Meng (2011)	A decision tree approach
	Weng and Meng (2012)	An ensemble tree approach
	Zheng et al. (2011)	A neural-fuzzy logic approach
Simulation approaches	Arguea (2006)	CORSIM
	Chatterjee et al. (2009)	VISSIM
	Heaslip et al. (2009)	A hybrid approach
	Heaslip et al. (2011)	CORSIM
	Ping and Zhu (2006)	CORSIM

2.3 Work Zone Traffic Delay

Traffic congestion occurs when the traffic demand on the roadway exceeds roadway capacity. The work zone, as a main reason, leads to non-recurrent congestion and contributes a high portion of the total traffic congestion. In general, work zone traffic delay can be defined as the actual increased travel time compared with a roadway segment without a work zone. The moving delay and queuing delay caused by the work zone is the primary component of work zone traffic delay (McCoy et al., 1980; Chen and Schonfeld, 2006; Tang and Chien 2008).

2.3.1 Macroscopic Analytical Approach

Deterministic queuing approaches have been the commonly applied macroscopic analytical approaches for decades. The deterministic delay is normally illustrated as the diagram in Figure 2.3, with the primary input of demand volume, freeway segment capacity, work zone capacity, and work zone duration. By assuming there is no queue formed when the demand volume is less than the work zone capacity, the traffic delay would be equal to the moving delay caused by the work zone speed limit (McCoy et al. 1980) When the traffic flow exceeds the work zone capacity, queues will form upstream of the work zone. In this situation, the traffic delay is evaluated as the sum of the queuing delay and the moving delay caused by the work zones.

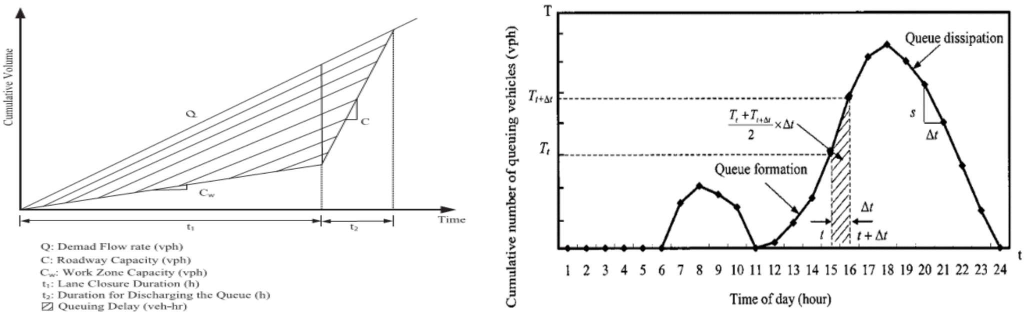


Figure 2.3 Deterministic Queuing Diagram

Although the deterministic queuing approach is easy to use and implement, it has two major limitations: First, drivers will decelerate their speed before entering the work zone, and then accelerate their speed immediately after passing through the work zone, in reality. Such maneuvers have been observed using 74 work zone data from Wisconsin (Qu et al., 2012). Jiang (1999) proposed an enhanced analytical delay estimation model to complement this weak point by taking into account acceleration and deceleration delay in addition to the deterministic queuing approach. Second, due to the randomness of the traffic flow, a queue may still form, even though the traffic flow is lower than the work zone capacity.

2.3.2 Macroscopic Simulation Approach

Unlike the studies made on the basis of analytical approaches, several macroscopic simulation tools were developed for estimating traffic delay in work zones. Lee et al. () developed the software program named Work Zone Capacity Analysis Tool (WZCAT) to predict delays and queues for freeway work zones. Such type of analytical software program including QUEWZ, FRESIM, and QuickZone was widely used in past literature. However, all these macroscopic simulation models share one limitation that lack of flexibility to account for complex work zone characteristics such as driver behaviors associated with car following and lane changing. It has been reported that those software could overestimate the vehicle speeds under queuing condition, and underestimated the queue lengths and delays compared with the field data.

2.3.3 Microscopic Simulation Approach

A number of microscopic models including Paramics, AimSUN, CORSIM, and VISSIM are available to simulate work zone traffic and have been applied to analyze work zone impact on traffic flow at the individual vehicle level. Among these simulation tools, CORSIM is the most widely used software while the two commercial software Paramics and VISSIM can predict higher accuracy result in comparison with other software. One advantage of commercial software is they are able to model complex traffic dynamics at the individual level, which could provide more accurate traffic delay estimates. To enhance the computational efficiency and estimation accuracy, researchers (Chien et al, 2002; Yang et al., 2008) proposed a hybrid approach which integrates the concept of the deterministic queuing theory and microscopic simulation tools.

Another emerging technique to improve computational efficiency and estimation accuracy is to develop a cellular automata (CA) model to simulate work zone traffic and then estimate the resulting traffic delays. The CA model was first introduced in this area by Nassb et al. (2006). To better represent driver behavior such as lane changing maneuver or acceleration and deceleration, further improvements was made by various researchers (Gundaliya et al., 2008; Weng and Meng, 2010).

2.4 Freeway Work Zone Optimization

In the past, there have been a number of studies related to work zone optimization. Most of them focused on individual work zone optimization in terms of optimal work zone length, work crew assignment, and minimum of total delay (queuing delay, moving delay) or total cost (agency's cost, user cost, constructor's cost).

2.4.1 Work Zone Length

McCoy, Pang, and Post (1980) developed a framework to optimize the length of a work zone with crossover (i.e., two-lane two-way operation) on existing four-lane divided highways by minimizing the total cost, including speed reduction delay cost, accident cost, additional vehicle operating cost and traffic control costs based on 1979 data in Nebraska. Because of changes in road user cost and accident rates, McCoy and Peterson (1987) obtained the optimal work zone length that was about 60 percent longer than what was found in his Nebraska study (McCoy, 1980). Martinelli and Xu

(1996) integrated the queuing delay cost into McCoy's model (1980), and concluded that the optimal work zone length is not affected by queuing delay for long-term work zones.

Chien and Schonfeld optimized work zone lengths and the associated traffic control cycles considering static traffic conditions. They reported four major impact factors on optimal work zone lengths: traffic volumes, travel speed within the work zone, maximum discharge flow rate and work zone setup cost. Later on, they applied the proposed model for finding the optimal work zone length of four-lane highways by minimizing the total cost. One assumption in their model is if the ADT is lower than the work zone capacity, no queue is formed. However, due to the randomness and variation of the traffic flow, the result could be inaccurate, at least for part of the day. Furthermore, the variation of the demand pattern (e.g. time of day, day of week, seasonal factor) was not taken into account in their model.

Jiang and Adeli (2003) optimized work zone length and traffic delay for multi-lane freeways by minimizing the total cost considering the user delay cost C_d, the accident cost C_a, and the work zone maintenance cost C_m. Two variables were taken into account the model: the length of work zone segment and the starting time of the work zone using ADT.

$$C_w = C_d + C_a + C_u = \left(\frac{c_{vh} t_d}{lN} \right) + \left(\frac{a_n n_a c_a t_d}{10^8 lN} \right) + \left(\frac{a_n c_1}{lN} + a_n c_2 \right)$$

where t_d is the total user delay time derived based on deterministic queuing diagram. l is work zone segment length, N is the number of lane closure, a_n is the factor for darkness, n_a is the number of accidents per 100 million vehicle hours, and c_1, c_2, c_a, c_{vh} are constant for fixed cost, maintenance cost, accident cost, and delay user respectively.

2.4.2 Work Zone Scheduling

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

To consider possible maintenance breaks, Chien, Tang, and Schonfeld (2002) introduced labor and equipment idling costs into the total cost function developed by Schonfeld and Chien (1999) for two-lane two-way highways. This enhancement enables the model to handle more practical conditions (e.g., scheduling a maintenance break to avoid peak hours). A sequential search method was developed to optimize the project starting time and the schedule of work zones (e.g., timing and length) subject to time dependent traffic demand. Considering traffic diversion through detour routes, Chen (2003) developed an optimization model for scheduling work zones on four-lane two-way and two-lane two way highways. Four alternatives were evaluated, including (1) one-lane closure, (2) onelane closure with single or multiple detour route(s) carrying partial traffic on the same direction, (3) full closure on one direction while all traffic diverted to single or multiple detour route(s), and (4) full closure on one direction with the crossover of all traffic into the opposite direction. By minimizing project total cost, a preferable combination of alternatives was selected for each work zone of the project. Chen (2006) included a time constraint into the previous optimization model (2003) to reflect the allowable lane closure time in construction practice. A high penalty cost is imposed on the work zone schedules that violate the time constraints. Hajdin et al. applied the dynamic corridor concept to determine optimum work zones and intervention package with consideration of both budget constraints and distance constraints (maximum permissible work zone length, minimum spacing between work zones).

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

2.4.3 Optimization Algorithms

When work zone optimization is based on steady traffic inflow, it often can seek for the results directly with analytical method. When time-dependent inflows or detour networks are considered, the work zone scheduling problem could be a big combinatorial nonlinear optimization problem where the solution set is constituted by multiple decision variables, such as starting time, ending time and duration of each project, spacing between connected work zones where applicable, work zone lengths, and work zone type. Hereby, solving the problem requires a powerful and effective searching algorithm to look for a near optimum solution. Chen and Schonfeld (2006) and Tang and Chien (2008) applied simulated annealing (SA) algorithm and generic algorithm (GA) to find the optimal work zone strategy with time window constraints, respectively. Other algorithms such as ant colony algorithm, tabu-search, are also found in literature (Ng and Zhang, 2009; Chang et.al., 2000).

The Genetic Algorithm (Michalewicz, 1999), which is a stochastic algorithm that mimics natural evaluation processes, is adapted in this study. It has been widely used to solve the problem of timetabling and scheduling problems. Compared to the traditional optimization algorithms, such as the climbing algorithms, one of the major merits of the GA is that it could move the population away from local optima.

2.5 Travel Time Reliability

Travel time is an important parameter of interest for both users and highway operators. However, traditional average-based travel time only tells part of the story. Both users and agencies are also interested in the degree of variability or the (un)reliability of a corridor/facility. Hence, travel time reliability - how consistent travel conditions are from day to day - has drawn more attention in recent year.

2.5.1 Definition of Travel Time Reliability

Generally, travel time reliability is the distribution of travel time of trips using a facility over an extended period of time (HCM2010), and can be used to describe both how often particular operational conditions occur and how bad conditions can get. This distribution arises from the interaction of a number of factors that influence travel times:

1. Recurring variations in demand, by hour of day, day of week, and month of year;
2. Severe weather that reduces capacity;
3. Incidents that reduce capacity;
4. Work zone that reduce capacity and may also influence demand; and
5. Special events that produce temporary, intense traffic demands.

Figure 2.4 shows the sources of variability that lead to travel time unreliability:

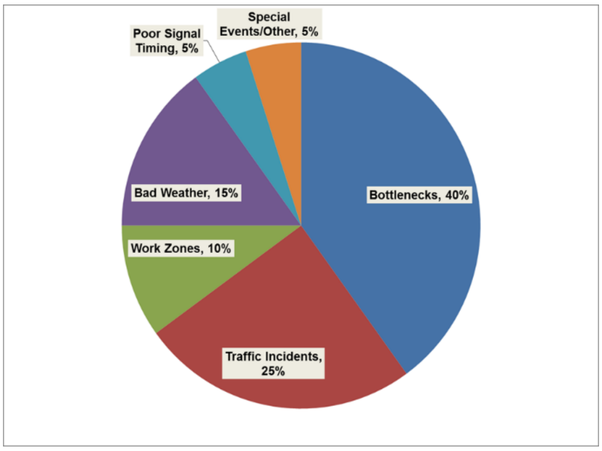


Figure 2.4 Source of Congestion

In a broader sense, reliability is a dimension of mobility and congestion. Traditionally, the dimensions of congestion have been spatial (how much of the system is congested?), temporal (how long does congestion last?), and severity-related (how much delay is there or how low are travel speeds?). Reliability adds a fourth dimension: how does congestion change from day to day?

2.5.2 Travel Time Reliability Performance Measures

From a measurement perspective, reliability is quantified from the distribution of travel times, for a given facility/trip and time period, that occurs over a significant spam of time. Then a variety of metrics can be derived once the travel time distribution has been established: (a) statistical range measures, (b) percentile-based measures, on-time/failure measures, and (d) skewness measures (10). Table 2.4 show a few reliability metrics recommended by practitioners and researchers.

Table 2.4 Recommended Set of Reliability Performance Measure

Reliability Performance Measure	Description
Variability measures / Travel time window	Standard deviation $T_{avg} \pm Standard\ deviation$
Coefficient of Variation	$\frac{Standard\ deviation}{T_{avg}}$
Buffer time	$T_{95} - T_{avg}$
Buffer time index (**BI**)	$\frac{T_{95} - T_{avg}}{T_{avg}}$
Median based buffer time index	$\frac{T_{95} - T_{50}}{T_{50}}$
Planning time	T_{95}
Planning time index (**PTI**)	$\frac{T_{95}}{T_{min}}$
λ^{skew}	$\frac{T_{90} - T_{50}}{T_{50} - T_{10}}$
λ^{var}	$\frac{T_{90} - T_{10}}{T_{50}}$
$P(T_{avg} + ATTV)$	Percentile value for which acceptable travel time variation (ATTV) is greater than T_{avg}
$P(T_{avg} - DTTR)$	Percentile value for which desired travel time reduction (DTTR) is less than T_{avg}
Semi-standard deviation	Deviation measures with respect to T_{min} instead of T_{avg}
Misery Index	average of the highest 5% of travel times/T_{min}

HCM recommends planning time index and Buffer Index as primary metrics for unreliable highway section. The PTI is used for estimating how much extra travel time must be budgeted to ensure an on-time arrival for 95% of their trips, while BI represents the extra time that may be expected for a trip, as a percentage of average.

Figure 2.5 (a) shows an actual travel time distribution derived from roadway detector data, and how it can be used to define reliability metrics. The shape of the distribution is skewed toward higher travel time caused by unreliability sources. Therefore, most of the useful metrics for reliability are focused on the right half of the distribution. The travel time distribution can also be converted to a distribution of TTIs by dividing each observed travel time by the travel times under free flow conditions (Figure 1 (b)). The unitless TTIs thus can be used for comparing highway sections of different lengths.

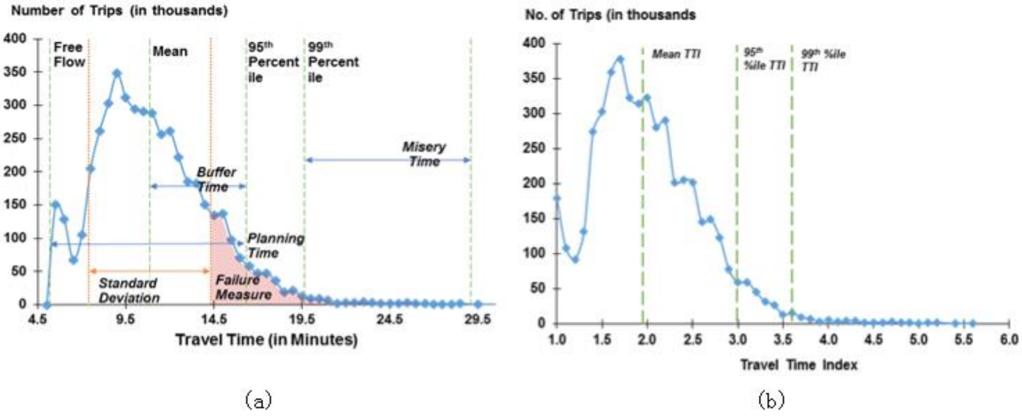


Figure 2.5 Demonstration of Reliability Performance Measures from the Travel Time Distribution

2.5.3 Value of Travel Time Reliability

The concept of value of travel time (*VOT*) has a long established history through the formulation of time allocation models from consumer theory background, while the value of travel time reliability (*VOR*) is a “newcomer” to this field (Carrion and Levison 2012). The procedures for quantifying it are still a topic to debate, although it draws increased attentions. Consequently, the estimation of *VOR* shows a significant variation across studies due to the difference among existing studies span almost every aspect, such as experimental design, theoretical framework, variability measures, and data sources. In this literature review, two theoretical frameworks, the centrality-dispersion model and the scheduling delay model, are carefully reviewed, and the results from existing studies are summarized. Future study will keep following the development of *VOR*.

Centrality-Dispersion

Jackson and Jucker (1982) proposed a mean-variance framework based on the notion that the utity, *U*, is a function of usual (or mean) travel time μ_T and the variance σ_T, assuming both are sources of disutility, and the objective is minimize their sum:

$$U = \beta_1 \mu_T + \beta_2 \sigma_T$$

Where β_1, β_2 are parameters measuring the influence of variance in travel times.

Later on, Senna (1994) incorporated the expected utility, $E(U)$, and added the cost attribute to estimate value of reliability:

$$E(U) = \beta_1 E(T) + \beta_2 \sigma_T + \beta_3 C$$

Where β_1, β_2 and β_3 are the estimated parameters for the expected travel time $E(T)$, the standard deviation σ_T, and the travel cost C respectively.

Hence the marginal rates of substitution could be computed to obtain important quantities such as the *VOT* and *VOR*.

$$VOT = \frac{\partial U / \partial E(T)}{\partial U / \partial C}$$
$$VOR = \frac{\partial U / \partial \sigma_T}{\partial U / \partial C}$$

Note that the *VOR* also measure travellers willing to pay (WTP) for a unit reduction in variability in travel time.

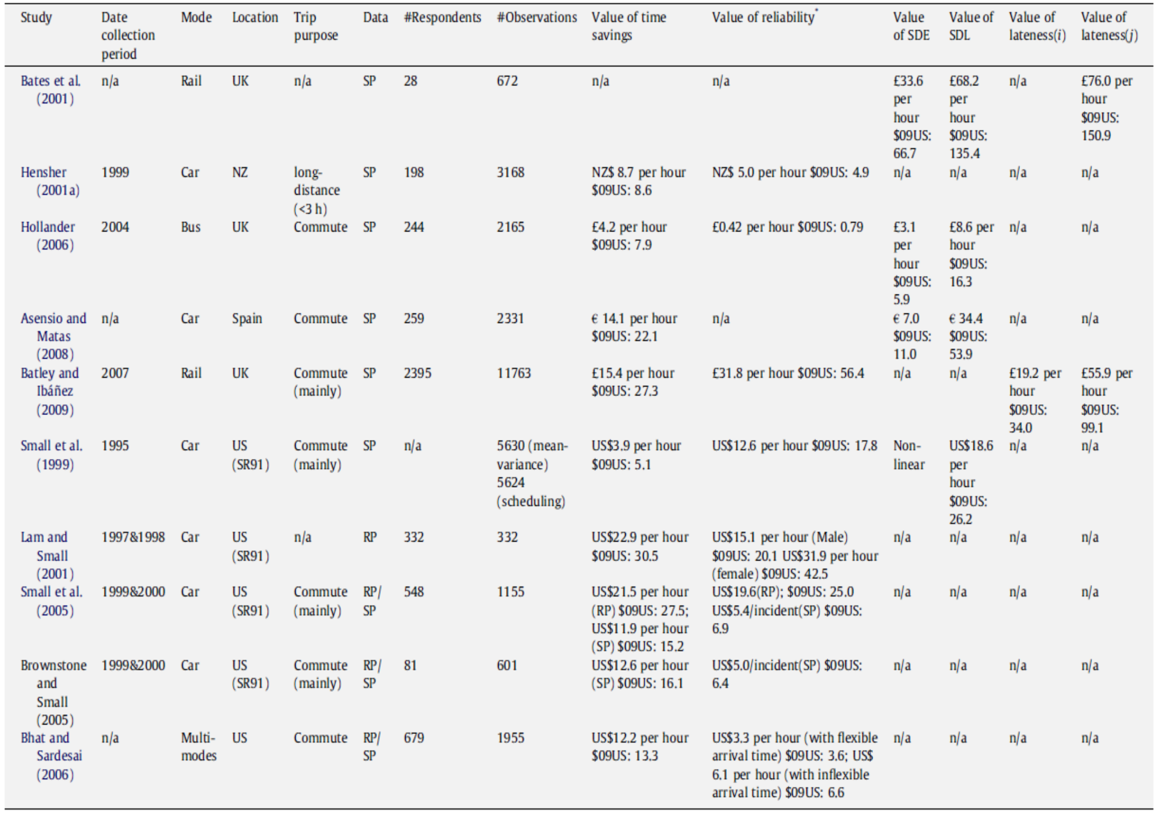
Scheduling Model

This scheduling model (small, 1982;) approach to model travel time reliability takes into account the consequences of unreliable travel time. Unlike centrality-dispersion model, it considers that disutility is incurred when not arriving at the preferred arrival time (*PAT*), no matter late or early. The utility function is expressed as follow:

$$U = \gamma_1 T + \gamma_2 SDE + \gamma_3 SDL + \gamma_4 DL$$

T is the travel time, SDE is schedule delay early, SDL is schedule delay late, DL is a dummy variable equal to 1 when there is SDL and 0 otherwise. And the estimated parameters ($\gamma_1, \gamma_2, \gamma_3, \gamma_4$) are assumed to be negative. In this utility form plus a cost attribute, the quantities such as VOT can be computed to obtain as the way using in centrality-dispersion model.

Li et.al (2010) summaries existing empirical studies regarding estimation of value of travel time reliability and time saving, as shown in Figure 2.5.



Study	Date collection period	Mode	Location	Trip purpose	Data	#Respondents	#Observations	Value of time savings	Value of reliability*	Value of SDE	Value of SDL	Value of lateness(*i*)	Value of lateness(*j*)
Bates et al. (2001)	n/a	Rail	UK	n/a	SP	28	672	n/a	n/a	£33.6 per hour $09US: 66.7	£68.2 per hour $09US: 135.4	n/a	£76.0 per hour $09US: 150.9
Hensher (2001a)	1999	Car	NZ	long-distance (<3 h)	SP	198	3168	NZ$ 8.7 per hour $09US: 8.6	NZ$ 5.0 per hour $09US: 4.9	n/a	n/a	n/a	n/a
Hollander (2006)	2004	Bus	UK	Commute	SP	244	2165	£4.2 per hour $09US: 7.9	£0.42 per hour $09US: 0.79	£3.1 per hour $09US: 5.9	£8.6 per hour $09US: 16.3	n/a	n/a
Asensio and Matas (2008)	n/a	Car	Spain	Commute	SP	259	2331	€ 14.1 per hour $09US: 22.1	n/a	€ 7.0 $09US: 11.0	€ 34.4 $09US: 53.9	n/a	n/a
Batley and Ibáñez (2009)	2007	Rail	UK	Commute (mainly)	SP	2395	11763	£15.4 per hour $09US: 27.3	£31.8 per hour $09US: 56.4	n/a	n/a	£19.2 per hour $09US: 34.0	£55.9 per hour $09US: 99.1
Small et al. (1999)	1995	Car	US (SR91)	Commute (mainly)	SP	n/a	5630 (mean-variance) 5624 (scheduling)	US$3.9 per hour $09US: 5.1	US$12.6 per hour $09US: 17.8	Non-linear	US$18.6 per hour $09US: 26.2	n/a	n/a
Lam and Small (2001)	1997&1998	Car	US (SR91)	n/a	RP	332	332	US$22.9 per hour $09US: 30.5	US$15.1 per hour (Male) $09US: 20.1 US$31.9 per hour (female) $09US: 42.5	n/a	n/a	n/a	n/a
Small et al. (2005)	1999&2000	Car	US (SR91)	Commute (mainly)	RP/ SP	548	1155	US$21.5 per hour (RP) $09US: 27.5; US$11.9 per hour (SP) $09US: 15.2	US$19.6(RP); $09US: 25.0 US$5.4/incident(SP) $09US: 6.9	n/a	n/a	n/a	n/a
Brownstone and Small (2005)	1999&2000	Car	US (SR91)	Commute (mainly)	RP/ SP	81	601	US$12.6 per hour (SP) $09US: 16.1	US$5.0/incident(SP) $09US: 6.4	n/a	n/a	n/a	n/a
Bhat and Sardesai (2006)	n/a	Multi-modes	US	Commute	RP/ SP	679	1955	US$12.2 per hour $09US: 13.3	US$3.3 per hour (with flexible arrival time) $09US: 3.6; US$ 6.1 per hour (with inflexible arrival time) $09US: 6.6	n/a	n/a	n/a	n/a

Figure 2.6 A Summary of Recent Valuation of Travel Reliability Studies (Source: Li et.al 2010)

2.5.4 Summary of SHRP2 Research on Travel Time Reliability

The research on travel time reliability (TTR) is currently led by the second Strategic Highway Research Program (SHRP2). There are for primary focus area in SHRP2, shown in Table 2.5:

Table 2.5 List of SHRP2 Research Focus

Area	Focus
Safety	Prevent or reduce the severity of highway crashes by understanding driver behavior
Renewal	Address the aging infrastructure through rapid design and construction methods that cause minimal disruption and produce ling-lived facilities
Reliability	Reduce congestion and create more predictable travel times through better management and operations
Capacity	Integrate mobility, economic, environmental, and community need in the planning and designing or transportation capacity

Several key research areas are identified and grouped into three matter themes including data collection and archiving, simulation and estimation, and applications.

- Data Collection and Archiving: Unlike traditional estimation methods, TTR based performance measures requires well-designed data collection and estimation procedures and architecture (ITRE final report). Therefore, the data needed is not restricted to traffic detector data, but event data including incident, lane closure, inadequate base capacity, traffic control, and weather.

- Simulation and Prediction Methods: the SHRP2 L05 project classified TTR prediction into five major categories: sketch planning; project planning; facility performance; travel demand forecasting; and traffic simulation. The latter three method are computational intense and require software to implement, such as FREEVAL-RL and VISSIM. Generally, TTR evaluation methods proposed in SHRP2 program can be categorized as: 1) HCM methods; 2) travel demand model based methods; and 3) microscopic or mesoscopic simulation base methods.

- Application in Decision Making and Project Evaluation: TTR is a significant performance measures to be incorporated into the operational and planning process at transportation agencies (L05). TTR indexes are also useful performance measures to a prioritization process and evaluation of program trade-off.

2.5.5 HCM Travel Time Reliability Method and FREEVAL-RL Tool

In contrast to average based facility methods, the TTR prediction methods in HCM requires inputs of the main source of variability that lead to travel time unreliability, such as variability in traffic demand, incidents, weather events, work zones, and special event. Scenarios with probability of occurrence are then built from combinations of conditions associated with each sources of travel time variability. Because of hundreds of scenarios that are generated, a computation engine is desired to run through all scenarios and generate results.

The FREEVAL-RL (FREeway EVALuation - RLiability) is designed to faithfully implement HCM freeway reliability methodology. It also contains cell-transmission model based algorithms for oversaturated freeway facilities, and is able to track queue accumulation and dissipation over multiple segments, as well as multiple time periods. Figure 2.6 shows the procedures to automate reliability methodology. The comprehensive output of FREEVAL-RL is listed in Appendix A.

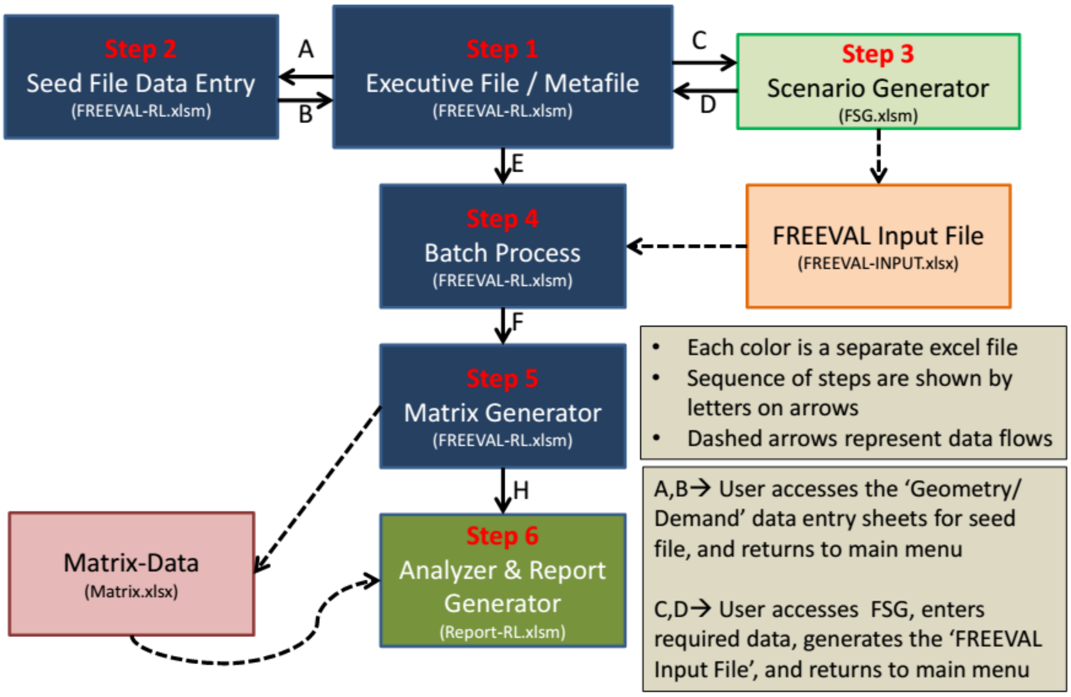


Figure 2.7 HCM Freeway Reliability Methodology Automation Process Flow

2.6 Summary

In this section, a summary is given for the findings and conclusions on the comprehensive literature review, as follow:

(1) Work zone scheduling relies on estimation of work zone capacity and traffic delays. Although many researches have been proposed different approaches to estimate the work zone capacity, due to a variety of factors affecting work zone capacity, there is no one universal approach can estimate work zone capacity from

site to site. The HCM (2010) method with its simplicity and acceptable accuracy is widely applied to studies on work zone operation and scheduling. However, existing work zone capacity estimation approaches can only output a static value for a given work zone type. In reality, work zone capacity fluctuates across the time because of variation of exogenous factors and non-recurring events such as severe weather and incidents. Regarding the traffic delay estimation in work zones, the queuing theory can be used to formulate the delays with the key input parameters such as the estimated work zone capacity and time-dependent traffic volumes that may be directly collected form field observations. It should be noted that although average hourly traffic flow was used to capture the time-dependent flow variation, it is still too large to estimate queuing delay at a detailed level.

(2) In terms of work zone scheduling and optimization, the state-of-practice shows that analytical comparison of several competing alternatives based on subjective engineering experience and judgment is widely used. It might be highly inefficient when the analysis scale and complexity increase. The state-of-art of the academic research focuses on developing advanced optimization method to find the optimal schedule and the best operation strategy. Several earlier research efforts optimized work zone length (McCoy, et al. 1980 and 1987; Martinelli ad Xu, 1996) and crew assignment (Fwa and Cheu, 1998; Ma, et al. 2004) to minimize total travel delay. However, the project start time, which has significantly effect on total work zone

delay, were not taken into account in these earlier studies. But the problem is that if the different start time is considered, the minimization model may tend to schedule the work zones at nighttime or during the weekend, which could increase the maintenance and labor costs. The agency cost (Jiang and Adeli, 2003; Yang et.al 2008; Tang and Chien, 2008) was therefore introduced to balance the trade-off between agency cost and user cost. However, there are two major limitations in these cost-effective scheduling methods: 1) they solely focused on individual work zone project, and cannot be extended to multiple work zones scheduling; and 2) the maximum time window for work zone scheduling is one day, which is not able to schedule work zones having loner duration.

(3) The HCM travel time reliability method is desirable for estimating excess travel time incurred to travelers since it can reveal the nature of traffic condition variation comparing to average-based estimation. For example, as Figure 2.8 illustrated schedule A has higher average delay but better reliability than schedule B. In worse than average cases, schedule B may lead to more congestion than schedule A.

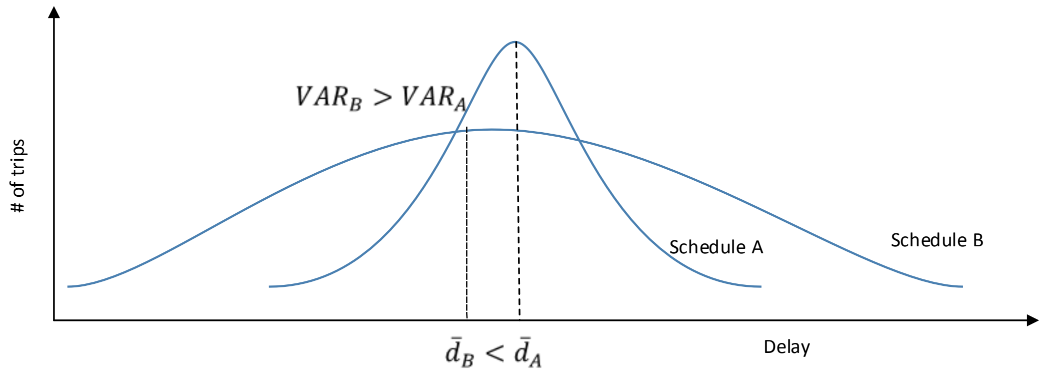


Figure 2.8 Delay based work zone scheduling vs. TTR Based Work Zone Scheduling

In addition, large amount of qualified historical data are desired to perform the reliability measures calculation and evaluation. The calculation is computational intense, and requires software such as FREEVAL-RL to implement for higher accuracy and time saving. However, using them in practice to evaluate the large set of planning scenarios in work zone scheduling is quite computationally inefficient.

3. Proposed Methodology

Given a set of work zone projects and days required to be performed, the intent is to develop an efficient optimization framework to identify reasonably optimal schedule with consideration of travel time reliability. Figure 3.1 shows the overall flowchart of the methodology.

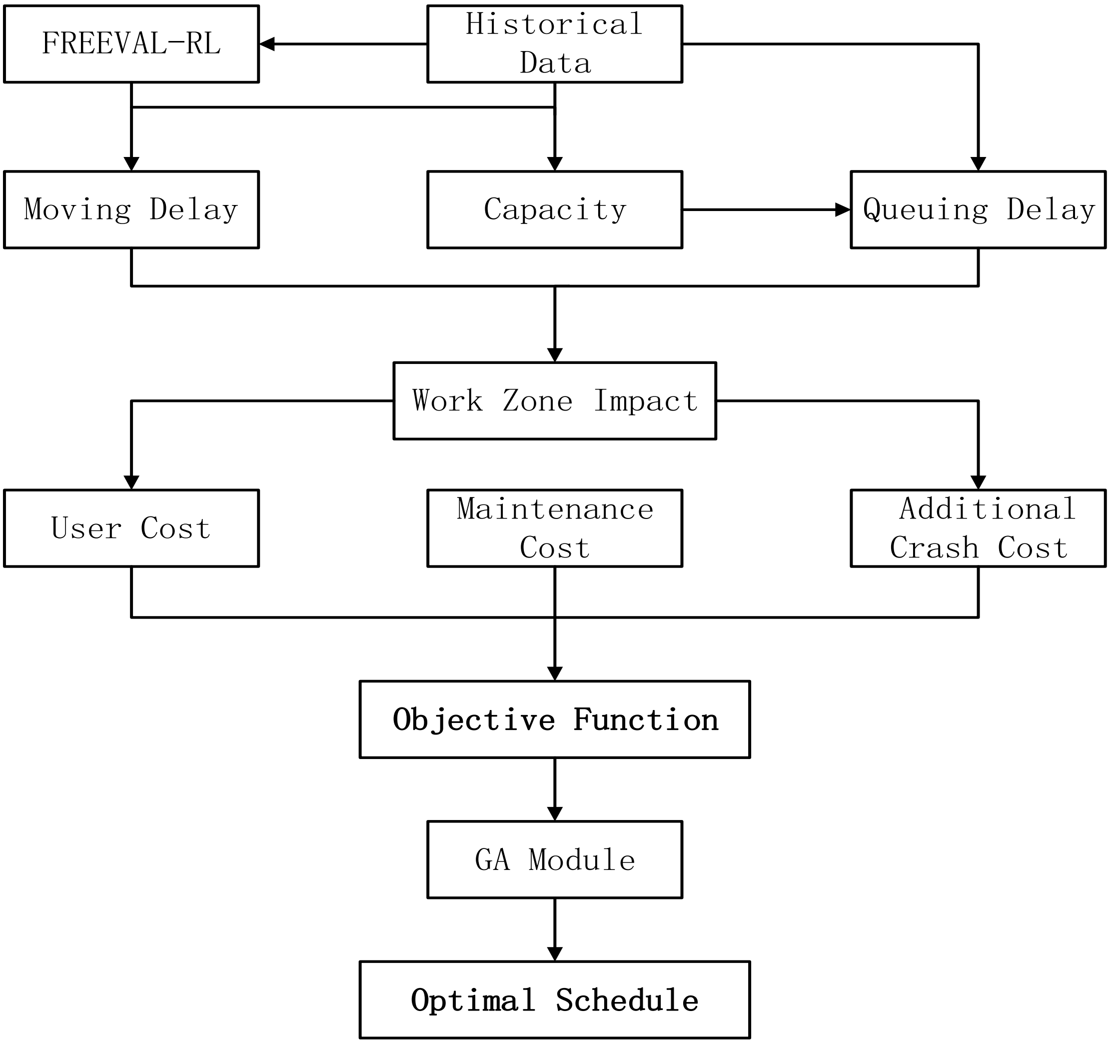


Figure 3.1 Flowchart of Proposed Methodology

The methodology comprises two major parts: the impact of work zones on travel time reliability, and the optimization model for work zone scheduling. The FREEVAL-RL tool is used for simulating the base condition and work zone condition, and generating sufficient scenarios for different traffic condition.

3.1 Impact of Work Zone on Travel Time

The road user might experience traffic disruption and delay at a work zone because of the capacity drop and lower speed limit at the work zone section compare with non-work zone condition. Normally, the excess travel time should be expected to a trip that involves active work zones. Since the traffic condition varies with the time of day and day of week, the average-based delay estimation models are not sufficient for roadway operations and trip planning. In other word, the analysis of work zone impact should expand beyond the traditional congestion measures that focus solely on recurring congestion, to capture the non-recurrent event (weather, incidents) that affects travel time reliability.

The development of the FREEVAL-RL computational tool, which faithfully implements the HCM reliability method, provides a good opportunity to evaluate the performance of freeway reliability. Detailed geometric data, historical traffic data, weather data, incident/crash data, and work zone characteristics are needed to be collected and processed in order to simulate the base condition and work zone condition for each 15-min time interval of day (consistence with FREEVAL-RL) and each day of week. Some attributes and performance measures are retrieved from the output for each scenario and each time interval, listed in Table 3.1. The selected output are grouped by each day of week then time interval of day, and reordered by actual travel time for calculating desired percentiles.

Table 3.1 Selected Entries from FREEVAL Output

Entry	Description
s	Scenario number
i	Analysis period / 15-min interval of day
P	Probability of scenario *s*
f_w	Capacity adjustment factor due to the weather event, associated with analysis period *i*, scenario *s*
f_I	Capacity adjustment factor applied to each of the open lanes as due to the incident, associated with analysis period *i*, scenario *s*
TTI	Facility TTI in the analysis period *i* (actual travel time/min travel time)
VMTD	Vehicle miles traveled as if all demand had been served in the analysis period
VMTV	Vehicle miles traveled of the vehicles actually severed during the analysis period

The work zone impact on travel time is measured by the difference of percentile travel times between the base condition and work zone condition. For each time interval (*i,j)*, the scenario generator of FREEVAL-RL can generate total number *S* of scenarios based on the input events data. And one scenario is a unique combination associated each sources of travel time unreliability. These scenarios form the travel time distribution of corresponding time interval. For each scenario *s*, the difference between the travel time under base condition $t_{wz}^{s}(i,j)$ and the travel time under work zone condition $t_{base}^{s}(i,j)$ is the delay $d^{s}(i,j)$ induced by work zone, namely:

$$d^{s}(i,j)=t_{wz}^{s}(i,j)-t_{base}^{s}(i,j) \tag{3.1}$$

As Figure 3.1 shown, this delay (excess travel time) comprises the moving delay $md^{s}(i,j)$ when vehicles pass through the work zones, and the potential queuing delay $qd^{s}(i,j)$ at the upstream of work zone, thus:

$$d^{s}(i,j)=md^{s}(i,j)+qd^{s}(i,j) \tag{3.2}$$

The magnitude of delay associated with the work zone mainly depends on the variation of traffic flow over time, the reliability of the roadway section, and the corresponding work zone capacity. The moving delay, incurred by vehicle traveling through the work zone area, varies with work zone speed reduction that caused by lower speed limit, disturbance of work zone, and variation of traffic density. And the queuing delay is incurred to motorists once the arrival rate exceeds the work zone capacity. It can be quantified by the waiting time in queue before the vehicle enters into the work zone.

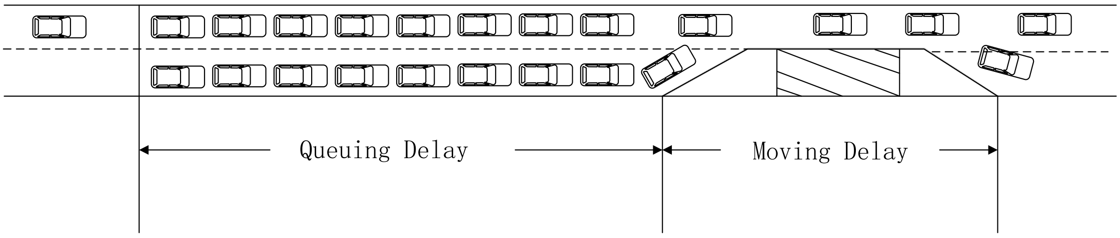


Figure 3.2 Demonstration of Vehicle Delay at Work Zone

Applying the Equation 3.1 to all scenarios associated with the time interval, we can develop the work zone delay distribution, and then calculating the mean delay and percentile delays. The mean delay can be treated as centrality measure of this delay distribution, while the difference between 95^{th} percentile delay and mean delay is included as dispersion measure. For sake of presentation, a number of matrixes are used to store values. The horizontal dimension is the day of week, while the vertical dimension is time interval of day.

3.1.1 Travel Time Reliability Measures

As discussed in literature, most reliability measures compare periods with high actual travel time with average travel time. Upper percentiles of travel time distribution are mostly used. Hence, for evaluating work zone impact, three travel time reliability measures are calculated to quantify the impact of work zone: the 95th percentile travel time, the buffer index, and the planning time index. Each of these measures is discussed as follow:

95th Percentile Travel Time/Rate:

The 95th percentile travel time indicates that 19 out of 20 trips will be ensured on time. For different length of work zone, it is difficult to combine segment travel times into a corridor average with this measure. To overcome this difficulty, the travel times can be converted into travel time rates through division of travel time by segment length. The normalized travel time is in units of minutes per mile.

Buffer Index:

The buffer index is computed as the difference between the 95th percentile travel rate and the average travel rate, divided by the average travel rate. For different definition and use, 80th or median might be used to calculate different buffer time. It general represents the extra time a traveler should budget to ensure on time for 95% of trips.

Planning Time Index:

The planning time index represents the total travel time that should be planned when an appropriate buffer time is included. The planning time index compares a near-worst-case travel time (95th percentile travel time) with a travel time in free flow condition or light traffic conditions.

3.1.2 Work Zone Vehicle Delay Estimation

The following assumptions are made to formulate the problem:

(A1). The traffic flow rate approaching work zone at time of day is approximated by the means of historical traffic demand at the beginning of this time interval. And traffic flow approaching work zone is equally distributed over each lane.

(A2). The proportion of heavy vehicles approaching work zone is assumed to be a constant.

(A3). There are no ramps or access points in work zone.

Moving Delay

Moving delay is incurred by motorists traveling through a work zone with reduced travel speed due to lower speed limit, limited roadway clearance, narrowed lanes, and rubbernecking factors, etc. This excess travel time can be estimated by the difference of actual travel times simulated by FREEVAL under base and work zone conditions. The actual travel time is normalized by the facility length L_C as the travel time for unit length (min/mi). The normalized travel rate can overcome the difficulty and complexity of simulating travel time for different length of work zone and of combining the link/route travel times into corridor level.

For sake of presentation and further calculation, four matrixes are used to store the travel time rates: $\mathbf{B}_{I\times J}^{m}$ for mean travel rate under base condition; $\mathbf{B}_{I\times J}^{95}$ for 95th percentile travel rate under base condition; $\mathbf{W}_{I\times J}^{m}$ for mean travel rate under work zone condition; and $\mathbf{W}_{I\times J}^{95}$ for 95th percentile travel rate under work zone condition.

Let $b_{i,j}^{95}, w_{i,j}^{95}$, $b_{i,j}^{m}$, $w_{i,j}^{m}$, respectively, denote the 95th percentile travel rate and mean travel rate at the *ith* time interval on *jth* day of week under base condition and work zone condition, thus:

$$b_{i,j}^{95} = \frac{T_{base}^{95}(i,j)}{L_C} \quad \forall i,j \tag{3.3}$$

$$b_{i,j}^{m} = \frac{T_{base}^{m}(i,j)}{L_C} \quad \forall i,j \tag{3.4}$$

$$w_{i,j}^{95} = \frac{T_{wz}^{95}(i,j)}{L_C} \quad \forall i,j \tag{3.5}$$

$$w_{i,j}^{m} = \frac{T_{wz}^{m}(i,j)}{L_C} \quad \forall i,j \tag{3.6}$$

The 95th percentile travel times and mean travel times are calculated based on result of FREEVAL-RL.

A time-interval-by-day selection matrix $\mathbf{H}_{I\times J}$ represents a work zone operation schedule, and each element has binary value either 1 for work zone appearance or 0 for without work zone. For a given work zone schedule, the moving delay rate can be expressed by the element-wise product (also called Hadamard product) of the difference between $\mathbf{W}_{I\times J}^{95}$ (or $\mathbf{W}_{I\times J}^{m}$) and $\mathbf{B}_{I\times J}^{95}$ (or $\mathbf{B}_{I\times J}^{m}$) and $\mathbf{H}_{I\times J}$. Let $\mathbf{MD}_{I\times J}^{95}$ and $\mathbf{MD}_{I\times J}^{m}$, respectively, denote the 95th percentile moving delay matrix and mean moving delay matrix, and each element represents the moving delay due to work zone at that time interval. Thus,

$$\mathbf{MD}^{95} = (\mathbf{W}^{95} - \mathbf{B}^{95}) \circ \mathbf{H} \tag{3.7}$$

$$\mathbf{MD}^{m} = (\mathbf{W}^{m} - \mathbf{B}^{m}) \circ \mathbf{H} \tag{3.8}$$

and

$$md_{i,j}^{95} = (w_{i,j}^{95} - b_{i,j}^{95}) \cdot h_{i,j} \tag{3.9}$$

$$md_{i,j}^{m} = (w_{i,j}^{m} - b_{i,j}^{m}) \cdot h_{i,j} \tag{3.10}$$

Table 3.2 gives an example of calculation of $\mathbf{MD}$ matrix for a work zone operated during 12:00pm on Tuesday and 5:00am on Friday.

Table 3.2 Example of Moving Delay Calculation

	Day of Week				
Time of day	*0*	*0*	…	…	$W_{1,5}$- $B_{1,5}$
	0	*0*	…	…	$W_{2,5}$- $B_{2,5}$
	…	…	…	…	…
	….	….	…	…	$W_{20,5}$- $B_{20,5}$
	…	…	…	…	…
	…	…	…	$W_{48,4}$- $B_{48,4}$	*0*
	…	…	…	…	…
	0	…	…	$W_{96,4}$- $B_{96,4}$	*0*

Work Zone Capacity

In this study, the work zone capacity is defined as the maximum 15-min flow passing through the work zone. Since there is no direct output for work zone capacity in FREEVAL-RL, to reveal to variations in capacity, the corresponding capacity adjustment factors for each of variability sources are used to estimate work zone capacity at each 15-min time interval. Let $\mathbf{CW}_{I\times J}^{95}$ and $\mathbf{CW}_{I\times J}^{m}$, respectively, denote the 95th percentile capacity matrix and mean capacity matrix, and each element in the capacity matrix, denoted as $cw_{i,j}^{95}$ and $cw_{i,j}^{m}$, is the roadway capacity at the i^{th} time interval on j^{th} day of week. Note if the days considered for completing work zones projects are more than a week, the matrix is expanded to fit the need. The percentile weather adjustment factor and percentile incident adjustment factor are calculated based on the FREEVAL-RL output. Given a work zone operation schedule $\mathbf{H}$, each element in the capacity matrix is calculated as follow:

$$cw_{i,j}^{95} = \begin{cases} c_{base}\times f_w^{95}(i,j)\times f_I^{95}(i,j)\times f_{wz^t}\times N_o, & if\ h_{ij}=1 \\ c_{base}\times f_w^{95}(i,j)\times f_I^{95}(i,j)\times N_b, & if\ h_{ij}=0 \end{cases} \tag{3.11}$$

$$cw_{i,j}^{m} = \begin{cases} c_{base}\times f_w^{m}(i,j)\times f_I^{m}(i,j)\times f_{wz^t}\times N_o, & if\ h_{ij}=1 \\ c_{base}\times f_w^{m}(i,j)\times f_I^{m}(i,j)\times N_C, & if\ h_{ij}=0 \end{cases} \tag{3.12}$$

where,

c_{base} : capacity for base condition,

f_{wz^t} : adjustment factor for work zone type *t*.

$f_w^{95}(i, j)$, $f_w^m(i, j)$: 95th percentile and mean weather adjustment

$f_I^{95}(i, j)$, $f_I^m(i, j)$: 95th percentile and mean incident adjustment

N_b, N_o: number of lane for base condition and work zone condition

Note the based capacity unit is converted to vehicle per lane per 15 minute for easy calculation and use. The Table 3.2 shows example work zone capacity adjustment factors computed based on the average result or previous studies. As discussed in literature, due to the capacity at work zone are highly variable and depend on site-specific factors, it is better to calibrate this adjustment on local data and experience.

Table 3.3 Work Zone Adjustment Factor Suggested by HCM

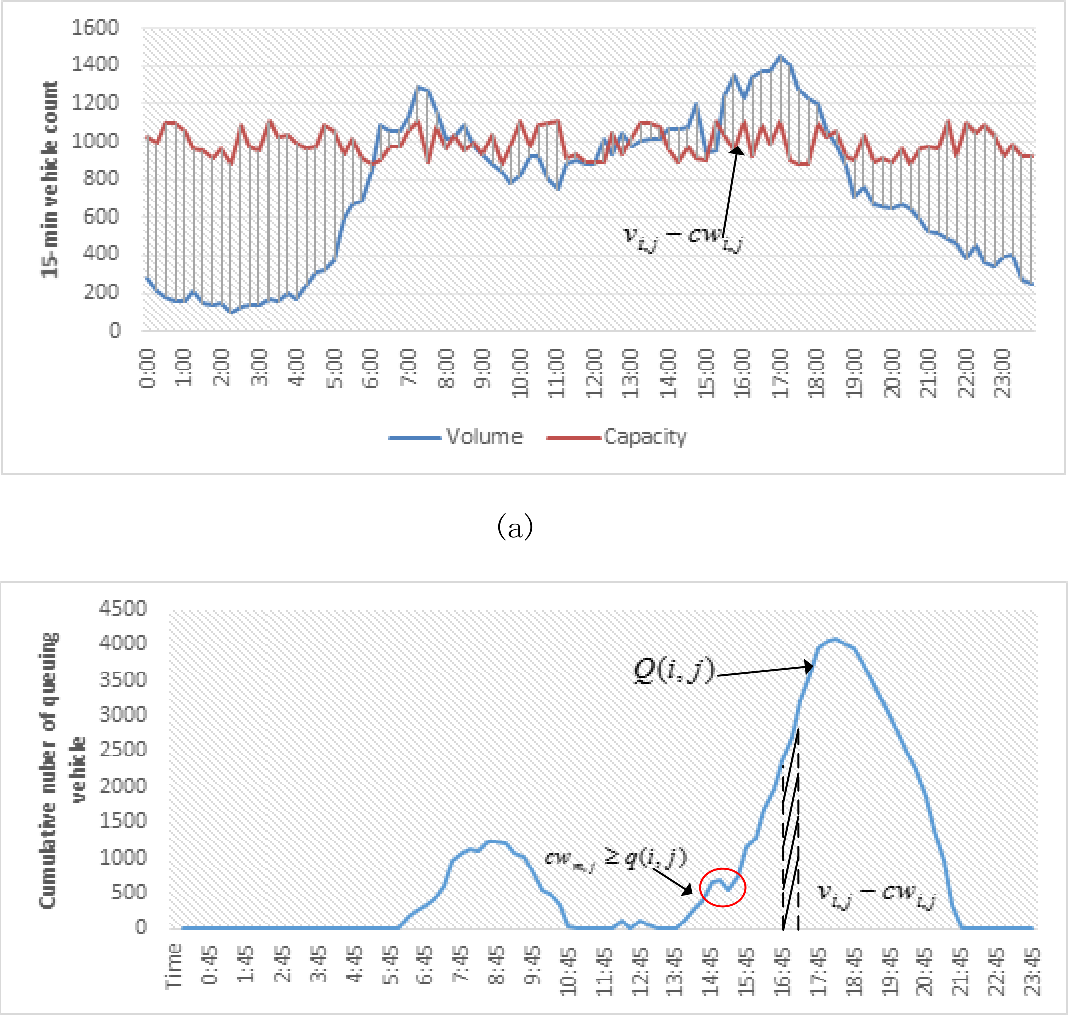
Directional Lanes	Shoulder closed	1 Lane Closed	2 Lane Closed	3 Lane Closed
2	**0.81**	**0.69**	**N/A**	**N/A**
3	**0.83**	**0.75**	**0.64**	**N/A**
4	**0.87**	**0.83**	**0.73**	**0.60**

Queuing Delay

Although computer simulation is a valuable method for estimating actual travel time and reliability metrics under variety of existing and pre-determined conditions, however, a single simulation run, which could be quite time consuming. For instance, a simulation for only one work zone operation strategy with fixed start time takes about half hour to run in FREEVAL. Since work zone scheduling is a complex problem in terms of combinatory combinations of non-recurring events, different starting time, length, and duration of work zones, it might take months to search for the optimal schedule for a set of work zone by running the FREEVAL-RL directly. In order to avoid simulating the huge number of situations, a method integrating the concept of deterministic queuing theory and limited simulation data is used.

To estimate vehicle delays with queuing theory, a work zone can be modeled as a server for vehicles to enter the work zone in order of the vehicle arrivals. A work zone with open lanes is thus a one server queuing system and the queue discipline is apparently first-come-first-served. The average arrival rate of vehicle is the traffic flow rate and the service rate of the system is the traffic capacity of the work zone.

Within a specific time period Δt (15-minute interval in this study), if the traffic flow approaching the work zone exceeds the work zone capacity, a queues will form or increase at upstream of work zone. The total vehicle queue increased in that time interval is difference between the numbers of vehicles arrived and the number of vehicles can be served (work zone capacity).



(a)

(b)

Figure 3.3 Diagram of Traffic Demand, Capacity, and Queue

Denote matrix $\mathbf{V}_{I \times J}$ as the time by day demand matrix, each element $v_{i,j}$ represents the average arrival rates at the i^{th} time interval of j^{th} day of week. For a given work zone schedule, the initial queue length for the i^{th} time interval of j^{th} day of week, denoted as $Q(i, j)$, can be calculated with the corresponding roadway capacity:

$$Q(i, j) = \begin{cases} \max\left\{Q(i-1, j) + (v_{i,j} - cw_{i,j}), 0\right\}, \ if \ i \neq 1 \\ 0, \ if \ i = 1 \end{cases} \tag{3.13}$$

Queue length at beginning of time interval *i* is also the number of vehicles in the waiting line. Therefore, when the first vehicle arrived during the time interval *i*, it become the $(Q(i,j)+1)$th vehicle in the queue. Note the queue length is defined as the number of vehicles stopping or slow moving at the upstream of work zone.

Let $\mathbf{QD}_{I\times J}^{95}$ and $\mathbf{QD}_{I\times J}^{m}$ denote the 95th percentile and mean queuing delay matrix respectively. Each element in matrix is waiting time incurred to the motorist that arrived at the beginning of that time interval. Because the accumulated queue in the current time interval may propagate to the next one, the following two cases should be considered to calculate the $qd_{i,j}$ ($qd_{i,j}^{95}$ and $qd_{i,j}^{m}$) :

Case 1: For the i^{th} time interval, the work zone capacity is greater than or equal to the number of vehicle in queue, namely

$$cw_{i,j} \geq q(i,j) \tag{3.14}$$

Since the work zone capacity at that time interval is $cw_{i,j}$ ($cw_{i,j}^{95}$ and $cw_{i,j}^{m}$), the time needed to clear all $qd_{i,j}$ vehicles from the queue can be expressed by:

$$qd_{i,j} = \frac{q(i,j)}{cw_{i,j}} \cdot \Delta t \tag{3.15}$$

In this case, the queuing vehicle at current time can be cleared during one 15-min time interval.

Case 2: The work zone capacity is lower than the number of vehicle in queue, namely:

$$cw_{i,j} < q(i,j) \tag{3.16}$$

In this case, more than one time interval is needed to have the vehicles in queue cleared. Since work zone capacity changes time interval by time interval due to the interaction of other unreliability sources, it would be inaccurate to use the same capacity value to estimate time needed to clear the queue. The number of interval needed for clearing the queue *k*, is first calculated, where k should satisfy:

$$\sum_{m=i}^{i+k-1} cw_{m,j} < q(i,j) \;\; and \;\; \sum_{m=i}^{i+k} cw_{m,j} \geq q(i,j) \tag{3.17}$$

Then the time needed to clear the queue for this case can be calculated by:

$$qd_{i,j} = (k-1)\cdot\Delta t + \frac{q(i,j) - \sum_{i}^{i+k-1} cw_{i,j}}{cw_{i+k,j}}\cdot\Delta t \tag{3.18}$$

The queue might disappear before the end of the last time interval, the second term on the right half part is the duration of the queue lasting during the last time interval. The overall procedures for the queuing delay estimation is presented in Figure 3.4.

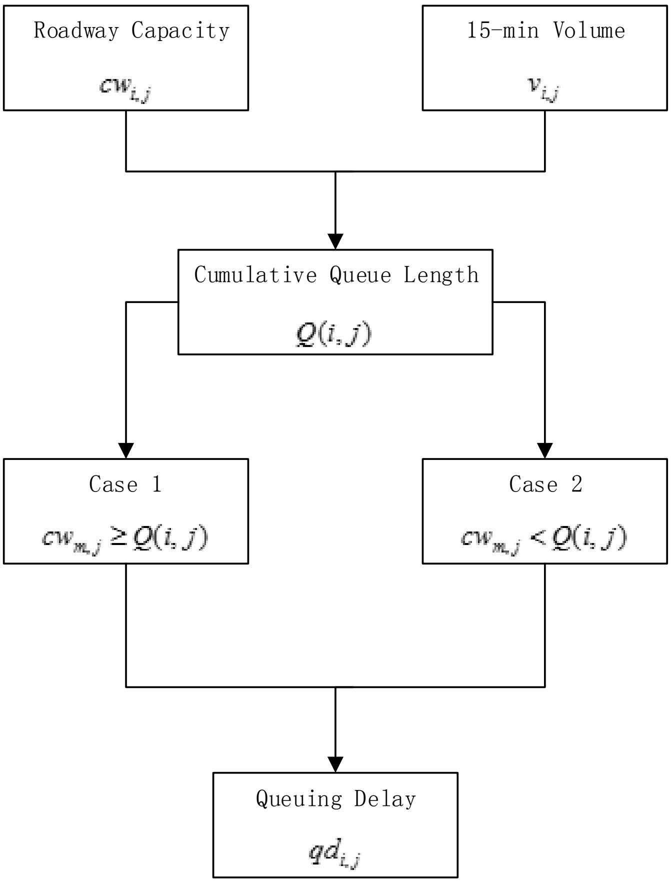


Figure 3.4 Queuing Delay Estimation Flow Chart

3.1.3 Work Zone Delay and Reliability Impact

Finally, for the given work zone schedule $\mathbf{H}$ with work zone length l, the difference of mean delay between work zone condition and base condition, denoted as $\mathbf{D}^m_{I\times J}$, is calculated by:

$$\mathbf{D}^m = \mathbf{QD}^m \circ \mathbf{H} + l\mathbf{MD}^m \tag{3.19}$$

$$d^m_{i,j} = qd^m_{i,j} \cdot h_{i,j} + md^m_{i,j} \cdot l \quad \forall i, j \tag{3.20}$$

Similarly, the difference of 95th percentile delay between work zone condition and base condition, denoted as, $\mathbf{D}^{95}_{I\times J}$ is calculated by:

$$\mathbf{D}^{95} = \mathbf{QD}^{95} \circ \mathbf{H} + l\mathbf{MD}^{95} \tag{3.21}$$

$$d^{95}_{i,j} = qd^{95}_{i,j} \cdot h_{i,j} + md^{95}_{i,j} \cdot l \quad \forall i, j \tag{3.22}$$

The impact of work zone on travel time reliability, measured by the buffer time (BT), can be calculated by the difference of buffer time between work zone condition and base condition. Let $\mathbf{DBT}_{I\times J}$ denote the buffer time difference matrix, and each element in this matrix, denoted as $dbt_{i,j}$, is calculated by

$$dbt_{i,j} = BT^{wz}_{i,j} - BT^{base}_{i,j} = (TT^{95}_{wz}(i,j) - TT^{m}_{wz}(i,j)) - (TT^{95}_{base}(i,j) - TT^{m}_{base}(i,j)) \tag{3.23}$$

where $TT^{95}_{base}(i,j), TT^{m}_{base}(i,j), TT^{95}_{wz}(i,j), TT^{m}_{wz}(i,j)$ are the 95th percentile and mean total travel time under base condition and work zone condition respectively. Since these total travel times cannot be obtained directly, the Equation 3.23 can be modified as follow:

$$\begin{aligned} dbt_{i,j} &= (TT^{95}_{wz}(i,j) - TT^{m}_{wz}(i,j)) - (TT^{95}_{base}(i,j) - TT^{m}_{base}(i,j)) \\ &= \left(TT^{95}_{wz}(i,j) - TT^{95}_{base}(i,j)\right) - \left(TT^{m}_{wz}(i,j) - TT^{m}_{base}(i,j)\right) \\ &= d^{95}_{i,j} - d^{m}_{i,j} \end{aligned} \tag{3.24}$$

Hence the buffer time difference can be calculated by the difference between 95th percentile delay and mean delay. Take the concept of travel time reliability, this difference can be treated as the "reliability" of delay.

In addition, the total average work zone delay for a given operation schedule, denoted as *TD*, is calculated by:

$$TD = \sum_{i=1}^{I} \sum_{j=1}^{J} (d_{i,j}^{m} \cdot v_{i,j}) \tag{3.25}$$

3.2 Objective Function

As discussed in previous studies (Schonfeld and Chien, 1999; Jiang and Adeli, 2003), to balance the interests of both the transportation agencies and road users, the optimal work zone schedule can be identified by minimizing the total cost consisting of maintenance cost, accident cost, and road user cost.

3.2.1 Total Work Zone Cost

Additional assumptions are made as follow to develop the objective total work zone cost function:

(A4). The time required for a work zone is a function of desired work zone length and unit maintenance time.

(A5). The unit maintenance cost and labor cost are same for daytime work, and a multiplier is used to calculate extra maintenance cost for nighttime work.

(A6). User delay can be converted into user delay cost by an average cost v_{vm}.

(A7) In accordance with MUTCD (2003), the length of a work zone can be calculated as the sum of the transition area length, buffer space length, the work space length, and the termination area length as shown in Figure 2.1. Except the work space length, other length of work zone components can be considered as constant coefficients. Hence, the work zone length l is expressed by the sum of work space length l_w and a fixed length required to set up a work zone l_f .

Let F denote the total work zone cost, consists of three components: total user cost C_U, total maintenance cost C_M including work zone setup cost, labor cost, and total additional accident cost C_A due to work zone activities.

Thus, the total cost for a given work zones schedule can be expressed by the sum of the total costs associated with each individual work zone *n* in the work zone set *N*, namely:

$$F = C_M + C_A + C_U = \sum_{n=1}^{N} (C_{Mn} + C_{An} + C_{Un}) \quad \forall n \tag{3.26}$$

All the three components are identified in dollars per length (mile) of work zone. The description and estimation of these three components is elaborated in following sections. Note if the only the cost of road users is taken into account, the total maintenance cost and the additional incident cost can be set to 0. In this case, the optimal work zone schedule is determined by minimum travel time reliability impact.

For the sake of presentation, let two row vectors S^n and E^n denote the start time and end time of the *n*th work zone respectively. The first element of S^n and E^n represents the time interval of day, and the second element represents the day of week, i.e. (48,4) is the 48th 15-minute time interval of the 4th day of week. Thus the duration of work zone *n*, is the elapse time between the start time and end time. Namely,

$$D_n = (E^n{}_2 \cdot I + E^n{}_1) - (S^n{}_2 \cdot I + S^n{}_1) \quad \forall n \tag{3.27}$$

where,

D_n is the duration of work zone *n*.

I is the total number of 15-minute time interval considered for work zone execution.

From assumption 5, the time required to complete a work zone D_n, can be also expressed by length of work space l_w^n, time required for setting a work zone t_1, and unit maintenance time t_2, namely:

$$D_n = t_1 + l_w^n \times t_2 \quad \forall n \tag{3.28}$$

Therefore, from Equation (3.15) and (3.16), the length of working space can be expressed by

$$l_w^n = \frac{D_n - t_1}{t_2} = \frac{(E^n{}_2 \cdot I + E^n{}_1) - (S^n{}_2 \cdot I + S^n{}_1) - t_1}{t_2} \quad \forall n \tag{3.29}$$

and the work zone length l_n is calculated by:

$$l_n = l_w^n + l_f \tag{3.30}$$

The time-interval-by-day selection matrix $\mathbf{H}^n{}_{I\times J}$ represents the *nth* work zone schedule. The number of rows I is the total number of 15-min time interval a day considered for work zone operation. The number of column J is the total number of days required to complete a set of work zone projects. Each element has binary value either 1 for work zone appearance or 0 for without work zone. The value of each element is determined by:

$$h^n{}_{ij} = \left\{\begin{array}{ll} 1, & if\ S^n{}_2 \cdot I + S^n{}_1 \le i + j \cdot I \le E^n{}_2 \cdot I + E^n{}_1 \\ 0, & otherwise \end{array}\right\} \quad \forall i, j, n \tag{3.31}$$

3.2.1 Maintenance Cost

Denote the maintenance cost of work zone *n* as C_{Mn}. It normally represents the combination cost for the maintenance and work activities including material, equipment, and labor costs, and is a function of unit maintenance cost and length of working area l_n.

Note in previous study, the material cost, equipment cost are taken account into the total cost as a function of optimal work zone length. It may impact on the performance of the optimization model, since the maintenance cost is overweighed. Actually, given the length of a work zone project, the total maintenance cost for day time operation is fixed. According to the assumption 6, the extra cost associated with nighttime operation or subwork zone strategy should be considered. Thus,

$$C_{Mn} = v_1 + (1 + \beta \cdot NT_n) \cdot v_2 \cdot l_n \quad \forall n \tag{3.32}$$

where l_n is the length of working area, v_1 is the fixed cost of setting and removing traffic control devices and equipment, and v_2 is unit maintenance cost in dollars normalized by length (mile). NT_n is the percentage of work zone activity at night. β is the multiplier for extra cost at nighttime.

By substituting the Equation (3.17) to Equation (3.19), the maintenance cost is derived as:

$$C_{Mn} = v_1 + \frac{(1 + \beta \cdot NT_n) \cdot v_2}{t_2} \times \left((E^n{}_2 \cdot I + E^n{}_1) - (S^n{}_2 \cdot I + S^n{}_1) - t_1 \right) \quad \forall n \tag{3.33}$$

3.2.2 Additional Accident Cost

The additional accident cost C_{An} refers to the cost of additional traffic accident occurring in the work zone and queue areas in the freeway. The traffic delay and costs of potential secondary incident are not taken into account. Applied the similar concept of previous studies (McCoy, Jiang and Adeli), the additional accident cost is estimated by the number of accidents, n_a, per 100 million vehicle hours multiplied by the total delay associated with work zone *n*, denoted as TD_n and the average cost per accident,

v_a. If additional data is available, the estimated crash rate could be more accurate. Then the work zone crash rate can be calculated by the total number of work zone crash n_{wz}, divided by sum of work zones duration in a given year D_{TWZ}. In this study, the greater one is used for estimating additional work zone accident cost, namely,

$$C_{An} = \max\left(\frac{n_a \times v_a \times TD_n}{10^8}, \frac{n_{wz} \times v_a \times TD_n}{D_{TWZ}}\right) \qquad \forall n \tag{3.34}$$

3.2.3 Road User Cost

User costs are determined by the amount and value of lost time and unreliability caused by work zone activities. Applying the similar concept of centrality-dispersion model (Small et.al, 1999), the total road user cost of individual work zone, C_{Un} is expressed by the sum of the total average user delay multiplied by the value of time *VOR*, and the total reliability impact multiplied by value of reliability *VOT*, namely:

$$\begin{aligned} C_{Un} &= \sum\left(\mathbf{D}^m_{(n)} \circ \mathbf{V}\right) \cdot VOT + \sum\left(\mathbf{DBT}_{(n)} \circ \mathbf{V}\right) \cdot VOR \\ &= \sum_{i=1}^{I}\sum_{j=1}^{J}\left(d^m_{(n)i,j} \cdot v^n_{i,j}\right) \cdot VOT + \sum_{i=1}^{I}\sum_{j=1}^{J}\left(d^{95}_{(n)i,j} - d^m_{(n)i,j}\right) \cdot VOR \end{aligned} \tag{3.35}$$

where,

$d^m_{(n)i,j}, d^{95}_{(n)i,j}$ are the mean delay and 95th percentile delay for the vehicle arrived at the i^{th} time interval of j^{th} day of week due to work zone *n*.

$v^n_{i,j}$ is the average arrival rates approaching work zone *n* at the i^{th} time interval of j^{th} day of week.

3.2.4 Objective Function and Variation

The optimal work zone schedule in terms of start time with the time window constraints for multiple work zone projects can be determined by solving the total work zone cost minimization model as follows:

$$\min F = C_M + C_A + C_U = \sum_{n=1}^{N} (C_{Mn} + C_{An} + C_{Un}) \tag{3.36}$$

subject to

$$U^s{}_2 \cdot I + U^s{}_1 \leq S^n{}_2 \cdot I + S^n{}_1 \leq U^e{}_2 \cdot I + U^e{}_1 \quad \forall n \tag{3.36a}$$

$$E^n{}_2 \cdot I + E^n{}_1 \leq U^e{}_2 \cdot I + U^e{}_1 \quad \forall n \tag{3.36b}$$

where the two row vectors $\mathbf{U^s}$ and $\mathbf{U^e}$ are, respectively, the earliest start time and the latest completion time.

For each isolated work zone, sub-work-zone strategy might be allowed or preferred. Hence a single work zone project can be divided into several smaller work zones. A variation of the total work zone cost minimization model for sub-work-zone schedule with respect to start time and length of each sub-work-zone is presented as follow:

$$\min F = C_M + C_A + C_U = \sum_{n=1}^{N} (C_{Mn} + C_{An} + C_{Un}) \tag{3.37}$$

subject to

$$\sum_{n=1}^{N} l_n = L \tag{3.37a}$$

$$D_{\min} \leq D_n < D_{\max} \tag{3.38b}$$

$$U^{s}{}_{2} \cdot I + U^{s}{}_{1} \leq S^{n}{}_{2} \cdot I + S^{n}{}_{1} \leq U^{e}{}_{2} \cdot I + U^{e}{}_{1} \quad \forall n \tag{3.39c}$$

$$E^{n}{}_{2} \cdot I + E^{n}{}_{1} \leq U^{e}{}_{2} \cdot I + U^{e}{}_{1} \quad \forall n \tag{3.40d}$$

where,

L = length of the work zone project

$D_{\min}$ = minimum duration of individual work zone

$D_{\max}$ = maximum duration of individual work zone

3.2 Optimization Algorithm

As discussed previously, to determine the optimal work zone schedule, the objective is to minimize the total cost function formulated in Equation 3.36, in which the decision variables include the number of work zones, the start time, and end time of each work zone. Hence, the total number of decision variables in this optimization problem is 2m + 1. Considering the combination and the interdependent relations among these decision variables, this optimization problem would be difficult to optimize analytically or sequentially. Therefore, a modern heuristic solution algorithm is needed.

The Genetic Algorithm (GA) is adopted in this study because of its supreme performance and ability to explore the enormous solution space due to the combinations and interdependent relation among the decision variables. A typical Genetic Algorithm first randomly generates a population of candidates (chromosomes or the genotype of the genome). The candidates encode solutions (also named as individuals, creatures, or phenotypes) to an optimization problem. The candidates are usually represented in binary strings of 0s and 1s. The fitness of every individual in the population is evaluated, for example, through a fitness function for each generation. The fitness function can defined to evaluate the candidate's genetic representation, or particularly in this thesis research, the quality of the represented solution. Typically, the evolution process starts from a population of randomly generated individuals and lasts for generations. After evaluating the fitness of the candidates, a number of candidates are selected from the current population according to their corresponding fitness. These candidates are then modified through the recombination (crossover) and/or mutation to generate the next generation and complete the so call evolution process. The new generation will then be used in the next iteration of selection and evolution. Through the evolution process, the candidates will be narrowed towards the optimal solutions. The algorithm will terminate when either reaching a maximum number of generations, or after successfully finds a candidate with satisfactory error threshold/fitness level.

The GA adopted in this study was developed upon built-in genetic algorithm in MATLAB global optimization toolbox with a genetic representation of the solution domain. It has five major components:

1. A criterion to evaluate the fitness and performance of a solution that generated at each iteration. The objective function formulated in previous

section is the criterion.

2. A genetic representation for encoding the feasible solution domain. An efficient genetic representation needs to accommodate all decision variables and reduce the difficulties of encoding and decoding a solution, which is the key component of a GA. This dissertation applies an integer string matrix representation to transform a work zone scheduling problem into a GA.
3. Reproduction processes to generate offspring solutions. Crossover and mutation operations corresponding to the genetic representation enable to produce new solutions in the potential solution space, which mimics the natural evolution processes. Through the evolution process, the candidates will be narrowed towards the optimal solutions.
4. A selection mechanism for promoting the evolution of good solutions.
5. A constraints handling method to guide the search to a feasible solution domain. Each constraints discussed in the previous sections are implemented based on the matrix representation.

The optimization procedure of GA is depicted in Figure 3.5.

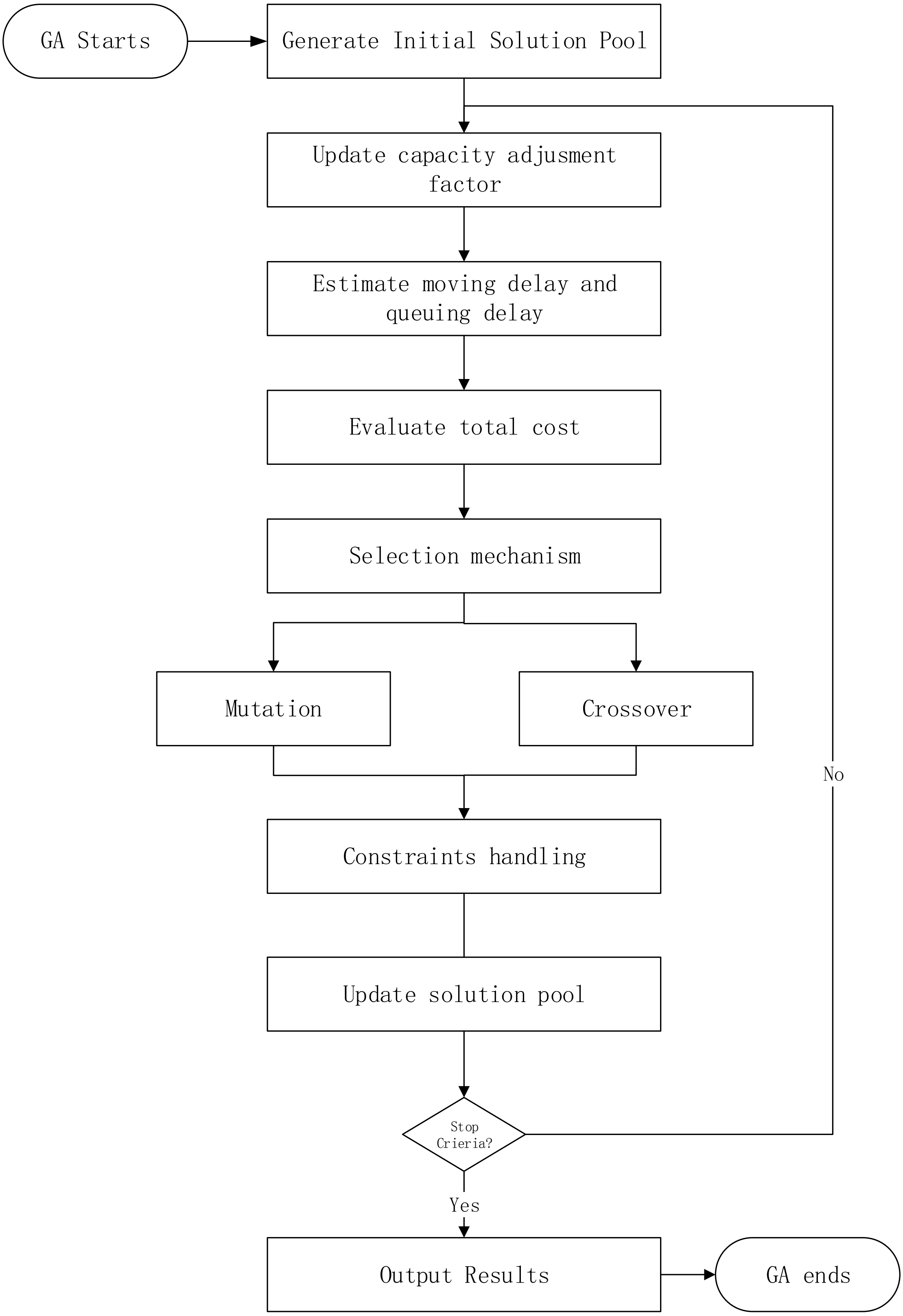


Figure 3.5 Flowchart of the Genetic Algorithm

Chapter 4 Data Processing

This study takes advantage of the archived empirical data to develop predictive relationships for reliability, rather than conducting a large number of simulation- based experiments. To achieve that, historical work zone data, traffic data, events data, safety data, and weather data are collected and processed. This Chapter aims to introduce the requirements and procedure to create analysis dataset which involves acquiring, cleaning, and integrating data archived in ITS data system. The required data for freeway reliability and data sources that used in this study is firstly introduced, followed by quality control process for traffic data. The integration between traffic data and work zone data is also presented.

4.1 Required Data

The HCM freeway reliability evaluation method requires large amount of historical data to generate sufficient scenarios. Those scenarios are combination of traffic condition associated with each source of travel time variability including recurring and non-recurring congestion events. Table 4.1 lists the required data input for reliability evaluation and proposed work zone scheduling algorithm, in association with the data sources used in this study.

Table 4.1 List of Required Data and Sources

Data Category	Description	Data Source
Demand patterns / Traffic counts	Day-of-week by month-of-year demand factors.	VSPOC detector data system
Weather	Probabilities of various intensities of rain, snow, cold, and low visibility by month.	WisTransPortal RWIS Data Query Tools.
Incidents	Probabilities of occurrence of shoulder and lane closures and average durations. Alternatively, crash rate and incident-to-crash ratio for the study facility	TIA Traffic Incident Alert System. MV4000 Crash Data Resources.
Work zones and special events	Scheduled work zone activities and special invents that result in lane closure or capacity reduction. Used in alternative dataset.	WisLCS Wisconsin Lane Closure System

4.1.1 Demand Patterns

Demand pattern data are used by the reliability method to adjust base demands to reflect demands during the other portion of the reliability reporting periods. It can be expressed as ratios of day-of-week and month-of-year demand relative to AADT. Demand fluctuations are represented in the methodology in terms of systematic and random demand variation by hour of day, day of week, and month of year. In addition, traffic counts for each analysis period are needed for the proposed time-dependent based delay estimation model

In this study, we use the loop detector data from Milwaukee metropolitan area as the source of field traffic flow data. The archived data contain one-minute volume, speed, and occupancy data obtained from WisDOT ATMS freeway detectors in five major transportation regions. Milwaukee area is within the southeast region which includes 959 freeway count locations. It should be noted that in Milwaukee area loop detectors on the freeway are all “traps” (dual loop detectors) which can provide an accurate reading of spot speed at the detector location. The V-SPOC (Volume, Speed, and Occupancy) is a web-based interface for data query (see Figure 4.4), data visualization, data exporting, quality reporting, and corridor analysis. A significant GIS enhancement project is underway to geo-code all detector and controller locations to WisDOT's state trunk network (STN) linear referencing system. With the increased availability of this geo-coded ITS data archive, it has been possible to study and evaluate the mobility and safety impact of work zones and incidents.

4.1.2 Weather data

The reliability method uses weather data to adjust the facility’s capacity to reflect the effects of weather events on operation. The historic weather data are calculated as the probabilities of occurrence of seven specific weather events (the snow condition are exclude since rare work actives during the winter). The probability is expressed as the fraction of time during the study period for the month that the weather event is present. In addition to the probabilities of occurrence, an average duration is also required for each of weather events. According to the SHRP2 L08 (2012), the weather events are defined in Table 4.2:

Table 4.2 Weather Event Categories

Weather Event	Definition
Medium rain	>0.10 ≤ 0.25 in./h
Heavy rain	>0.25 in./h
Light snow	>0 ≤ 0.05 in./h
Low visibility	<1 ≥ 0.50 mi
Very low visibility	<0.50 ≤ 0.25 mi
Minimal visibility	<0.25 mi
Non-severe weather	All other conditions not listed above

There are two sources of weather data used in this study: 1) The National Climatic Data Center (NCDC) that provides rainfall, snow, temperature statistics, and average precipitation rate; and 2) WisTransportal RWIS weather station database (2014), which contains an archive of atmospheric and road surface weather data.

4.1.3 Incident and Crash Data

In consistent with the HCM reliability method, incident data or safety data is needed to adjust the study facility's capacity to reflect the effects of lane or shoulder closure in case of incident. The monthly probability and average duration of certain incident types are required to represent the fraction of time during the scheduling period where a given incident type occurs. Incidents type are defined as: no incident, shoulder closure, one lane closures, two lane closures, etc.

The TOPS Lab WisTransPortal system contains a complete database of Wisconsin MV4000 Traffic Accident Extract data from 1994 through the current year. This database contains information on all police reported crashes in Wisconsin, including the location of each crash, vehicles involved, and general crash attributes. The TOPS Lab also maintains a real-time traffic incident data exchange and archive system that contains detailed incident log including incident type, location, and duration. By cross matching these two database, the average durations of each incident type can be obtained.

4.1.4 Work Zone Operation Data

Long term work zone affects roadway capacity and operation speed. Therefore, detailed traffic control plan for each work zone in or near study site should be consulted to determine the starting and ending time and locations of lane closures. In addition, in order to calibrate the capacity reduction due to each type of work zone, a relative large of historical work zone data are needed.

The work zone data and characteristics are extracted from the WisLCS (2012) data system that provides a centralized management system for highway lane closures statewide since April 2008. The detailed information of each lane closure in Wisconsin includes work zone operation time, GIS information, work zone types, traffic impact etc. Meanwhile, its data archiving and retrieving system allows all the lane closure to be easily selected, classified and managed. It improves the completeness, reliability, and timeliness of lane closure data on state highways in Wisconsin.

4.2 Data Processing

4.2.1 Data Quality

Quality control and quality assurance of archived data ensure the applicability of the archived data and quality of related research and its application. However, the archived ITS traffic detector data has data quality issue. Among a variety of sources, the most common problems are data loss or noise, which typically result from network connectivity and communication failures. The detector itself may have deficiency that leads to erroneous output, as well as detector configuration errors (Shi, Parker, etc. 2012). In addition, Work zones may cause issues to the electrical and communication system for detectors and field crew may sometimes shut down the detectors to protect those systems. Meanwhile, the work zone operations can also cause false alarms and calibration errors with the loop detectors.

A recent enhancement to current VSPOC data system can better promote the efficiency in using and mining the archive data system with a proposed interactive data quality examination tool. This study utilized this tool to ensure quality data for model developing and experimental design. Specifically, predefined validity test, based on characteristics of data, are used to initially flag erroneous data with a fault type.

Six tests for speed validity and occupancy validity, and seven tests for volume validity are developed as fault detection criteria. In each category, it breaks down to one test on missing data issue, two tests on repeating data issue, one test on data range, and another two for tests on the data characteristics, with the exception of the volume health category, which targets to spike singularities. All tests are conducted sequentially within each category, and only one flag in each category would be marked (See Appendix B). A temporally table are created to indicate each test result, which the unsatisfied tests mark with value 1, otherwise have the value of 0. Once one of tests are not satisfied in each category, the remaining of test criteria are excluded. The result are then aggregated to hierarchic location and time dimensions, and an overall health criteria is introduced to screen out unqualified data.

4.2.2 Spatial-Temporal Correlation between WisLCS and VSPOC data

TOPS lab is in the process of geocoding all loop detectors onto the STN-Link system and currently, all loop detectors in the Milwaukee area have been geocoded with several GIS coordinate systems including longitude and latitude, state plane, and the linear referencing coordinates in STN-Link and STN-Chain. STN-Link is a straight line bi-directional representation of state highways with the accurate link length; while STN-chain is a curvature representation that matches the geometry of state highways. Using the route and route offset information in the STN-Link system, each work zone can be spatially matched with detector locations that are within, upstream, and downstream of the work zone and all traffic data within the work zone duration and the corresponding non-work-zone data at the same time of the day can be obtained. Figure 4.2 illustrate the three detector location associated with a given work zone location. The buffer distance *d* is a parameter that decides the distance between detector and work zone.

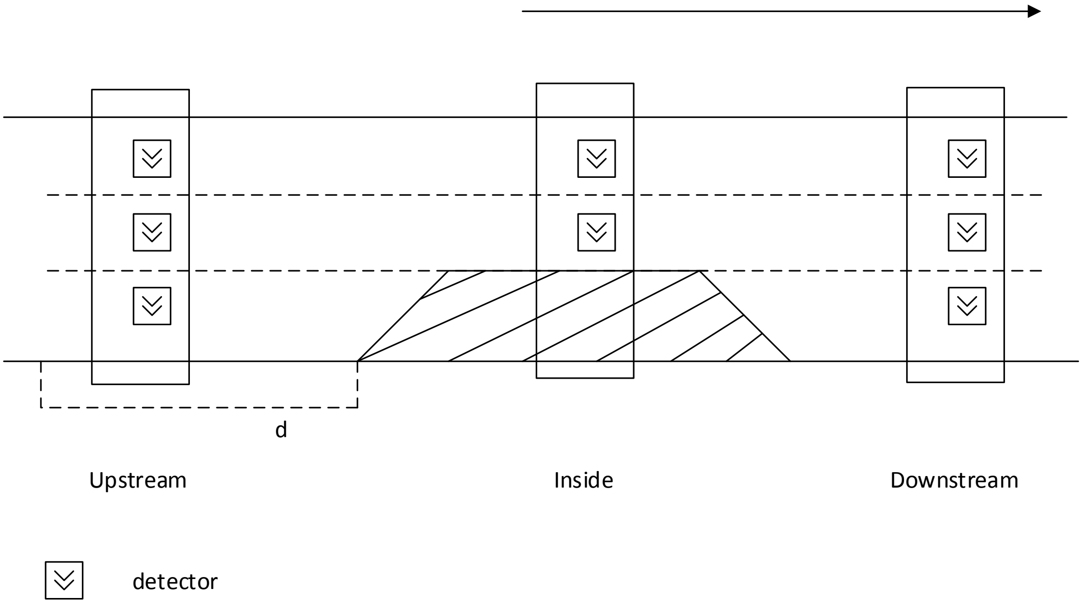


Figure 4.1 Demonstration of Detector Locations Associated with a Work Zone

In general, the temporal-spatial correlation between work zone data and traffic detector data follows the steps below:

1. Find the geo-location attribute of work zone in STN system.
2. Find the geo-location attribute of traffic detectors in STN system.
3. Screen out unavailable work zone sites.
4. Identify the detectors associated with each work zone
5. Retrieve qualified traffic data within work zone operation period.
6. Aggregate the traffic data across lanes.

The correlation procedure is implemented in Oracle database, and the correlation results are stored in a separate view. The integrated database enables systematic analysis for work zone study, and can be as valuable data source not only for this study, but only for other work zone mobility and safety research.

5. Experiment Design and Results

The experiment design includes details of model validation and calibration. A case study is applied to evaluate propose work zone scheduling optimization framework.

5.1 Model Calibration

In the proposed model, segment capacity and travel speed have huge impact on the accuracy of delay and reliability impact estimation. To reveal the variation of traffic condition, both of them are expressed as adjustment factors refer to base values. Therefore, a large amount of historical traffic data related to crash, severe weather, and work zone, are retrieved to determine the capacity and travel speed in these traffic conditions. As discussed in Chapter 2, capacity is defined as the maximum sustained flow. Using the rescaled cumulative vehicle arrival curves, the maximum sustained flow can be observed during queue discharge (Edara, 2012). This method is automated in MATLAB, and used to identify capacity for each traffic condition. The calibration result for CAF and SAF is summarized in Table 5.1, and incident effect on capacity is listed in Table 5.2.

Table 5.1 Calibrated Weather CAF and SAF

Weather Event	CAF	SAF
Medium rain	0.91	0.93
Heavy rain	0.83	0.84
Light snow	0.94	0.95
Low visibility	0.91	0.98
Very low visibility	0.85	0.95
Minimal visibility	0.83	0.92
Non-severe weather	1	1

Table 5.6 Calibrated Incident CAF

# of lanes	Shoulder blocked	1 lane blocked	2 lane blocked
2	0.91	0.70	N/A
3	0.95	0.84	0.55
4	0.99	0.89	0.61

5.2 Model Validation

The proposed dynamic flow based delay and reliability impact estimation model is developed based on the HCM reliability evaluation methodology, since the existing Highway Capacity Manual (HCM) toolbox of evaluating travel time reliability (FREEVAL-RL) is complex and inefficient to be integrated into the optimization framework of work zone scheduling problem. The difference between HCM method and proposed model is depicted in Figure 5.1. As presented in Chapter 3, the analytical approach for moving and queuing delay estimation needs to be validated. The data used for validation follows the procedure introduced in Chapter 4.

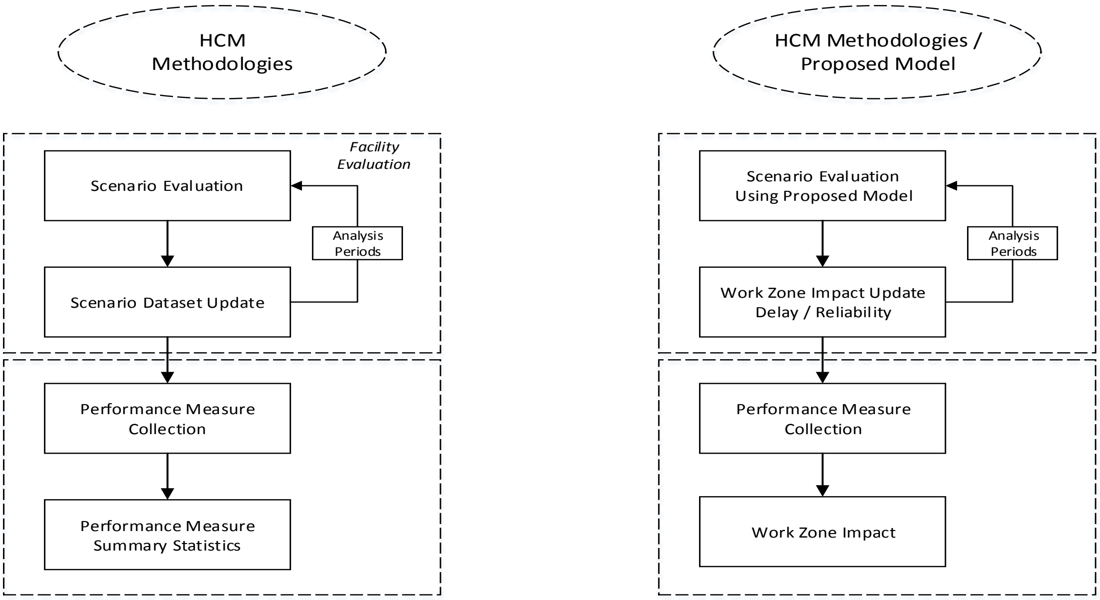


Figure 5.1 Difference between HCM Model and Proposed Model

Moving Delay

In proposed model, the average travel time and 95th percentile travel time have liner relationship with the work zone length. Therefore, a work zone dataset is inputted into FREEVAL-RL with varied work zone length to ranging from 10,000 ft to 80,000 ft. The validation result is summarized in Figure 5.2.

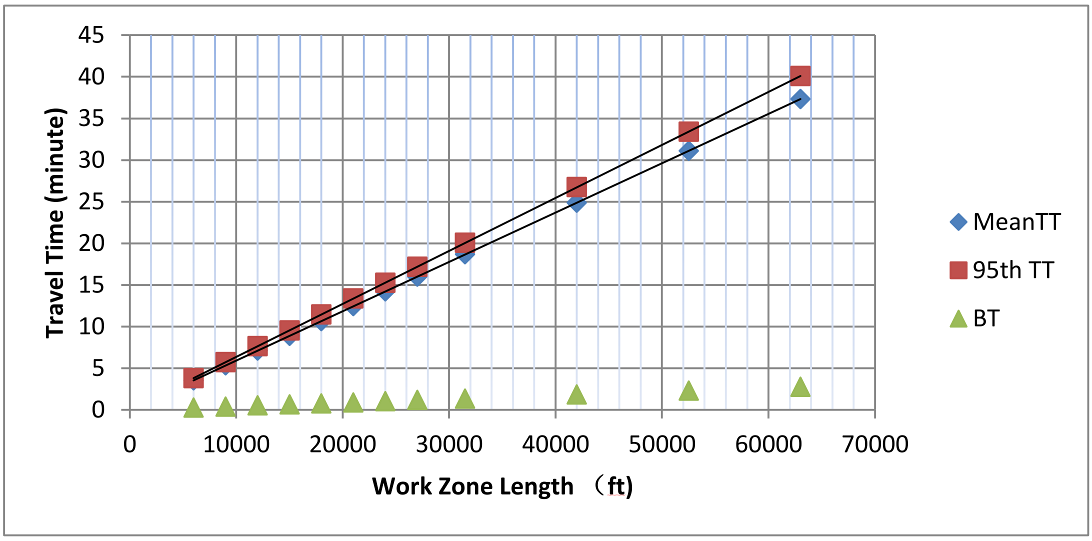


Figure 5.2 Validation of Moving Delay Estimation

It can be observed that the results from the computational tool also show the linear relationship between travel time and work zone length. And the estimated moving delay by proposed model is same as the result from the computational tool. The result also indicates that the underlying model for travel time estimation of FREEVAL is only using the average travel speed at each time interval.

Queuing Delay

The queuing delay estimation is more complex than moving delay estimation since time-depend traffic volume is used. In order to verify the accuracy of estimated queuing delay by applying the proposed model, a 6-hours work zone is implemented in FREEVAL-RL. The estimation result is presented in Figure 5.3.

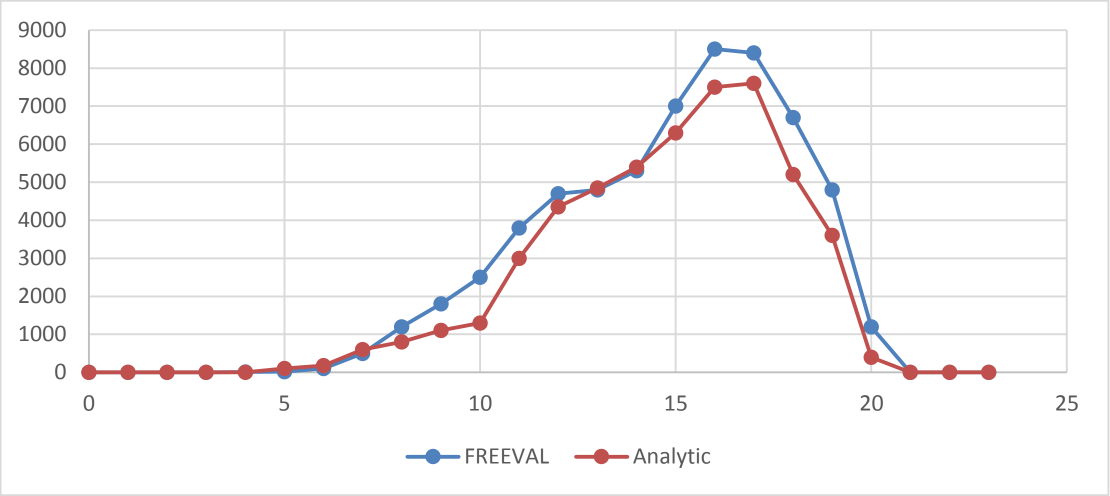


Figure 4.3 Validation of Queuing Delay Estimation

It shows that the queuing delay estimated by analytic approach is very close to the simulation result with average 4.2% difference. The proposed model tends to underestimate the delay in congested condition. Two possible reasons are considered: 1) FREEVAL-RL implements a cell-transmission based travel time estimation model, while the proposed model is developed based on deterministic queuing diagram. 2) In case of incident and weather event, there might be a speed adjustment factor applied in FREEVAL-RL, which would result in more queuing vehicles at upstream of work zone.

5.3 Case Study

5.3.1 Study Site

In order to apply the proposed work zone scheduling optimization method, field data are collected for a freeway segment on Interstate 894 (I-894), which is an auxiliary Interstate Highway of nearly 10 miles long in Milwaukee metropolitan area in Wisconsin. It serves as a bypass of downtown Milwaukee and provides a shorter distance for travelers heading to Chicago or the Mitchell International Airport. Several sections of I-894 suffer from a daily recurrent congestion during both morning and afternoon peak hours, due to the high volumes from Zoo interchange, Hale interchange, and Mitchell Interchange.

A maintenance work zone project was conducted on interstate highway I-894 east bound with three travel lanes. One lane was closed for a 1.5-mile-long highway segment maintenance. As illustrated in Figure 5.1, the work zone site was situated between cross street W. Forest Home Street and 60th Street. Originally, this project maintenance work was performed continuously from 7: 00pm May 17th, 2013 to 2: 30am May 18th, 2013.

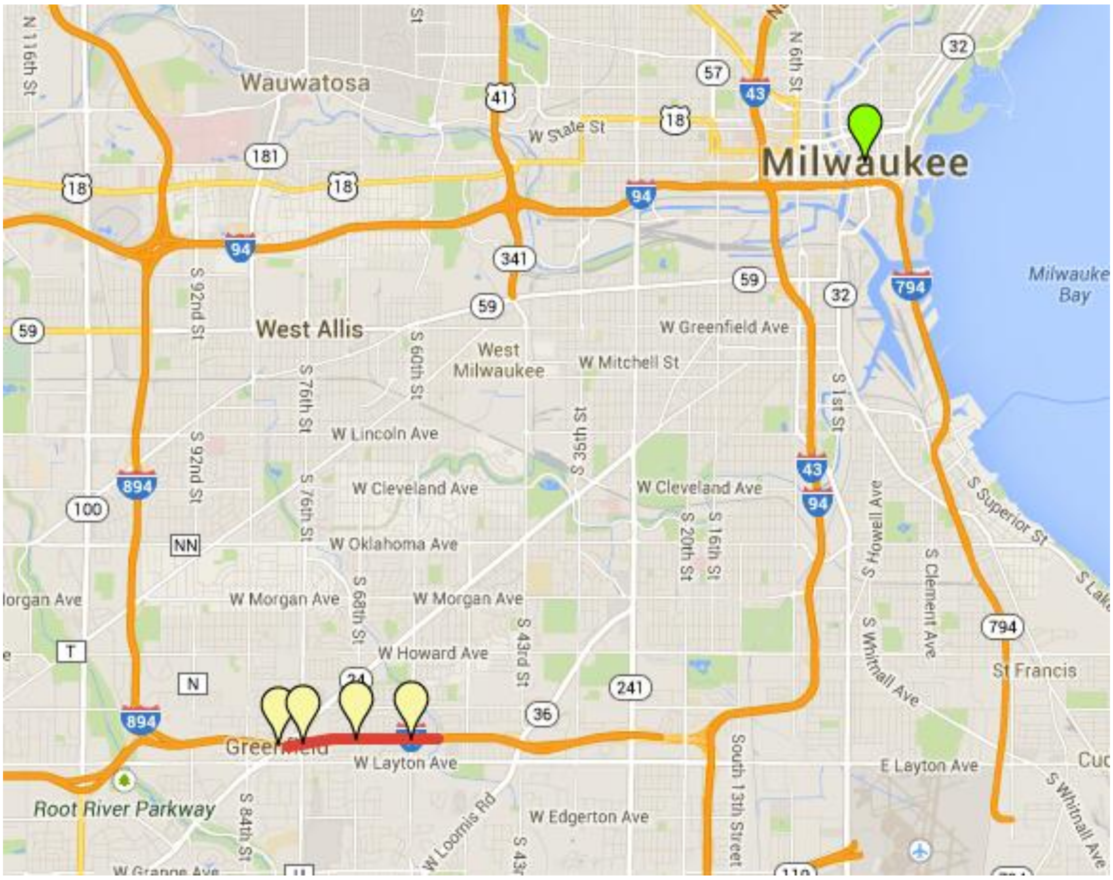


Figure 5.4 Study Site

As shown in Table 6.1, the proposed work zone scheduling method is adapted to find optimal solution for several scheduling scenarios with time-depended traffic flow. The scheduling scenarios include:

- Scenario A1: Both daytime (7:00am – 8:00pm) and nighttime (8:00pm – 7:00am) of weekday are considered for work zone operation.
- Scenario A2: Only daytime of weekday is considered for work zone operation.
- Scenario B1: Both daytime and nighttime of the whole week are considered for work zone operation.

- Scenario B1: Only daytime of the whole week is considered for work zone operation.

Table 5.3 List of Studied Scenarios

Operation Time	**Weekday only**	**Weekend Included**
Daytime & Nighttime	Scenario A1	Scenario B1
Daytime	Scenario A2	Scenario B2

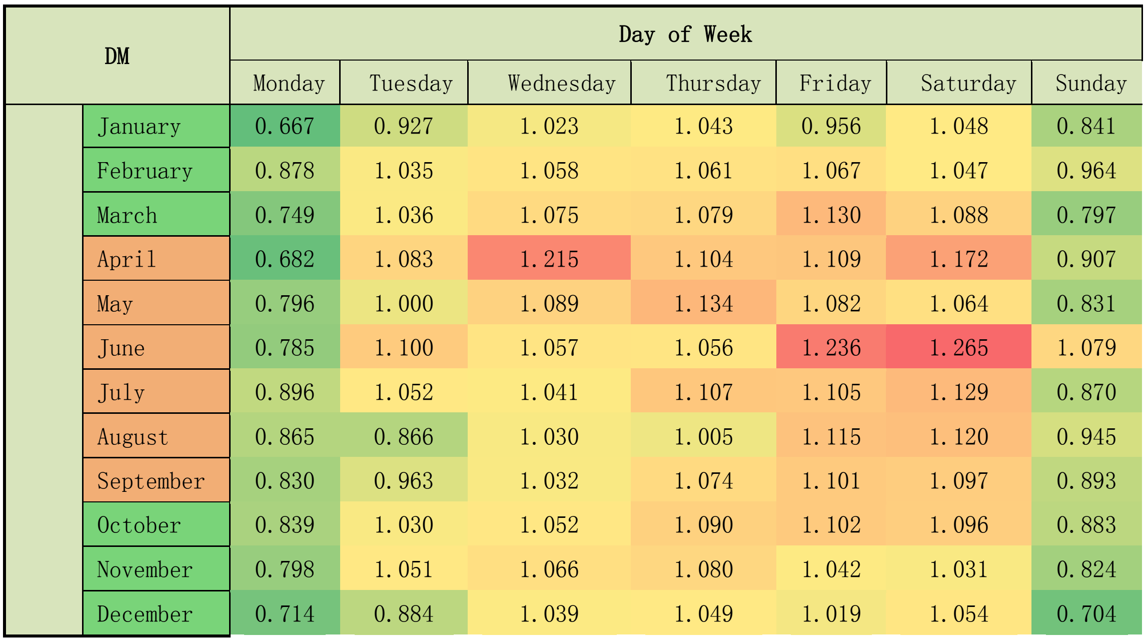
Based upon a set of model parameters with given baseline values, the work zone schedules for aforementioned five scenarios are optimized by minimizing the total cost. The optimized solutions are then analyzed to evaluate the performance and applicability of proposed method and benefits of each scheduling scenario.

5.3.2 Preliminary Analysis of the Reliability Data

Demand Multiplier

The HCM freeway reliability method accounts for demand variability by adjusting the traffic volume for a given analysis period by a demand ratio, which is the average demand for a given combination of analysis period day and month relative to average demand in the specific day and month (the day that work zone was performed in this case). The method assumes that variability across analysis periods is consistent throughout the study period (SHRP2 L08). The demand variation due to other work zones and special event are excluded. The Table shows the demand ratio for the study site using archived data. The ratio of highest to lowest demand ratios is 1.265, indicting a strong calendar effect on the magnitude of demand.

Table 5.7 Demand Ratios for Study Site



DM		Day of Week						
		Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
	January	0.667	0.927	1.023	1.043	0.956	1.048	0.841
	February	0.878	1.035	1.058	1.061	1.067	1.047	0.964
	March	0.749	1.036	1.075	1.079	1.130	1.088	0.797
	April	0.682	1.083	1.215	1.104	1.109	1.172	0.907
	May	0.796	1.000	1.089	1.134	1.082	1.064	0.831
	June	0.785	1.100	1.057	1.056	1.236	1.265	1.079
	July	0.896	1.052	1.041	1.107	1.105	1.129	0.870
	August	0.865	0.866	1.030	1.005	1.115	1.120	0.945
	September	0.830	0.963	1.032	1.074	1.101	1.097	0.893
	October	0.839	1.030	1.052	1.090	1.102	1.096	0.883
	November	0.798	1.051	1.066	1.080	1.042	1.031	0.824
	December	0.714	0.884	1.039	1.049	1.019	1.054	0.704

Traffic Count

Table 5.5 depicts the average hourly traffic volumes for each day of the week from the upstream of studied work zone (the actual volume used in the proposed model is 15-min traffic count). Six months historical data are retrieved from WisTransPortal VSPOC (2012) data system which is a statewide detector data archiving and retrieving system. The comprehensive detector screening tool introduced in Chapter 4 is executed to ensure quality traffic data. Since approaching traffic is varied by day of the week, it will significantly effect on scheduling result because of capacity reduction caused by lane closure. In Figure 5.5, it can be observed quite different traffic pattern across the week, especially for weekday and weekend.

Table 5.8 Hourly Traffic Volumes by Day of Week

Hour	*Mon.*	*Tue.*	*Wed.*	*Thur.*	*Fri.*	*Sat.*	*Sun.*
0-1	371	534	465	629	511	665	656
1-2	363	379	289	440	317	376	380
2-3	379	392	302	428	318	300	275
3-4	484	502	383	499	399	291	247
4-5	864	893	773	861	742	417	313
5-6	1,770	1,918	1,779	1,781	1,602	729	476
6-7	3,417	3,778	3,715	3,569	3,334	1,072	709
7-8	4,260	4,584	4,656	4,388	4,222	1,649	1,113
8-9	3,574	3,867	3,908	3,771	3,553	2,237	1,530
9-10	2,793	2,993	3,019	3,173	3,085	2,754	2,158
10-11	2,896	2,841	2,916	3,052	3,223	3,268	2,894
11-12	3,096	3,035	3,133	3,212	3,495	3,541	3,413
12-13	3,348	3,185	3,361	3,359	3,618	3,777	3,791
13-14	3,311	3,313	3,475	3,520	3,929	3,723	3,660
14-15	3,764	3,832	3,982	3,914	4,285	3,696	3,707
15-16	4,217	4,403	4,504	4,451	4,649	3,668	3,759
16-17	4,619	4,887	4,957	4,773	5,010	3,488	3,671
17-18	4,800	5,037	5,139	5,128	5,087	3,289	3,348
18-19	3,525	3,702	3,869	3,921	3,939	2,826	2,910
19-20	2,596	2,607	2,714	2,790	2,872	2,383	2,515
20-21	2,168	2,169	2,276	2,296	2,274	2,049	1,992
21-22	1,726	1,685	1,795	1,816	1,991	1,843	1,454
22-23	1,206	1,199	1,271	1,290	1,568	1,406	962
23-0	862	827	888	899	1,132	1,054	602

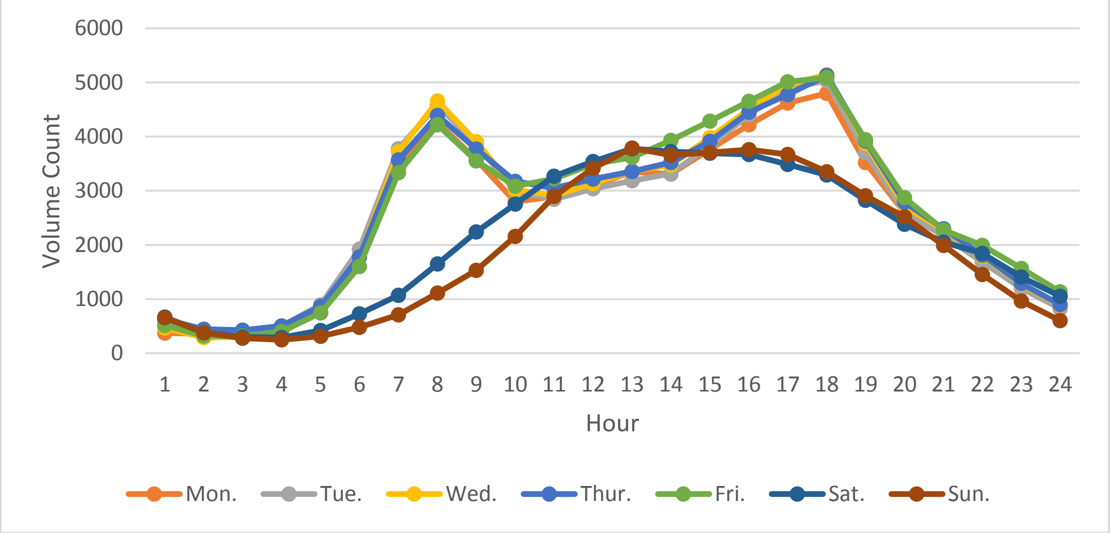


Figure 5.5 Diagram of Hourly Traffic by Day of Week

Crash Data

The 2012 crash data on the study freeway section is retrieved from MV4000 data system as the source of incident events generation. As shown in Figure 5.6, there were 190 crash happened on I-894 corridor, and six of those were related to a work zone. Most of them were property-damage only crashes.

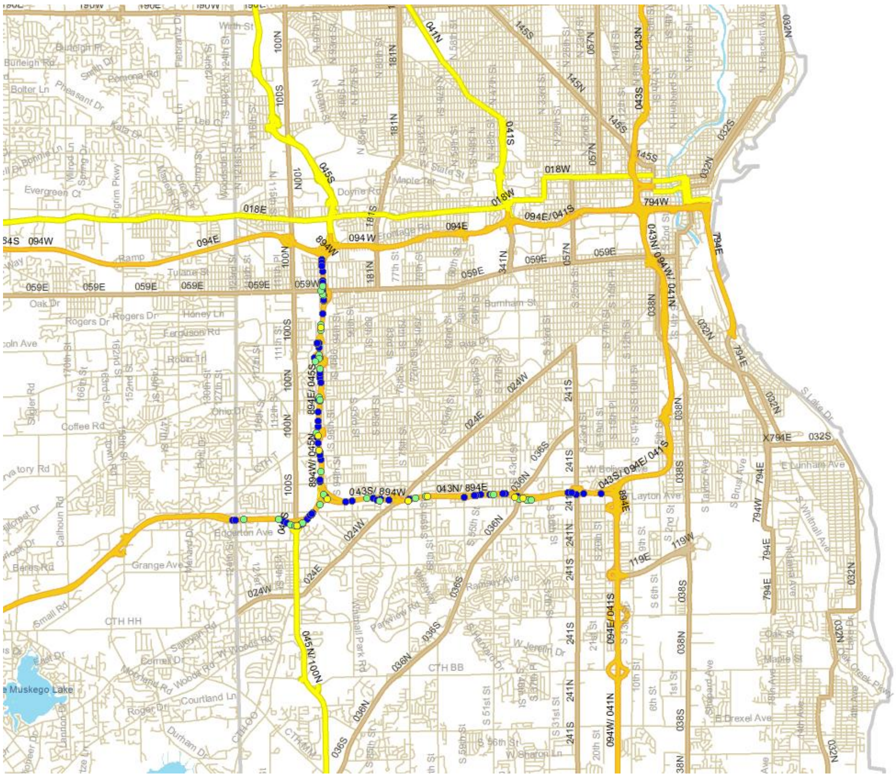


Figure 5.6 Crash Map of Study Freeway

TTR of Study Site

The aforementioned data is entered to FREEVAL-RL for generating traffic scenarios and base value. Figure 5.7 shows the probability distribution function (PDF) and the cumulative distribution function (CDF) of travel time index (TTI) that is the ratio of actual travel time and free-flow travel time. According to the FREEVAL-RL report, the percentage of recurring delay is 36%, while the weather and incident events lead to 64% of delays.

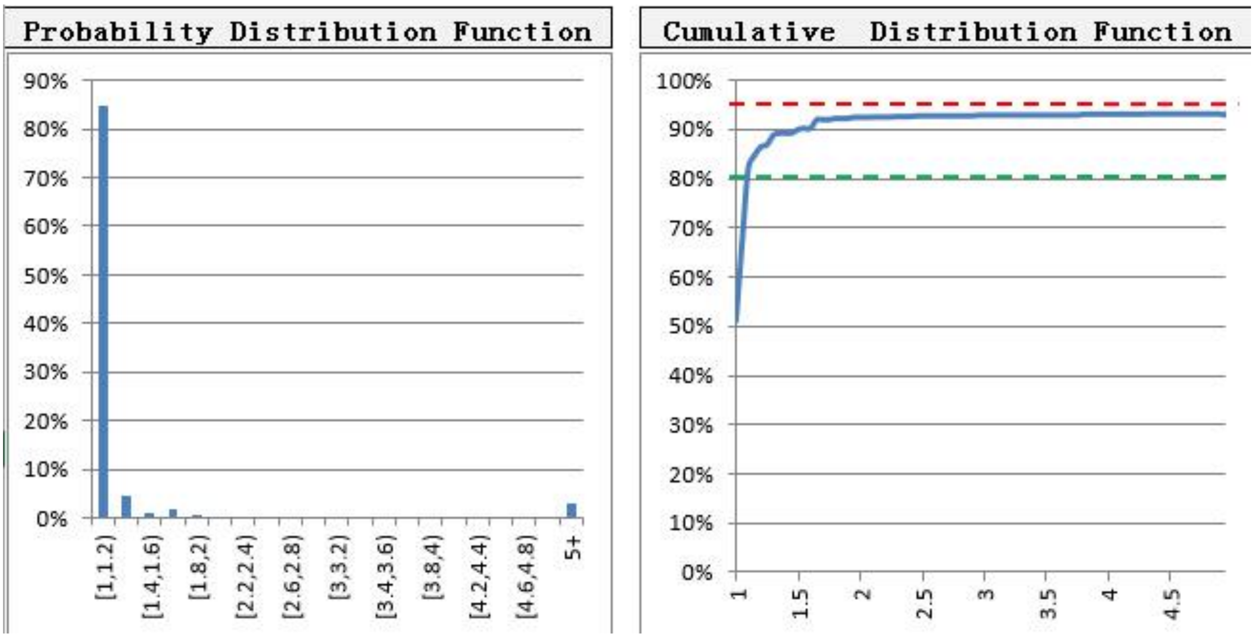


Figure 5.7 PDF and CDF of TTI on Study Highway Segment

5.3.3 Model Parameters

Table 5.6 shows the baseline values of other model parameters used in this case study. The unit maintenance time t_2 is calculated based on the actual work zone length and completion time. Similar to Tang and Chien (2002), the average unit maintenance cost is referred to the Mean Heavy Construction Cost Data (2005), which suggests $32,000 per mile. The value of time is assumed $18 per vehicle hour and $6.5 per vehicle hour increased in reliability. Both values are referred to a study conducted by Brownstone and Small (2005), and converted from the 2005 dollar value to the current value through an inflation factor. Since work activities may result higher operation coast, the cost multiplier for night time operation is set to 1.5. If there is no extra cost for nighttime operation, this factor can be defaulted to 0.

Table 5.6 Model Parameters Used in the Numerical Example

Parameter	Description	Input Value
v_1	Fixed cost for setting up work zone	\$2000/ zone
t_1	Fixed time for setting up work zone	1 hour/ zone
v_2	Unit maintenance cost	\$32000 / mile
l_f	Total length of taper and buffers	0.2 mile
t_2	Unit maintenance time	5 hr/mile
I	Number of 15-min intervals considered for work zone operation a day	96
c_{base}	Base roadway capacity	2200
VOT	Value of time	\$18/veh-hour
VOR	Value of reliability	\$6.5/veh-hour
v_a	Average cost per accident	NA
$D_{\min}$	The minimum duration of a sub work zone / work break	1 hour
$D_{\max}$	The maximum project duration	36 hour
L	Total length of work zone	1.5 mile
β	Cost multiplier for night time operation	1.5
f_{wz^t}	Work zone adjustment factor	0.89

5.3.4 Optimization

First of all, work zone schedules are optimized with different numbers of sub-work-zone using actual time-dependent traffic count. The number of work zones can be either self-adjusted or controlled by a binary parameter. All decision variables (Start time and end time of each work zone) can be solved simultaneously. This mechanism can provide flexibility and efficient in solving large combinatorial problem where the number of decision variables might be varied.

Table 5.7 summarizes the optimized weekday only work zone schedule with different number of sub-work-zones considered and the resulting work zone cost.

Table 5.7 Optimized Schedule with Given Number of Sub Work Zone (A1, A2)

	# of Work zones	*Start and End time*	*Total Duration*	*Maintenance Cost*	*Cost of Delay*	*Cost of Reliability*	*Total Cost*
Scenario A1	1	20:30 Thur.-04:00 Fri.	8.5	73,000	954	127	74,081
	2	01:30 - 14:00 Mon.	12.5	64,400	380	2,300	**67,080**
	3	00:15 - 14:15 Mon.	14	58,900	32,762	77,140	168,802
Scenario A2	1	11:30.-20:00 Fri.	8.5	49,000	225,430	107,130	381,560
	2	07:45 - 19:45 Mon.	12	50,000	142,780	100,310	293,090
	3	09:00 - 15:00 Mon. 11:00 - 15:30 Tue.	30.5	51,000	32,762	77,140	**160,902**

Due to light traffic in the night, the work activities can be done with two sub-work-zones without significantly impact on traffic. If nighttime operation is not considered, the total work zone costs gradually declines with the number of sub-work-zone increases. Three sub-work-zones are the best strategy to schedule the work actives with total 30.5 hours duration (since nighttime must be scheduled as work break). In compare with Scenario A1, although the maintenance cost slightly declines, the cost from road user side increases significantly no matter in average traffic condition or near-worst traffic condition.

The detail of optimal work zone schedule and associated cost components for weekday operation only are summarized in Table 5.8. For Scenario A1, the best starting time 01:30 on Monday and the resulting total project duration is 12.5 hours. Two sub-work-zones are scheduled, including a nighttime off-peak period and a mid-day off-peak period. Between these two work activities, a 3-hour work break is scheduled to avoid the additional delay and reliability impact due to morning rush hours. The total cost is $67,080. For Scenario A2, three sub-work-zones are scheduled with project staring at 09:00 Monday, and the resulting total work zone cost is $120,902. It gives the explanation that why planning agency tends to schedule work activities during night hours in practice. One mid-day off-peak break and one nighttime break are also scheduled to reduce additional user cost at perk hour period. Note that the overnight break may have higher operational cost than intra-day break. Since lack of supporting data, this cost is not added to the total work zone cost.

Table 5.8 Detail of Optimized Work Zone Schedule (A1, A2)

Activities	*Start and end time*	*Duration*	*Work length*	*Maintenance Cost*	*Cost of Delay*	*Cost of Reliability*	*Total Cost*
Work	01:30 - 06:30 Mon.	5	0.8	38,500	114	30	38,644
Break	06:30 - 09:30 Mon.	3		0	0	0	0
Work	09:30 - 14:00 Mon.	4.5	0.7	25,900	266	2,270	28,436
						Scenario A1 total cost:	***$67,080***
Work	09:00 - 12:00 Mon.	3	0.6	20,200	9,146	13,250	42,596
Break	12:00 - 13:00 Mon.	1	0				
Work	13:00 - 15:00 Mon.	2	0.2	7,400	77,40	8,110	23,250
Break	15:00 Mon.-11:00 Tue.	20	0				
Work	11:00 - 15:30 Tue.	4.5	0.7	23,400	15,876	15,780	55,056
						Scenario A2 total cost:	**$120,902**

If there is no additional cost for weekend operation, work zone operation during weekend has lower total cost due to lower traffic volume. The optimized weekend included work zone schedule with different number of sub-work-zones considered and the resulting work zone cost are summarized in Table 5.9. It indicates that three sub-work-zones combination has lowest total cost, while a single work zone operational strategy is the best choice when nighttime operation is prohibited. In light traffic condition, the cost of more repetitive setups can be compensated by the reduction of user cost. However, in case of heavy or unreliable traffic condition, the total cost does not always decline as the number of sub-work-zones increases, which indicates that single work zone strategy is more suitable.

Table 5.9 Optimized Schedule with Given Number of Sub Work Zone (B1, B2)

	# of Work zones	*Start and End time*	*Total Duration*	*Maintenance Cost*	*Cost of Delay*	*Cost of Reliability*	*Total Cost*
Scenario B1	1	04:15 - 11:45 Sat.	8.5	68,000	4,210	5,905	78,115
	2	00:45 - 11:15 Sun.	10.5	62,550	45	412	63,007
	3	**00:15 - 14:45 Sun.**	**14.5**	**59,200**	**1,030**	**1,325**	**61,555**
Scenario B2	**1**	**7:15 - 15:45 Sun.**	**8.5**	**49,000**	**28,926**	**31,149**	**109,075**
	2	7:45 - 20:00 Sun.	12.25	50,000	24,005	45,956	119,961
	3	7:15 - 20:00 Sun.	12.75	51,000	30,779	54,340	136,119

Table 5.10 lists the detail of optimal work zone schedule and associated cost components for the two scenarios of weekend included operation. For Scenario B1, the best starting time 00:15 on Sunday and the total work zone cost is $61,555. Between these two work activities, two short breaks are scheduled. It is unconventional that there is a short break during 03:00 to 05:00 in the morning. This is because the developed GA searches for the lowest total cost, although there might be an alternative solution has better potential for practice but higher cost.

Table 5.10 Detail of Optimized Work Zone Schedule (B1, B2)

Activities	*Start and end time*	*Duration*	*Work length*	*Maintenance Cost*	*Cost of Delay*	*Cost of Reliability*	*Total Cost*
Work	00:15 - 03:15 Sun.	3	0.4	19,200	0	213	19,413
Break	03:15 - 04:45 Sun.	1.5	0				
Work	04:45 - 07:15 Sun.	2.5	0.3	14,400	26	322	14,748
Break	07:15 - 08:15 Sun	1	0				
Work	08:15 - 13:15 Sun.	5	0.8	25,600	1,004	790	27,394
							Scenario B1 total cost: $61,555
Work	7:15 - 15:45 Sun.	8.5	1.5	49,000	28,926	31,149	109,075
							Scenario B2 total cost: $109,075

The cost components are their relationships are depicted in Figure 5.10. The optimized results show that the proposed optimization framework is able to determine the optimal schedule for different work zone operation strategies. It can be seen that there is no big difference among these scenarios. This is because the assumed values of fixed setup costs and nighttime operation multiplier are relatively small. Since these data is varied project by project and state by state, it is not the focus of this study.

From road users' point of view, the nighttime work zone operation would be the best choice because it causes minimum traffic disruption and least impact of travel time and reliability. However, the extra cost of working during nighttime and weekend is not the only issue that planning agency and contractors confront. The lack of work crews, lower productivity, safety concerns, and potential legal issues are all the impact factors for scheduling work zones at off-time. In reality, the optimal work zone strategy may be a comprise solution among road users, contractors, and planning agencies.

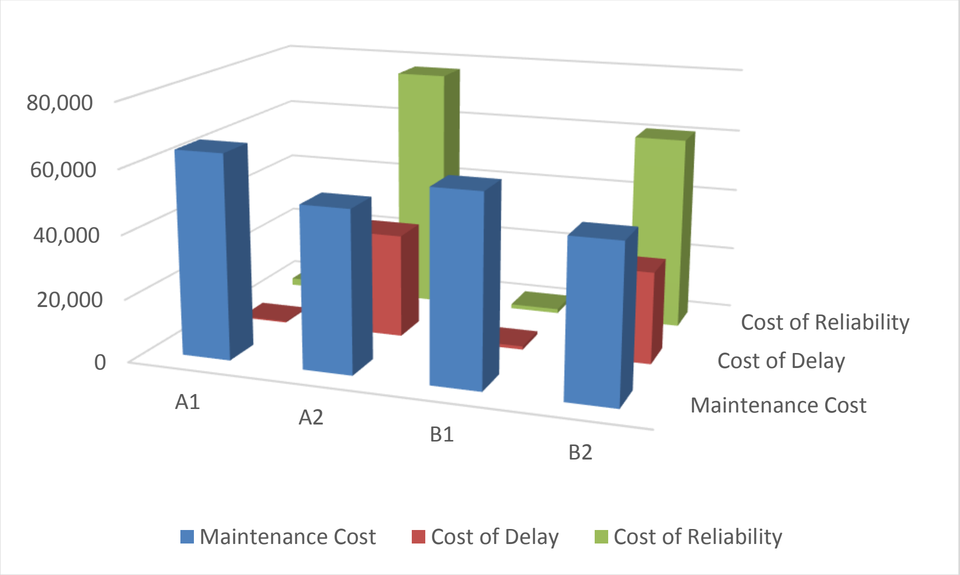


Figure 5.8 Cost Components of Each Schedule Scenario

5.3.5 Sensitivity Analysis

Found in the experiment, with a tight maximum project duration, especially for daytime only operation, the total cost may increase significantly. Therefore, a sensitivity analyses is conducted with respect to the maximum project duration ranging from 24 hours to 90 hours for daytime and all-day operation. Figure 5.09 indicates the minimum total cost generally decreases when the maximum project duration increases, specifically between the upper threshold and lower threshold. As maximum duration exceeds upper threshold, increased duration will not affect the total cost noticeably. In contrast, shorter duration than upper threshold will not affect total cost either since there is no choice but the highest schedule. Both thresholds would be valuable to planning agencies to determine appropriate duration and operation strategy.

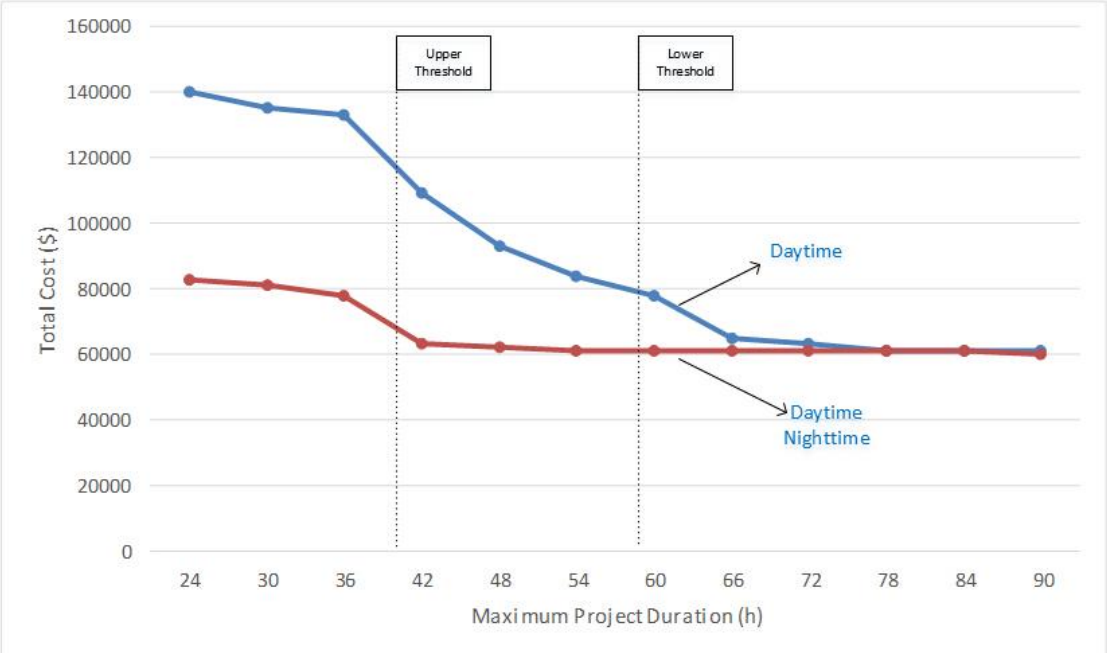


Figure 5.09 Minimized Total Cost vs. Maximum Project Duration

To evaluate the impact of VOR optimization model, work zone length is doubled, and the VOR are varied from 5.5 to 8.5. In Figure 5.10, it can be seen that the total cost and reliability reduction cost increases as VOR increases. It indicates the baseline VOR used in proposed model doesn't affect the result significantly, because the proposed model can jointly optimize the work zone cost in the maintenance coast, delay cost and reliability cost.

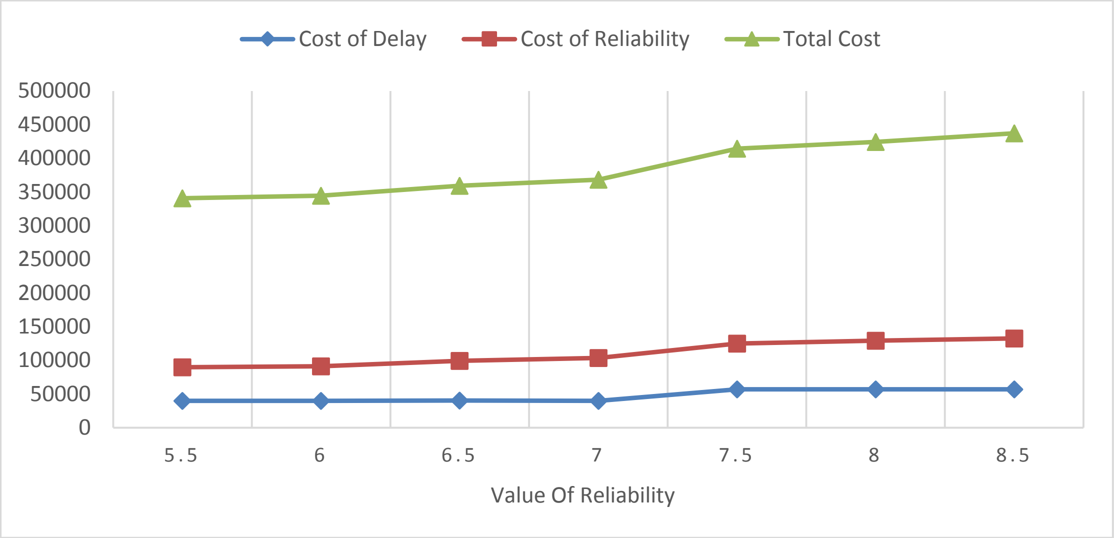


Figure 5.12 Minimized Cost vs. Value of Reliability

6. Conclusion and Future Work

This study proposes a new freeway work zone scheduling framework incorporating travel time reliability. A genetic optimization framework is utilized to optimize a combinational, multidimensional work zone scheduling based on a developed dynamic traffic flow model based TTR impact evaluation method. Experimental results show the proposing method is effective and promising.

6.1 Summary of Chapters

Chapter 1 introduces the background information of work zone management and operation, work zone scheduling problem, and the importance of work zone scheduling in congestion reduction and traffic operation. Problem statement, the objectives and scope of research and major research contributions are also presented in this chapter.

Chapter 2 is the literature review. It includes the review of work zone capacity and delay estimation methods, the research on work zone scheduling, and the development of travel time reliability (TTR). The need and potential of incorporating TTR to work zone scheduling is also discussed.

Chapter 3 presents the methodology. The methodology includes two parts: the dynamic traffic flow based work zone impact estimation method and work zone optimization framework. For the impact estimation method, a more efficient method (comparing with TTR evaluation tool FREEVAL-RL) is proposed to estimate moving delay and queuing delay based on historical traffic data, weather information, and incident event logs which can reveal traffic condition. For the optimization framework, a total work zone cost function is proposed. The optimal work zone schedule can be determined by optimizing the total cost function with the developed genetic algorithm. Since the objective total cost function is a mix-integer non-differentiable minimization function with respect to the starting time, ending time, and number of work zones, it cannot be solved by the conventional exact solution algorithms. Therefore, a genetic algorithm is applied to search for the optimal solution.

Chapter 4 introduces the required data for the proposed scheduling optimization framework. Those data are used for creating different scenarios that reveal daily traffic condition. A large portion of the data needed is archived operational data, which may have data quality issue. To overcome the bad or noise data issue in traffic detector data, a comprehensive data validity test tool is adopted. In addition, to automate work zone data collection, a data integration procedure is also provided.

Chapter 5 first discusses the model calibration and validation. Then a case study is presented with field work zone data and detector data in Wisconsin. The experiment reveals the flexibility of the proposed model in scheduling different work zone scenarios such as with or without weekends, number of sub-work zones and different VOR values. The proposed framework can efficiently optimize the overall cost of the schedule of multiple work zones without the need for extended computational time.

6.2 Conclusion Remarks

This study proposes a new freeway work zone scheduling framework incorporating travel time reliability. A genetic optimization framework is used to optimize a combinational, multidimensional work zone scheduling. To reveal the traffic demand variation and non-recurrent events, this study also provides a dynamic traffic flow model based TTR impact evaluation method which is consistent with but more efficient than the FREEVAL-RL tool. Field work zone data from the Wisconsin Lane Closure System (WisLCS) system are used to establish a work zone scheduling problem. Historical traffic detector data from the WisTransPortal VSPOC suite is used to generate baseline travel time reliability estimates. The experiment reveals the flexibility of the proposed model in scheduling different work zone scenarios such as with or without nighttime and weekends, number of sub-work zones and different VOR values. The proposed framework can efficiently optimize the overall cost of the schedule of multiple work zones without the need for extended computational time. Sensitivity analysis also indicates the benefits of incorporating weekends in work zone schedules with significant reduction of travel time cost and reliability costs in the overall work zone costs. The increase of VOR values does result in increase in the optimized work zone costs. However, the impact on the modeling results is found to be insignificant due to the savings at in other cost items in the optimized schedule. The proposed method includes the procedures to incorporate reliability into planning and scheduling work zone activities using archived traffic data and events data. It is also an offline application which means the experimental results can be applied in future uses. The practitioners or model users can investigate the relationship between each type of work zone and reliability ratings with the proposed model.

6.3 Future Work

Despite the demonstrated capabilities of the proposed work zone impact evaluation model and optimization framework, we recognize that this study can be further improved. The future work would include the model improvement and enhancement to incorporate more complicate work zone scheduling scenarios, and identifying and solving the possible issues arising from implementation and deployment as well.

6.3.1 Short-term Future Work

Short-term future work for this study would focus on the enhancement and extension of the proposed methodology.

- Incorporate detour models

  Work zone planning agency may provide detour route to road users since diverting traffic to alternative routes might mitigate the mobility impact due to work zone. Several models found in literature have potential to be adopted in work zone scheduling by utilizing spare capacity in road network:

  System Optimization (SO) model can return the optimal diversion strategy based on minimized total delay on mainline and detour routes.

  Logit-based Route Choice (RC) model can estimate diversion rates based on the travel time difference between mainline and detour route. It has been observed that the RC model has great potential to provide detour information to road users who are not familiar with the facilities.

  User Equilibrium (UE) model can minimize the difference in travel time between mainline and detour routes. It is suitable for situations in which travelers are familiar with road network and traffic conditions.

- Enhance GA performance

  The GA adopted in this study was developed upon the built-in optimization package in MATLAB. Although it is suitable for such a nonlinear, integer and discontinuous optimization problem, there is still a need to test the convergence of optimization results based on addition statistical test and analysis. For better performance, further calibration on the population size, ratios crossover and mutation, stop criterion would be desired. In addition, scenario-specified genetic operators and representations would be developed to improve efficiency and stability of GA.

- Enhance incident handling

  As reviewed in literature, work zone could cause safety issues. In this study, the work zone impact on safety is modeled by an additional crash cost, which is a function of crash rates and total user delays. It is better to know more about incident characteristics and associated costs. Although the incident impact on travel time are carefully estimated by incorporating TTR to work zone scheduling, work activities and other work zone characteristics may also attribute to crash rate. In addition, with the increase of volume, certain types of accident may also increase. The relationship between traffic demand and probability of occurrence is needed to investigate. To better support decision making, a better measure of safety impacts based on field study and statistical analysis would be needed.

- Development of TTR

  In this study, the buffer time as a performance measure of TTR is adopted to measure work zone impact on reliability. Although it is quite sensitive to the variation of traffic condition, the applicability of other performance measure of TTR are worth to investigate.

TTR is an emerging topic that is increasingly important to understand. With the development of TTR and its application, the TTR will be incorporated planning and operation process more. However, since the concept is relatively new to the field, its applicability and performance measure are still being improved. Although current research efforts on TTR are led by SHAR 2 (2012), there is a need to validate and evaluate the methodology and analytical procedure. On the other hand, the value of reliability is still under debate since there is no universal standard to quantify. Therefore, this research will keep following the development of TTR estimation method, the computational engine FREEVAL-RL (2013), as well as the value of reliability.

- Queuing delay estimation

  The current approach to estimating queuing delay is using pointing queue formulation method. It is desired to explore if we can advance to physical queue estimation method. In addition, the time spent in acceleration and deceleration are not covered in current model, which can increase the accuracy of queuing delay estimation.

- Uncertainty of Input Parameters

  This study aims to provide an offline work zone scheduling model, which means the scheduling practitioner don’t need to build up the simulation environment every time. A portion of results would be stored for further use including the model parameters and scenarios modeling. In addition, in current optimization framework, the delay and reliability impact estimation scheduling model requires large amount of historical data, and all parameters are assumed to be accurate and deterministic. Incorrect estimation of the effect of combined events should be addressed in the future studies by quantifying the uncertainty of evaluation outputs and enhancing the robustness of the proposed optimization framework.

6.4.2 Long-term Future Work

Long term research on work zone scheduling includes several following topics in general:

- Multi-objective Optimization

  Found in literature, some innovative time-related contracting methods (e.g. lane rental, and cost (A) and time (B) bidding) that utilize incentive or disincentive agreement on project duration would be considered in further development of this framework. Since the new contracting methods may create a unique situation in which different decision makers may have different concerns so that a total cost optimization model may not be suitable. To increase the applicability of the optimization tool or considering the objectives of different kinds of tool users, the proposed optimization models should be modified to reflect the needs of transportation agencies, contractors, or other involved stakeholders. Therefore, a multi-objective optimization that can simultaneously minimizes the total cost and total operation time would be desirable, along with enhanced solution algorithm.

- Concurrent work zone scheduling

  The current framework is suited for isolated work zone project on freeway. In case of concurrent work zone scheduling, the interrelationship and combined effects among work zones should be taken into account. It raises to a challenge that how to better schedule the concurrent work zones temporally and spatially. The adjacent work zones may affect each other depends on the distance, since the queue propagates backward and cause congestion on downstream work zone. In that case, the current dynamic flow based delay and reliability estimation model could underestimate the work zone impact for downstream work zone. More empirical data or simulation results are needed to improve the model. Moreover, if there are one more work zones on a transportation corridor, the emphasis should be the travel time of entire corridor instead of a freeway section, which requires more accurate estimation.

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Appendix A. Summary of FREEVAL Output

ENTRY	DESCRIPTION
Scenario Number	Scenario number
Parent Scenario Number	A scenario with '*normal weather*', '*no incident'* with identical demand pattern as the current scenario is called the Parent Scenario. Also, for weather and incident scenarios, the 'weather only', and 'incident only' scenarios are called sub-parent scenarios. Each reliability scenario therefore has (only) one parent scenario. This attribute is useful when estimating additional delay due to weather and/or incidents relative to the demand-only parent scenario.
Analysis Period	Analysis period # (varies from 1 to # of AP's in study period)
Probability	Probability of a scenario (from FSG)
Demand Adjustment Factor	A multiplicative factor of demand relative to the base scenario
Weather Type	Weather condition description in the scenario
Weather Event Start Time	Start time of the weather event; either start of the study period or middle of it
Weather Event Duration (min)	Duration of the weather event in minutes
Weather Event CAF	Capacity adjustment factor due to the weather event
Weather Event SAF	Speed adjustment factor due to the weather event
Incident?	A Boolean value indicating the presence of an incident in the study period: 0 for no incident, 1 for incident
Incident Start Time	Start time of the incident (start or middle)
Incident Duration (min)	Duration of the incident in minutes
Incident Segment Number	Segment number where the incident occurs
Segment Number of Lanes	Total number of lanes on the incident segment
Number of Closed Lanes	Total number of lanes closed due to the incident
Per Open Lane Incident CAF	Capacity adjustment factor applied to each of the open lanes as due to the incident
Incident's SAF	Speed adjustment factor of the incident (defaulted at 1.0)
TTI	Facility travel time index in the analysis period
Max d/c Ratio	Maximum demand to capacity ratio for all the segments in the analysis period
Queue Length (ft.)	The queue length at the end of analysis period
Total Denied Entry Queue Length (ft.)	Queue length of vehicles unable to enter the facility at the first segment
Total On-Ramp Queue Length	Queue length of vehicles on On-Ramps
Average Travel Time per Vehicle (min)	Average travel time experienced by each vehicle traveling the facility in the analysis period
Free Flow Travel Time (min)	Facility travel time experienced by each vehicle if travelled at free flow

	speed
ENTRY	**DESCRIPTION**
Freeway Mainline Delay (min)	Delay experienced per vehicle. Calculated by subtracting free flow travel time from average travel time per vehicle.
System Delay – Includes On-Ramp (min)	Total delay of the analysis period is the summation of mainline delay and all on-ramp delays
VMTD Demand	Vehicle miles traveled as if all demand had been served in the analysis period
VMTV Volume	Vehicle miles travelled of the vehicles actually served during the analysis period
VHT travel/interval (Hrs.)	Vehicle hours travelled by all served vehicles during the analysis period
VHD delay/interval (Hrs.)	Vehicle hours of delay experienced by all served vehicles during the analysis period
Space mean speed =VMTV/VHT (mph)	Space mean speed at the analysis period calculated by dividing served vehicles miles travelled by total vehicles hours of travel
Facility Average Density (pc/mi/lane)	The average density on the facility in passenger cars per mile per lane
Density-Based Facility LOS	Facility level of service based on the facility average density
Demand-Based Facility LOS	Facility level of service based on demand

Appendix B. Quality Check Criteria and Testing Flow

The quality check criteria and testing flow is developed by TOPS lab (Shi, Parker, etc. 2012).

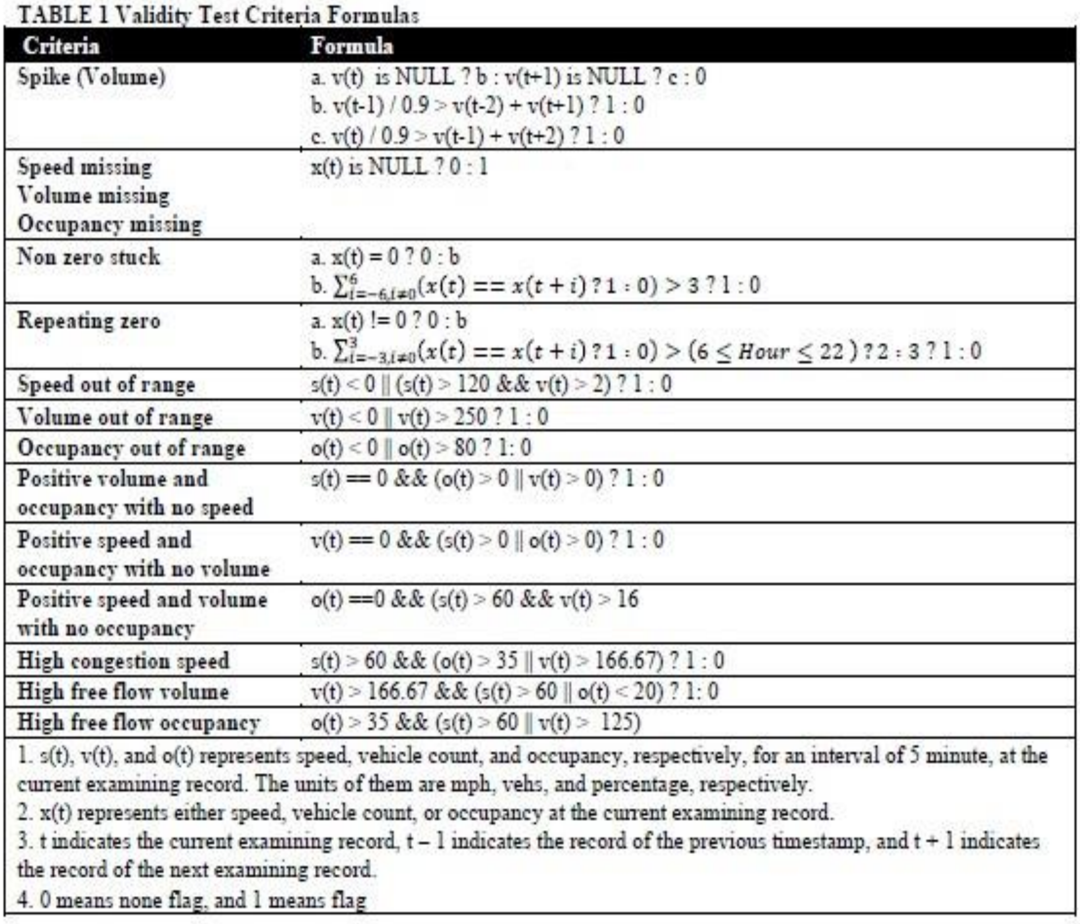
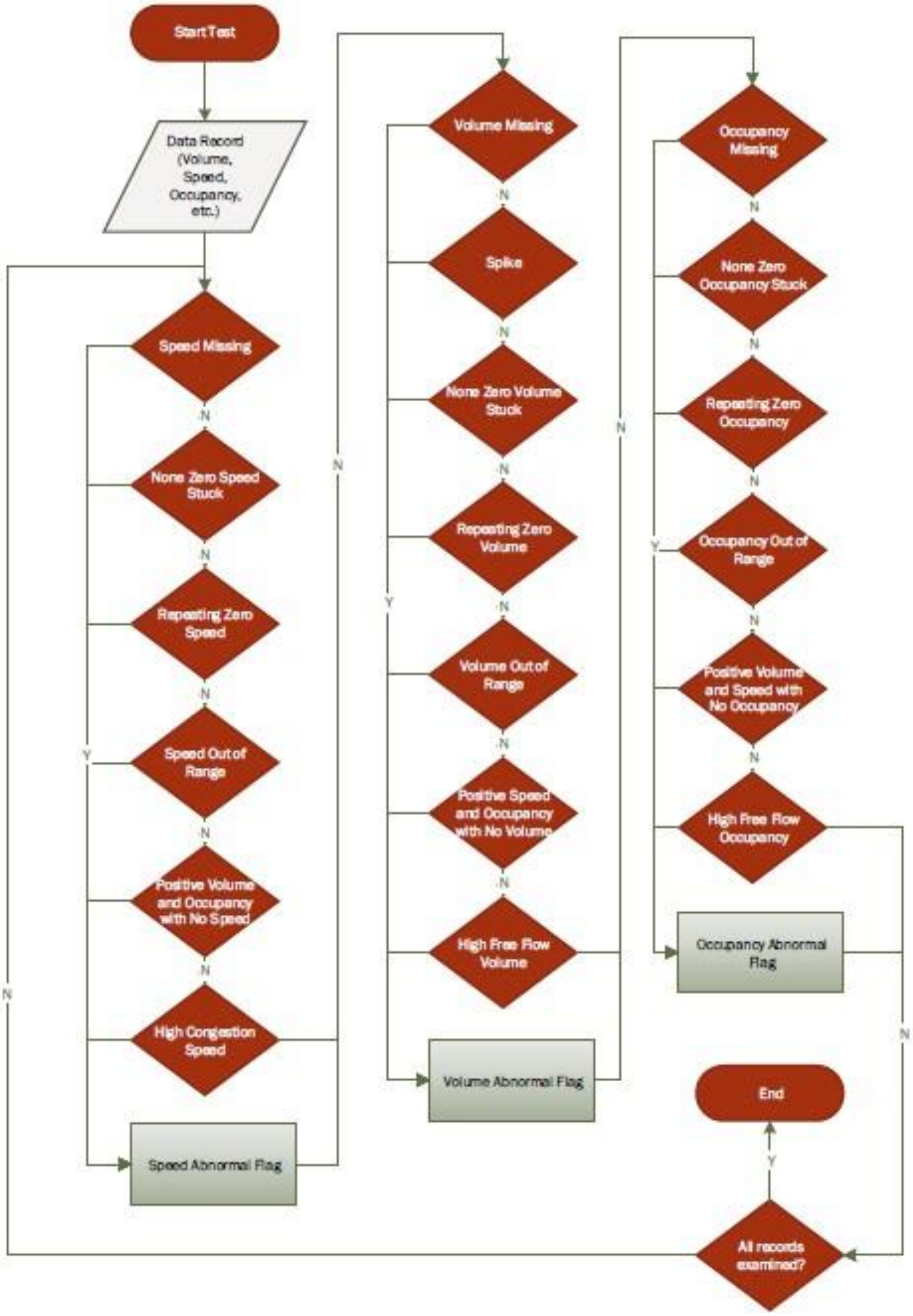


TABLE 1 Validity Test Criteria Formulas

<table>
<tr><th>Criteria</th><th>Formula</th></tr>
<tr><td>Spike (Volume)</td><td>a. v(t) is NULL ? b : v(t+1) is NULL ? c : 0
b. v(t-1) / 0.9 > v(t-2) + v(t+1) ? 1 : 0
c. v(t) / 0.9 > v(t-1) + v(t+2) ? 1 : 0</td></tr>
<tr><td>Speed missing
Volume missing
Occupancy missing</td><td>x(t) is NULL ? 0 : 1</td></tr>
<tr><td>Non zero stuck</td><td>a. x(t) = 0 ? 0 : b
b. $\sum_{i=-6,i\neq0}^{6}(x(t) == x(t+i) ? 1 : 0) > 3 ? 1 : 0$</td></tr>
<tr><td>Repeating zero</td><td>a. x(t) != 0 ? 0 : b
b. $\sum_{i=-3,i\neq0}^{3}(x(t) == x(t+i) ? 1 : 0) > (6 \leq Hour \leq 22\ ) ? 2 : 3 ? 1 : 0$</td></tr>
<tr><td>Speed out of range</td><td>s(t) < 0 || (s(t) > 120 && v(t) > 2) ? 1 : 0</td></tr>
<tr><td>Volume out of range</td><td>v(t) < 0 || v(t) > 250 ? 1 : 0</td></tr>
<tr><td>Occupancy out of range</td><td>o(t) < 0 || o(t) > 80 ? 1: 0</td></tr>
<tr><td>Positive volume and occupancy with no speed</td><td>s(t) == 0 && (o(t) > 0 || v(t) > 0) ? 1 : 0</td></tr>
<tr><td>Positive speed and occupancy with no volume</td><td>v(t) == 0 && (s(t) > 0 || o(t) > 0) ? 1 : 0</td></tr>
<tr><td>Positive speed and volume with no occupancy</td><td>o(t) ==0 && (s(t) > 60 && v(t) > 16</td></tr>
<tr><td>High congestion speed</td><td>s(t) > 60 && (o(t) > 35 || v(t) > 166.67) ? 1 : 0</td></tr>
<tr><td>High free flow volume</td><td>v(t) > 166.67 && (s(t) > 60 || o(t) < 20) ? 1: 0</td></tr>
<tr><td>High free flow occupancy</td><td>o(t) > 35 && (s(t) > 60 || v(t) > 125)</td></tr>
<tr><td colspan="2">1. s(t), v(t), and o(t) represents speed, vehicle count, and occupancy, respectively, for an interval of 5 minute, at the current examining record. The units of them are mph, vehs, and percentage, respectively.
2. x(t) represents either speed, vehicle count, or occupancy at the current examining record.
3. t indicates the current examining record, t – 1 indicates the record of the previous timestamp, and t + 1 indicates the record of the next examining record.
4. 0 means none flag, and 1 means flag</td></tr>
</table>


Start Test
Data Record (Volume, Speed, Occupancy, etc.)
Speed Missing
N
None Zero Speed Stuck
N
Repeating Zero Speed
N
Speed Out of Range
N
Positive Volume and Occupancy with No Speed
N
High Congestion Speed
Y
Speed Abnormal Flag
N
Volume Missing
N
Spike
N
None Zero Volume Stuck
N
Repeating Zero Volume
N
Volume Out of Range
N
Positive Speed and Occupancy with No Volume
N
High Free Flow Volume
Y
Volume Abnormal Flag
N
Occupancy Missing
N
None Zero Occupancy Stuck
N
Repeating Zero Occupancy
N
Occupancy Out of Range
N
Positive Volume and Speed with No Occupancy
N
High Free Flow Occupancy
Y
Occupancy Abnormal Flag
N
All records examined?
Y
End
N