University Transportation Research Center - Region 2

Final Report

Optimizing Work Zones for Highway Maintenance with Floating Car Data (FCD)

Performing Organization: New Jersey Institute of Technoogy

December 2015

Sponsor:
University Transportation Research Center - Region 2

University Transportation Research Center - Region 2

The Region 2 University Transportation Research Center (UTRC) is one of ten original University Transportation Centers established in 1987 by the U.S. Congress. These Centers were established with the recognition that transportation plays a key role in the nation's economy and the quality of life of its citizens. University faculty members provide a critical link in resolving our national and regional transportation problems while training the professionals who address our transportation systems and their customers on a daily basis.

The UTRC was established in order to support research, education and the transfer of technology in the field of transportation. The theme of the Center is "Planning and Managing Regional Transportation Systems in a Changing World." Presently, under the direction of Dr. Camille Kamga, the UTRC represents USDOT Region II, including New York, New Jersey, Puerto Rico and the U.S. Virgin Islands. Functioning as a consortium of twelve major Universities throughout the region, UTRC is located at the CUNY Institute for Transportation Systems at The City College of New York, the lead institution of the consortium. The Center, through its consortium, an Agency-Industry Council and its Director and Staff, supports research, education, and technology transfer under its theme. UTRC's three main goals are:

Research

The research program objectives are (1) to develop a theme based transportation research program that is responsive to the needs of regional transportation organizations and stakeholders, and (2) to conduct that program in cooperation with the partners. The program includes both studies that are identified with research partners of projects targeted to the theme, and targeted, short-term projects. The program develops competitive proposals, which are evaluated to insure the mostresponsive UTRC team conducts the work. The research program is responsive to the UTRC theme: "Planning and Managing Regional Transportation Systems in a Changing World." The complex transportation system of transit and infrastructure, and the rapidly changing environment impacts the nation's largest city and metropolitan area. The New York/New Jersey Metropolitan has over 19 million people, 600,000 businesses and 9 million workers. The Region's intermodal and multimodal systems must serve all customers and stakeholders within the region and globally.Under the current grant, the new research projects and the ongoing research projects concentrate the program efforts on the categories of Transportation Systems Performance and Information Infrastructure to provide needed services to the New Jersey Department of Transportation, New York City Department of Transportation, New York Metropolitan Transportation Council , New York State Department of Transportation, and the New York State Energy and Research Development Authorityand others, all while enhancing the center's theme.

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16. Abstract

One of the main tools that the Department of Transportation (DOT) of each state in the United States should have to support their work zone activities is a sound model that produces adequate work zone schedules for roadway maintenance and construction projects; this should be able to to produce reliable estimates of the impacts on traffic flow characteristics due to work zone activity. Existing analytical models used by DOTs have been developed based on traditional volume/capacity formulas with deterministic traffic queuing theory. However, the shortcomings of these models often result in inaccurate estimates of traffic flow delay, speed and associated costs. The objective of this report is to develop a methodology that accomplishes the following: 1) Estimates the traffic flow characteristics in work zones using Floating Car Data (FCD) also know as vehicle-probe data. 2) Minimizes the impact of work zones on traffic flow characteristics. 3) Minimizes the total work zone impact cost (including maintenance cost, idling cost, vehicle emissions, and user cost) yielded by the optimized work zone lengths and the associated schedule. The developed methodology takes advantage of the fact that the majority of freeways throughout the United States are now monitored through vehicle probe data that are based on the following technologies: 1) The proliferation of a GNSS (Global Navigation Satellite System) in vehicles and cellular phones that provide vehicle location and speed data every second. 2) The proliferation of Bluetooth Technology (BT), in which vehicle location and speed/travel time are estimated using BT installed at the side of the roadway – while BT is currently under more limited coverage, which is expanding rapidly. These FCD technologies provide an added dimension to the estimation of traffic flow characteristics in work zones, namely travel time, speed, and associated delay. To test this methodology, two case studies were conducted using a real work zone on a segment of Interstate I-287 in New Jersey.

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EXECUTIVE SUMMARY

The management of the work zones is one of the main functions of each Department of Transportation (DOT) in the United States. One of the tools that is necessary to support the management of work zones is a model that could produce work zone schedule for roadway maintenance and construction projects. Such a model should be capable of producing reliable estimates of traffic flow characteristics within the vicinity of the work zones. Current analytical models used by DOTs have been developed based on traditional volume/capacity formulas with deterministic traffic queuing theory. However, the shortcomings of these models often result in inaccurate estimates of traffic flow delay, speed and associated costs.

The models developed in this study are primarily based on two main technological advances in vehicle data gathering at the major freeways of the United States and other developed countries:

1) The proliferation of a GNSS (Global Navigation Satellite System) in vehicles and cellular phones that provide vehicle location and speed data every second.

2) The proliferation of Bluetooth Technology (BT), in which vehicle location and speed/travel time are estimated using BT installed at the side of the roadway. BT is under more limited coverage but is rapidly expanding.

Known as Floating Car Data (FCD) technologies, they provide an added dimension to the estimation of traffic flow characteristics in work zones, namely travel time, speed, and associated delay.

The objective of this report is to develop a methodology that accomplishes the following:

1) Estimates the traffic flow characteristics in work zones using FCD.

2) Minimizes the impact of work zones on traffic flow characteristics.

3) Minimizes the total work zone impact cost (including maintenance cost, idling cost, vehicle emissions, and user cost) yielded by the optimized work zone lengths and the associated schedule.

The problem is formulated as follows: The objective is to minimize the total work zone cost subject to some practical constraints, such as the project length, minimum duration of maintenance activities, and maximum duration of project constraints. The total work zone cost is comprised of three components: the Maintenance Cost (Agency Cost), the Idling Cost, and the User Cost. Each component is the sum of the costs incurred by individual work zones and breaks (i.e., the work zone idling time between each working period).

The above problem was solved using the heuristic method of Genetic Algorithms (GA) The GA applied in this study was developed using the “Genetic Algorithm” function of the Global Optimization Toolbox in MATLAB.

The main characteristics of the new total cost GA method are:

1) The developed method in optimizing the work zone schedule with respect to various input parameters and constraints (such as options with different production rates), traffic flow, and speed information from FCD.

2) The new GA developed method defined a new data structure to reduce the number of variables in the optimization process and adopted a penalty function to more efficiently handle the constraints including total project length (L_M), minimum duration of a work zone $(D_{\min})$, and maximum project duration (D_M).

To test this methodology, two case studies were conducted using a real work zone on a segment of Interstate I-287 in New Jersey. The first case study with a total length of 1.8 miles resulted in a predicted 9-hour completion time by deploying one work zone during the nighttime. The second case study resulted in an optimal three-period work zone completion: two night shifts and one off-peak period.

The methodology developed can be further extended to incorporate the discretization of time into 15-minute time intervals or less under the premise that the corresponding traffic volumes and travel times/speeds will be available. In addition, if such traffic flow data are available in real-time then a the model could be adapted to be continuously calibrated and executed in a rolling horizon approach to produce up to date optimal work zone schedules.

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CHAPTER 1: INTRODUCTION

An urban mobility report (Schrank, D., Eisele, B., and Lomax, 2012) indicated that the cost of traffic congestion to road users in the US was $121 billion in 2011, as a result of 5.5 billion hours of delay and 2.9 billion gallons of wasted fuel. Delays caused by work zones on freeways were nearly 24% of total non-recurring delays and 10% of overall delay. According to a study sponsored by the Environmental Defense Fund, US carbon dioxide emissions account for 45% of total production worldwide. The Environmental Protection Agency reported in 2013 that 27% of US greenhouse gas (GHG) emissions were from the transportation sector (EPA, 2013). A mission of each DOT is to keep roadway networks safe, efficient, attractive, repairable, and environmentally sustainable. One report has indicated that nearly 40% of the New York state highway system has either a fair or poor pavement condition and must be resurfaced (Joan and Andrew, 2011).

The major components that influence the total user cost for a work zone include work zone length, work zone schedule, work zone time horizon from start to finish, corresponding work zone traffic management, and traffic flow characteristics parameters (e.g., travel time expressed as the delay occurred upstream of the location of the work zone, fuel consumption, greenhouse gas (GHG) emissions, and travel cost). Work zone management is a multi-dimensional scheduling problem that falls under the category of combinatorial optimization.

The main models utilized by DOTs to estimate the traffic flow characteristics of work zones are based on national volume-to-capacity and queuing models (NYSDOT, 2001). In addition, the travel time and speed were estimated using oversimplified travel time functions (e.g., the BPR function). However, these analytical models do not consider the temporal and spatial traffic flow variations. With the availability of FCD (travel time, speed, and time stamps at the one-minute aggregation level), more accurate models can be developed to estimate traffic measures more accurately than traditional analytical models developed with the deterministic queuing concept. The traffic data technologies utilizing FCD have improved dramatically in terms of geographic coverage, sample size, precision in detecting vehicle location, and data processing algorithms. These improvements have resulted in greater accuracy and reliability of estimated vehicle speed and travel time.

This study has developed a practical method that utilizes FCD to optimize the work zone lengths and the associated schedule subject to a project duration constraint, which minimizes the sum of the aforementioned costs (maintenance, idling, vehicle emission, fuel consumption, and user delay).

CHAPTER 2: LITERATURE REVIEW

This section provides a comprehensive review of previous studies on related topics, including applications of FCD, work zone lane closure policy, work zone impact analysis, work zone schedule optimization, and their solution algorithms.

2.1 Floating Car Data (FCD) Technologies

In the advent of Intelligent Transportation Systems (ITS), transportation safety, mobility, and enhanced productivity may be significantly improved by integrating advanced communication technologies into vehicles and transportation infrastructure. A broad range of communication technologies, including wireless communication, computational technologies, FCD sensing technologies, microwave radar detection, inductive loop detection, and video vehicle detection, are applied for real-time data collection, processing, and management. The goal is to systematically capture real-time, multi-modal data from vehicles, devices, and infrastructure and develop an environment that enables the integration of high-quality data from multiple sources for transportation management and performance measures. In the application of FCD, effective methods were developed to instantaneously determine and predict future traffic conditions for providing timely information to road users.

FCD can be applied to determine the network-wide traffic speed, which is based on the collection of localization data such as speed and directions of travel. FCD is now the defacto source of travel time/speed for traffic flow information at the roadway link level and for most ITS applications. Based on this data, traffic congestion can be identified, travel times can be calculated, and traffic reports can be rapidly generated. In contrast to traffic cameras, plate recognition systems, and inductive loop sensors embedded in the roadway, no additional substantial hardware on the road network is necessary.

FCD techniques involve direct measures of travel time along with sample vehicle data on a route. For example, Bluetooth and toll tag techniques identify vehicles passing a pair of consecutive roadside readers and measure the travel time between the readers by checking the time stamps of vehicles at each reader (Cambridge Systematics, 2012). In the case of wireless (cellular) location technology, crowd sourcing and private provider data are based on tracking vehicles through either cell phone triangulation using cell site or GPS location tracking technologies. These two types of FCD technologies provide direct travel time measurement in which speed can be estimated by identifying the distance between the detector (reader) locations. Private probe vehicle data provided by commercial vendors, such as INRIX, TomTom, and HERE, are based on GPS tracking systems, which locate the movement of vehicles during a given time period (e.g., 1 second) (Mudge et al., 2013); speed can then be calculated by the change in location and time. Each of these FCD technologies is further discussed next:

2.1.1 Bluetooth

Bluetooth is an open, wireless communication platform used to connect a myriad of electronic devices. Many computers, car radios, dashboard systems, PDAs, cellular phones, headsets, and other personal equipment are, or can be, Bluetooth-enabled to streamline the flow of information among devices (KMJ Consulting, 2010).

Manufacturers typically assign unique Median Access Control (MAC) addresses to Bluetooth-equipped devices. Bluetooth-based travel time measurement involves identifying and matching the MAC addresses of Bluetooth-enabled devices carried by motorists passing a detector. The matching of Bluetooth devices can then be used to measure arterial travel time, average running speed, and travelers' origin-destination patterns. Since MAC addresses are not tracked when the device is sold within the marketplace, these unique addresses can be detected and matched without establishing a relationship to personal or otherwise sensitive information, thus keeping the traveling public and their personal information anonymous (Cambridge Systematics, 2012; KMJ Consulting, 2010). The sample size of data is also critical in providing accurate and up-to-date travel times. A research study conducted at University of Maryland suggests that a 4% detection rate is required for roadways of 36,000 AADT or greater (Puckett and Vickich, 2010). Roads with lower volumes would require a larger match percentage to attain an adequate sample.

<u>Advantages</u>

Bluetooth technology is new but rapidly maturing as the percentage of vehicles with Bluetooth devices (smartphones, in-vehicle connections, tablets, etc.) increases rapidly; it is also easy to install and maintain. With the cost per unit being relatively low, the estimations of travel times performed by Bluetooth technology have been compared to floating car methods and radio-frequency identification (RFID) as an accurate and cost-effective alternative (KMJ Consulting, 2010; Mendez, 2011).

<u>Disadvantages</u>

Currently, the estimated number of vehicles equipped with Bluetooth devices is only 5%. Bluetooth readers also cannot directly provide volume data (Cambridge Systematics, 2012). Additionally, multiple Bluetooth devices may exist on a single vehicle, such as cell phones. Although a small amount of the total data would be collected under these conditions, this multiplicity may skew data on corridors with a large volume of transit passengers (Mudge et al., 2013).

<u>Costs</u>

Recent cost data has revealed that an estimated cost per Bluetooth-installed reader is about $10,000. Two readers are needed per mile for accurate data collection, thus approximating the cost to $20,000 (Cambridge Systematics, 2012; KMJ Consulting, 2010; Vo, 2011).

2.1.2 Toll Tag

The toll tags used for electronic toll collection can be used by their readers, which are deployed at various points on a roadway network to obtain average travel time and speed information. There are four components in a toll tag travel time system: electronic tags, antennas, readers, and a central computing and communication facility (Cambridge Systematics, 2012). As a vehicle with an electronic tag passes underneath a toll tag reader, the time and toll tag identification number are recorded. If the same vehicle passes the next reader location, the travel time and average speed between the two locations can be determined. The toll tag identification number can also be coded to protect privacy.

Sample size requirements for a toll tag travel time system depend on the toll tags' market penetration. Ferman et al. (2005) suggest that a 3% penetration rate on freeways and a 5% rate on arterials are adequate. According to the New Jersey Turnpike Authority (NJTA), more than 70% of vehicles registered in New Jersey have E-Z Pass toll tags.

Advantages

Similar to Bluetooth technology, toll tag readers are mature due to their capability of providing a huge number of data points. With its simplicity in installation and maintenance, the percentage of toll transactions in New Jersey was estimated to be more than 70% in 2010 (INRIX). The cost per unit is also relatively low.

Disadvantages

The iFlorida project tested the use of toll tags to estimate travel time in Orlando (Cambridge Systematics, 2012). It was found that speeds were not very accurate unless the readers were spaced at half a mile or less. Therefore, not only does the technology of toll tag readers require a dense reader deployment to obtain accurate travel time data, they also cannot provide volume data directly. Furthermore, sample sizes depend significantly on toll tags' market penetration (Vo, 2011; Wright, 2000).

Costs

Recent cost data has found that an estimated cost per installed reader is about $15,000. Like Bluetooth-installed readers, two readers are needed per mile for accurate data collection, approximating the cost to $30,000 (Cambridge Systematics, 2012; Vo, 2011).

2.1.3 INRIX

INRIX traffic speed information is generated by blending the data from a variety of sources. The primary source of the INRIX data is GPS-enabled vehicle fleets (e.g., delivery vans, taxi cabs, and long-haul trucks); this data is supplemented by sensor-based data and GPS-equipped mobile devices **(**Seymour et al., 2011). The collected data is then compiled into an average speed profile for most freeways and arterials. The initial system spans from New Jersey to Georgia covering more than 7,000 center line miles of freeways and 38,000 arterial miles [19]. INRIX data attributes consist of three levels: real-time data for the specific segment, historical data (e.g., road reference speeds), and the combination of these two (Middleton et al., 2011).

Generally, the sample size is determined by the number of contracted GPS-enabled vehicles. White et al. (2010) suggest that because INRIX data is based largely on fleet-based GPS probe vehicles, its use may be an issue for arterials due to reduced sample size, as well as the fact that commercial vehicles operate differently than other vehicles in terms of their acceleration and deceleration characteristics. Data quality specifications are in effect when flow exceeds 500 vehicles per hour and are applied to both freeways and arterials (INRIX, 2007).

<u>Advantages</u>

Unlike toll tag readers and Bluetooth-installed readers, INRIX requires no installation or maintenance cost for transportation agencies. The data providers have great incentive to provide accurate data at a low cost.

<u>Disadvantages</u>

Data accuracy tests have found that speeds were fairly accurate on freeways but less so on arterials (INRIX, 2014). The method of speed calculation, underlying data, and the mix of real-time and historic data that is used to make the speed estimates is unknown; the data providers are thus unable to provide volume data.

<u>Costs</u>

Costs are generally negotiated for individual projects by the data providers. In 2010, INRIX quoted a price for mobilization at $150 per centerline mile and Annual Fee for data of $750 per centerline mile (Cambridge Systematics, 2012). In their most recent webcast titled “Agency Project Team Webcast to introduce VPPII”, the project team mentioned that they can provide reduced prices for NJDOT.

2.1.4 Microwave Radar Detection (MRD)

Microwave Radar Detection (MRD) is a non-intrusive, radar-based system operating in the microwave band. It needs to be mounted on a roadside pole above a certain height. The radar sensor provides per-lane presence, volume, occupancy, speed, and classification information in up to twelve user-defined detection zones. Output information is provided to existing controllers via contact closure and to other computing systems by serial port, IP communication port, or optional radio modem. A single radar unit can replace multiple inductive loop detectors and the attendant controller. RTMS (Remote Traffic Microwave Sensor), one of the more advanced radar detectors, is all-weather accurate and virtually maintenance-free. The detection range of one RTMS is up to 250 feet, providing coverage for up to eight lanes of traffic (Image Sensing Systems, Inc.).

Advantages

Microwave radar detector technology is mature due to its ability to provide accurate spot speed data, despite its inaccuracy for volumes. Radar units are easy to maintain and can be conducted without having to close traffic lanes (Cambridge Systematics, 2012).

Disadvantages

Radars generally require preventative maintenance and occasional repairs. In addition, radar sensors perform poorly at intersections as volume counters and cannot detect stopped vehicles (Wright et al., 2000).

Costs

Recent cost data found that an estimated cost per radar site installed is about $8,000. Following suit of the aforementioned technologies, two radar units per mile are needed for accurate travel time data collection, approximating the cost per mile to $16,000 (Cambridge Systematics, 2012).

2.2 Implementation of FCD

To enhance transportation mobility, safety, and perform accurate analyses of important regional transportation management and operations issues, nineteen agencies have deployed FCD technologies and are using real-time data to power their 511 systems in the NY/NJ region. The I-95 Corridor Coalition, in partnership with various agencies and organizations along the Eastern Seaboard, initiated a regional traffic monitoring project in 2006 based on FCD technology. The project established a system that acts as a continuous source of real-time transportation system status information along a major portion of the corridor (I-95 Corridor Coalition, 2010), as FCD technology is meant to provide comprehensive and continuous travel time information on freeways and arterials to State Agencies.

This data provides travel times statewide and comply with the forthcoming interstate traffic monitoring requirements of 23 CFR 511 (I-95 Corridor Coalition, 2010). As a result of implementing FCD technology in North Carolina, the cost of installation and maintenance cost was reduced by 25% and greater area coverage has been achieved. The FCD technology replaced side fire radar detectors, increasing the coverage from 300 miles to 1,200 miles for the same cost. The added benefit of the technology is that it can also obtain travel time and speed data (I-95 Corridor Coalition, 2010). The cost, coverage, and convenience of the technology without roadside intrusion were the deciding factors for Maryland, South Carolina and North Carolina to follow suit (I-95 Corridor Coalition, 2010). The floating car system is also used to estimate and display travel times on variable message signs and agencies' web sites.

Therefore, to develop a robust and practical model that optimizes work zone length and schedule, this study employs FCD to calculate the corresponding travel times, delays, and associated GHG emissions. Fuel consumption caused by highway work zones as temporal and spatial traffic characteristics, such as traffic volume and vehicle composition, are also considered.

2.3 Work Zone Lane Closure Policy

Several state DOTs have developed lane closure policies that provide guidance in determining permitted lane closure times, particularly during the time of day, week, or season a lane closure is allowed on a facility and at which specific location or segment. In conjunction with policies, software planning tools were also developed to assess the impacts of lane closures in work zones on the motorist. These impacts are then used to assist the DOTs in scheduling the lane/roadway closures.

The New Jersey DOT Road User Cost Manual (NJDOT, 2001) describes the analytical approach of calculating operating costs and delay costs to motorists resulting from construction, maintenance, or rehabilitation activity. The costs are a function of the characteristics of the work zone (e.g., duration, scope, etc.), the volume and operating characteristics of the traffic affected, and the corresponding dollar cost rates assigned to vehicle operations and delays.

The Maryland State Highway Administration (MDSHA) developed a Lane Closure Analysis Program based upon the Work Zone Lane Closure Analysis Guidelines to support state traffic engineers with a method to analyze work zone impacts (MDSHA, 2006). It is an analytical tool designed to quantify queues and delays resulting from capacity decreases in freeway work zones.

The California DOT (Caltrans) developed a lane closure approval process for its engineers and contractors to use when requesting a lane closure for construction and/or maintenance activities (Caltrans, 2007). The lane closure system ensures that the closure is consistent with any corridor transportation management plans.

The Ohio DOT (ODOT) lane closure policy provides more detailed information for specific corridors and includes the queue analysis methodologies used to determine the lane closure restrictions, as well as suggestions for mitigation strategies that can help reduce the impact of lane closure (ODOT, 2007).

The Wisconsin DOT (WisDOT) included lane closure and delay guidelines in the 2007 update of its Facilities Development Manual (WisDOT, 2007). The guidelines provide information on queue and delay estimation tools that can be used to assess the effects of lane closures on motorists during a project.

The Colorado DOT lane closure policies provide engineers and contractors with information regarding lane closure schedules, procedures used to determine lane closures, and detailed flowcharts explaining how to calculate delays due to lane closures.

2.4 Work Zone Impact Analysis

Earlier studies have focused on various aspects of work zones, including capacity, estimating the speed through a work zone, user delay, and optimal work zone length and schedule. Dudek and Richard (1982) and Krammes and Lopez (1994) developed methods to estimate road capacity during maintenance work. Their studies provide a basic concept of work zone activities analysis. Cassidy and Han (1992) used empirical data to estimate vehicle delays and queue lengths on two-lane highways operating under one-way traffic control without optimizing the work zone length. However, the cost of highway maintenance was not considered.

Schnell et al. (2001) evaluated traffic flow analysis tools applied to work zones. The Highway Capacity Software (HCS), Synchro, CORSIM, NetSim, QUEWZ-92, and the ODOT spreadsheet were used to estimate the capacity and queue length of four work zones on multi-lane freeways in Ohio. The estimated results were then compared with the field data. The simulation models could not be calibrated for oversaturated conditions that existed at the work zone areas, so these models consistently underestimated the queue lengths. QUEWZ-92 was the most accurate in estimating the work zone capacity. When this capacity estimate was used in the ODOT spreadsheet, it produced realistic estimates of queue lengths as compared to the estimates from other tools.

A manual was designed by NJDOT for estimating the road user cost caused by work zone activities, including ten potential cost components classified into two categories based on traffic states (i.e., base case and queue situation) (NJDOT, 2001). “Work zone” is defined as an area of a highway in which maintenance and construction operations are taking place that impinge on the number of lanes available to traffic or affect the operational characteristics of traffic flowing through the area. User costs in the work zone are added to vehicle operating costs, delay costs, and crash costs to highway users resulting from construction, maintenance, or rehabilitation activity.

Chitturi and Benekohal (2004) compared the performance of QUEWZ-92, FRESIM, and QuickZone with field data in eleven freeway work zones in Illinois while some did not cause queues. The results of the study showed that none of these models gave an accurate representation of real field conditions. QUEWZ-92 overestimated the capacity and underestimated the queue lengths mainly because of its use of an outdated speed-flow relationship. FRESIM consistently overestimated the speeds under queuing conditions, overestimated the queue lengths for half of the cases, and underestimated the queue lengths for the other half of the cases. QuickZone consistently underestimated the queue length and delay when compared to the field data. The UIUC-developed model that explains this report produced more accurate results that matched reasonably well the corresponding field data. The study concluded that IDOT should consider using the UIUC-developed procedures in work zone capacity, delay, and queuing analyses while these procedures should be more refined as additional data become available.

Khanta (2008) evaluated several traffic simulation models (e.g., QUEWZ, Quick Zone, CORSIM and VISSIM) for work zones in the New England area. CORSIM and VISSIM were found to be effective tools in estimating the traffic flow characteristics at work zones as long as traffic flow data is available. It was noted that it is rather difficult to have traffic flow sensors throughout the transportation network, especially in work zone locations, to produce estimates of traffic volumes, thereby making the utilization of such microscopic simulation software more difficult to implement. However, these sensors should still be considered as part of a broader policy to install them at each work zone to gather traffic flow data before, during, and after the work zone duration.

Previous studies have also focused on optimizing work zone length based on the minimization of the total cost (Schonfeld and Chien, 1999; Chien et al, 2002; Chien and Schonfeld, 2001, 2005; Tang and Chien, 2008, 2009). Schonfeld and Chien (1999) developed a mathematical model to optimize the work zone length and associated traffic control for two-lane, two-way highways where one lane at a time is closed. The objective was to minimize the total cost, including agency cost and user delay cost, without considering any alternate route. Their model provides researchers a primary formulation to estimate the total cost and minimize it to optimize the work zone lengths. Chien and Schonfeld (2001) also developed a mathematical model to optimize the work zone lengths on four-lane highways using a single-lane closure approach. Their basic method comprised of formulating a total cost function and optimizing work zone lengths by minimizing the total cost, including agency cost, accident cost, and user delay cost, without considering alternate routes. Each component of the objective function in their study is included in the model developed in this study.

Chien et al. (2002) developed an optimized work-zone scheduling and traffic control model for two-lane two-way highways where one lane at a time is closed. Their objective was to minimize the total cost, including maintenance, labor/equipment idle costs, and user-delay costs while considering traffic flows varying over time. In that study, the concept of optimal schedules was considered to help highway agencies schedule maintenance activities more efficiently, such as planning a longer working area of work zone during the low traffic demand period or managing the working crew break during a peak period.

Chien and Schonfeld (2005) developed a methodology to minimize the total cost by optimizing the work zone length while simultaneously considering four different alternative routes. That study extended their previous work on four-lane and two-lane highways considering the possibilities offered by alternative routes or traffic crossover. Tang and Chien (2008) optimized work zone scheduling considering a discrete relationship between maintenance time and the associated cost. The decision variables include the number of work zones and breaks, as well as their corresponding starting times, ending times, and lengths. Tang and Chien in 2009 presented a method to optimize the work zone schedule considering time-varying traffic diversion, which was formulated analytically. The objective function was to minimize the total cost, including agency cost and user cost.. However, in those studies, the travel time delay and queuing length of the travelers was formulated based on the deterministic queuing concept, which has limitations as the temporal characteristics of queue formation are not taken into consideration.

In a study conducted by Chung and Recker (2012), a methodological approach for estimating the temporal spatial extent of delays caused by freeway accidents was presented. The Inductive Loop Detectors (ILDs) were used to estimate the traffic flows and the maximum extent of the accident influence and congested region. Similarly, they used the same method to analyze the work zones on freeways by segmenting the freeway into separated segments while obtaining traffic flow and speed information from the ILDs.

A final report of concepts and applications involving work zone user costs was developed by the Federal Highway Administration; it provides practitioners with information on work zone user cost analysis techniques using case studies drawn from real-world projects and includes a methodology to estimate vehicle operating costs and emission costs (FHWA, 2011). The NCHRP Project 20-68A Scan Report (2005) indicates that many of the state transportation agencies already consider the road user cost (RUC) in their project decisions. Their developed spreadsheet includes tools to estimate the RUC, whereas others reported using software such as QUEWZ-98 and QuickZone for basic freeway sections and more sophisticated simulation software (e.g., Synchro 5 or TSIS-CORSIM 6) for other types of roadways or more complicated sections.

Mallela and Sadasivam (2011) discussed key components of RUC in a work zone, input needs, and available tools. The main RUC components they considered include user delay costs, vehicle operating costs, crash costs and emission costs. The expected increase in emissions by emission type was estimated as a function of vehicle type, reduced work zone speed, and increased congestion due to queuing and detours. Once the emission rates by vehicle type were estimated, the cost of emissions was calculated as a function of vehicle-miles of travel and unit cost.

2.5 Optimization Algorithms

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

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

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

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

In the aforementioned studies (Schonfeld and Chien, 1999; Chien and Schonfeld, 2001), the cost function was minimized by using the classical optimization approach because the models are differentiable (i.e., setting derivative equations equal to zero and solving them). Closed-form formulas were derived at several levels of complexity to match the data availability and user-desired precision. However, for a highway maintenance project, variable construction production rates, realistic maintenance time-cost relation, and project duration are also critical factors affecting a project's total cost and work zone schedule. Tang and Chien (2008, 2009) then developed a GA to optimize the combinatorial, multi-dimensional scheduling problem; a discrete maintenance time-cost relation and user cost can therefore be considered while developing the objective total cost function.

CHAPTER 3: METHODOLOGY

This study considers the work zone activities in which a highway maintenance project may be divided into several work zones sequentially along one direction of the mainline roadway. The basic method followed here is to formulate a total cost objective function and use it to optimize work zone lengths and schedules. The traffic volume approaching a work zone, normal speed with no work zone activities, and work zone speed are estimated by FCD.

The total cost function includes all cost components that significantly influence the optimal work zone length. The nonlinear, mix-integer, and discontinuous cost function is minimized by using the Genetic Algorithm as shown here in **Figure 1.**

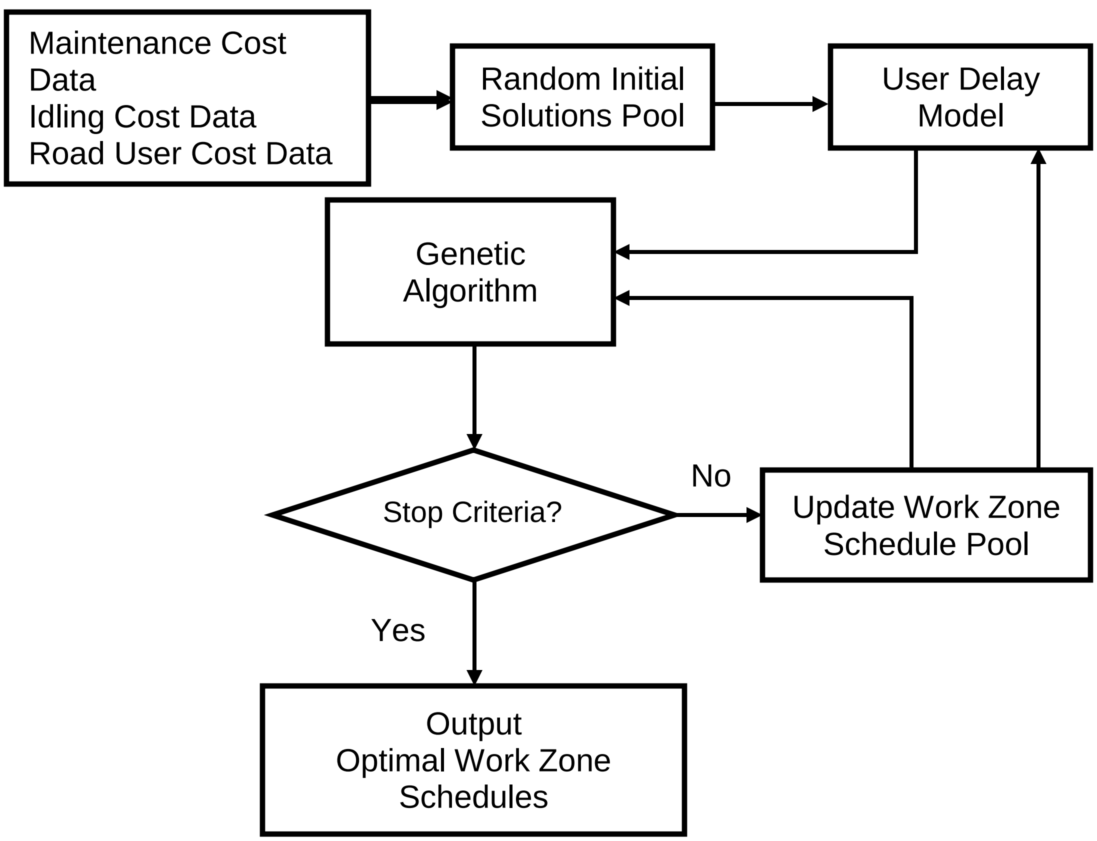

Figure 1: Work Zone Total Cost Solution Methodology

3.1 Assumptions

To optimize a work zone schedule on a multi-lane highway, the objective total cost function is formulated based on the following assumptions:

1. The model assumes that 100% of the automobiles in the studied work zone area are covered. Different vehicle classifications (e.g., buses and trucks) may be applied by using the corresponding passenger car equivalents (PCEs) suggested by the Highway Capacity Manual.
2. The speeds under normal and work zone conditions are constant within each time interval of the model.
3. The duration of the work zone is linearly related to its length.

3.2 Model Formulation

In this section, the model developed to estimate the cost for work zones is presented.

Work Zone Total Cost ($\mathbf{C_T}$)

The objective function $\mathbf{C_T}$ is comprised of three components: the Maintenance Cost (Agency Cost) Module ($\mathbf{C_M}$), the Idling Cost Module ($\mathbf{C_I}$), and the User Cost ($\mathbf{C_U}$). Each component is the sum of the costs incurred by individual work zones and breaks (i.e., the work zone idling time between each working period). Thus,

$$\boldsymbol{C_T = C_M + C_I + C_U} \quad (1)$$

Therefore, for a maintenance project involving a set of work zones, Eq. 1 can be formulated as Eq. 2:

$$\boldsymbol{C_T = \sum_{i=1}^{I} C_{m_i} + C_{I_i} + C_{U_i}} \quad (2)$$

Where **i** is an index of work zones and **I** denotes the total number of work zones (including work breaks).

The objective function $\mathbf{C_T}$ shall be minimized subject to some practical constraints, such as the project length, minimum duration of maintenance activities, and maximum duration of project constraints.

Project length ($\mathbf{L_M}$)

The sum of the work zone lengths must equal the total project length ($\boldsymbol{L_M}$):

$$\boldsymbol{\sum_{i=1}^{I} l_i^k = L_M, \forall i, k} \quad (3)$$

Where l_i^k is the length of work zone i. The superscript k represents the index of available production options.

Minimum duration of maintenance activities (D_{min}):

$$D_i \geq D_{\min}, \forall i$$

(4)

$D_{\min}$, is the minimum duration of maintenance activities, which presents the time consumption of installing and removing the maintenance equipment or break period for work crew. (i.e., work zones/breaks).

Maximum duration of project (D_M):

$$\sum_{i=1}^{I} D_i \leq D_M, \forall i \quad (5)$$

D_M and L_M represent the maximum project duration (hours) and the project length (miles) respectively. The three cost components are formulated and discussed next.

Maintenance Cost (C_{M_i}):

The maintenance cost of work zone *i* denoted as C_{M_i}, which includes the fixed cost and variable cost, where the latter cost is a function of the working area length denoted as l_i^k. Thus,

$$C_{M_i} = z_1 + z_2^k \cdot l_i^k \quad (6)$$

where z_1 is the fixed cost for setting and removing a work zone and z_2^k is the unit maintenance cost in $/lane-mile with respect to the index of feasible production options (i.e., different levels of productive efficiency) to perform a given type of maintenance work denoted as k. It is assumed that the maintenance cost is linearly related to the length of the work zone.

The duration of maintenance activity in work zone *I* denoted as D_i is the duration between the starting (S_i) and ending (E_i) times of zone i. D_i can also be defined as a function of l_i^k and the unit production time z_4^k (i.e., hours needed to complete one-mile maintenance) corresponding to the production option. Thus,

$$D_i = E_i - S_i = z_3 + z_4^k \cdot l_i^k \tag{7}$$

where z_3 is the time required for setting up and removing a work zone.

Thus, l_i^k can be derived as:

$$l_i^k = \frac{E_i - S_i - z_3}{z_4^k} \tag{8}$$

And C_{M_i} can be derived as:

$$C_{M_i} = z_1 + z_2^k \cdot \frac{E_i - S_i - z_3}{z_4^k}, \forall i,k \tag{9}$$

Work Zone Idling Cost (C_{I_i}):

A work break (idling or no-work performed) is considered a dummy work zone with variable duration but with zero-mile length. The cost of a work break C_{I_i} is the product of its duration D_i and the average idling cost v_d .

Thus,

$$C_{I_i} = v_d \cdot D_i = v_d \cdot (E_i - S_i), \forall i \tag{10}$$

Road User Cost (C_U)

C_U is the sum of the delay cost, vehicle operating cost, emissions cost and accident cost for each work zone ***i***, denoted as $C_{d_i}, C_{V_i}, C_{e_i}, C_{A_i}$ respectively. Thus,

$$C_U = \sum_{i=1}^{I} C_{U_i} = \sum_{i=1}^{I} (C_{d_i} + C_{V_i} + C_{e_i} + C_{A_i}) \tag{11}$$

User Delay cost (C_{d_i})

The User Delay Cost is represented by the total volume multiplied by the average delay time upstream of the work zone location. The derivation for the user delay cost is discussed in **Appendix II**:

$$C_{d_i} = v \cdot \sum_{s \in S} \sum_{t=S_i}^{E_i} (t_{ts}{}^n - t_{ts}{}^w) \cdot \mathrm{V}_{ts} \tag{12}$$

where ***S*** is the set of sections affected by work zone and ***s*** is the corresponding index. $t_{ts}{}^n$ is the travel time on section ***s*** under normal conditions and $t_{ts}{}^w$ is the travel time for section ***s*** with work zone ***i*** during time period ***t***. $\mathbf{V}_{ts}$ stands for the volume in segment ***s*** during time period ***t*** and v for monetary value of time.

Vehicle Operating Cost (C_{V_i})

The vehicle operating cost (C_{V_i}) is caused by work zone ***i***, which is the product of delay as calculated in the user delay cost and the unit vehicle idling cost, denoted as v_o , and the corresponding traffic volume that is being delayed upstream of the location of the work zone. Thus,

$$C_{V_i} = v_o \sum_{t=S_i}^{E_i} d_{it} \cdot V_{it} \tag{13}$$

Where d_{it} the average delay is caused by work zone ***i*** during time period ***t***, and V_{it} is the traffic volume in work zone ***i*** during time period ***t***.

Accident Cost (C_{A_i})

The number of accidents considered here is based on the number of vehicle-hours traveled through a work zone, whose cost can then be defined as the product of the accident rate denoted as r_a (i.e., the number of accidents per 100 million vehicle-hour), the work zone delay and the average cost per accident denoted as v_a . Thus,

$$C_{A_i} = v_a \sum_{t=S_i}^{E_i} d_{it} \cdot V_{it} \cdot r_a \tag{14}$$

Emissions Cost (C_{e_i})

The emissions cost component of the work zone is the difference between the emissions cost resulting from the work zone and the corresponding costs caused under normal traffic flow conditions. Thus,

$$C_{e_i} = \sum_{t=S_i}^{E_i} (C_{e_{it}}^{n} - C_{e_{it}}^{w}) \cdot V_{it} \tag{15}$$

Where $C_{e_{it}}^{n}$ and $C_{e_{it}}^{w}$ represent the emission damage cost under normal and work zone ***i*** conditions during time period ***t*** (FHWA, 2011).

Finally, the objective total cost function in Equation 1 can be derived as

$$\boldsymbol{Min}.\mathrm{C}_{\boldsymbol{T}} = \sum_{\boldsymbol{i}=1}^{\boldsymbol{I}} \left| \begin{array}{l} \boldsymbol{z}_1 + \boldsymbol{z}_2^{\boldsymbol{k}} \cdot \dfrac{\boldsymbol{E}_{\boldsymbol{i}} - \boldsymbol{S}_{\boldsymbol{i}} - \boldsymbol{z}_3}{\boldsymbol{z}_4^{\boldsymbol{k}}} + \boldsymbol{v}_{\boldsymbol{d}} \cdot (\boldsymbol{E}_{\boldsymbol{i}} - \boldsymbol{S}_{\boldsymbol{i}}) \\ + \boldsymbol{v} \cdot \sum_{\boldsymbol{s} \in \boldsymbol{S}} \sum_{\boldsymbol{t}=\boldsymbol{S}_{\boldsymbol{i}}}^{\boldsymbol{E}_{\boldsymbol{i}}} (\boldsymbol{t}_{\boldsymbol{ts}}^{\boldsymbol{n}} - \boldsymbol{t}_{\boldsymbol{ts}}^{\boldsymbol{w}}) \cdot \boldsymbol{V}_{\boldsymbol{ts}} + \boldsymbol{v}_{\boldsymbol{o}} \sum_{\boldsymbol{t}=\boldsymbol{S}_{\boldsymbol{i}}}^{\boldsymbol{E}_{\boldsymbol{i}}} \boldsymbol{d}_{\boldsymbol{it}} \cdot \boldsymbol{V}_{\boldsymbol{it}} \\ + \boldsymbol{v}_{\boldsymbol{a}} \sum_{\boldsymbol{t}=\boldsymbol{S}_{\boldsymbol{i}}}^{\boldsymbol{E}_{\boldsymbol{i}}} \boldsymbol{d}_{\boldsymbol{it}} \cdot \boldsymbol{V}_{\boldsymbol{it}} \cdot \boldsymbol{r}_{\boldsymbol{a}} + \boldsymbol{C}_{\boldsymbol{e}_{\boldsymbol{i}}} = \sum_{\boldsymbol{t}=\boldsymbol{S}_{\boldsymbol{i}}}^{\boldsymbol{E}_{\boldsymbol{i}}} (\boldsymbol{C}_{\boldsymbol{e}_{\boldsymbol{it}}}^{\boldsymbol{n}} - \boldsymbol{C}_{\boldsymbol{e}_{\boldsymbol{it}}}^{\boldsymbol{w}}) \cdot \boldsymbol{V}_{\boldsymbol{it}} \end{array} \right\rfloor \quad (16)$$

Subject to:

Project Length:

$$\sum_{\boldsymbol{i}=1}^{\boldsymbol{I}} \boldsymbol{l}_{\boldsymbol{i}}^{\boldsymbol{k}} = \boldsymbol{L}_{\boldsymbol{M}}, \forall \boldsymbol{i}, \boldsymbol{k} \quad (3)$$

Minimum Duration of Maintenance Activities:

$$\boldsymbol{D}_{\boldsymbol{i}} \geq \boldsymbol{D}_{\mathbf{min}}, \forall \boldsymbol{i} \quad (4)$$

Maximum Project Duration:

$$\sum_{\boldsymbol{i}=1}^{\boldsymbol{I}} \boldsymbol{D}_{\boldsymbol{i}} \leq \boldsymbol{D}_{\boldsymbol{M}}, \forall \boldsymbol{i} \quad (5)$$

CHAPTER 4: SOLUTION ALGORITHM

The objective total cost function formulated in Eq. 13 is a discontinuous function in which decision variables include the working area starting time (S_i), ending time (E_i), and the production index (***k***) of work zone ***i*** (***i*** from 1 to **I**).

Tang and Chien (2008, 2009) developed a Genetic Algorithm to solve this combinatorial, multi-dimensional optimization problem. The GA in various studies (Chien et al., 2001; Tang and Chien, 2007, 2008, 2009) was demonstrated to be an efficient method in solving combinatorial optimization problems. A GA is usually comprised of five major components: a genetic representation of potential solutions, a criterion for evaluating the performance of a solution (i.e., objective function), a selection mechanism for promoting the evolution of good solutions, a reproduction function to produce new solutions (i.e., crossover and mutation), and a constraint handling method to fix invalid solutions (Fwa et al., 1998).

The detailed development of a GA can be referred to in the paper by Tang and Chien (2009). Detailed information about a GA may also be consulted in the book authored by Michalewicz (1999). **Figure 2** (given below) illustrates the frame work of the developed solution algorithm. The GA applied in this study is developed using the "Genetic Algorithm" function of the Global Optimization Toolbox in MATLAB.

4.1 Genetic Representation and Data Structure

A solution of the work zone scheduling problem is defined as an integer variable S_1 and an integer solution list **L**. Thus,

$$L = \{(D_1, k_1), (D_2, k_2) \ldots (D_i, k_i), \ldots (D_I, k_I)\} \tag{17}$$

Where S_1 represents the starting time of first work zone (***i=1***), which is the starting time of the whole maintenance project. The list of intervals with an identical duration T are arranged in an ascending order starting from interval zero to ***N***. Note that ***N*** represents the total number of intervals based on the maximum project duration called D_M, where D_i represents the elapsed time between the starting time S_i and ending time E_i; and k_i is the production index associated with work zone ***i***. Then, (D_i, k_i) can be abstracted as a "node" element. The length of a linked list is designated as the number of nodes in the list, which represents the number of work zones. This developed data structure is based on a study conducted by Tang and Chien (2007), but with S_i and E_i replaced by D_i to make the algorithm fit the MATLAB input more easily and reduce the number of variables from $(3I+1)$ to $(2I+2)$.

4.2 Evaluation Criterion

The performance of solutions in each generation is evaluated based on the objective value of the total cost function. For the cost minimization problem discussed here, the solution that achieves the lowest total cost is deemed the best.

4.3 Elitist Selection

The elitist selection method is utilized to guarantee that the best solution in the current generation can always evolve to the next generation. The Global Optimization Toolbox in MATLAB handles this component with its own function codes. The selection ratio is a parameter set by the user to decide whether the solution is sufficient for evolution to the next generation.

4.4 Crossover and Mutation

The MATLAB GA function codes the coordinate sequence of the solution as a gene. The crossover operators combine the coordinates from two parenting genes while mutations occur randomly at each coordinate. In this study, the elapsed time $\boldsymbol{D_i}$ and production index $\boldsymbol{k_i}$ are the decision variables that form the optimization targets. The probabilities of performing crossover and mutation are defined as crossover ratio and mutation ratio, which can be set in MATLAB by the user. Detailed information about the crossover and mutation principle may be consulted in the study by Tang and Chien (2007).

4.5 Constraint Handling Method

The prevailing constraint handling methods in a GA include a penalty function method and a repair method discussed in a study by Cheu and Muntasir (1998). Tang and Chien (2007) developed a repair method to overcome the drawback of a penalty function so that promising solutions would not be discarded by correcting possible constraint violations in offspring solutions. Since the penalty function is easy and effective in MATLAB, a developed solution algorithm program code has been conducted in this study to avoid this drawback. Therefore, the penalty function is adopted in this study and the handing method contains three constraints, defined in Eq. 2 and discussed below:

4.5.1 User Specified Project Length (L_M)

The equality constraint that defines the sum of work zone lengths must be equal to the total project length ($\boldsymbol{L_M}$). Thus, the penalty function **J** is as follows:

$$\boldsymbol{J} = (Total\ Length\ - L_{\boldsymbol{M}})^2 \times Penalty\ Factor^{+} + \boldsymbol{C_T} \qquad (18)$$

The purpose of introducing this penalty function is to achieve in the optimization process that the total work zone length (*Total Length*) be close to the L_M , but as far as possible, by minimizing **J**. The penalty factor is a large number (e.g.,10^8) to control the *Total Length* accuracy. The optimization process stops when the error between *Total Length* and L_M cannot be smaller to achieve lower cost.

4.5.2 Minimum Duration of a Work Zone (D_{min})

The work activities violating this constraint are isolated fragments (i.e., nodes with very short duration) in a solution list. The method is set to the lower bound and upper bound for each variable to achieve the minimum duration of each work zone. An odd number **I** (i = 1, 3, 5…) indicates that there is a work zone, while an even number **i** (i = 2, 4, 6, …) indicates that this duration **i** is idling. This arrangement of variables can avoid the isolated fragment issue (i.e., two contiguous durations are both in the work zone, but only one should be considered because there is no break between them).

4.5.3 Maximum Project Duration (D_M)

This constraint is warranted by the developed genetic representation because the maximum number of time intervals in a solution schedule corresponds to the maximum project duration. Mentioned previously, **Figure 2** is given below.

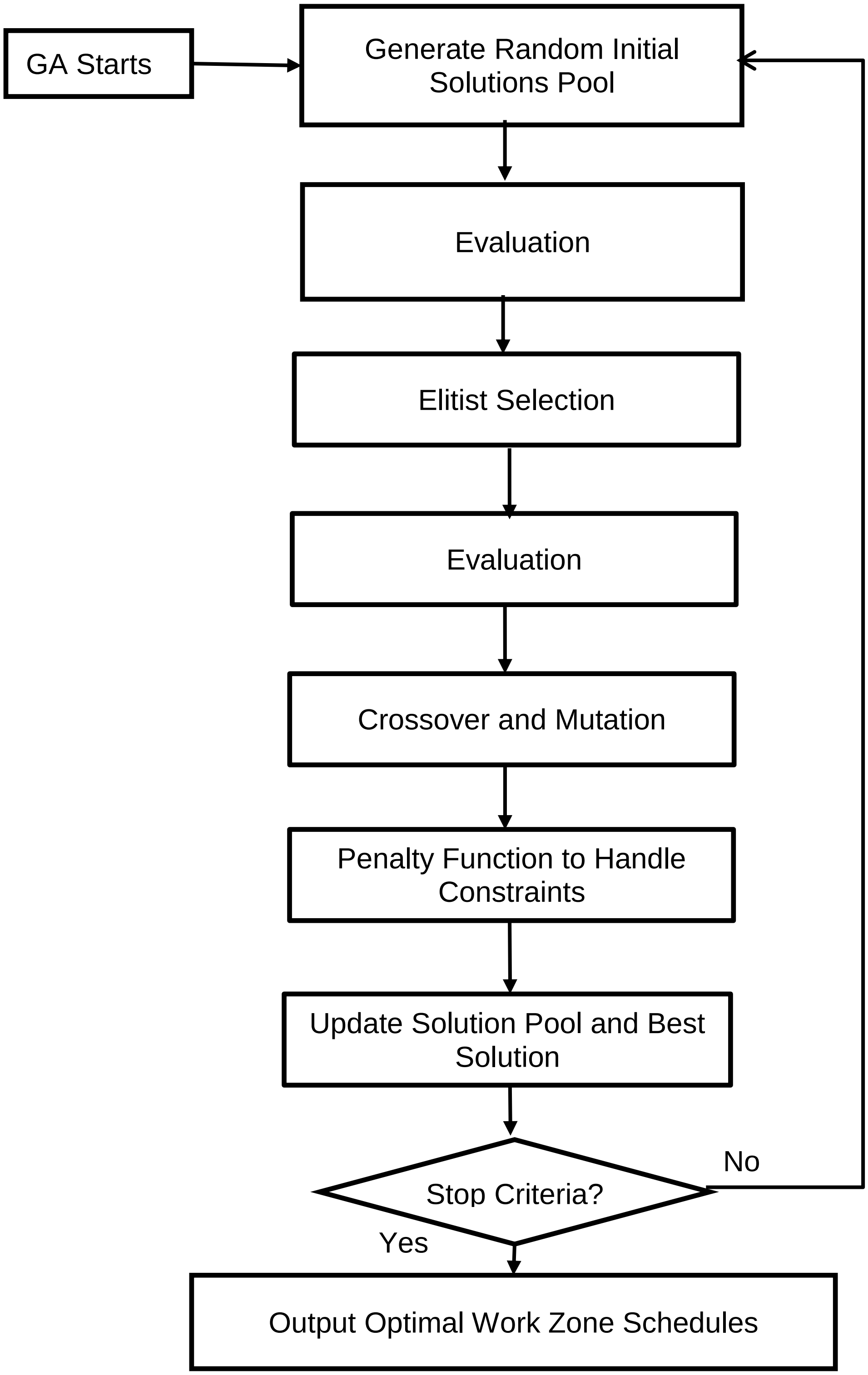

Figure 2: Flow Chart of the Developed GA

CHAPTER 5: CASE STUDIES

A real work zone on a segment of Interstate I-287 in New Jersey (four lanes in each direction) was utilized to demonstrate the methodology developed in this project. This work zone was selected because of the availability of detailed work zone data on this segment and FCD. Two case studies were conducted for this work zone and are described next.

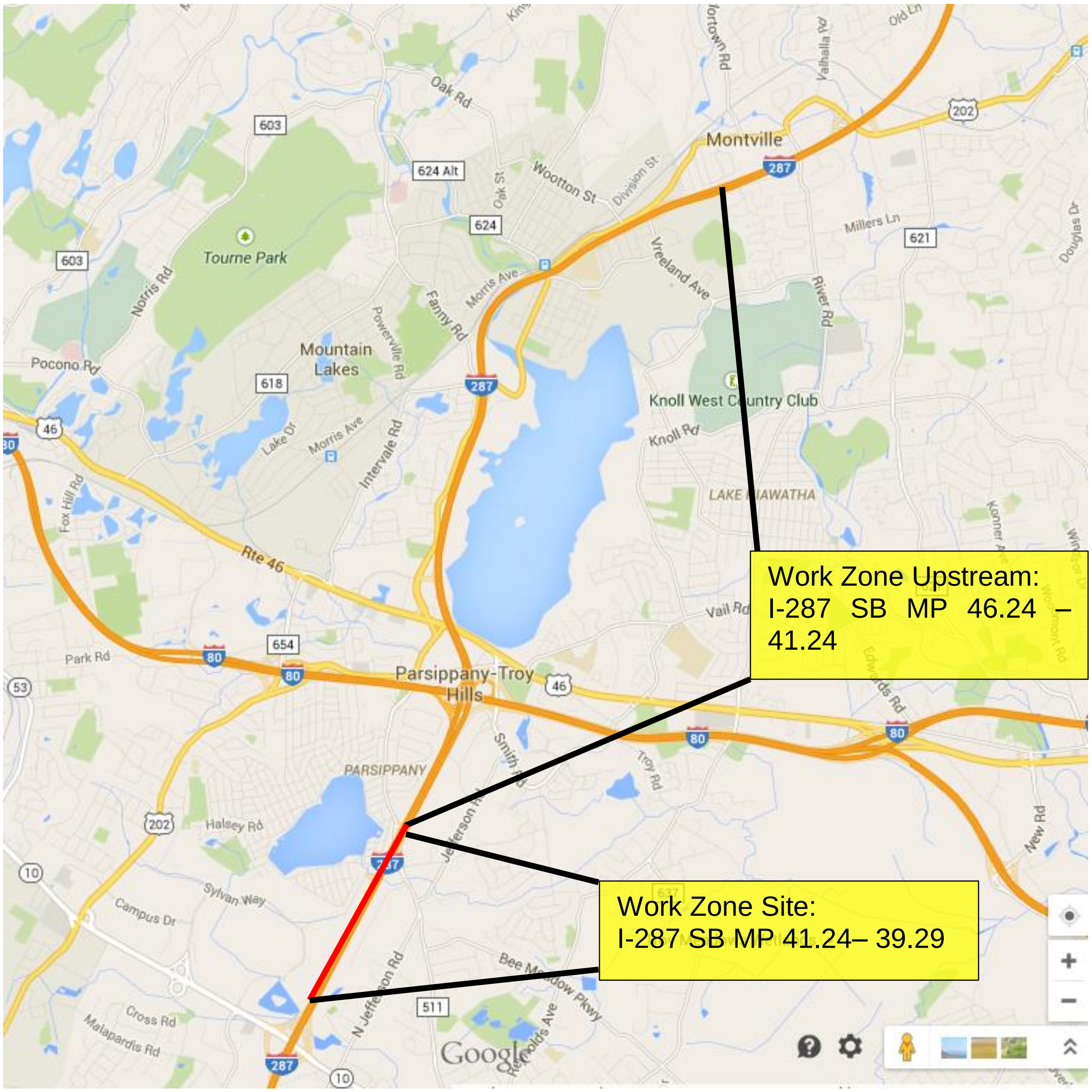

Figure 3: Location of Work Zone Site on I-287

5.1 Case Study 1

The maintenance work is scheduled to close one travel lane at a time for resurfacing a 1.80-mi long segment, covered by two predefined INRIX Traffic Message Channel (TMC) freeway segments.

One short-term work zone site on I-287 was selected for evaluating the proposed model. The work zone segment was 1.8-miles long and involved a one-lane closure on a four-lane segment of I-287 southbound from milepost 41.24 to milepost 39.29 (see **Figure 3** above), which were covered by two predefined INRIX TMCs. In addition to the INRIX data, traffic volume data at the work zone location was obtainable from the NJDOT Traffic Counts Database (NJDOT, 2013).

5.1.1 Traffic and Work Zone Parameters

Figure 4 below depicts the hourly traffic volumes on the studied highway that were derived from the NJDOT Traffic Counts Database (NJDOT, 2013). The baseline values of unit maintenance cost z_2^k and production time z_4^k for constructing a 2-inch asphalt pavement are presented in **Table 2**, where the Means Heavy Construction Cost Data 2006 were referred to in (Plotner, 2005). The alternative production options shown in **Table 1** were developed by adjusting the baseline labor/equipment cost and the daily production. The baseline values of other model input parameters are also given in **Table 1**. Note that the users's value of time (VOT) was assumed to be $15/vehicle-hour (Goulias, et al., 2001). **Table 3** shows the upstream parameter of work zone on I-287 applied by the delay model to estimate work zone speed.

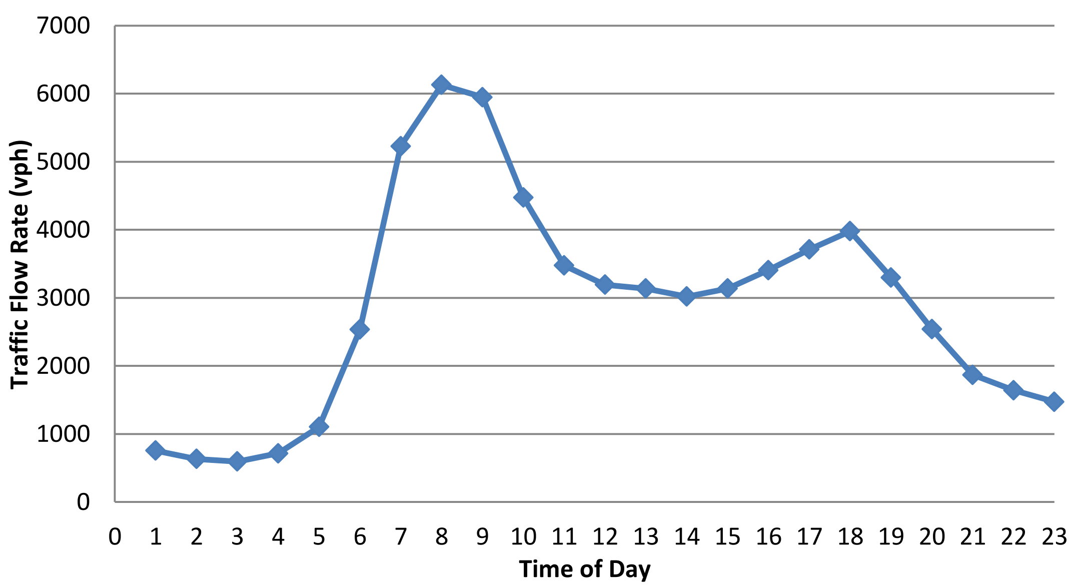

Figure 4: I-287 Traffic Flow Rate vs. Time

Table 1- Baseline Values of Input Parameters

Parameters	Definitions	Value	Unit
D_M	Maximum project duration	32	hour
$D_{\min}$	Minimum duration of maintenance activities	3	hour
L_M	Project length	1.8	mile
$\mathbf{r_a}$	Number of accidents per 100 million veh-hour	40	
$\mathbf{r_{ol}}$	Ratio of number of open lanes to number of lanes	0.75	
$\mathbf{s_n(t_m, s)}$	Normal speed at section s during time interval m	See **Appendix II**	mph
$\mathbf{s_w(t_m, s)}$	Work zone speed at section s during time interval m	See **Appendix II**	mph
$\mathbf{V_{(t_m,s)}}$	Volume of vehicles in segment s during time interval m	See **Appendix II**	
v	Monetary value of time	15	\$/veh-hour
$\mathbf{v_d}$	The average idling cost	800	\$
$\mathbf{v_o^j}$	Unit vehicle operating cost of vehicle class j	0.91	\$/veh-hour
$\mathbf{vc_{ij}}$	Rate of vehicle class j	1	
$\mathbf{v_a}$	The average cost per accident	78000	\$
$\mathbf{z_1}$	Fixed setup cost	1000	\$/zone
$\mathbf{z_3}$	Fixed total time of setting and removing a work zone	2	hours/zone

Table 2- Unit Maintenance Cost and Production Time

Crew	Unit Maintenance Cost $\mathbf{z_2^k}$ (\$/lane-mile)	Unit Production Time $\mathbf{z_4^k}$ (hour/lane-mile)
1	24,860	6.75
2	24,983	5.50
3	25,243	4.75
4	26.211	3.89

Table 3- Upstream Parameters of Work Zone on I-287

TMC Code	TMC Length (mile)	Distance to Work Zone (mile)
120-04492	0.51	0.15
120N04493	0.51	0.66
120-04493	0.20	1.17
120N04494	0.01	1.37
120-04494	0.11	1.38
120N04495	0.32	1.50
120-04495	0.52	1.81
120N04496	0.65	2.34
120-04496	0.58	2.99
120N04497	0.31	3.57
120-04497	0.53	3.87
120N04498	0.03	4.40
120N04499	0.25	4.60
120-04499	0.92	4.85

5.1.2 Genetic Algorithm Model Results

The work zone schedules were optimized using the developed GA for different normal speed distributions and project starting times. There are two schedules in two scenarios. The difference between Scenario A and B is that A fixes the starting time at 9:00 PM based on the historical data, whereas Scenario B does not.

The schedule in Scenario A, with fixed starting time 9:00 PM and optimized based on historical speed data in **Table 4**, indicates that the minimum project cost is $58,788 with a resulting project duration of 9 hours. The total maintenance work was scheduled for only one period. Because the total project length was not long enough to divide into smaller work zones, it would have increased the corresponding maintenance cost and total duration. Consequently, it would have either impacted the morning peak hour or would have required another night to be completed. Since the work zone is completed in a 9-hour continuous work zone, the associated idling cost is zero (i.e., no work break). The minimum total project cost consists of $48,166, $10,615, and $7 of maintenance cost, user cost (sum of delay cost, vehicle operating cost and accident cost), and emissions cost, respectively.

The schedule in Scenario B, without a fixed starting time and optimized based on historical speed data in **Table 4**, indicates that the best project starting time is 8:15 PM; the resulting project duration is 9 hours. The minimum total project cost is $54,451 and consists of $48,166, $6,279, and $6 of maintenance cost, user cost, and emissions cost, respectively. Comparing Scenarios A and B, the schedule in B was found to have the better project starting time and avoids both excessive travel delay and associated user costs.

Table 4: Optimized Work Zone Schedule of the 1.8-mile Segment

	Scenarios	
	A	**B**
Starting Time	9:00 PM	8:15 PM
Ending Time	6:00 AM	5:15 AM
Duration (Hours)	9	9
Maintenance Crew	4	4
Work Zone Length (mile)	1.8	1.8
Maintenance Cost	48,166	48,166
User Delay Cost	8,831	5,243
Vehicle Operating Cost	546	326
Accident Cost	1238	710
Idling Cost	0	0
Total User Cost	10,615	6,279
Emission Cost	7	6
Total Cost ($/Project)	58,788	54,451

To demonstrate how the selection of a production option in **Table 2** (work crew) may affect the optimization of work zone schedules as well as the total project cost, Scenario B is optimized in **Table 5** with a fixed work crew from 1 to 4. If a different work crew option is applied for the schedule in Scenario B, the maintenance cost can be reduced to the lowest point by deploying production option 3 and the user cost can be reduced to the lowest point with production option 4. Out of the four potential work-production scenarios, work crew 4 was found to be the most competitive in completing all maintenance work, although the corresponding maintenance and idling cost may increase. This trend is clearly indicated in **Figure 5,** where production option 4 is deemed the most cost-effective.

Table 5: Optimized Scenario B with Fixed Production Options

Cost	Production Option			
	1	2	3	4
Minimized Total Cost ($/Project)	62,087	59,084	56,141	54,449
Road User Cost ($/Project)	6,488	9,590	9,964	6,287
Maintenance and Idling Costs ($/Project)	55,596	49,488	46,172	48,166

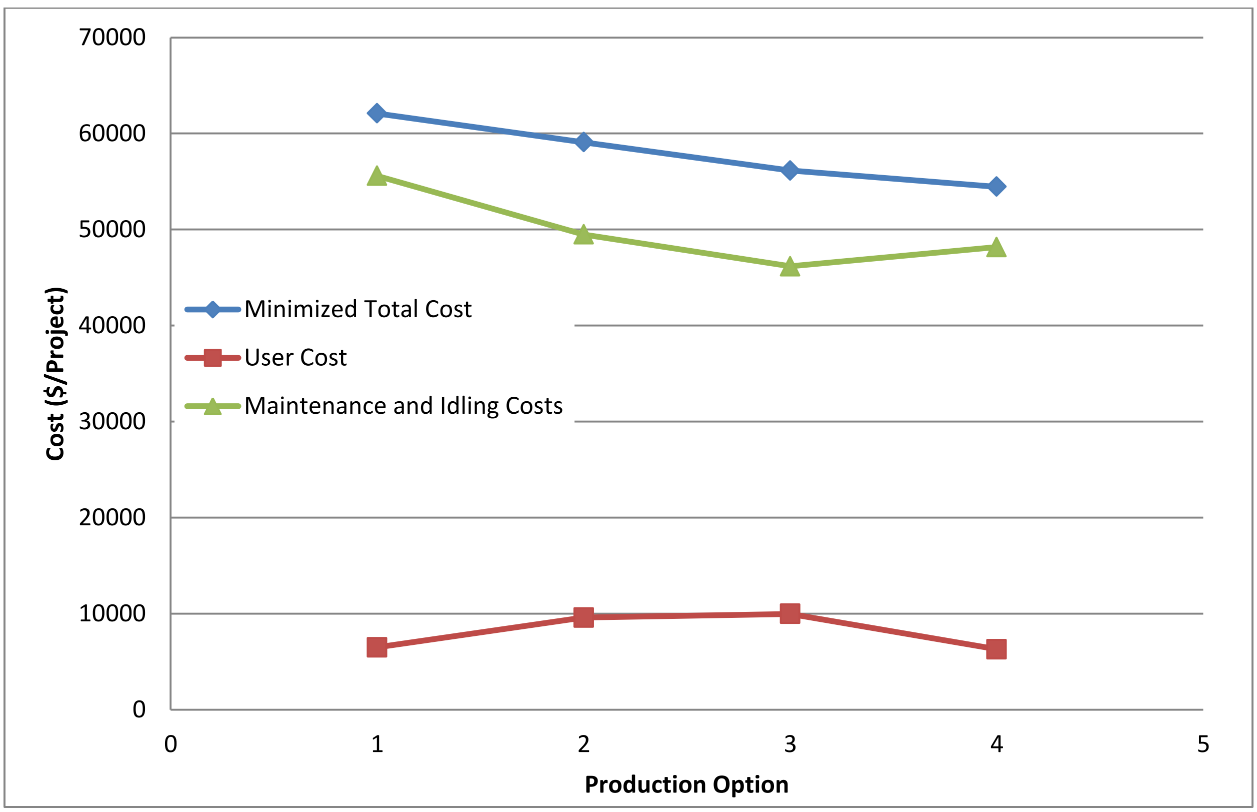

Figure 5: Maintenance, Idling and Road User Costs vs. Production Options

5.2 Case Study 2

The second case study involved an intended 5-mile maintenance project which is based on the location of Case Study 1. The main data for Case Study 2 is described below.

5.2.1 Traffic and Work Zone Parameters

The main parameters which are altered, compared to those in Case Study 1, include D_m and the project length, which are 64 hours and 5 miles respectively. All other parameters remain the same as in Case Study 1. The basic hourly traffic volume is derived from INRIX data collected on 11/21/2013 and different volume levels are calculated based on this data. The speed distributions, which are associated with traffic flow levels, are derived by using the speed-flow curves found in Traffic Stream Characteristics (FHWA, 2005). The derivation for speed and volume is discussed in **Appendix III.**

5.2.2 Case Study 2: Genetic Algorithm Model Results

The schedule in **Table 6** indicates that the best project starting time is 8:15 PM; the resulting project duration is 34 hours. The maintenance work is scheduled during two overnight off-peak periods and a midday off-peak period. Two work breaks during peak hours were scheduled to avoid excessive travel delay and associated user costs.

The high work-production options k_1=4, k_3=1, and k_5 =4 were deployed to complete all maintenance work. The minimum project cost is \$155,807, which consists of \$131,199, \$18,608, and \$6,000 of maintenance cost, user cost, and emissions cost. In both cases, the work zone activities did not yield any significant emissions cost.

Table 6: Optimized Work Zone Schedule of the 5-mile Segment

	Scenarios					
	1	**2**	**3**	**4**	**5**	**Total**
Starting Time	8:15 PM	5:45 AM	11:15 AM	4:30 PM	6:30 PM	N/A
Ending Time	5:45 AM	11:15 AM	4:30 PM	6:30 PM	6:15 AM	N/A
Duration (Hours)	9.5	5.5	5.25	2	11.75	34
Maintenance Crew	4	0	1	0	4	N/A
Work Zone Length (mile)	1.92	0	0.48	0	2.6	5
Maintenance Cost	51,535	0	12,969	0	66,695	131,199
User Delay Cost	936	0	10,277	0	998	12,211
Vehicle Operating Cost	69	0	673	0	342	1,084
Accident Cost	1,398	0	1,162	0	2,750	5,310
Total User Cost	2,403	0	12,112	0	4,090	18,608
Idling Cost	0	4,400	0	1,600	0	6,000
Emission Cost	8	0	3	0	16	27
Total Cost ($/Project)	53,947	4,400	25,085	1,600	70,802	155,807

5.3 Sensitivity Analysis

The sensitivity analyses were based on Case Study 2, where the traffic volume level on I-287 ranged between -40% to + 40% of the observed volume.. The maximum project time varied between 40 to 64 hours and the project starting time from 12:00 am to 11:00 pm. These time frames illustrate the relationship among variables and identify the relative importance of causal factors in the figures below. The main conclusion from this sensitivity analysis is that the minimum work zone total cost increases as traffic volume increases.

Figure 6 shows that when the hourly traffic volume is low – between -40% to -10%, the corresponding total cost is not affected significantly. Furthermore, either Crew 3 or Crew 4 can be most cost-effective with volume increasing when only one production option has been employed in the project. Crew 3 is also better than Crew 4 with volume lower than roughly 25%. However, the lowest minimized total cost was observed by optimizing the combination of these crew options for the project, as it outperforms all other crew options.

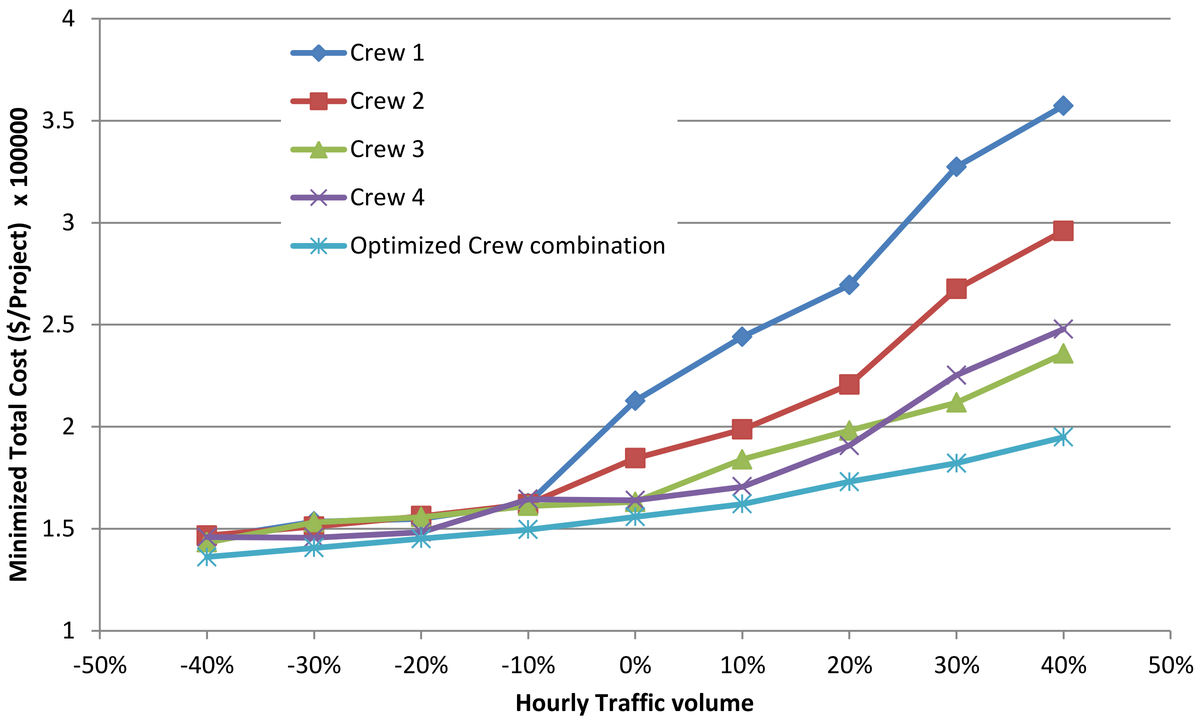

Figure 6: Minimum Total Cost vs. Volume

As indicated in **Figure 7**, the minimum total cost decreases as D_m increases; the longer project duration provides more flexibility in scheduling work zones to reduce both the maintenance cost and the user cost. Also, the total cost is not affected when D_m exceeds 48 hours or is lower than 43 hours because the upper and lower thresholds have been reached. These thresholds can be very helpful for transportation agencies in determining appropriate project duration, which can be determined for each work zone project based on this methodology.

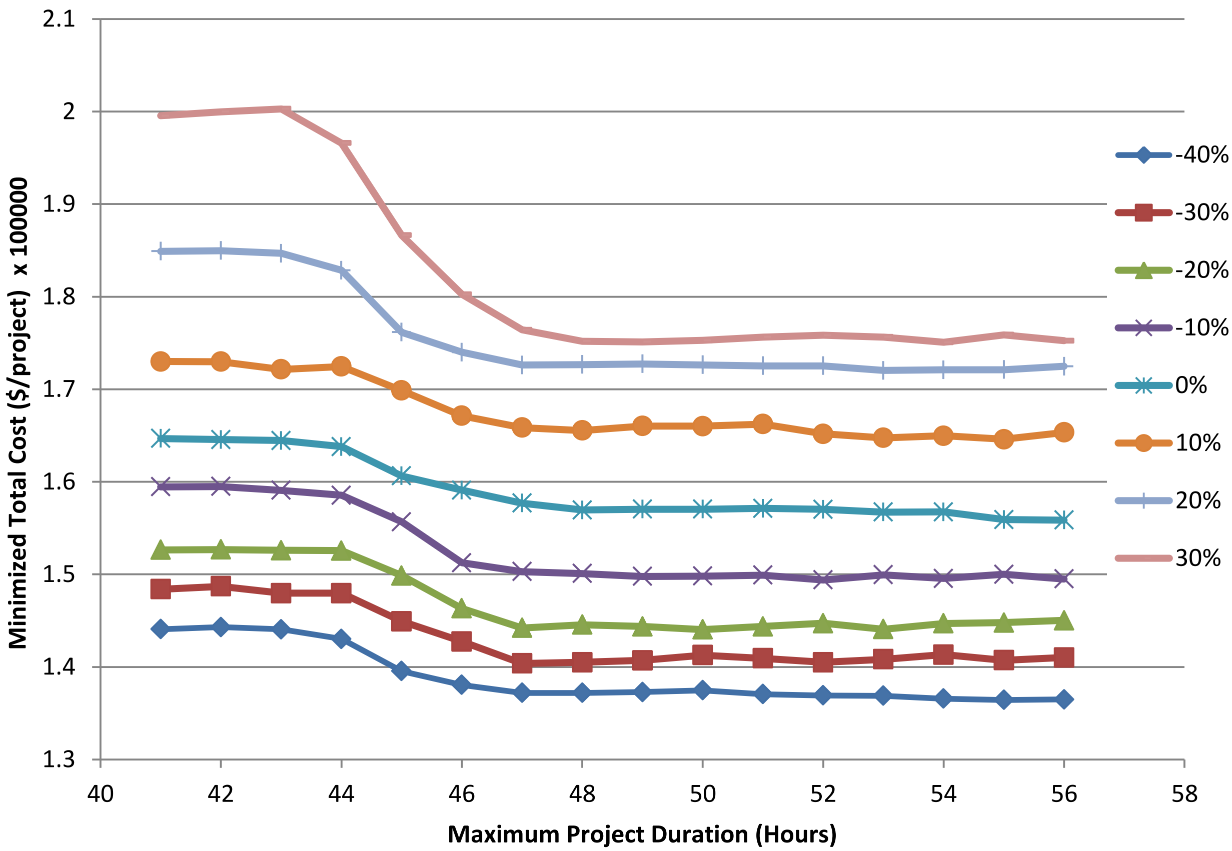

Figure 7: Minimized Total Cost vs. D_M

It was also found that the project starting time will affect the minimum total cost and user cost mainly due to the corresponding change in the traffic volume. As shown in **Figure 8**, the lowest minimized cost is achieved when the project starts at 20:00. After 20:00, the working period may include the high volume duration so that the cost will be increased. The trend for both volume and minimum total cost vs. project starting time is similar with the exception for the starting time between 20:00 to 24:00. This is an important result where the developed methodology could be deployed to estimate the optimal project starting time in order to minimize the total cost.

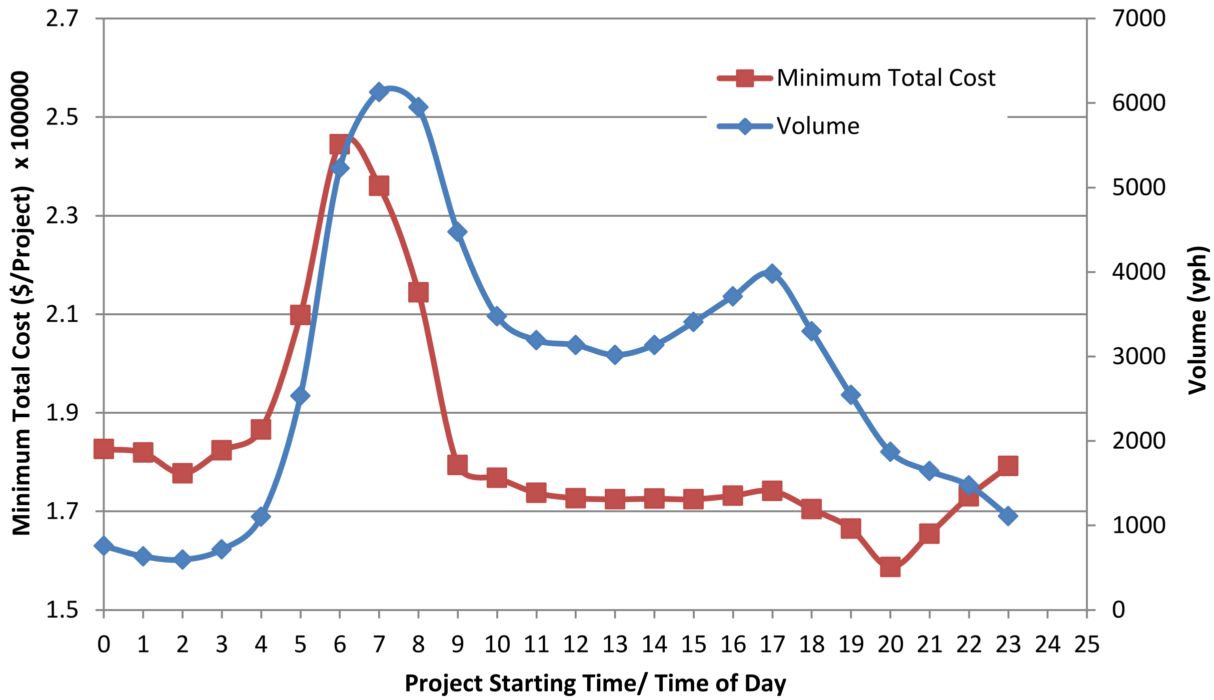

Figure 8: Minimum Total Cost and Volume vs. Project Starting Time / Time of Day

CHAPTER 6: CONCLUSIONS

A methodology was developed to optimize a combinatorial, multi-dimensional work-zone scheduling problem to minimize a work zone's total cost. By considering a realistic, discrete time-cost relationship and time-varied traffic demand, this study provides a practical approach to schedule minimum total cost operations for highway maintenance work. This new method is based on a Genetic Algorithm model and FCD to estimate and predict the user delay cost, which is more realistic than traditional moving delay and queuing delay models.

The main characteristics of the new total cost GA method are:

1) It optimizes the work zone schedule with respect to various input parameters and constraints (such as options with different production rates), traffic flow, and speed information from FCD.

2) It defined a new data structure to reduce the number of variables in the optimization process and adopted a penalty function to more efficiently handle the constraints including total project length (L_M), minimum duration of a work zone $(D_{\min})$, and maximum project duration (D_M).

The effectiveness of the new total cost GA method was demonstrated using two case studies on the NJ I-287 four-lane highway. The first case study with a total length of 1.8

miles resulted in a predicted 9-hour completion time by deploying one work zone during the nighttime. The second case study resulted in an optimal three-period work zone completion: two night shifts and one off-peak period. A sensitivity analysis was conducted to explore the relation between the production options, the maximum project duration, the traffic volume, the project starting time, and the minimized work zone total cost. Transportation agencies may use this new model to determine the appropriate project durationn, starting time, and schedule.

6.1 Future Work

The developed method relies primarily on hourly traffic volumes. A more detailed model could be developed that utilizes 15-minute traffic volumes or less depending on the availability of such data. In addition, a calibrated microscopic traffic simulator may be implemented that will yield the impact of traffic flow conditions on the entire corridor, including the nearby upstream and downstream network, and consider the optimization of route diversion strategies. Furthermore, such a comprehensive model could be implemented in real time - where pertinent traffic flow data is available - and produce optimal starting times, schedules, route diversions, and appropriate project duration on demand. Under such an online model, the transportation agencies will be able to continuously monitor the best work zone characteristics and take appropriate actions in coordination with the contractor to minimize the total cost.

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APPENDIX I - NOTATION

The following symbols are used in this paper:

C_T	Total cost (unit: dollars);
C_M	Maintenance cost (unit: dollars);
C_U	User cost (unit: dollars);
i	Working zone i;
l_i^k	The lengths of the working area of zone i (unit: mile);
k	The index of production;
D_i	Duration of working area of zone (unit: hours);
D_{min}	Minimum duration of maintenance activities (unit: hours);
D_M	Maximum project duration (unit: hours);
L_M	Project length (unit: mile);
z_3	Time required for setting and removing a work zone (unit: hours).
z_4^k	Unit production of time (unit: hours/lane-mile);
E_i	Starting time of zone i;
S_i	Ending time of zone i;
v_d	Average idling cost (unit: dollars);
C_{Di}	User delay cost (unit: dollars);
C_{Vi}	Vehicle operating cost (unit: dollars);
C_{Ai}	Accidents cost (unit: dollars);
C_{Ei}	Emission cost (unit: dollars);
s_w	Average work zone speed over space and time (unit: mph);
l_i^k	Length of working area of zone i. (unit: mile);
r_{ol}	Ratio of number of open lanes to number of lanes;
D_i	Work zone i duration (unit: hour);
l_d^i	Distance to the bottleneck of working area i(unit: mile);
S_i	Work zone starting hour (unit: hour);
s_n	Average normal speed over time and space (unit: mph);
L_s	The length of section s (unit: mile);
$V_{(t_m,s)}$	Volume of vehicles in segment s during time m;
v	Monetary value of time;
d_i	Delay time caused by work zone (unit: hours);
v_o	Unit vehicle operating cost (unit: $/veh-hour);
r_a	Number of accidents per 100 million vehicle hour;
v_a	Average cost per accident (unit: dollars);
$\boldsymbol{C_{e_{it}}^{n}}$	Emission damage cost at normal speed S_n and for vehicle class j (unit: $/VMT);
$\boldsymbol{C_{e_{it}}^{w}}$	Emission damage cost at work zone speed S_w and for vehicle class j (unit: $/VMT);
V_i	Volume passing the working area i;

APPENDIX II - DERIVATION FOR USER DELAY COST

1. Section Definition

For purposes of delay cost caused by work zone activities, the studied freeway is divided into segments based on the TMC locations as shown in **Figure 9**.

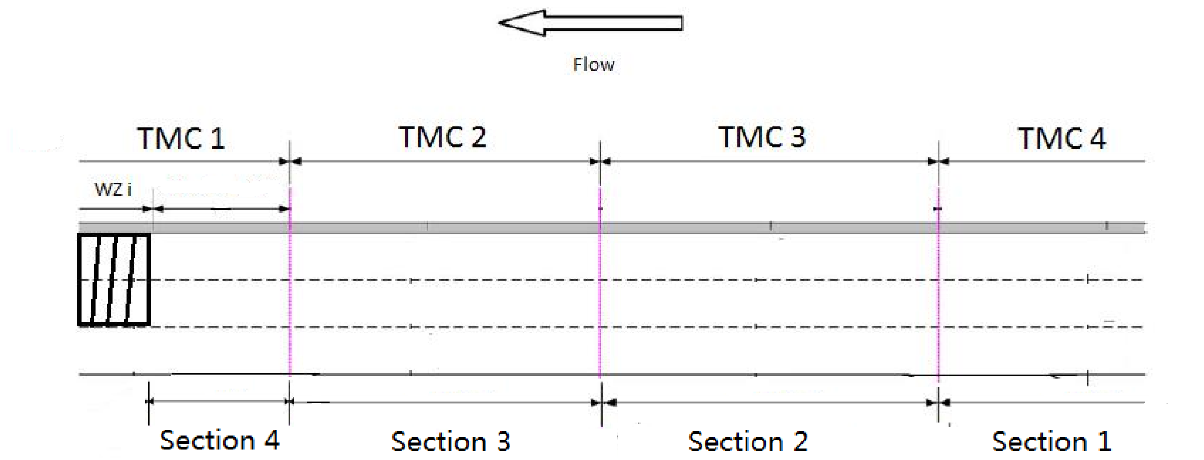


Figure 9: Section Definition

Based on the TMC section and their FCD for each section, the normal speeds are recorded and work zone speed is calculated for each time interval (e.g., at 15-min intervals) during the analysis period.

2. Work Zone Speed

The normal speed $\boldsymbol{S}_n(\mathrm{t}_m, s)$ is provided and the work zone speed $\mathrm{s_w}$ is based on the following linear regression model:

$$\mathrm{s_w}(t_m, \mathrm{s}) = \mathrm{f}[\mathrm{l_i^k},\ \mathrm{r_{ol}},\ \mathrm{D_i}, \mathrm{l_d^i},\ \mathrm{S_i},\ \mathrm{s_n}(t_n, \mathrm{s})] \text{ (A1)}$$

Where $\mathrm{l_i^k}$ is the length of working area of zone i, $\mathrm{r_{ol}}$ represents the ratio of number of open lanes to number of lanes, $\mathrm{D_i}$ is work zone **i** duration, $\mathrm{l_d^i}$ is the distance to the bottleneck of working area i (as **Figure 10** indicates) and $\mathrm{S_i}$ is the work zone starting hour.

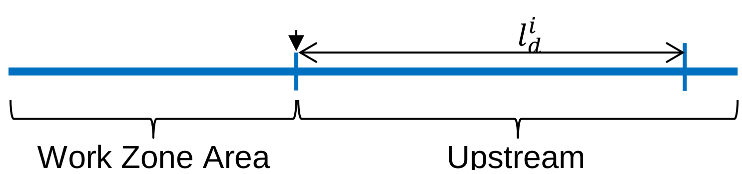


Figure 10: Distance to Bottleneck

Models for work zone speed:

Two-lane freeway segments:

$s_w(t_m, s) = 0.09l_i^k - 0.76r_{ol} - 0.01D_i + 0.06l_d^i - 0.02S_i + 0.96s_n(t_n, s) + 1.16$ (A2)

Three-lane freeway segments:

$s_w(t_m, s) = 0.15l_i^k + 0.27r_{ol} - 0.01D_i + 0.12l_d^i + 0.04S_i + 1.17s_n(t_n, s) - 13.9$ (A3)

Four-lane freeway segments:

$s_w(t_m, s) = 0.09l_i^k - 0.76r_{ol} - 0.01D_i + 0.06l_d^i - 0.02S_i + 0.96s_n(t_n, s) + 1.16$ (A4)

This model can estimate the work zone speed $s_w(t_m, s)$, which is defined in speed distribution, for any 0.5-mile section of the work zone upstream on the freeway, based on the milepost of each TMC between another.

3. Speed distribution

For each freeway section **s** and time intervals $\mathbf{t_m}$**,** two tables were formulated for normal speed $s_n(t_m, s)$ and work zone speed $s_w(t_m, s)$ distributions as follows:

Table 7: Normal Speed Distribution

	s	**s-1**	**s-2**	**s-3**	**…**	**1**
$\mathbf{t_1}$	$s_n(t_1, s)$	$s_n(t_1, s-1)$	$s_n(t_1, s-2)$	$s_n(t_1, s-3)$	…	$s_n(t_1, 1)$
$\mathbf{t_2}$	$s_n(t_2, s)$	$s_n(t_2, s-1)$	$s_n(t_2, s-2)$	$s_n(t_2, s-3)$	…	$s_n(t_2, 1)$
$\mathbf{t_3}$	$s_n(t_3, s)$	$s_n(t_3, s-1)$	$s_n(t_3, s-2)$	$s_n(t_3, s-3)$	…	$s_n(t_3, 1)$
⋮	⋮	⋮	⋮	⋮	⋮	⋮
$\mathbf{t_{m-1}}$	$s_n(t_{m-1}, s)$	$s_n(t_{m-1}, s-1)$	$s_n(t_{m-1}, s-2)$	$s_n(t_{m-1}, s-3)$	…	$s_n(t_{m-1}, 1)$
$\mathbf{t_M}$	$s_n(t_M, s)$	$s_n(t_M, s-1)$	$s_n(t_M, s-2)$	$s_n(t_m, s-3)$	…	$s_n(t_m, 1)$

Table 8: Work Zone Speed Distribution

	s	**s-1**	**s-2**	**s-3**	**…**	**1**
$\mathbf{t_1}$	$s_w(t_1, s)$	$s_w(t_1, s-1)$	$s_w(t_1, s-2)$	$s_w(t_1, s-3)$	…	$s_w(t_1, 1)$
$\mathbf{t_2}$	$s_w(t_2, s)$	$s_w(t_2, s-1)$	$s_w(t_2, s-2)$	$s_w(t_2, s-3)$	…	$s_w(t_2, 1)$
$\mathbf{t_3}$	$s_w(t_3, s)$	$s_w(t_3, s-1)$	$s_w(t_3, s-2)$	$s_w(t_3, s-3)$	…	$s_w(t_3, 1)$
⋮	⋮	⋮	⋮	⋮	⋮	⋮
$\mathbf{t_{m-1}}$	$s_w(t_{m-1}, s)$	$s_w(t_{m-1}, s-1)$	$s_w(t_{m-1}, s-2)$	$s_w(t_{m-1}, s-3)$	…	$s_w(t_{m-1}, 1)$
$\mathbf{t_M}$	$s_w(t_M, s)$	$s_w(t_M, s-1)$	$s_w(t_M, s-2)$	$s_w(t_M, s-3)$	…	$s_w(t_M, 1)$

Where **M** is the maximum number of subinterval time periods that define the maximum duration assumed for congestion caused by the work zone, $\mathbf{t_m}$ is the time intervals, and **s** is the sections.

4. Determining the influence region of the work zone activities

Considering that the speed of traffic will be lowered in sections adversely affected by a traffic accident, the basic idea behind discriminating between these two regions is to compare the work zone speed s_w and normal speed s_n, then assign some level of confidence for the s_n. If the level of confidence is limited to at least $\alpha^*\sigma_{s_n(t_m,i)}$, where α is a positive number below the mean speed of the distribution of $s_n(t_m, i)$, the affected vs. unaffected cases according to the difference between the mean speed and the threshold can be identified.

Thus,

$s_w(t_m, s) \leq s_n(t_m, s) - \alpha^*\sigma_{s_n(t_m,s)}$ (A5)

where the section i at time interval m is affected by the work zone and

$s_w(t_m, s) > s_n(t_m, s) - \alpha^*\sigma_{s_n(t_m,s)}$ (A6)

where the section I at time interval m is not affected by the work zone.

$\mathbf{t_m} = \mathbf{0}$ at time interval **m** is affected by the work zone and $\mathbf{t_m} = \mathbf{1}$ at time interval **m** is not affected by the work zone. The example table is shown as **Table 9**.

Table 9: Binary Matrix of Work Zone Speeds

Section Time intervals	s	s-1	s-2	s-3	s-4	s-5	s-6	s-7	s-8
$\mathbf{t_1}$	0	1	1	1	1	1	1	1	1
$\mathbf{t_2}$	0	0	1	1	1	1	1	1	1
$\mathbf{t_3}$	0	0	0	1	1	1	1	1	1
$\mathbf{t_4}$	0	0	0	0	1	1	1	1	1
$\mathbf{t_5}$	1	0	0	0	0	1	1	1	1
$\mathbf{t_6}$	1	1	0	0	0	0	1	1	1
$\mathbf{t_7}$	1	1	1	0	0	0	0	1	1
$\mathbf{t_8}$	1	1	1	0	0	0	0	1	1
$\mathbf{t_9}$	1	1	1	1	1	1	0	0	1
$\mathbf{t_{10}}$	1	1	1	1	1	1	1	1	1

Merely applying the above procedures, however, is not enough to estimate the true boundary of affection of the work zone due to uncertainties and other externalities; assigning an outcome based on a significance test related to the null hypothesis that the cell speed actually came from the work zone's free speed distribution will generally result in less-than-accurate conclusions regarding the affected region [10].

To begin solving this problem, the above is restated here:

P_{sm} = 0, if $s_w(t_m, s) \leq s_n(t_m, s)$ - $\alpha * \sigma_{s_n(t_m,s)}$; (A7)

P_{sm} = 1, if $s_w(t_m, s) > s_n(t_m, s)$ - $\alpha * \sigma_{s_n(t_m,s)}$; (A8)

Thus,

δ_{sm} = 0, if cell is affected by the work zone;

δ_{sm} = 1, if cell is not affected by the work zone;

A BIP problem is formulate to determine the number of cells truly affected by the work zone:

Min Z = $\sum_{\forall s,m}[P_{sm} * \delta_{sm} + (1 - P_{sm}) * (1 - \delta_{sm})$ (A9)

Subject to:

$$\delta_{s+k,m} \leq [1- (\delta_{s,m} - \delta_{s+1,m})] * R \forall s, m \forall k \leq S - s; \text{ (A10)}$$

$$\delta_{s,m+r} \leq [1- (\delta_{s,m} - \delta_{s,m+1})] * R \forall s, m \forall r \leq M - m; \text{ (A11)}$$

$$\delta_{s,m+k} \leq [1- (\delta_{s,m} - \delta_{s+1,m})] * R \forall s, m \forall k \leq M - m; \text{ (A12)}$$

where **R** is a large number and **S** is the maximum number of upstream sections.

5. Delay cost model

The delay cost is calculated as follows:

$$C_{Di} = \sum_{s \in S} L_s * \left(\frac{1}{s_n(t_m,s)} - \frac{1}{s_w(t_m,s)}\right) v * V_{(t_m,s)} \quad \text{(A13)}$$

where **S** is the total number of sections affected by the work zone, L_s is the length of section **s**, and $V_{(t_m,s)}$ is the volume of vehicles in segment **s** during time **m** and **v** for monetary value of time.

APPENDIX III - DERIVATION OF VOLUME-SPEED RELATIONSHIP

Among the major efforts involved before solving the optimization model is the derivation of the volume-speed relationship under different situations so that the normal speed $\boldsymbol{S_n}(\mathrm{t}_{\boldsymbol{m}}, \boldsymbol{s})$ can be generated.

Figure 11 shows the relationship between traffic speed and flow under ideal conditions. As the flow increases from zero to maximum flow (road capacity) under uncongested conditions, the speed will decrease from free-flow speed to the jam speed. When the flow continues to increase, the speed will drop to zero because there are too many vehicles that prevent movement. It is possible to have two different speeds for a given flow.

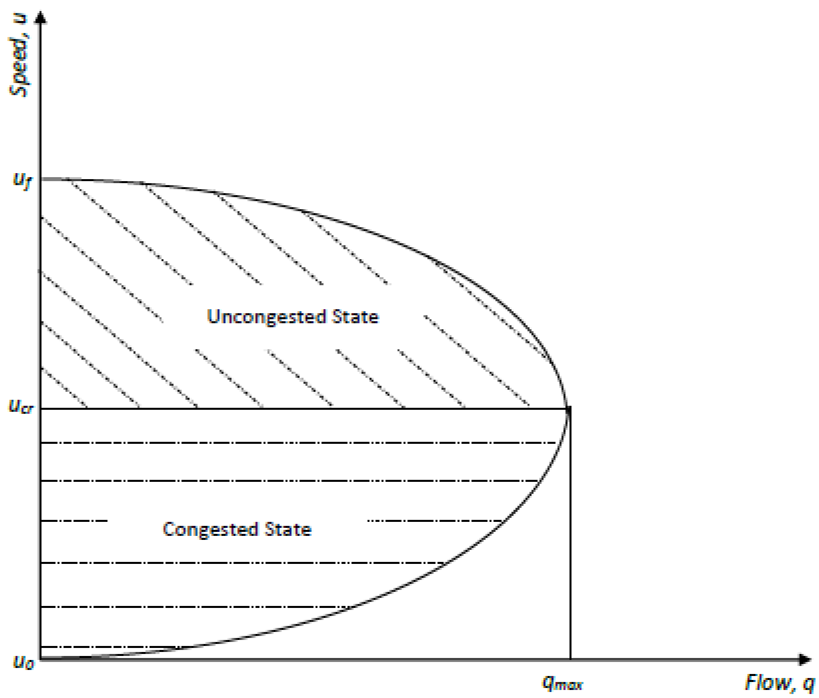


Figure 11: Generalized Relationships between Speed and Flow Rate

Using the traffic volume provided by the NJDOT Traffic Counts Database and traffic speed provided by INRIX (2013), the speed-flow relations are identified. Both the traffic volume (hourly based) and speed data (aggregated to one-hour intervals) of the study routes were collected between 11/21/2013 and 11/22/2013. The speed data provided by INRIX contains three categories: historical, the blend of historical and real time, and purely real time. In this study, only purely real time speed reported by INRIX was used to develop the speed-volume relations. The normal speed $\boldsymbol{S_n}(\mathrm{t}_{\boldsymbol{m}}, \boldsymbol{s})$ can then be expressed as a function of traffic volume.

Thus,

$$S_n(t_m,s) = f(V_{t_m,s}) = \begin{cases} 67.61 & 4V_{t_m,s} = V_n < 3200vph \\ -2\times10^{-5}V_{t_m,s}{}^2 + 0.0212V_{t_m,s} + 60.744 & 3200 \le 4V_{t_m,s} = V_n < 9000vph \end{cases}$$

Where $V_{t_m,s}$, V_n and $S_n(t_m,s)$ represent the traffic volume (vp15min) of section **s** at time interval $\mathbf{t_m}$, hourly traffic volume (vph), and normal speed respectively.

For the sensitivity analysis, the variation of traffic volume is shown as **Figure 12**.

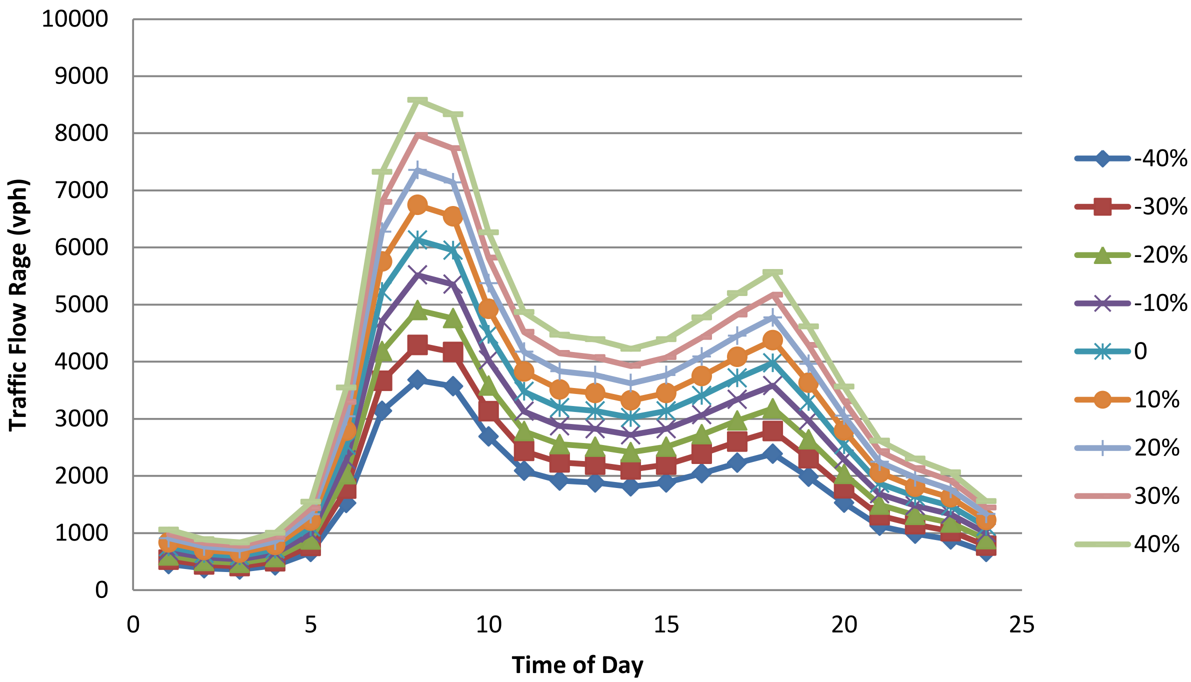
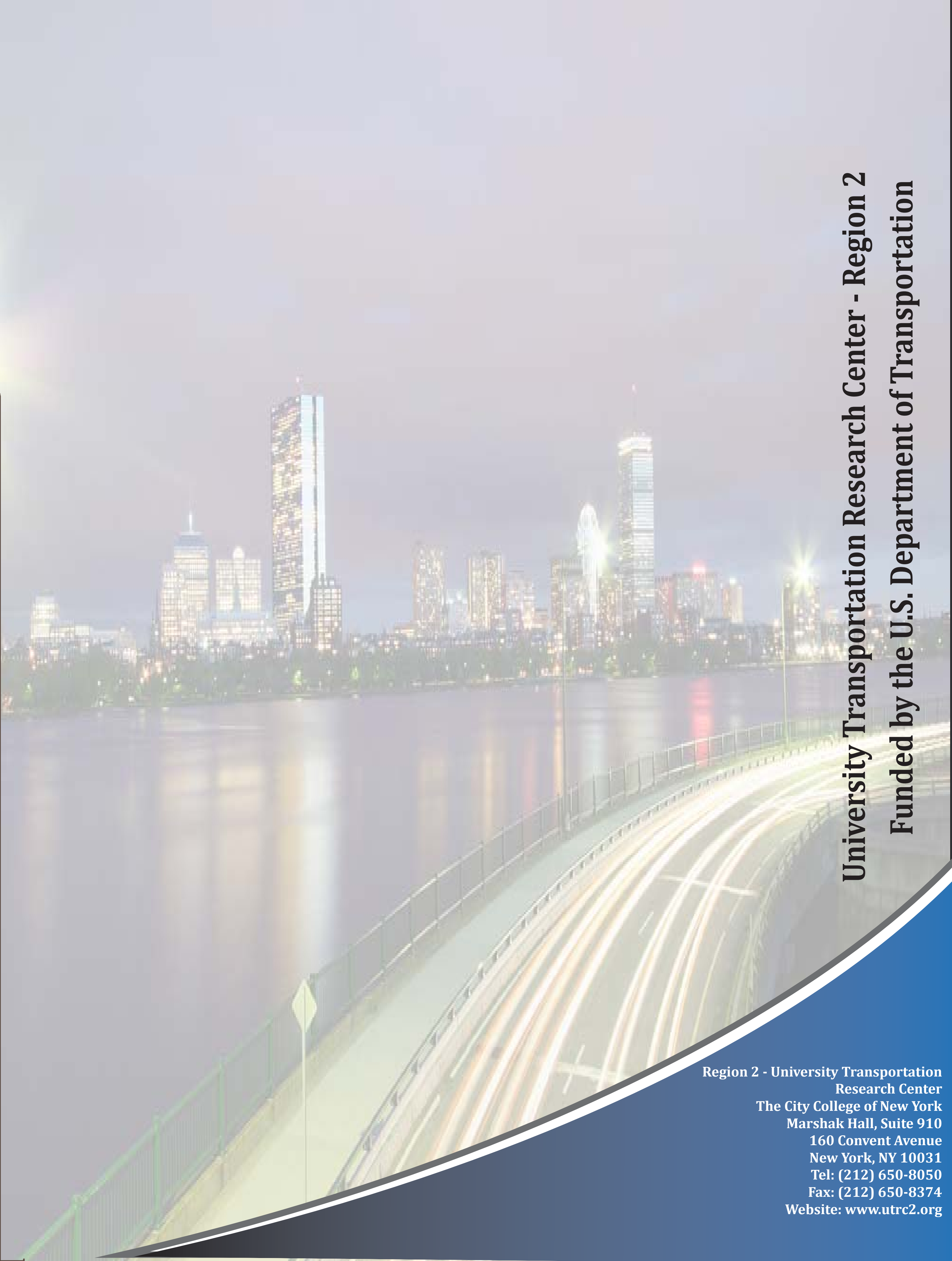


Figure 12: I-287 Traffic Flow Rate (associated with Traffic Flow Level) vs. Time



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