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COORDINATION OF IVI AND TRANSIT SIGNAL PRIORITY ON TRANSIT EVACUATIONS

FINAL REPORT

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Table of Contents

List of Figures

List of Tables

COORDINATION OF IVI AND TRANSIT SIGNAL PRIORITY ON TRANSIT EVACUATIONS

1.0 Abstract

During an emergency evacuation, execution time is always critical to the evacuees who are transit dependent. Transit Signal Priority (TSP) can speed up the transit services by prioritizing the approaching bus at a signalized intersection. With the emergence of IntelliDrive (formerly known as IVI), which is a wireless communication technology used to transfer data among vehicles and infrastructures, a TSP system can obtain more accurate traffic data and react to the approaching bus in a wider area. This report proposes an adaptive TSP system to facilitate the transit-based emergency evacuation on the basis of the U.S. Department of Transportation (DOT)'s IntelliDrive initiative.

The objective of this project is to study the TSP and IntelliDrive coordination and to evaluate the impacts of the proposed TSP strategies on the transit-based emergency evacuation. The emergency evacuation model consists of two optimization models: a TSP optimization model and a bus routing optimization model. The TSP optimization model includes bus travel time prediction and traffic signal optimization. The bus travel time prediction is used to estimate the bus arrival time at the intersection. The traffic signal optimization considers both the bus delay and the network-wide vehicle delay. It determines when and which TSP strategy will be applied. The principal inputs for the TSP optimization model are: bus speed, position, busload, queue length, and traffic signal status. The bus routing optimization model is proposed to optimize the transit vehicles allocation and routing. The Dijkstra Algorithm has been modified to find out the shortest paths among the pickup points and the shelters in the network. Additionally, a hybrid intelligence algorithm consisting of a Genetic Algorithm and a Hill Climbing Algorithm, which was developed under the sponsorship of a previous project, has been applied to solve the transit vehicle routing and allocation problem.

A case study of the proposed TSP system based on the Hurricane Gustav evacuation in Gulfport was investigated. CORSIM, one of the most commonly used micro-simulation software, served as both a developmental environment as well as a test bed for evaluating the proposed TSP system. Detailed traffic network elements including geometric features, traffic flow, traffic control, etc. were coded in CORSIM. CORSIM RTE (Run Time Extension) was developed in order to embed the optimization models and the algorithms and simulate the IntelliDrive functions in CORSIM.

CORSIM outputs provide various measures of effectiveness. The results obtained from CORSIM simulation show significant improvement on the transit vehicles delay and insignificant increase on the total vehicle delay by implementing the proposed TSP optimization model.

Key Words: Transit Signal Priority, Emergency Evacuation, IntelliDrive, CORSIM RTE, Signal Optimization.

2.0 Introduction

Transit Signal Priority (TSP) is an operational strategy that provides traffic signal controllers a way to react to the impending arrival of a bus or other special vehicle. A TSP system can improve the transit service quality by prioritizing the transit vehicle and optimizing the traffic signal timing plan. Compared with the traditional traffic signal preemption, which is often used for emergency vehicles such as ambulances and fire trucks, TSP usually accommodates buses and alleviates the negative impacts on general traffic. Baker et al. [1] reviewed the application of signal preemption and priority and highlighted their differences.

Transit has played an important role in evacuating citizens without access to a private car, as the situation of Hurricane Katrina vividly demonstrated, where a large number of people were not able to get out of the affected areas by themselves. In response to the lessons learned from the recent hurricanes Katrina and Rita, many city transit agencies, state Departments of Transportation, and emergency management agencies have begun to take a more active role in the planning and management of hurricane evacuations. Past research [2] shows that the delay caused by the operations of traffic signals accounts for about 10-25% of total travel time of buses. To minimize the bus delay at intersections, transit agencies are considering implementing advanced TSP systems along the transit corridor. Currently, with recent development in communication and detection technology, transit agencies have successfully implemented TSP system in cities including Los Angeles, Portland, Chicago, etc. Experience from those deployments indicates an average of 15% savings on bus travel time [3].

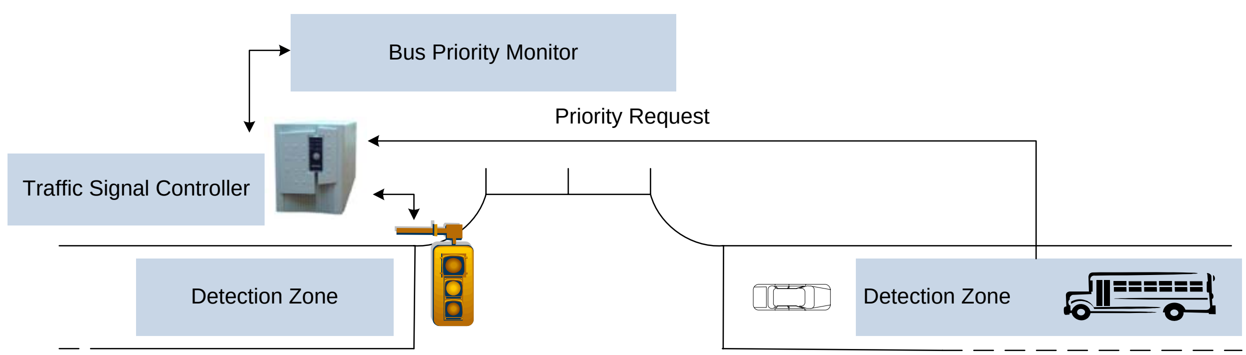

Figure 1. Transit Priority at Traffic Signalized Intersections

Figure 1 reveals a simple TSP approach. When a bus travels on the detection zone upstream of a signalized intersection, a "check-in" priority request call is sent to the traffic signal controller. After the bus passes through the intersection and travels on the detection zone downstream of the intersection, a “check-out” message is sent to the controller to clear the request for priority. When the controller receives the priority request, it will assess whether to provide signal priority. Then, if the bus meets the user-specified criteria, the controller will modify the existing signal timing plan using a TSP strategy. Depending on the traffic signal status when the bus arrives at the intersection, a TSP strategy can extend the green time or reduce the red time for the bus. A critical drawback of the simple TSP approach is that it is difficult to predict the bus arrival time at the intersection because of the uncertainty of traffic conditions. Such uncertainty may consequently result in the TSP system failure or reduction in the TSP system’s efficiency.

IntelliDrive (previously known as Vehicle Infrastructure Integrated, VII) is a wireless communication technology used to transfer data among vehicles and infrastructures. Information, including vehicle status data, infrastructure status data, and transit information, is collected through the Dedicated Short Range Communications (DSRC) of IntelliDrive. The communication distance of an IntelliDrive device is up to 3000 ft. As the development of the wireless communication technique, IntelliDrive is capable of providing more precise transit information to the signal controller in a wider area. Major IntelliDrive projects have been initiated in the states of California, Michigan, and Arizona. The Emergency VII (E-VII) program in Arizona has identified key capabilities of the TSP operations at traffic signals [4]. Figure 2 shows the perspective of TSP and IntelliDrive coordination in our point of view.

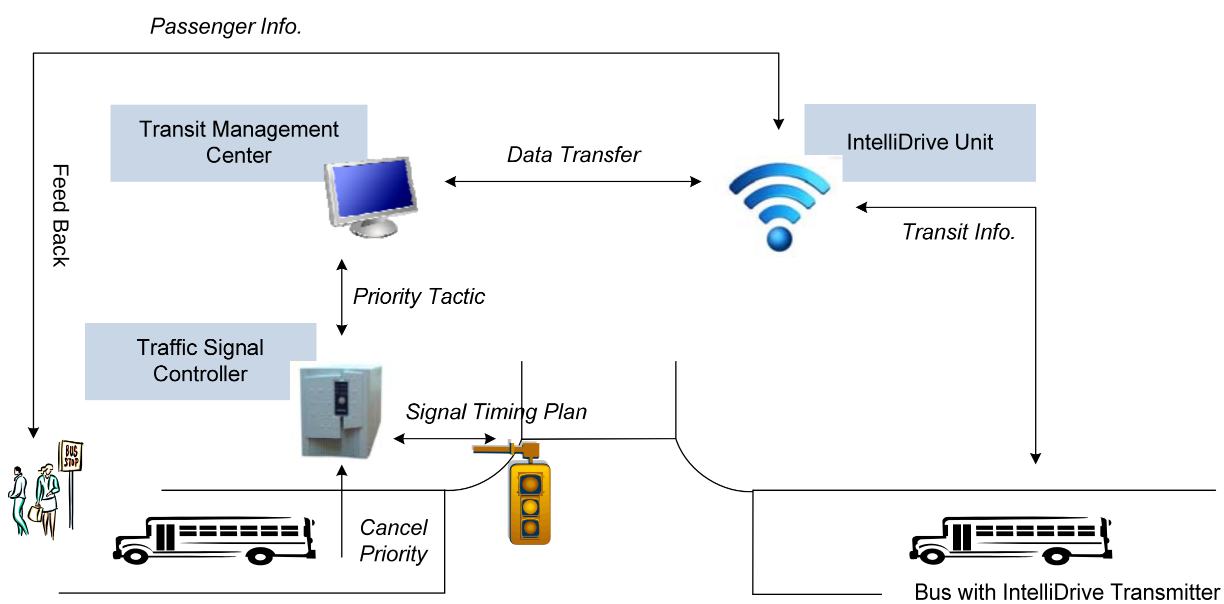

Figure 2. Coordination of TSP and IntelliDrive

This project aims to coordinate TSP and IntelliDrive in an effective manner. The objective is to evaluate the impacts of the proposed TSP strategies on the transit-based emergency evacuation and to provide an implementable and practical TSP system during the evacuation. The specific challenges associated with this project are:

- Predicting the bus arrival time based on the information collected by the IntelliDrive road side unit
- Providing the adaptive TSP treatments in real time
- Minimizing the negative impacts on the normal traffic when considering a TSP treatments
- Efficiently handling the conflicting priority requests from more than one approach
- Determining the measures of effectiveness and evaluating the proposed TSP strategies

Considering the above elements, several possible signal priority treatments are proposed and evaluated in terms of their impacts on transit vehicle delay and intersection average delay. A TSP optimization model and a bus routing optimization model were proposed to perform transit signal optimization and vehicle routing optimization. Traffic simulation software, CORSIM, provided simulated traffic data, and worked as a platform to evaluate the proposed models. CORSIM Run Tim Extension (RTE), which is a developer toolkit allowing users to interface customized functions with the CORSIM simulation, was developed to embed the proposed models and algorithms.

3.0 Literature Review

The objective of this project is to study the TSP and IntelliDrive coordination and evaluate the impacts of the proposed TSP strategies on transit-based emergency evacuation. In this section, basic TSP system components, signal optimization, IntelliDrive Initiative, and transit vehicle routing optimization are reviewed. The literature review is summarized at the end of this section.

3.1 TSP System Components

Transit Signal Priority is an operational strategy that allows a traffic signal controller to react to the impending arrival of a bus or other specific vehicle, and to prioritize the bus transit through the intersection by the traffic signal control. Before discussing the general concepts of transit signal priority, one must distinguish signal priority and preemption. According to the TSP handbook 2005 [3], preemption is the process of transfer from the normal control of traffic signals to a special signal control mode in order to give the transit vehicles, emergency vehicles, or other special task vehicles the utmost priority to pass the intersection. In contrast with the conception of TSP, preemption is a compelling strategy that ensures special tasks are not interrupted, and that vehicles using the preemption signal are always noticeable. It requires interrupt normal traffic signal operations. By contrast, transit signal priority only modifies the normal signal operations to better accommodate transit vehicles without interrupting the general timing relationship between specific green indications at adjacent intersections.

Basic components for simulating TSP include priority treatments, detection of buses, priority request generators, transit priority strategy generators, communication links between buses and traffic signals, bus movements in the traffic stream, dwell time at bus stops, etc [2].

Generally speaking, there are three possible signal priority treatments to provide priority to transit vehicles [1]. Passive priority operates continuously regardless of whether a transit vehicle is present or not. It does not require a transit vehicle detection system or a priority generator. Passive priority uses static signal timing coordinated for transit vehicles flow. Under this priority treatment, normal vehicles may suffer significant delay. This priority treatment is generally used when transit frequencies are high and traffic volumes are low. The second treatment is active priority. Active priority strategies provide priority treatment to a specific transit vehicle following detection. Several types of active priority strategies, including early green, green extension, red truncations, actuated transit phases, phase insertion, and phase rotation, are reviewed in TSP handbook [3].

The third control logic is adaptive control. It is based on the real time traffic data inputted by detectors that can assess the current status of the network and determine the optimum priority control strategies. Adaptive control could continuously optimize the effective timing plan based on real-time, observed data. It is becoming wide spread and can be implemented in different scenarios on the basis of advanced vehicle detection technology.

Unlike the traditional vehicle detection method, such as Selective Vehicle Detection (SVD), Automatic Vehicle Location (AVL)/Global Position System (GPS) can locate the transit vehicles more accurately in real time. AVL/GPS can also provide adequate time for the priority server to optimize the signal plan. Shalaby and Farhan [5] proposed a bus travel time prediction model using AVL and Automatic Passenger Counting (APC) data. The model has two separate sub-models: bus travel time prediction model and bus dwell time prediction model. Two separate algorithms, Link Running Time Prediction Algorithm, which was used to predict bus travel time using historical data, and Passenger Arrival Rate Prediction Algorithm, which was used to predict bus dwell time at a bus stop, were developed based on the Kalman filter method. To evaluate the performance of the proposed model, it was compared with three existing models: historical average model, regression model, and an artificial neural network model. Results from the above four models were tested in VISSIM. Since the parameters of the proposed algorithms could be continuously updated based on dynamic AVL and APC data, the proposed model showed the best prediction performance and provided the minimum error measures.

Once a transit vehicle has been detected, the priority request generator is responsible for initiating a request for priority based on predefined criteria [3]. There are two different approaches to generate a priority request. The first approach is to generate the priority request unconditionally. This approach provides priority for all approaching transit vehicles and minimizes delay at intersections for transit vehicle. The disadvantage of the unconditional priority generator is that the priority may be granted unnecessarily. For example, if three consecutive transit vehicles arrive at a TSP equipped intersection, and the first transit vehicle is running ahead of its schedule while the second and third transit vehicle are behind schedule, it is unlikely that the second and third transit vehicles can be granted the signal priority under unconditional priority generator because the first transit vehicle is detected at first and receives unconditional priority [6]. Another approach is to generate a priority request conditionally. A conditional priority generator grants priority based on certain criterion. The most common criterion is the lateness of the transit vehicle relative to its schedule. This approach has been made feasible by recent technological developments, such as AVL and GPS. In contrast to the unconditional priority generator, the conditional priority generator provides a means of operational control on the priority generation. A conditional priority generator is capable of minimizing the negative impacts on the other vehicles. Furth and Muller [7] discussed the major advantage of conditional priority generator over unconditional priority generator.

The increased demand of communicating and operating among different equipments with different protocols in a TSP system hastened the development of the NTCIP (National Transportation Communications for ITS Protocol) standard for TSP. NTCIP provides both communication protocols and vocabulary necessary to allow electronic equipments from different manufacturers to communicate with each other. U.S. DOT [8] introduced the NTCIP 1211 and 1202, which are related to the traffic signal control and the transit signal priority control. The NTCIP 1211 (Object Definitions for Signal Control and Prioritization) defines standards for use in the design of TSP applications within the traffic signal systems. The NTCIP 1202 (Object Definitions for Actuated Signal Controllers), which includes a number of signal timing parameters, was developed to control the actuated controllers in order to implement the TSP strategies. Furthermore, the Transit Communications Interface Profiles (TCIP) Standard Working Group proposed an interface standard in 2004, which is described in the TCIP 3.0 Draft Standard for Transit Communications Interface Profiles. The interface standard provides mechanisms for the exchange of information in the form of data among transit business systems, subsystems, components, and devices.

Liu et al. [9] proposed a simulation model specifically designed to evaluate a TSP system. The logical and physical structure of a TSP system was interpreted in detail. The proposed simulation model has three layers: an operational layer, a monitoring layer, and an analysis layer. NTCIP 1211 was adopted as the standard protocol to be used in the communication among the three layers. Therefore, TSP elements, such as bus detectors, signal monitors, bus monitors, and priority servers, could be addressed in a systematic manner. The simulation results demonstrated the advantage of the application of NTCIP 1211 in a TSP system. Liao [10] used the DSRC 802.11p protocol to wirelessly communicate between vehicles and road infrastructure. The bus travel time and dwell time were predicted using data from an on-board GPS. Simulation results showed that considerable delay reduction could be achieved by providing signal priority for transit vehicles.

3.2 Transit Signal Priority Optimization

Various types of TSP strategies can be used to reduce the transit vehicle delay as discussed in the TSP Handbook [3]. A “Green Extension” strategy extends the green time for the approaching transit vehicle to allow it to pass through the intersection. This strategy only applies when a transit vehicle arrives in a short period after the green phase. An “Early Green” strategy shortens the green time of preceding phases to start the green phase early for the approaching transit vehicle. This strategy only applies when a transit vehicle arrives in a short period right before the green phase. A “Phase Insertion” strategy inserts a special priority phase into the normal signal phase for the approaching transit vehicle. This strategy applies when the green extension and early green strategies are not applicable. Other TSP strategies, such as phase rotation, phase omission, etc., are generally available in most traffic control environments but are not considered in this project since those strategies are far more sophisticated for an adaptive TSP system.

Li et al. [11] developed an adaptive TSP system on closed-loop actuated control systems. The proposed TSP system attempted to facilitate the movement of behind-schedule transit vehicles through signalized intersections. The system consisted of a detection system, a signal control system, and a priority request system. GPS/AVL was used to monitor the transit vehicles locations. In the priority request system, a bus arrival time predictor calculated the bus travel time to the next signalized intersection based on the GPS data and historical data. There are two TSP strategies, green extension and early green, used in the system. Li used a pre-defined time window to determine which TSP strategy would be applied. The proposed TSP system was validated through Paramics simulation and a field test. Compared with the Valley Transportation Authority (VTA) actuated system, the proposed TSP system showed more time savings in terms of transit delays while maintaining an acceptable delay level for the minor traffic than the VTA actuated system.

Ghanim et al. [12] proposed a real time traffic signal control model integrated with transit signal priority. The system optimized traffic signal timing using a Genetic Algorithm (GA) and an Artificial Neural Network (ANN). The GA was used to optimize the traffic signal timing plan. The ANN was used to predict transit vehicle arrival time. The model considered both network performance and transit performance. Users can assign different weights between network performance and transit performance in the objective function so that the model meets different needs from transit agency and general traveler's perspective.

Liao et al. [10] developed an adaptive TSP strategy that considered bus schedule adherence. First, bus travel time on the link was estimated, which considered the bus dwell time at the bus stop and passenger arrival rate. Then, he proposed a priority model to determine the priority level of an approaching bus according to the parameters such as bus schedule, number of passengers, etc. Therefore, the traffic signal controller could decide whether or not to grant the priority request, and then, decide which bus would have the priority if there were multiple requests at the intersection. Two priority strategies, green extension and early green, were applied based on the estimated bus arrival time.

Dion and Rakha [13] presented a low-pass filtering algorithm for predicting average link travel time using Automatic Vehicle Identification (AVI) data. Existing algorithms, such as TransGuide, TranStar, and TransMIT, were evaluated in the study. They improved the existing algorithms by dynamically adjusting the data validity window. To validate the algorithm, they applied it to two

AVI data sets from San Antonio. Results showed that the proposed algorithm could effectively track link travel time variation while suppressing high frequency noise signals.

Dion et al. [14] evaluated the potential benefits of implementing transit signal priority along a bus corridor. Two priority strategies, green extension and early green, were considered within a fixed-time traffic signal control environment. The proposed TSP strategies were evaluated using the INTEGRATION microscopic traffic simulation model. Performance measures, such as person travel times, person delays, vehicle stops, fuel assumptions, etc., were generated and analyzed, which showed that there were minor negative impacts on the network by implementing TSP especially when the traffic volume was not extremely high.

Ma and Yang [15] investigated the relationship among the departure frequency of a BRT (Bus Rapid Transit) bus line, the cycle length of a signalized intersection, and the number of different signal statuses when buses arrived at the intersection. The bus travel speed on links was considered a constant since there is an exclusive bus lane in the BRT system. Therefore, the number of different signal statuses when buses arrive at the intersection could be determined by the bus frequency and cycle length. The objective of the study is to minimize bus delay by optimizing the bus frequency and signal cycle length. Three signal priority strategies, green extension, green phase rotation, and green phase splitting, were proposed. Vissim simulation was used to validate the proposed TSP strategies. The results showed the impacts of the bus departure headway and the signal cycle length on bus delay.

Park et al. [16] evaluated three stochastic actuated traffic signal control optimization methods, Genetic Algorithm, Simulated Annealing, and Opt-Quest engine, and tested their performance by traffic simulation. Based on the existing optimization programs, he presented a stochastic traffic signal optimization method, which considered stochastic variability in drivers' behavior and vehicular inter-arrival times. Compared with commonly used software, such as SYNCHRO, TRANSYT-7F, results from the proposed method outperformed existing software in the optimization of parameters including cycle length, green split, offset, and phase sequence.

3.3 IntelliDrive Initiative

IntelliDrive is a multimodal initiative that aims to enable safe, interoperable networked wireless communications among the vehicles, the infrastructure, and the passengers' personal communications devices [17].

Amanna [4] reviewed the application of IntelliDrive in the U.S. Major projects, which were initiated in the states of California, Michigan, and Arizona, were discussed in the study. The IntelliDrive project in California established an intersection collision avoidance system and a curve over-speed warning system using controller-to-computer-to-radio roadside equipments. The IntelliDrive development in Arizona focused on supporting emergency responders and incident management activities. The project implemented the TSP operations at intersections and at ramp meters. DSRC was used to transfer data between transit vehicles and roadside infrastructures. It used 5.9G band and had a cover range up to 3000 ft. The system also supported to send the lane and road closure information to the Transportation Operations Center (TOC).

Dion et al. [18] focused on demonstrating the capability of simulating the Vehicle-Infrastructure Integration (VII, the predecessor of IntelliDrive) probe vehicle snapshots generation and collection in Paramics. The VII simulation module was developed using the Paramics Application Programming Interface (API). Beacon objects in Paramics were utilized as the roadside communication equipments (RSEs) emulators which were commonly used in field evaluations. Through the development of API functions, Beacon objects could collect snapshots generated by VII probe vehicles and then output the snapshots to a data file. The simulation was conducted on the basis of the U.S. DOT's Proof-of-Concept VII test bed near Detroit. Several alternative scenarios were developed to evaluate the effects of input parameters on VII. The results demonstrated the effectiveness of the simulator in evaluating and analyzing the VII implementation. In the following study, Dion et al. [19] worked on assessing various issues associated with the use of IntelliDrive. A virtual IntelliDrive probe vehicle data generator was created in Paramics. They compared different data sampling strategies and analyzed the potential data sampling biases. Furthermore, issues, such as tracking vehicles over short distance, estimating link travel time, determining queuing condition, data latency, etc., were investigated in detail. The results from the simulation were compared with the snapshots collected in existing field test. Certain improvements, such as optimized data collection interval, privacy protection, etc., on the existing protocol were provided.

Abu-Lebdeh and Chen [20] developed a dynamic speed control (DSC) model for a signalized traffic network. The DSC model collected the road condition and the vehicle information from IntelliDrive and then optimized the vehicle speed according to the information so that the vehicle could accommodate the signal coordination. A dynamic speed control algorithm, which made the best use of green time by controlling the vehicle arrival time, was proposed. The algorithm reduced bus delay and stops without influencing the normal traffic. Although it did not provide detailed information about how to implement IntelliDrive in the network, the study showed a good prospect of IntelliDrive application.

3.4 Vehicle Routing Optimization

Another way to reduce the bus delay is to minimize the trip length. Bus route planning is similar to the vehicle allocation-routing problem (VARP). VARP involves solving the joint problems of finding the optimal set of vehicle routes while determining the optimal allocation of transit vehicles among shelters. Many uncertain factors present challenges when solving VARP.

Berman [21] worked on finding a tour that minimizes the expected distance traveled by a salesman who followed the tour but skipped the customers who did not require service. He used a branch-and-bound algorithm to solve the probabilistic traveling salesman location problem. Bertsimas [22] solved the probabilistic traveling salesman facility location problem by simultaneously optimizing the location of the facility and the sales man's routing. He proposed a concept of a-priori tour in order to minimize the travel distance. The traveling salesman visited the customers in the same order as they appeared in the a-priori tour and skipped nodes which had no demand in current step. He used the space filling curve location heuristic to find out the a-priori tour when the distance metric is Euclidean.

Laporte et al. [23] studied a similar problem, in which both depot locations and a-priori routes must be planned before the exact level of demand is known. It might result in exceeding the vehicle capacity on a route, known as a route failure. If a route failure occurs, the vehicle returns to the depot prematurely and then resumes service to the remaining customers. The cost of this additional journey was considered as a penalty. The objective function of the model is to minimize the depot and a-priori route costs. Two sets of constraints were considered: (a) a limit on the probability of route failure or (b) a limit on the expected penalty of a route.

In the problem studied by Albareda-Sambola et al. [24], the customer demand was considered stochastic. The a-priori route might then omit some customers if the total demand is such that the vehicle capacity is exceeded. Un-serviced customers results in a penalty. They proposed a two-phase heuristic for the stochastic VARP. In the first phase, an initial solution was found by solving a sequence of sub-problems, which are location-allocation problem and vehicle routing problem. After the initial solution was obtained, the solution was improved by a local search in the second phase. The local search consists of a reassignment of customers, interchange of customers, interchange of depots, insertion of new depots, and swap of route segments. The objective function is the sum of depot costs, expected costs of a-priori routes, and expected penalty costs.

Goel and Gruhn [25] worked on a real-life vehicle routing problem with randomly generated demands after planning started. They considered a set of practical constraints, such as time window restrictions, heterogeneous vehicle fleets, vehicle compatibility constraints, etc. To cope with the complexities of the problem, they improved the Large Neighborhood Search method by using fast insertion methods. Two insertion methods were developed. One is a sequential insertion method in which unscheduled transportation requests are randomly chosen and all feasible insertion possibilities are considered. The second one is an auction method in which vehicles only consider the unscheduled requests with low incremental cost. The second method was used to optimize the vehicle routing with a time window.

3.5 Summary

Past studies on the development of a TSP system were summarized in this section in detail. Also, the application of IntelliDrive and other vehicle-to-infrastructure communication techniques were reviewed, which shows the perspective of incorporating IntelliDrive in an emergency evacuation. Moreover, the literatures of vehicle routing study were discussed to investigate the feasibility of implementing a bus routing optimization model in the proposed TSP decision tool.

Previous studies indicate that transit signal priority control can efficiently reduce the transit vehicle delay and improve transit service. Twenty-two states and regions in the U.S. have implemented the TSP system already [3]. But, there are few studies on the application of transit signal priority control on emergency evacuation. The current studies mostly focus on the signal preemption control for emergency vehicles instead of considering the network coordination by prioritizing buses at the intersection. To ensure that the whole evacuation can be performed most efficiently, the benefits of a TSP system on emergency evacuation need to be investigated.

4.0 Methodology

This section describes the model construction and the solution algorithm. In the model construction section, system parameters, model variables, constraints, and objective functions are introduced. In the solution algorithms section, applicable algorithms are discussed, and then efforts on improving existing algorithms for the proposed TSP system are presented in detail.

4.1 Model Construction

The proposed TSP system consists of two optimization models – the TSP optimization model and the bus routing optimization model. Model parameters, decision variables, objective functions, and constraints are discussed in this section.

4.1.1 Traffic Signal Priority Optimization Model

Currently, most TSP systems are typically implemented within fixed-time control. In order to study the coordination of IntelliDrive and TSP and its benefits to existing TSP systems, fixed-time control is assumed to be used at the intersections along the bus routes in this project. This assumption may result in larger benefits to buses with potentially larger negative impacts on normal traffic since a fixed-time controller is not able to adjust the signal timing plan in response to the traffic detection. In other words, fixed-time control represents a worst-case scenario with respect to the actuated control in terms of the ability to accommodate a TSP system. Furthermore, the proposed TSP model is tested under near-saturated or saturated conditions in this project. Therefore, a fixed-time controller working under near-saturated or saturated conditions will most likely act the same as an actuated controller if they have the same maximum green time.

For intersections using fixed-time traffic signal control, three TSP strategies are modeled within the framework of the proposed TSP system. These TSP strategies are defined based on the concept of “Priority Phase”, which is a portion of the signal timing cycle that is allocated to the bus movements. The priority phase is typically made up of three intervals: green, yellow, and all red. A bus can pass through the intersection in the green interval of a priority phase. “Green extension” extends the green interval in the priority phase to allow the bus to pass through the intersection. “Phase insertion” generates an additional priority phase for the bus. “Early green” terminates the green interval in the conflicting phase in order to start the green interval in the priority phase early for the bus. In particular, it has been argued that phase skipping could confuse drivers and interrupt signal coordination, thus causing significant delay or accidents [14]. Therefore, phase skipping is not applied in this project. Moreover, a minimum green time and a clearance time for each phase are enforced.

The type of priority strategy used depends on the estimated bus arrival time at the intersection. For example, Figure 3 shows the diagram of the time window for each priority strategy applied on the signal timing cycle. Bus priority phase is defined as the phase which includes green interval for bus movement. "Preceding" phase is the phase right before bus priority phase. "Following" phase is the phase right after the bus priority phase. If a bus' estimated arrival time at the intersection is located in the green extension time window, it can request green extension. If a bus arrives during the phase insertion time window, it can request phase insertion. If a bus' estimated arrival time is within the early green time window, it can call early green. The three priority time windows are located in the red time of the bus movement. In most situations the priority time windows overlap, which means more than one priority strategy is applicable if a bus arrives within the overlapped area. However, only one priority strategy can be selected at a time. Thus, it is necessary to determine how to split the overlapped area once a bus arrives within it.

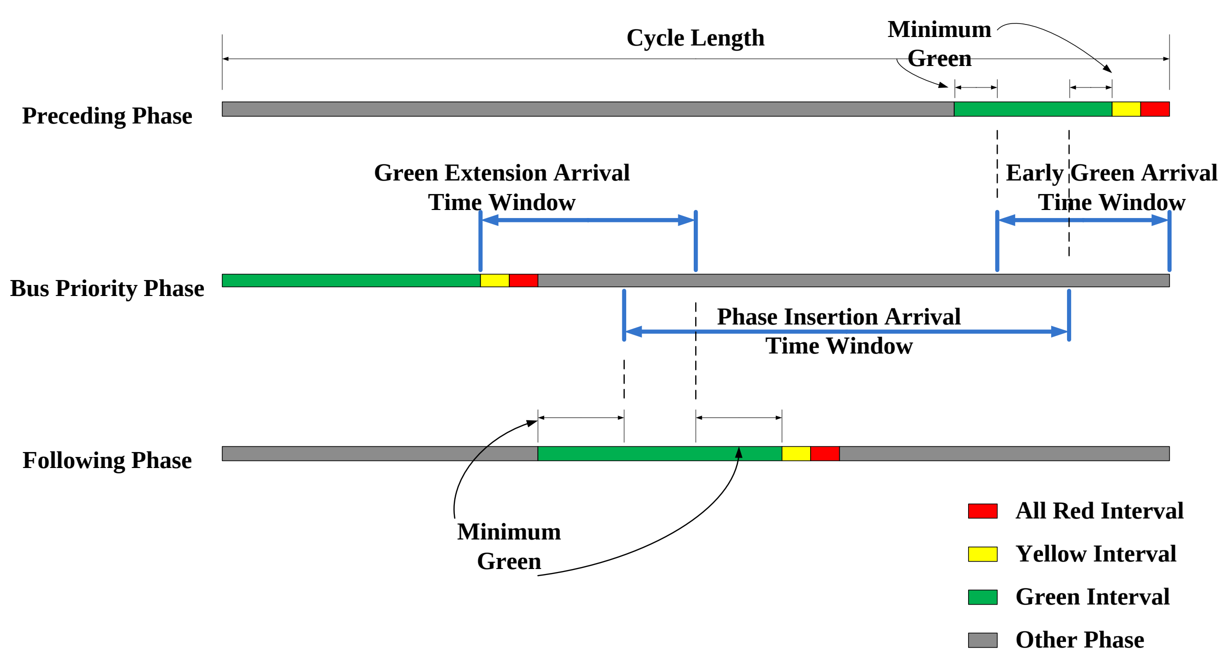

Figure 3. Time Window for Transit Signal Priority Request

In Figure 3, one of the most important parameters required to determine a priority strategy is the bus arrival time at the intersection. Currently, bus arrival time is estimated using detector data. Generally, there are two types of bus detection system, point detection system and zone detection system. Unlike the traditional detection devices that sense the presence of bus at fixed locations or within a limited distance, the IntelliDrive enables vehicles and signal controllers exchange data in a range of 3000 ft with high frequency. In this project, IntelliDrive is simulated using CORSIM RTE. Per-second bus data including position, speed, busload, etc., is transferred to the signal controller so that it can calculate the bus arrival time accordingly. The signal controller may adjust priority strategy according to the updated bus information.

The bus travel time is defined as the time required by a bus to travel from its current location to the specified downstream signalized intersection. It is calculated using Equation (1).

$$tt = \frac{L}{v_b} + \sum_{stop}^{m} t_{stop} + \sum_{\text{int}}^{n} d_{\text{int}} + qh \tag{1}$$

Where:

tt	=	Bus travel time, in second
L	=	Distance from bus current location to the specified downstream fixed-time intersection, in feet
v_b	=	Bus speed, in feet per second
t_{stop}	=	Bus dwell time at pickup points, in second
m	=	Number of pickup points along L
$stop$	=	Pickup point identification number
d_{int}	=	Intersection delay, in s
n	=	Number of intersections along L
Int	=	Intersection identification number
q	=	Queue length ahead bus at the intersection
h	=	Discharge headway, in second

In Equation (1), the first term calculates the basic travel time required to travel from the bus' current location to the specified downstream intersection. It assumes that the bus travels steadily at the current speed. The second term of the equation is the summation of the bus dwell time at the pickup points on the route. According to the CTA's (Coast Transit Authority) information, a bus spends approximately 2 to 3 minutes at each pickup point. Therefore, t_{stop} is considered as a random variable with uniform distribution from 120 to 180 seconds. The third term is the summation of delay induced by the intersections along its path. The fourth term takes the queue discharge time into consideration. Queue length is detected by loop detectors at the intersection. The Highway Capacity Manual (HCM) [26] recommends a discharge headway of 1.9 seconds (equates to a saturation flow rate of 1900 passenger cars/h/lane).

Three parameters are required to implement the TSP strategies in a signal controller. These parameters govern the key details of the implementation and are common to existing TSP systems.

- Maximum Communication Distance: If the distance from the bus to the downstream signal controller is shorter than the maximum communication distance, the bus driver can send a priority request to the controller using an on-board device. Currently, the maximum communication distance is up to 3000 ft.
- Time Window Split: Determine which priority strategy should be applied when bus arrival time is within the overlapped area of the time window in Figure 3.
- Minimum Green Time: Each green interval has a minimum green time. This part of green time cannot be appropriated by bus priority signal. This ensures a minimum service time for each non-priority phase. In this project, minimum green time is set according to the "Min Green" time in its original timing plan, which is downloaded from Gulfport City Engineering's ACTRA server.

The TSP control logic applied in the TSP optimization model attempts to replicate the functionality of existing TSP systems. The key elements are outlined below:

- The fixed-time controller can receive bus information within a user specified distance (up to 3000 ft) upstream of the stop bar.
- Bus information is updated every one second interval and is uploaded to the controller via IntelliDrive.
- If a bus arrives within the green extension time window, green extension is executed until either the bus passes the intersection or the time reaches the end of the time window.
- If a bus arrives within the phase insertion time window, phase insertion is executed until either the bus passes the intersection or the time reaches the end of the time window.
- If a bus arrives within the early green time window, early green is executed until the time reaches the end of the early green time window.

- If a bus arrives within the overlapped area of two or more time windows, the sequential list is arranged as: green extension ≥ early green ≥ phase insertion. Green extension is the most preferred TSP strategy because it does not require additional clearance intervals. Therefore, it reduces the bus delay relative to waiting for an early green or special transit phase. Additionally, green extension and early green will not affect signal coordination in contrast with phase insertion.
- If a bus arrives within the transit priority phase, no action is taken.
- After the bus leaves the intersection, a clearance interval is required if green extension or phase insertion is applied. After the clearance interval, the signal controller will restore its original timing plan so that the coordination will not be interrupted.
- If the signal controller receives more than one priority request, bus prioritization is applied. There are several principles which can be considered as follows:
    - The “First come first serve” rule applies which means the first bus sending a priority request is granted priority.
    - Grant priority according to the busload.
    - Grant priority according to the bus schedule; the bus which falls farthest behind its schedule is granted priority.
    - Grant priority according to the queue length; the bus on which approach has the longest queue is granted priority
    - If multiple priority requests come from the same approach and are requiring the same signal, the green signal is extended until either the last bus has left the intersection or the maximum green time is reached

  In this project, priority is granted to the bus with the highest occupancy.
- The pedestrians are not considered in this project.

Based on the above TSP logics, a TSP optimization model is developed. The objective of the model is to minimize the bus delay at an intersection. The objective functions and constraints are shown as follows:

$$Minimize\ \ d_b \tag{2}$$

$$\sum_{i \in P}\left(G_i + Y_i + AR_i\right) = C \tag{3}$$

$$t_a = t_0 + tt = t_0 + \frac{L}{v_b} + \sum_{stop}^{m} t_{stop} + \sum_{\text{int}}^{n} d_{\text{int}} + qh, \quad L < D \tag{4}$$

$$str = f\left(t_a\right), \quad str \in STR \tag{5}$$

$$G_i \geq G_i^{\min},\ Y_i \geq 0,\ AR_i \geq 0, \quad \forall i \in P \qquad (6)$$

Where the parameters and variables used in the above model are:

d_b: Bus delay at intersections

G_i: Green time in phase *i*

Y_i: Yellow time in phase *i*

AR_i: All red time in phase *i*

$G^{min}{}_i$: Minimum green time in phase *i*

t_a: Bus arrival time at the intersection

t_0: Current time step

f: Priority selection function

C: Cycle length

P: Set of phases in a cycle

STR: Set of priority strategies

Decision variable:

str: Selected priority strategy

D: Maximum communication distance of IntelliDrive device

Equation (3) ensures the cycle length does not change in order to maintain coordination. Equation (4) is used to calculate the bus arrival time at an intersection based on Equation (1). Equation (5) is the priority selection function according to the TSP logics used in this project. Equation (6) ensures the minimum green time for each phase and no phase skipping is allowed in the TSP.

4.1.2 Vehicle Routing Optimization Model

The bus routing plan in evacuation could be converted to a mathematical model of the vehicle allocation-routing problem (VARP). Assume that each transit vehicle departs from a shelter and only has one destination shelter. The origin and destination shelters and routes are determined by finding the solutions to the model. The notations below provide information needed for the understating of the models.

Notations:

r: the number of pickup points

s: the number of candidate shelters

v: the number of buses

$R:\{m \mid m = 1,2,\cdots,r\}$ is the set of r pickup points

$S:\{n \mid n = r+1, r+2,\cdots, r+s\}$ is the set of s candidate shelters

H: the set of nodes including all pickup points and shelters, $H = R \cup S$

$V:\{k \mid k = 1,2,\cdots,v\}$ is the set of v buses

t_{ij}: the shortest traveling time from node i to node j, $i \in H, j \in H, and\ i \neq j$

q_m: the number of evacuees at pickup point m, $m \in R$

d_k: the number of unregistered evacuees carried by bus k, $k \in V$

O_k: the capacity of bus k, $k \in V$

U_n: the capacity of each shelter n, $n \in S$

L_k: the maximum travel time of bus k, $k \in V$

Min: return the minimum value of a variable

The objective of the model is to minimize the total evacuation time of all evacuees. The objective functions and constraints are shown as follows:

$$Minimize \sum_{i \in H} \sum_{j \in H} \sum_{k \in V} t_{ij} X_{ijk} \tag{7}$$

$$\left(d_k + \sum_{i \in H} \sum_{m \in R} q_m X_{imk} \right) \leq O_k, \ \forall k \in V \tag{8}$$

$$Z_n \sum_{k \in V} \sum_{m \in R} \left[X_{mnk} \left(d_k + \sum_{i \in H} \sum_{m \in R} q_m X_{imk} \right) \right] \leq U_n, \ \forall n \in S \tag{9}$$

$$\sum_{i \in H} \sum_{j \in H} t_{ij} X_{ijk} \le L_k, \ \forall k \in V \tag{10}$$

$$\sum_{k \in V} \sum_{i \in H} X_{imk} = 1, \ \forall m \in R \tag{11}$$

$$\sum_{i \in H} X_{imk} - \sum_{j \in H} X_{mjk} = 0, \ \forall k \in V, \ \forall m \in R \tag{12}$$

$$\sum_{n \in S} \sum_{m \in R} X_{nmk} = 1, \ \forall k \in V \tag{13}$$

$$\sum_{m \in R} \sum_{n \in S} X_{mnk} = 1, \ \forall k \in V \tag{14}$$

$$\sum_{k \in V} X_{ijk} = 0, \ \forall i, j \in S \tag{15}$$

$$\sum_{k \in V} \sum_{m \in R} X_{nmk} - Z_n \ge 0, \ \forall n \in S \tag{16}$$

$$\sum_{k \in V} \sum_{m \in R} X_{nmk} - v \cdot Z_n \le 0, \ \forall n \in S \tag{17}$$

$$X_{ijk} = 0 \text{ or } 1, \ \forall i, j \in H, \ \forall k \in V \tag{18}$$

$$Z_n = 0 \text{ or } 1, \ \forall n \in S \tag{19}$$

Model decision variables:

$$X_{ijk} = \begin{cases} 1, \ \textit{if bus } k \textit{ travels from } i \textit{ to } j, \ i \ne j \\ 0, \textit{otherwise} \end{cases}$$

$$Z_n = \begin{cases} 1, \ \textit{if shelter } n \textit{ is selected}, \ n \in S \\ 0, \textit{otherwise} \end{cases}$$

Equation (8) represents the bus capacity constraint. The left part of the inequality is the summation of the demand of all the pickup points along the bus *k*'s route, plus the demand d_k carried by the bus *k*, which should be less than or equal to the bus *k*'s capacity Q_k.

Equation (9) is the shelter capacity constraint. The left part of the inequality represents the summation of the bus load whose destination is the shelter *n.*

Equation (10) is the bus maximum travel time constraint. The left part of the inequality represents the summation of the travel time of the bus *k*.

Equation (11) ensures that each pickup point is visited only by one bus. Equation (12) is the route continuity constraint, which implies that every pickup point which is entered by a bus should be left by the same bus. The first term of the equation is used to check if the bus *k* arrives at the pickup point *m* and the second term is used to check if the bus *k* departs from the pickup point *m*.

Equation (13) constrains that each bus departs from one and only one shelter. Equation (14) guarantees that each bus arrives at one and only one shelter. Equation (15) ensures that there is no direct link between any two shelters.

Equation (16) and Equation (17) ensure that the bus *k* departs from the shelter *n* if and only if the shelter *n* is open. The first term of the left side of equations (16) and (17) is the total number of vehicles which depart from the shelter *n*.

Equations (18) and (19) designate the decision variables X_{ijk} and Z_n as binary variables.

4.2 Combined Genetic Algorithm

VARP belongs to the Non-deterministic Polynomial-time (NP) hard problem [27]. Traditional optimal methods are not satisfied in quality or in efficiency when solving the VARP. Genetic Algorithm (GA) is a stochastic search method based on the mechanics of natural selection and genetics. This methodology has manifested success in solving a variety of combinatorial optimization and uncertain optimization problems [28-31]. Liu [30] proposed a general structure of hybrid intelligent algorithms and some solution instances for stochastic programming problems. Song's [20] study showed that the Hill Climbing Method is useful for improving GA solutions. Based on those references, a Hybrid Intelligent Algorithm (HIA) combined the Hill Climbing Method with the GA is proposed as follows:

The general steps of HIA are presented as follows:

1. Build the initial generation, which includes pop_{size} chromosomes using the direct coding method.
2. Produce the variants of chromosomes by the crossover and mutation operations. The crossover rate P_{cross} and mutation rate $P_{mutation}$ are used to determine if a chromosome is selected to perform the crossover or the mutation operation.
3. The Hill Climbing Method is used to perform a neighbor search for improving the quality of the solution.
4. Calculate the objective values for all chromosomes. Record the best chromosome in the current generation.

5. Compute the fitness of each chromosome according to the objective value. Select the next generation chromosomes by spinning the roulette wheel.
6. Repeat the steps 2 to 7 for a given number of cycles until the algorithm's stop criterion is met. The stop criterion in this study is that the population of chromosomes reaches a predetermined number of generations.
7. Report the best chromosome among all the generations as the optimal solution.

Figure 4 shows the flowchart of the proposed HIA. Refer to the previous project for detailed HIA development and description.

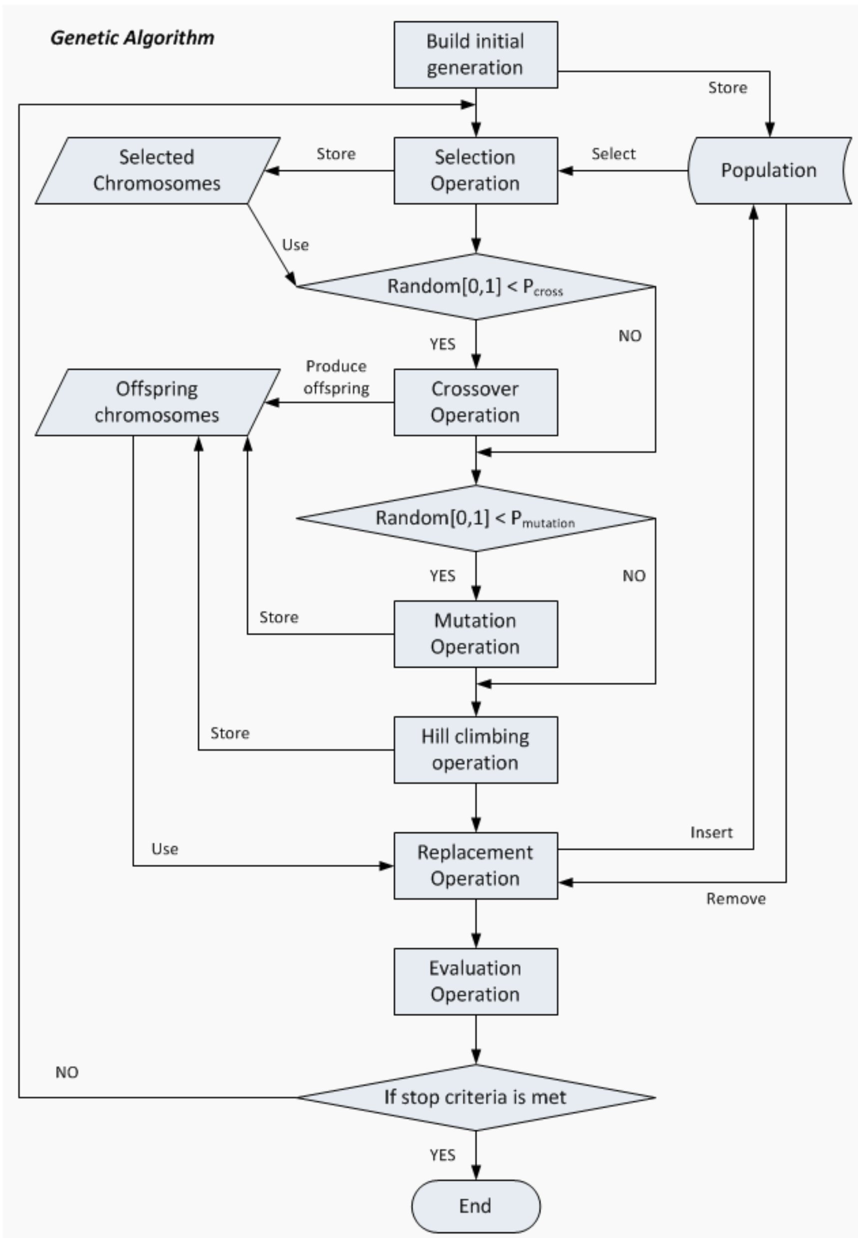

Figure 4. Flowchart of the Proposed HIA

Additionally, for making the emergency evacuation simulation more practicable, prohibited turns (e.g. U-turn) are considered in the street network. To find out the shortest path among pickup points and nodes in a network with prohibited turns, which is necessary to build initial generation of HIA, a modified Dijkstra Algorithm is proposed. Compared to the traditionally Dijkstra Algorithm [32], the modified Dijkstra Algorithm replaces a normal node by several dummy nodes where there are turn prohibitions. Each dummy node receives the traffic from one and only one adjacent node. If a turning movement is prohibited, the corresponding link that receives the turning traffic will be deleted.

Figure 5 shows an example of the modified Dijkstra Algorithm. Assume that the left turn from link A-B to B-E is prohibited. Applying the modified Dijkstra Algorithm, Node B is deleted and three dummy nodes, B1, B2, and B3, are inserted. Accordingly, links A-B, B-A, B-C, C-B, B-E, E-B are deleted and links A-B1, B1-E, B1-C, C-B2, B2-E, B2-A, E-B3, B3-A, and B3-C are created. Note that the travel time on link B1-E is set to infinity so that there is no chance that link B1-E is selected in the Dijkstra Algorithm. Therefore, vehicles from link A-B1 cannot make a left turn at node B1. At the end, the results which contain the dummy nodes in the minimum path are summarized. Dummy nodes B1, B2, and B3 in the results are replaced by Node B. Hence, the modified Dijkstra Algorithm can solve the shortest path problem where there are prohibited turns effectively.

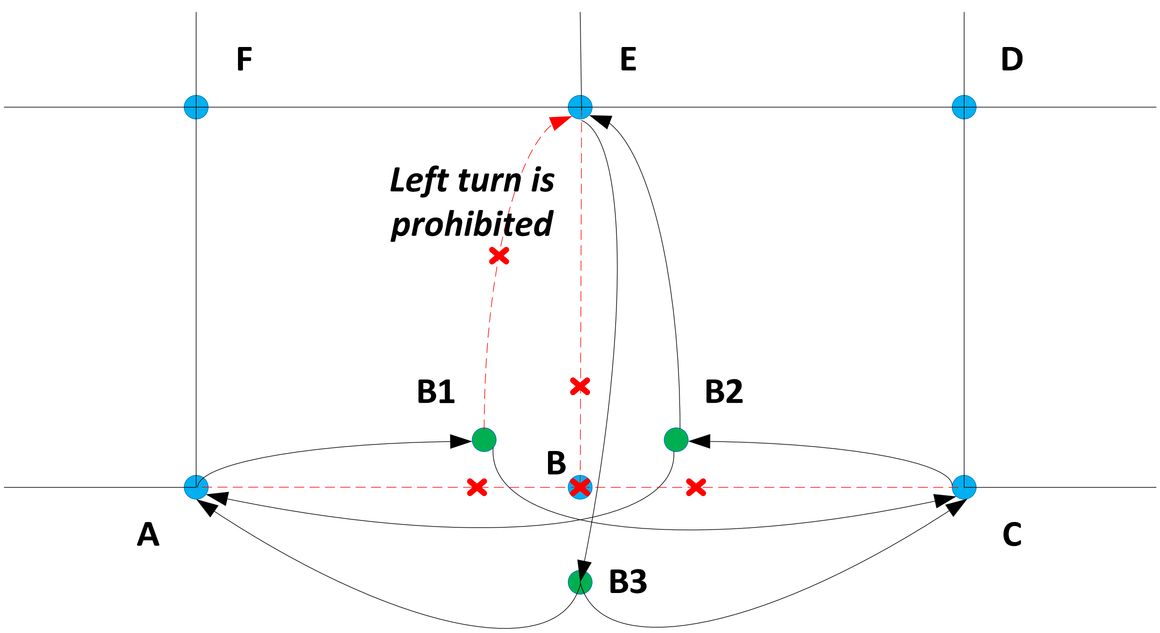

Figure 5. Road Network Sample with Dummy Nodes

5.0 System Architecture and Model Implementation

In the previous section, the TSP optimization model and bus routing optimization model have been formulated. Algorithms for solving the proposed models are presented as well. In this section, the implementation of those models and algorithms is discussed. We will first discuss the overall architecture of the software which is followed by a flow chart of the executions of the software.

5.1 System Architecture

The TSP system architecture is shown in Figure 6. The center part of Figure 6 is the scope of the proposed TSP system optimization models and solution. The simulation layer, which is executed by CORSIM, provides data to the model layer and outputs results. The real world layer shows the perspective of implementation of the proposed models in the real world.

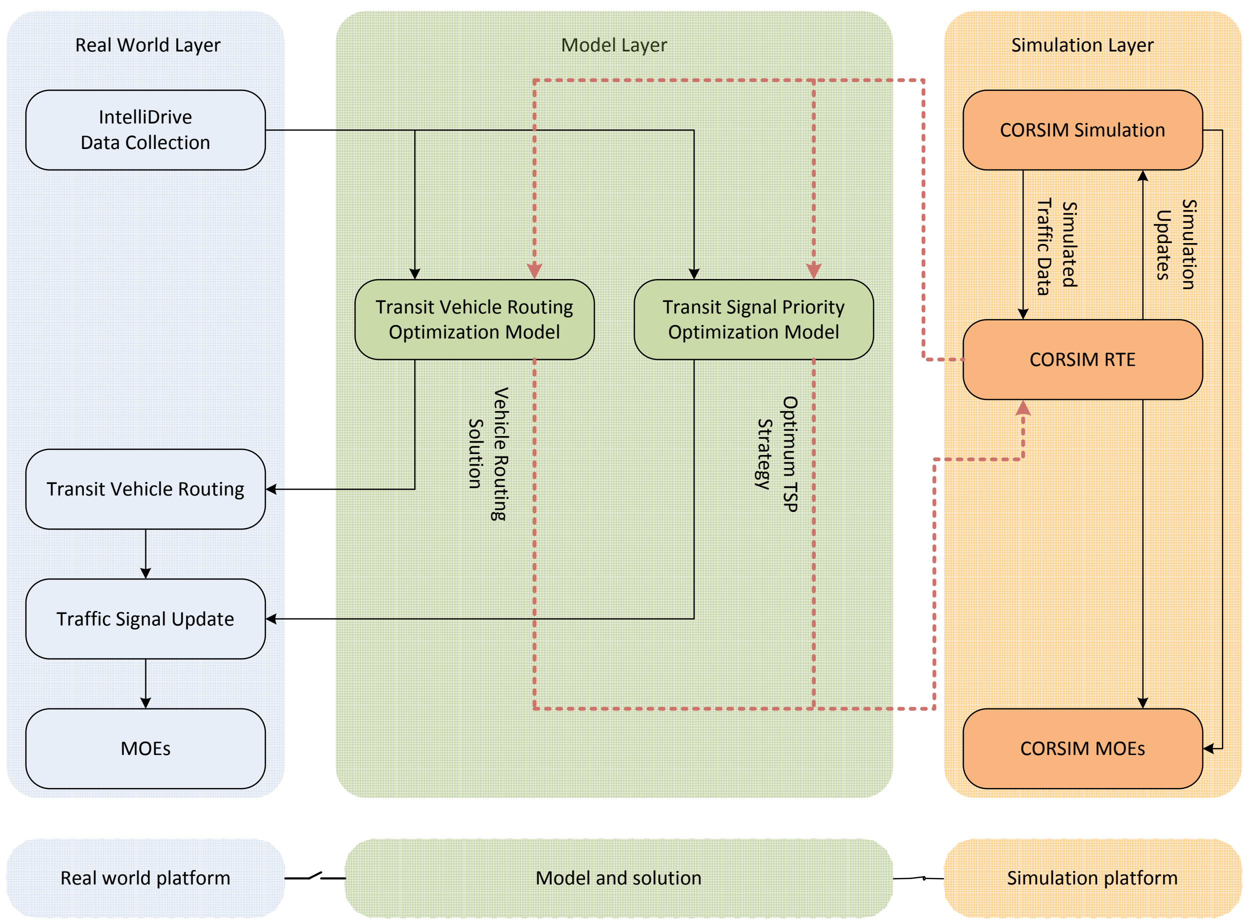

Figure 6. TSP System Architecture

5.2 Model Implementation

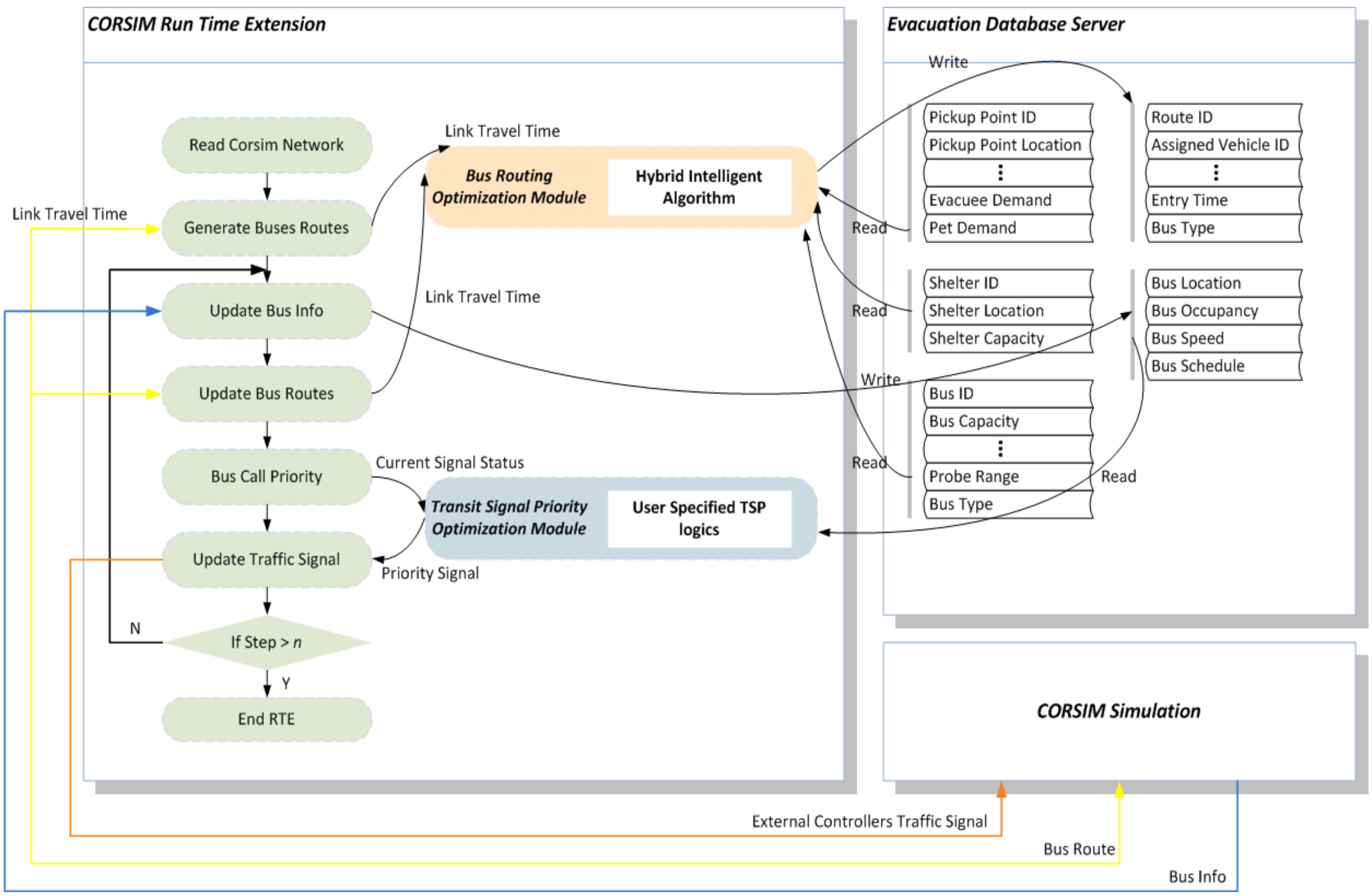

Figure 7. Flowchart of TSP System Implementation

Figure 7 shows the internal data flowchart of the proposed TSP system. First, CORSIM RTE reads the network data, including links, nodes, lanes, traffic signal states etc. Then, a "Generate Bus Route" function calculates average travel time on links by dividing the total travel time by the total discharged vehicles. Link travel time is exported into the bus routing optimization module. This module is capable of allocating buses among shelters and generating optimized bus routes using the proposed HIA algorithm. The bus routes are stored in the evacuation database server.

After generating buses and bus routes, RTE updates bus information at each simulation step. Bus information includes bus location, travel speed, occupancy, and current bus schedule. The dynamic bus information is stored in the evacuation database server. At the same time, the

“Update Bus Route” function invokes the bus routing optimization module at a fixed time interval to ensure the bus routes are kept optimal. The bus routes table in the database is also updated accordingly.

At each simulation step, the “Bus Call Priority” function watches bus information in the evacuation database server and sends priority requests to the TSP optimization module when the bus is within communication distance. The TSP optimization module determines whether to grant the bus priority according to the user specified internal TSP logics. Then, the TSP optimization module sends updated traffic signal states back to the “Update Traffic Signal” function which controls all the external traffic signal controllers in the simulation. The priority requests are continuously sent to the TSP optimization module as long as the bus is within the communication distance so that the TSP optimization module can update the optimum TSP strategy according to the up-to-date bus information.

5.3 Software Development

The RTE is programmed using Visual Studio C++. Microsoft SQL server 2005 is used to accommodate the evacuation database. The class view and functions of RTE are shown in Figure 8.

Class: CNetwork	
Read_TRF_File ()	: Read CORSIM TRF file
GetNodes ()	: Create node objects
GetLinks ()	: Create link objects
GetDetectors ()	: Create detector objects
CreateLanes ()	: Create lane objects
CreateSignalStates ()	: Create SignalState objects
UpdateSignalStates ()	: Update traffic signal at external nodes
FindLinkTravelTime ()	: Calculate average travel time on links
GeneticAlgorithm ()	: Bus allocation and routing optimization
PushPath ()	: Create bus routes objects
PushBus ()	: Create bus objects
ProcessPathVehicle ()	: Process bus information
ProcessDetectors ()	: Process detector information on links

Class: CNode	
SetSignalState ()	: Update signal states on connected links
ProcessPriorityInfo ()	: Process priority request and send out priority strategy to link

Class: CSignalState	
SetSignal ()	: Create signal array for this signal state
MapSignalCode ()	: Map the signal code to signal array

Class: CLink	
ProcessDetectors ()	: Process detectors information on this link
CreateSignalStates ()	: Create signal states on this link
AdjustSignalStates ()	: Adjust signal states on this link
SetSignalStates ()	: Update signal states of downstream node
CallPriority ()	: Execute priority strategy
CancelPriority ()	: Cancel current priority action

Class: CPathVehicle

Class: CBusRoute

Class: CPriorityInfo

Class: CLane

Class: CDetector

Class: CGraph

Figure 8. RTE Class View and Functions

The data dictionary of the evacuation database is shown in Figure 9. The evacuation database can synchronize with the CTA's database in a fixed interval even in real time so that it can stay up-to-date. RTE can access the evacuation database using Microsoft Open Database Connectivity (ODBC), which is a standard database access method developed by the SQL Access group.

Evacuation Database

Table: Pickup_Point_Info	
Pickup_Point_Id	: Pickup point's identification number
Pickup_Point_Name	: Pickup point's name
Pickup_Point_Address	: Pickup point's address
Pickup_Point_Evacuee_Demand	: Number of evacuees at this pickup point
Pickup_Point_Pet_Demand	: Number of pets at this pickup point

Table: Evacuee_Info	
Evacuee_Id	: Evacuee's identification number
Evacuee_Name	: Evacuee's name
Evacuee__Address	: Evacuee's address
Evacuee_Pickup_Point	: Assigned pickup point to the evacuee
Evacuee__Phone	: Evacuee's cell phone number
Evacuee_Mobility	: Evacuee's special requirement

Table: Bus_Info	
Bus_Id	: Bus identification number
Bus_Type	: Bus type
Bus_AssignedRoute	: Bus assigned route id
Bus_Capacity	: Bus capacity
Bus_Driver	: Assigned driver to the Bus
Bus_EntryTime	: Bus entry time in the network
Bus_EntryNode	: Bus departure shelter

Table: Shelter_Info	
Shelter_Id	: Shelter's identification number
Shelter_Name	: Shelter's name
Shelter_Address	: Shelter's address
Shelter_Capacity	: Shelter's capacity

Table: TravelTime_Info	
TravelTime_UPS_Node	: Link upstream node in the network
TravelTime_DNS_Node	: Link downstream node in the network
TravelTime_Time	: Link travel time in the network

Table: Bus_Route	
Route_Id	: Route's identification number
Route_Assign_Bus	: Assigned bus id on this route
Route_Assign_PickupPoints	: Assigned pickup points on this route
Route_EntryNode	: Bus departure shelter
Route_ExitNode	: Bus exit shelter

Table: Bus_DynamicInfo	
Bus_Id	: Bus identification number
Bus_Location	: Bus current location
Bus_Speed	: Bus current speed
Bus_Occupancy	: Bus current occupancy
Bus_Schedule	: Bus scheduled time arriving next node

Figure 9. Evacuation Database Dictionary

6.0 Illustration of Gulfport Transit Evacuation

In this section, a practical case study of Hurricane Gustavo evacuation in Gulfport is provided to illustrate the proposed TSP system as previously outlined. A detailed Gulfport road network is built in CORSIM/TSIS 6.2. CORSIM simulation with RTE is developed for the above model and algorithm. The purpose of the case study is to evaluate the proposed TSP system in terms of its impacts on travel times in the network, both for the buses and for other traffic, and in terms of its impacts on service reliability for the evacuation. Performance under alternate parameter settings is then evaluated, and operational recommendations are made.

6.1 Data Collection

6.1.1 Data Sources

Data was collected from several sources, including the CTA, the Office of Engineering, Google Map, and field surveys. Figure 10 shows the data collected from those sources.

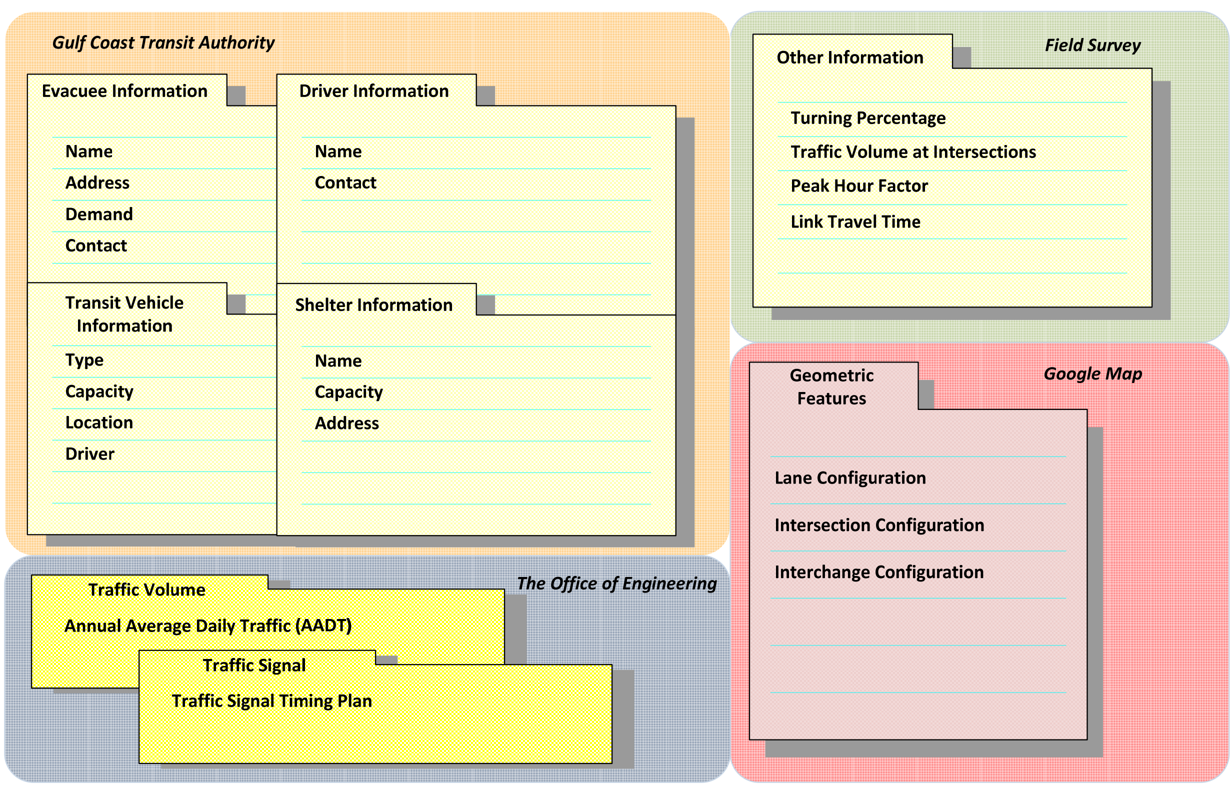

Figure 10. Data Sources

6.1.2 Field Surveys

The research team has conducted four field surveys in Gulfport. Close investigations were performed at 23 major intersections in Gulfport. These intersections are mainly distributed along Pass Road, Highway 605, Canal Road, and Popps Ferry Road. Table 1 shows the detailed locations of these intersections.

Table 1. Investigated Intersections Locations

No.	Location
1	Pass Road & 30th Avenue
2	Pass Road & 25th Street
3	Pass Road & Hewes Road
4	Pass Road & Anniston Avenue
5	Pass Road & Veterans Avenue
6	25th Street & 25th Avenue
7	Cowan Road & E. Pass Road
8	Eisenhower Drive & Pass Road
9	Howard Avenue & Caillavet Street
10	28th Street & 33rd Avenue
11	Washington Avenue & 54th Street
12	Lorraine Road & Seaway Road
13	3 Rivers Road & Dedeaux Road
14	Canal Road & Landon Road
15	Three Rivers Road & Creosote Road
16	Jordon Road & John Ross Road
17	Popps Ferry Road & Atkinson Road
18	Popps Ferry Road & D'iberville boulevard
19	Central Avenue & Rodriguez Road
20	Bayview Avenue & Caillavet Street
21	Backbay Avenue & Crawford Street
22	Howard Avenue & Oak Street
23	Popps Ferry Road & Cedar Lake Road

Traffic detection equipments, such as the NC-200 portable traffic analyzers, the remote traffic microwave sensors, and the JAMAR TDC-8 traffic data collectors, were used to investigate traffic volumes, peak hour volumes, truck volumes, and turning percentages at these intersections. The research team also conducted manual counts at several major intersections in order to calibrate the traffic data from those equipments. Additionally, the research team obtained the traffic data at major intersections along U.S. 49 and U.S. 90 from MDOT (Mississippi Department of Transportation) Planning Division and Neel-Schaffer Inc.

6.1.3 Other Activities

The research team has built a close connection with the CTA. The CTA provided the detailed evacuation information in terms of the evacuees, the shelters, the bus drivers, and the transit vehicles. Moreover, the CTA offered the records of the Hurricane Gustavo Evacuation, which was used to validate the proposed bus routing optimization model.

The research team collected the traffic signal timing plans from the Office of Engineering in Gulfport. These traffic signal timing plans were imported into an ACTRA server setup by Temple Inc. The ACTRA server can provide external control to the signal controllers in CORSIM simulation. In the future, the ACTRA server working with CORSIM simulation will be used to validate the applicability of the proposed TSP system.

In addition, the geometric features of the Gulf Coast traffic network were collected from Google Map. The geometric information, including lane configuration, intersection layout, interchange layout, road sign, etc, was coded into the CORSIM network.

6.2 Network Building

The network selected for the case study is located in the Mississippi Gulf Coast area. Interstate 10 runs east and west of the selected area. Other major roadways include I-110, U.S.90, U.S.49, Highway 605, and Highway 67. The CORSIM network consists of 1,632 links and 1,341 nodes, in which 146 nodes are signalized intersections. These signalized intersections are assumed to be running under fixed-time control. The traffic signal timing plans, which were originally extracted from the City Engineering ACTRA system, were modified to be used under fixed-time control using TRANSYT-7F.

Detailed network configuration is shown in Figure 11.

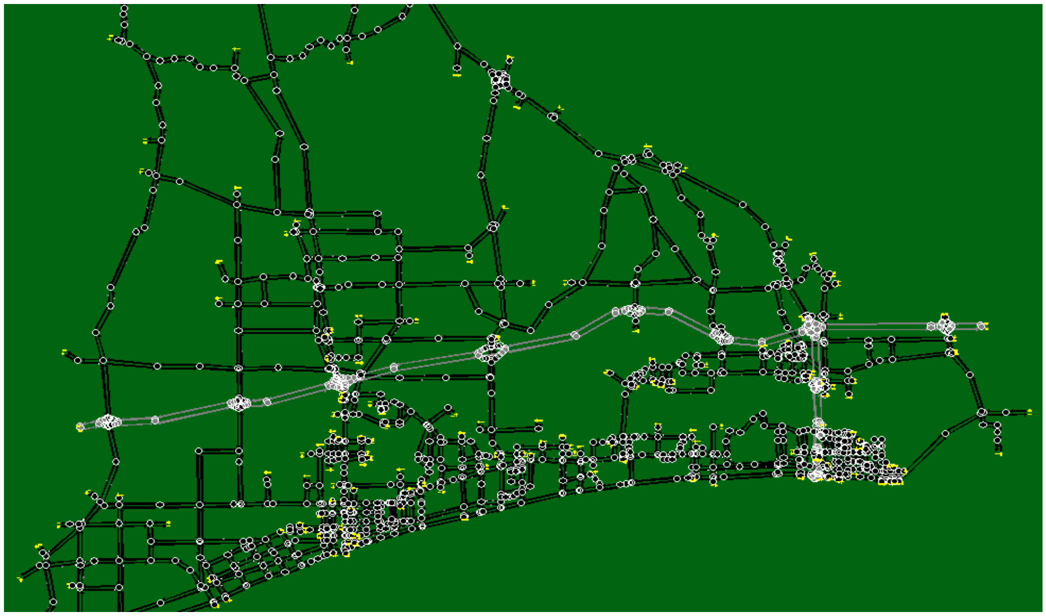

Figure 11. CORSIM Network of Gulfport Region

In addition to the intersections and transition nodes, pickup points and shelters were also coded into the network. The distribution of the pickup points and shelters is shown in Figure 12.

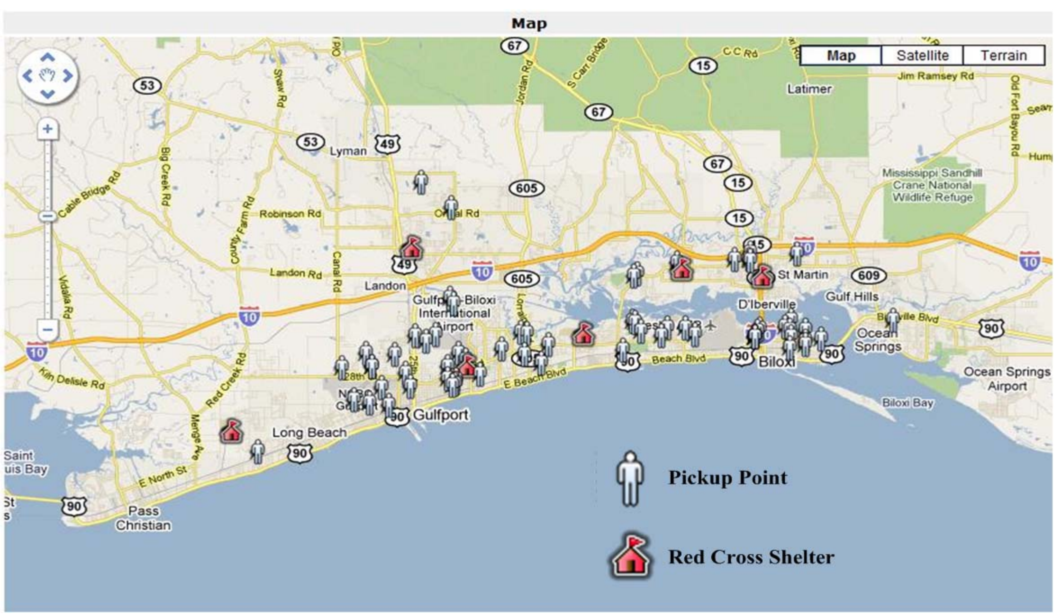

Figure 12. Pickup Points and Shelters Distribution

As shown in Figure 12, during Hurricane Gustavo, 99 evacuees were spread across 50 pickup points, and 6 shelters provided safe places for the evacuees. The maximum number of buses used in the simulation is 15. The capacity of the bus is 28. The evacuation time frame is set as two hours, according to the CTA's evacuation plan. All the buses depart from shelters between 4:00 pm to 4:15 pm with one minute headway. Within the network, the dwell times at the pickup points are uniformly distributed between a lower bound of 120 seconds and an upper bound of 180 seconds. A detailed bus schedule was determined through discussions with the CTA traffic engineers. Buses are equipped with on-board IntelliDrive devices, which can communicate with the IntelliDrive road side unit.

AADT data collected from the GRPC (Gulf Regional Planning Commission) traffic count database is the source of the traffic volume information. AADT is converted into peak hour volume by Equation (20).

$$PHV = AADT \times K \times D \tag{20}$$

Where:

PHV	=	Peak hour directional volume, veh/h
AADT	=	Annual average daily traffic, veh/d
K	=	Peak hour factor
D	=	Directional split factor

The *K*- and *D*-factors are usually determined on the basis of regional or route-specific characteristics. Generally, the K-factor ranges from 0.07 to 0.15, while the D-factor ranges from 0.50 to 0.65 in urban and suburban areas. In this project, an estimated *K*-value of 0.085 is used. This *K*-value comes from the field surveys at 23 major intersections. Since the *D*-factor cannot be easily determined, a default *D*-factor of 0.55 is used [26].

6.3 Results of Case Study

To evaluate the effectiveness of the proposed model, the following signal control scenarios are developed:

Scenario 1 – Scenario 1 is used as a basic scenario. A bus routing optimization model is implemented in the simulation with no signal priority.

Scenario 2 – Scenario 2 is developed as only the transit signal preemption working in the simulation. A bus is granted an unconditional green light without any clearance time.

Scenario 3 – In scenario 3, the TSP model is implemented without IntelliDrive function. A bus can only call priority when it is 300 ft away from the intersection.

Scenario 4 – In Scenario 4, TSP is coordinated with IntelliDrive. An optimized TSP strategy is generated in this scenario.

For each scenario, 10 simulation runs, at which level the law of Large numbers (central limit theorem) starts to work [33], are conducted to account for the stochastic nature of the simulation. The simulation is run from 4:00 to 6:00 PM, corresponding to the evening peak hour and preceded by a thirty-minute “warm-up” period. The simulation is run with a fixed demand level throughout the entire period. Within each run, performance measures including bus travel time, bus delay, person delay, person travel time, bus schedule adherence, etc., are output and summarized. The statistics of bus travel time, which has the highest standard deviation, is selected to measure the level of accuracy. CORSIM has an output processor, which enables users to accumulate selected Measures of Effectiveness (MOEs) and summary data during multiple runs. The estimated error of bus travel time calculated by the processor, at a 95% confidence level, for ten replications is ±3.2%, and this level of accuracy is considered sufficient. Additionally, CORSIM allows users to add and configure customized tools to generate MOEs in the RTE. In this project, network-wide MOEs were calculated by the CORSIM output processor. Moreover, we developed functions to capture and analyze the bus operations and summarized the MOEs of bus in a spreadsheet. The results are shown below:

Table 2. Network-Wide Average Statistics

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Delay Time (Second/Mile)	23.4	24.6	24.0	23.4
Average Speed (mile/hour)	34.70	34.26	34.29	34.69

Table 3. Bus Travel Time on Each Route (minutes)

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Route 1	25.3	18.4	19.9	17.6
Route 2	61.3	48.7	52.7	51.0
Route 3	33.9	28.7	31.1	30.4
Route 4	35.4	33.3	33.8	33.5
Route 5	35.3	26.8	28.8	28.3

Route 6	14.3	12.9	13.3	13.8
Route 7	69.9	64.3	70.1	60.8
Route 8	26.6	21.8	22.6	23.2
Route 9	12.2	11.8	12.1	12.1
Route 10	11.9	10.2	10.0	11.6
Route 11	60.6	49.2	51.8	49.7
Route 12	47.3	48.6	51.0	46.1
Route 13	27.5	23.6	23.7	24.7
Route 14	39.4	32.9	37.2	34.4
Route 15	25.8	20.8	22.9	22.2
Average	35.1	30.1	32.1	30.6
Percentage Change (%)	0.00	-14.25	-8.55	-12.82

Furthermore, to investigate the impacts of the proposed TSP strategies on specific intersections, we considered splitting a portion of the network as shown in Figure 13.

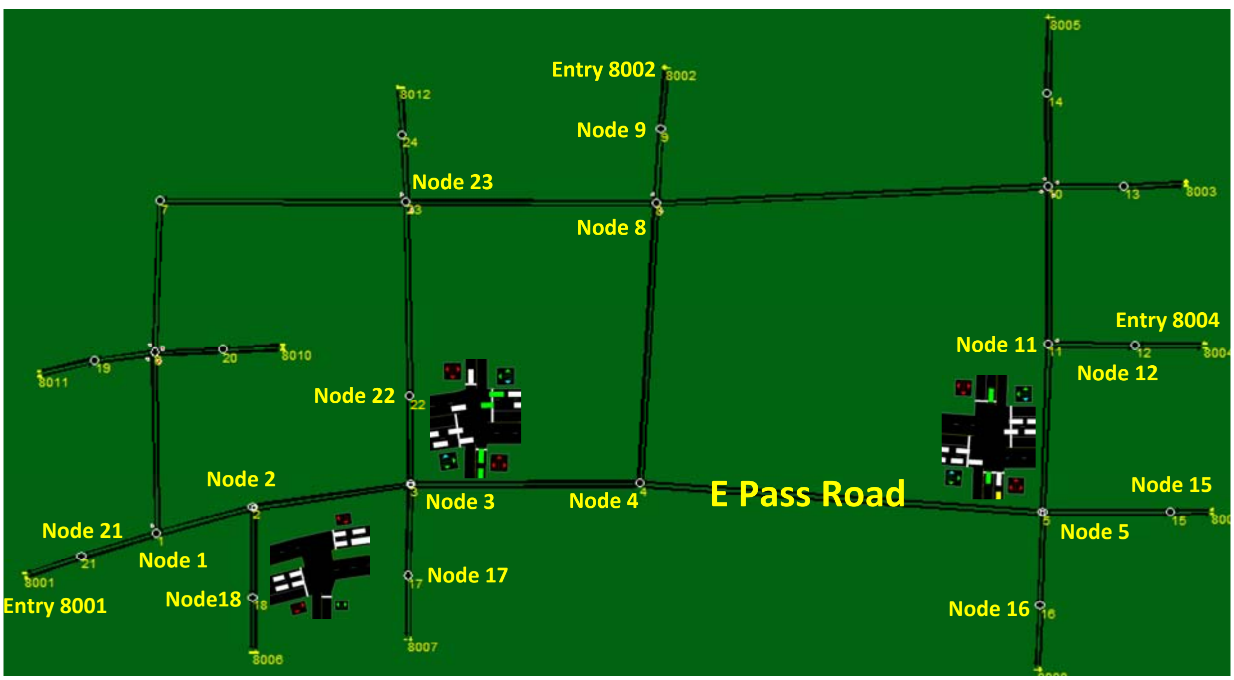

Figure 13. Small Network Sample

The network in Figure 13 is located in Gulfport near the Mississippi Gulf Coast Community College, which is selected as red-cross shelter in this project. E. Pass Road is the main road in this area. The eastbound intersection is E. Pass Road & Pine Street, which is marked as Node 1.

The westbound intersection is E. Pass Road & Debuys Road, which is marked as Node 5. There are three signalized intersections: Node 2, Node 3, and Node 5, which are configured as external fixed-time control intersections. Two transit bus routes pass this area. Route 1 is configured as “Entry 8001 – Node 21 – Node 1 – Node 2 – Node 3 – Node 4 – Node 5 – Node 11 – Node 12 – Exit 8004” and Route 2 is configured as “Entry 8002 – Node 9 – Node 8 – Node 23 – Node 22 – Node 3 – Node 2 – Node 1 – Node 21 – Exit 8001.” Two buses are assigned on those routes separately, and two pickup points are assigned to those two buses; one is located between Node 11 and Node 12, and the other one is located between Node 22 and Node 23.

Results from the small network are shown as follows: Table 4 shows the average bus delay on Route 1 and Route 2. Table 5 presents the network-wide average delay per mile in seconds. Table 6 summarizes the two-hour period statistics from upstream links of the external signalized intersections in the network. The links in Table 6 are further broken down by functionality, such as main road or minor road. Several measures of effectiveness including total person delay, average person delay, total vehicle delay, average vehicle delay, average speed, etc., are presented in Table 6.

Table 4. Average Delay on Each Route (Second)

Bus Delay (Second)	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Route 1	67	15	19	20
Route 2	73	20	54	39

Table 5. Network-Wide Delay (Second/Mile)

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Delay Time (Second/Mile)	65.4	69.6	65.9	64.2

Table 6. Two-hour Period Statistics on Upstream Links of Intersections for All Traffic

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Person Delay (Person-Minute)	Main Road			
Link 1-2	24.3	23.6	22.9	21.0
Link 3-2	48.0	33.6	43.8	44.1
Link 2-3	88.7	82.1	82.7	84.8
Link 4-3	114.2	133.2	111.5	111.4
Link 4-5	175.3	156.9	172.2	165.6
Link 15-5	115.8	121.5	116	111.2

Total Person Delay (Person-Minute)	Minor Road			
Link 18-2	9.8	12.3	11.6	11.8
Link 17-3	13.7	19.7	20.2	17.8
Link 22-3	17.6	22.5	21.4	19.8
Link 11-5	28.0	35.1	28.2	29.8
Link 16-5	34.6	34.2	35.4	36.4
Average Person Delay (Second/ Person)	Main Road			
Link 1-2	6.6	6.4	6.2	5.7
Link 3-2	13.4	10.8	12.1	12.1
Link 2-3	24.9	22.6	23.2	23.8
Link 4-3	32.6	37.8	31.8	31.8
Link 4-5	47.8	45.4	47.5	45.7
Link 15-5	32.3	33.7	32.3	31.0
Average Person Delay (Second/ Person)	Minor Road			
Link 18-2	20.6	24.7	24.3	24.8
Link 17-3	30.1	45.5	44.4	39.1
Link 22-3	39.6	50.0	48.8	45.3
Link 11-5	24.4	28.9	24.6	26.0
Link 16-5	29.1	31.6	30.3	30.6
Total Vehicle Delay (Vehicle-Minute)	Main Road			
Link 1-2	18.7	18.2	17.7	16.2
Link 3-2	37.0	25.9	33.8	34.0
Link 2-3	68.4	63.5	63.8	65.4
Link 4-3	88.1	102.8	86.0	85.9
Link 4-5	135.3	121.2	132.9	127.8
Link 15-5	89.3	93.8	89.5	85.7
Total Vehicle Delay (Vehicle-Minute)	Minor Road			
Link 18-2	7.5	9.5	8.9	9.1
Link 17-3	10.6	15.1	15.6	13.7
Link 22-3	30.7	32.7	41.9	36.4
Link 11-5	21.6	27.0	21.7	22.9
Link 16-5	26.7	26.3	27.3	28.0

Average Vehicle Delay (Second/Vehicle)	Main Road			
Link 1-2	6.5	6.3	6.1	5.6
Link 3-2	13.9	11.6	12.8	12.7
Link 2-3	23.5	21.2	22.0	22.5
Link 4-3	31.5	36.7	30.8	30.7
Link 4-5	43.7	41.2	43.2	41.5
Link 15-5	31.1	32.8	31.2	29.9
Average Vehicle Delay (Second/Vehicle)	Minor Road			
Link 18-2	20.2	23.9	23.7	24.1
Link 17-3	29.8	44.4	42.3	37.5
Link 22-3	43.7	46.0	61.4	52.5
Link 11-5	22.6	28.5	22.6	24.0
Link 16-5	28.5	31.7	29.4	29.9
Average Delay Per Mile (Second/Mile)	Main Road			
Link 1-2	0.9	0.9	0.9	0.8
Link 3-2	1.2	0.9	1.1	1.1
Link 2-3	2.2	2.0	2.0	2.1
Link 4-3	2.0	2.3	1.9	1.9
Link 4-5	1.6	1.6	1.6	1.6
Link 15-5	3.5	3.6	3.5	3.3
Average Delay (Second/Mile)	Minor Road			
Link 18-2	3.1	3.8	3.7	3.8
Link 17-3	4.5	6.8	6.7	5.9
Link 22-3	6.8	7.3	9.8	8.3
Link 11-5	2.0	2.4	2.0	2.1
Link 16-5	4.3	4.7	4.5	4.5
Average Speed (Mile/Hour)	Main Road			
Link 1-2	26.8	27.1	27.5	28.4
Link 3-2	24.1	26.5	25.2	25.2
Link 2-3	17.2	18.3	17.9	17.7
Link 4-3	18.3	16.7	18.5	18.6
Link 4-5	20.3	20.8	20.3	20.8

Link 15-5	12.5	12.1	12.5	12.9
Average Speed (Mile/Hour)	Minor Road			
Link 18-2	11.7	10.4	10.5	10.4
Link 17-3	9.2	6.8	6.9	7.6
Link 22-3	6.8	6.5	5.1	5.8
Link 11-5	15.0	13.7	15.0	14.5
Link 16-5	9.6	9.0	9.3	9.2

Table 7 and Table 8 present the results in terms of percentage change from the base scenario.

Table 7. Change in Bus Delay for Different Scenarios

Bus Delay (Second)	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Route 1	0.00%	-77.61%	-71.64%	-70.15%
Route 2	0.00%	-81.65%	-36.70%	-64.22%

Table 8. Change in Network-Wide Average Delay per Mile for Different Scenarios

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Delay Time (Second/Mile)	0.00%	6.42%	0.76%	-1.80%

6.4 Results Analysis

6.4.1 Results Analysis for the Entire Gulfport Network

Table 2 presents the network-wide average statistics in terms of average delay and speed. Scenario 1 has relatively less delay and higher speed compared to the other three scenarios. But, the difference can be deemed negligible since it is within [-1.5%, +1.5%]. This result is consistent with Garrow [34] and Baker's [1] observations that a well developed TSP system offers significant benefits to the buses without compromising conflicting traffic.

Results from the route travel time comparisons of different scenarios are shown in Table 3. The average bus route travel time in Scenario 4 is 30.6 minutes, which is 12.82% lower than Scenario 1. Scenario 2 has the similar average bus route travel time as Scenario 4, while Scenario 3 has a slightly larger bus route travel time. Travel time on Route 2, Route 7, and Route 11 exceeds 60 minutes in Scenario 1, which is considered risky since there may be interruptions during emergency evacuation if the travel time is longer than 60 minutes. By implementing TSP and IntelliDrive in Scenario 4, travel times on those three routes are reduced from 61.3, 69.9, and 60.6 to 51.00, 60.75, and 49.67 minutes, which indicates a substantially improvement on transit reliability. In Table 6, longer travel time receives larger reduction in absolute value after implementing TSP. It implies that there may be more intersections on a bus route with longer travel time. Therefore, a bus traveling on that route may receive more benefits from TSP implementation. This phenomenon is important for the emergency evacuation because a longer route may experience many more interruptions than a shorter route in evacuation.

6.4.2 Results Analysis for the Small Network

For the small network, Figure 14 graphically shows the bus delay reduction by implementing TSP and IntelliDrive. In both Scenarios 2 and 3, bus delay is remarkably improved compared to Scenario 1. The bus travel time on Route 1 reduces from 256 seconds to 209 seconds by implementing TSP and IntelliDrive in Scenario 4 in comparison to Scenario 1. Correspondingly, bus delay on Route 1 is reduced from 67 seconds to 20 seconds. Similarly, Bus 2's delay time is reduced from 73 to 39. Baker et al. [1] indicated that TSP systems typically could reduce bus delay at individual intersections ranging from 6% to 57%. In this case, the bus delay is reduced by 70.2% and 46.6% which is beyond the average level. This reveals the benefit of IntelliDrive, which will be further demonstrated in the later part of this section.

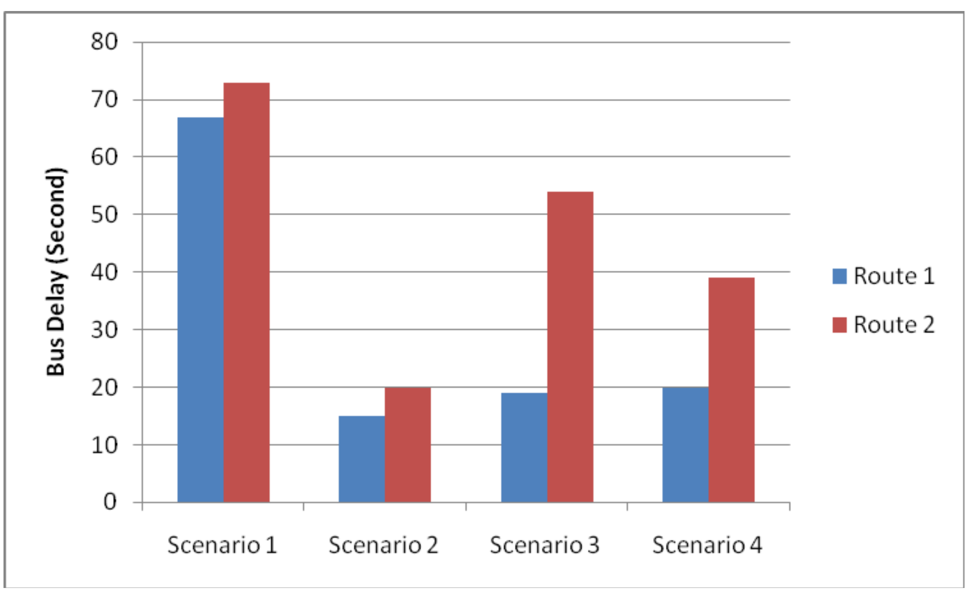

Figure 14. Average Bus Delay in Different Scenarios

Remarkably, Route 1 and Route 2 have similar length, but the bus travel time on Route 2 is much longer than the bus travel time on Route 1 in Scenario 3 and Scenario 4. Observation of the simulation shows that this is due to the bus prioritization logic built in the TSP optimization model. For example, in Figure 15, Bus 1 on Route 1 and Bus 2 on Route 2 are both approaching the intersection from the conflict approaches. Since occupancy is used to determine the bus prioritizations when multiple TSP requests are received, Bus 1, which has a higher occupancy, is granted priority even though Bus 2 arrives earlier than Bus 1 and there are queuing vehicles ahead of it. As a result, Bus 1 can go through the intersection with no stop, while Bus 2 has to stop and wait longer than a red interval since the red interval is extended. This causes Bus 2's delay to be significantly higher than Bus 1's delay.

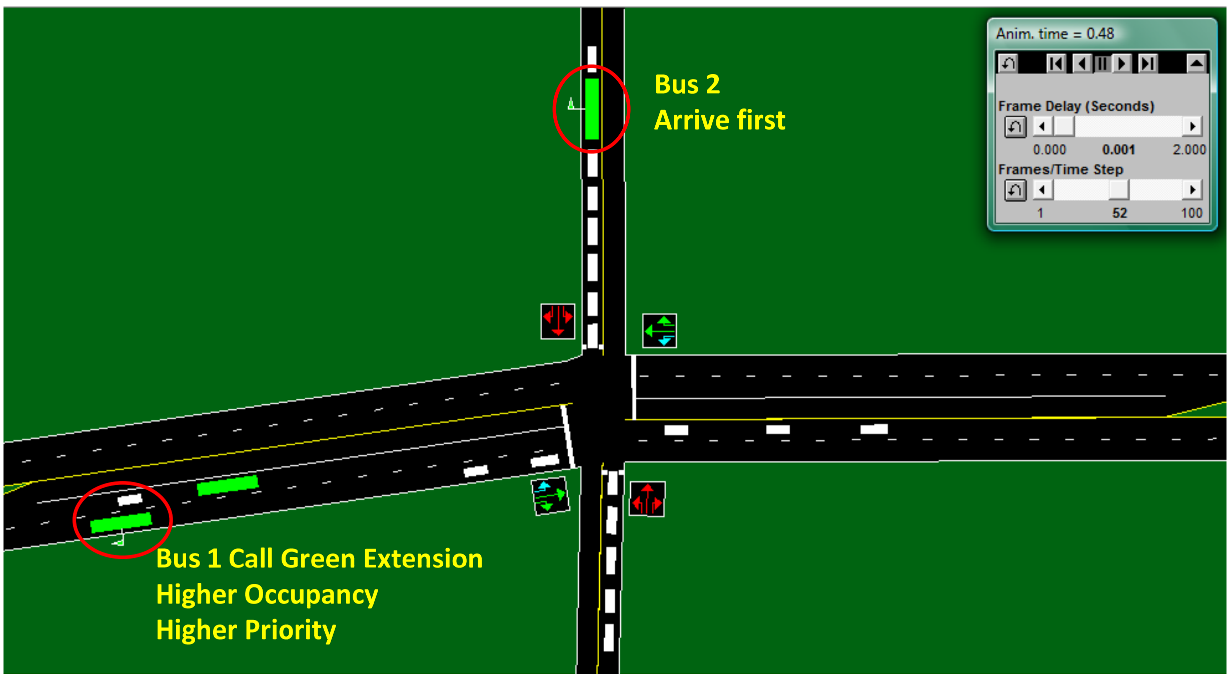

Figure 15. Bus Prioritization Example

Results from Table 8 indicate that no significant delay is caused by the implementation of TSP and IntelliDrive. The differences between Scenario 1, Scenario 3, and Scenario 4 are within ±5%, which is considered insignificant in a stochastic environment. Note that implementing transit signal preemption in Scenario 2 causes a 6.42% increase in network-wide delay. It looks insignificant, but results from Table 9 show that when the traffic volume is high, the delay caused by implementing the transit signal preemption increases rapidly. To amplify the effects of the increased demand, different cases under different volumes are tested. When traffic volume is increased by 20%, the difference between Scenario 1 and Scenario 2 can reach 13.92%, which means an extra 13.92% of delay is caused by implementing the transit signal preemption. Considering there is usually high traffic volume during an evacuation, traffic signal preemption's negative effect on network performance cannot be ignored. By contrast, TSP and IntelliDrive used in Scenario 4 can maintain the network-wide average delay within [-3%, +3%] of the base scenario, even the traffic volume increases 20%, and has proved its robustness in reducing bus delay. Many literatures [3, 14, 35] indicate that TSP has negative impacts on the network performance, particularly when traffic demand is high. But, during emergency evacuation, most buses run only once on a specified pickup route. Therefore, there is no aggregate impact coming from recursive buses on the route, resulting in insignificant impacts on network performance. The simulation results for the TSP strategy and IntelliDrive functionality in this project show only small increases in network delay with a 20% increase in traffic volume. This means that TSP can be a very desirable application during emergency evacuation.

Table 9. Change in Network-Wide Average Delay under Different Volumes

Average Delay (Second/Mile)	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Volume +20%	0.00%	+13.92%	+7.56%	+1.32%
Volume +15%	0.00%	+9.70%	+6.09%	+0.87%
Volume +10%	0.00%	+7.96%	+5.31%	+2.65%
Volume +05%	0.00%	+9.09%	+3.06%	+0.91%
Volume 00%	0.00%	+6.42%	+0.76%	-1.80%
Volume -05%	0.00%	+5.81%	+0.94%	+0.93%
Volume -10%	0.00%	+4.92%	+1.03%	-0.02%
Volume -15%	0.00%	+6.12%	+2.21%	+0.23%
Volume -20%	0.00%	+5.85%	+1.03%	+1.02%

It is important to analyze the impacts of TSP on general traffic. Table 6 summarizes the measures of effectiveness on the links connected to the signalized intersections. Consider Node 5 as an example. Node 5 is a signalized intersection on Route 1. Bus 1 travels from major road 4-5 to Node 5 and makes a left turn to minor road 5-11.

Table **10** presents the change in average person/vehicle delay for Scenario 1 and Scenario 4, categorized by major road and minor road. Delay on the major road links is reduced by 3-5%, while delay on the minor road links increases by 4-7%. The absolute value of increment of delay on minor road links is slightly larger than that on major road links. But, considering there is higher volume on major links, the overall measures of delay for the intersection remain unchanged.

Table 10. Change in Average Person/Vehicle Delay on Links for Scenario 1 and Scenario 4

Average Person Delay (second/person)	Scenario 1	Scenario 4	±%
Major Road			
Link 4-5	47.8	45.7	-4.39%
Link 15-5	32.3	31	-4.03%
Minor Road			
Link 11-5	24.4	26	6.56%
Link 16-5	29.1	30.6	5.15%
Average Vehicle Delay (second/vehicle)			
Major Road			
Link 4-5	43.7	41.5	-5.03%
Link 15-5	31.1	29.9	-3.86%
Minor Road			
Link 11-5	22.6	24	6.19%
Link 16-5	28.5	29.9	4.91%

As discussed in the previous section, one of the most critical parameters for the implementation of a TSP system is the maximum communication distance of IntelliDrive devices. For example, if the estimated bus arrival time is located in the green extension window, but it is detected during the red interval, green extension cannot be executed since the green interval has passed. At this time, the TSP system has to choose phase insertion instead of green extension. As indicated in TSP handbook [3], green extension is more favorable than the other two strategies because it causes less delay on normal traffic. Therefore, it is necessary to extend the communication distance in order to request green extension in this case. Additionally, longer communication distance allows the signal controller to have more time to adjust the signal timing plan. For example, if a bus is detected 3000 ft away from the controller, the controller could have enough time to slightly adjust the timing plan and coordination so that it could create a green band for the approaching bus. Figure 16 illustrates the sensitivity of the results to the maximum communication distance. The bus delay time on Route 1 and Route 2 decreases when the communication distance increases from 100 to 400 ft. This pattern indicates that the controller is able to choose a more appropriate TSP strategy as the maximum communication distance increases. But, there is no improvement on the bus travel time when the maximum communication distance reaches 400 ft, because the signal controllers are not programmed to adjust signal timing plans in this project. This function will be considered in the future project. Furthermore, there is no obvious trend to the network-wide average delay per trip. It almost keeps around 71 seconds per trip even though the maximum communication distance runs from 100 ft to 2000 ft. Therefore, the network-wide average delay per trip is not affected by the maximum communication distance. But, it can be expected that the network-wide average delay can be reduced with increasing the maximum communication distance if the controller is programmed to adjust the signal timing plan based on the real time traffic data. This perspective of this work is discussed in the future work section.

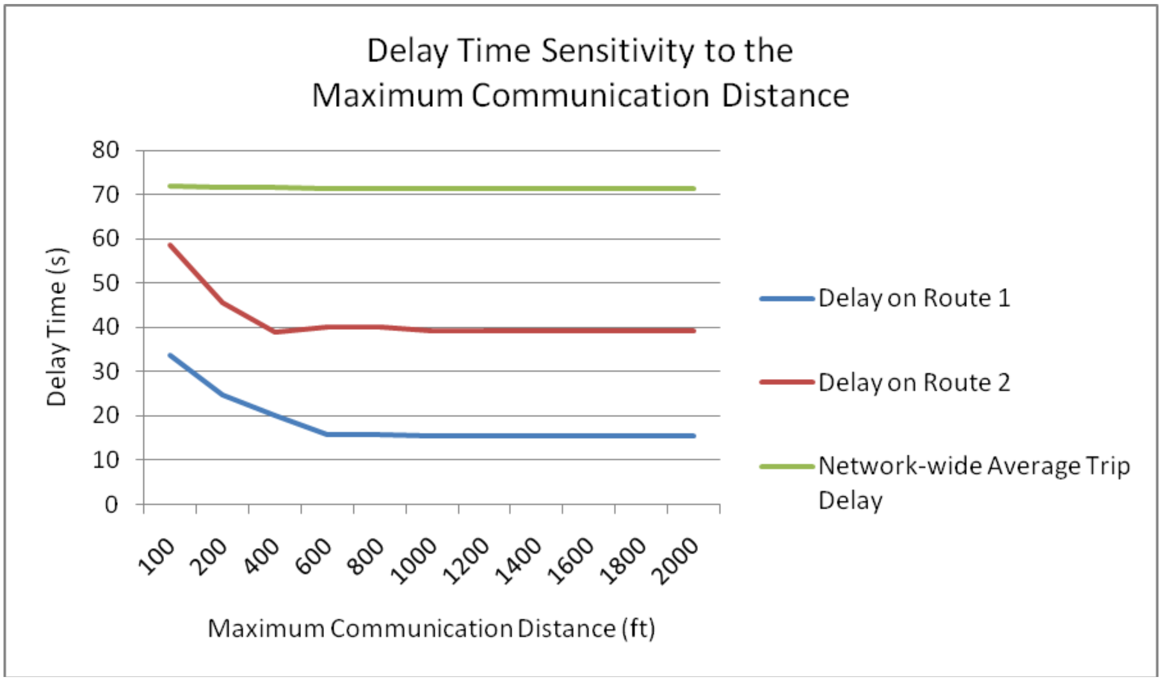

Figure 16. Bus Travel Time under Different Maximum Communication Distances

During an emergency evacuation, traffic conditions may be unstable. Buses may experience extreme high traffic volumes or unexpected interruptions on their routes. IntelliDrive can help bus drivers communicate with traffic signal controllers or the Traffic Management Center (TMC) dealing with unexpected conditions. In this project, IntelliDrive can help traffic signal controllers adjust the optimum TSP strategy when the bus is approaching. For example, when Bus 1 is traveling on link 4-5, the signal controller at Node 5 keeps updating the TSP strategy for Bus 1. The TSP strategies are updated as following:

Phase Insertion → Early Green → Green Extension

First, phase insertion is selected when the bus is 400 ft away from the controller. Since there is congestion at Node 5, bus arrival is delayed more than estimated. Therefore, the signal controller updates the TSP strategy from phase insertion to early green, as shown in Figure 17. But, when the bus is preparing a left turn, there is no gap available because of too many through vehicles from the opposite link 15-5. As a result, the signal controller updates the TSP strategy from early green to green extension. After clearance of the opposite vehicles, the bus takes the opportunity to make a left turn, as shown in Figure 18.

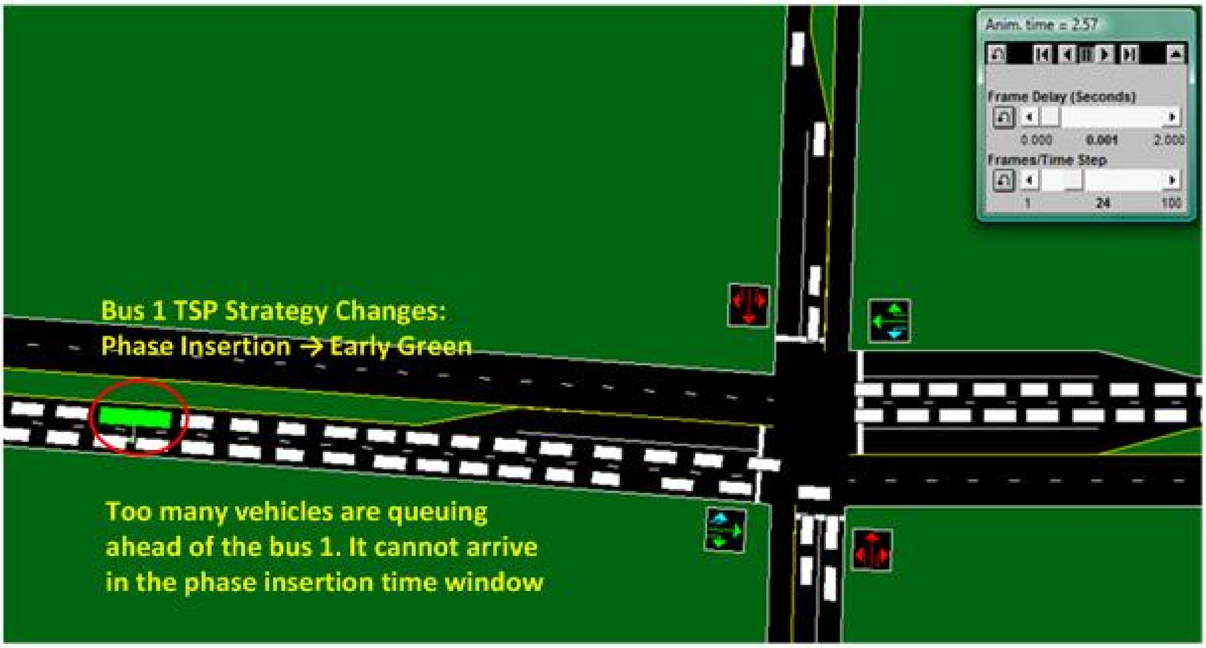

Figure 17. TSP Strategy Update from Phase Insertion to Early Green

Figure 18. TSP Strategy Update from Early Green to Green Extension

Another example observed in the simulation is shown in Figure 19. Bus 2, which is marked in the red circle, calls early green on the eastbound link, but the left turn pocket is blocked by through and right turn vehicles due to the high volume on the link. Therefore, the traffic signal controller has to terminate the current protected left turn phase and starts early green for the next all-green phase. After clearance of all the vehicles blocking the left turn pocket, Bus 2 is able to make a left turn.

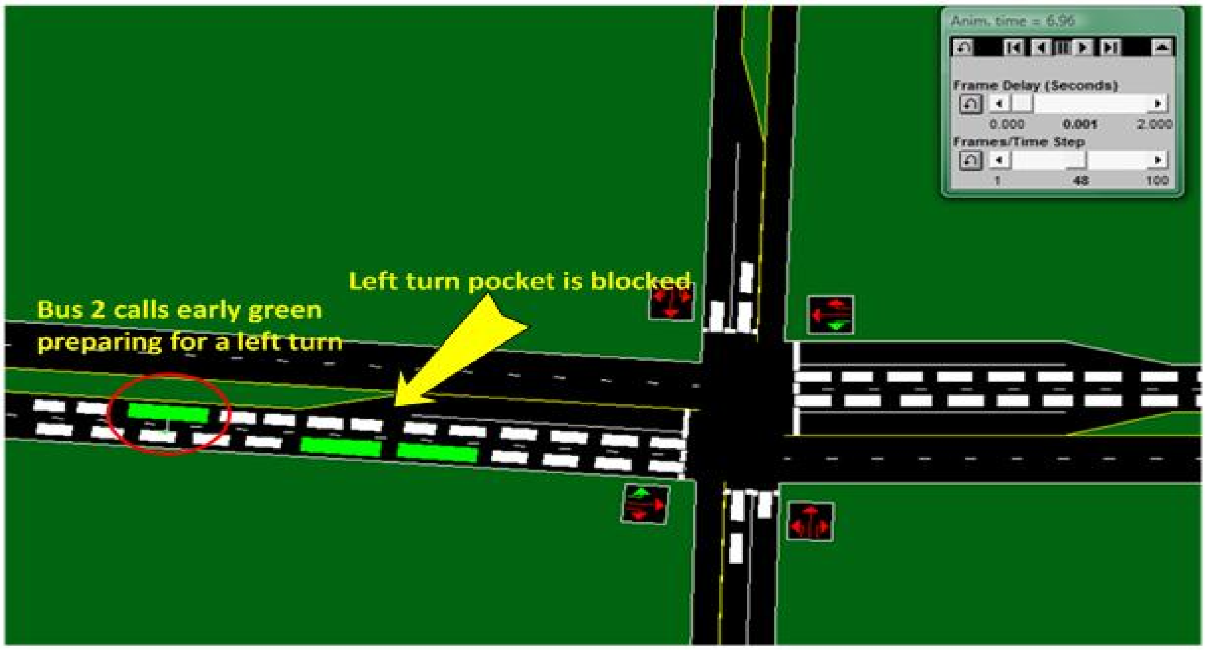

Figure 19. TSP Strategy Update from Early Green to Early Green

7.0 Conclusions and Future Work

The objective of this project is to explore the TSP and IntelliDrive coordination and evaluate the impacts of the proposed TSP strategies on transit-based emergency evacuation. This section highlights the major findings and conclusions reached from the analysis documented in this report. Also, future research needs are identified as part of this project and are summarized in this section.

7.1 Summary

This project has presented a study on the TSP and IntelliDrive coordination and application in transit-based emergency evacuation. A TSP optimization model that integrates with U.S. DOT's IntelliDrive Initiative functions has been developed. It has been designed with a generic control logic that allows us to simulate a wide range of TSP strategies. The control logic of the TSP optimization model is on the basis of a set of basic elements including bus arrival time, queue length, signal states, other signal controller status, bus schedule, etc. The generic logic allows the traffic signal controller to adjust the optimum TSP strategy according to the bus information and traffic conditions around the intersection. A bus travel time prediction model has been proposed to predict the bus arrival time at the intersection on the basis of the real time bus information from IntelliDrive. The IntelliDrive ensures that the bus data continues to be available to the signal controller at a wide range and at a required reliability level during emergency evacuation. This allows the signal controller to have more flexibility to update the TSP strategy in advance. A bus routing optimization model has been developed to formulate the bus allocation-routing problem. A hybrid Genetic Algorithm, which was developed under the sponsorship of a previous project, has been applied for solving the problem. This allows TMC to reschedule bus a route based on the real time traffic information collected by IntelliDrive.

CORSIM, advanced traffic simulation software commonly used in United States, has been utilized for simulating the proposed optimization models. CORSIM RTE has been developed to embed optimization models and algorithms in the simulation. In addition to CORSIM's built-in functions on traffic signal control and vehicle routing logic, RTE allows users to easily develop additional traffic signal control and vehicle routing functions. CORSIM also provides interface with other traffic signal management software for implementation of advanced TSP logic.

In order to identify the effectiveness of the proposed TSP optimization model, a case study of the Gulf Coast was conducted based on the actual traffic network and evacuation information.

Results from different scenarios, including a no-priority scenario, a preemption scenario, a TSP scenario, and a TSP with IntelliDrive scenario, were compared under various conditions and under alternate parameter settings.

7.2 Findings

Some of the important findings are listed below:

1. Implementation of TSP and IntelliDrive can substantially reduce the bus travel time of 12.8% without seriously interrupting conflicting vehicles. Especially for the buses with longer travel time, TSP coordinated with IntelliDrive can reduce their travel time at a more significant level.

2. IntelliDrive can help traffic signal controllers optimize TSP strategy. With the bus data from IntelliDrive, traffic signal controllers can have more than enough time to update the optimum TSP strategy in a very short interval.

3. Scenario 4 outputs much better results than Scenario 2 and Scenario 3 in network-wide performance. This indicates that IntelliDrive could help in reducing negative impacts on conflicting links, especially when the volume is high. The average network-wide delay increases only 1.3% in Scenario 4 comparing to 7.6% in Scenario 3 and 13.9% in Scenario 4.

4. The TSP strategy can be improved by increasing the maximum communication distance of IntelliDrive devices.

7.3 Future Work

While this project provides valuable insights into the coordination of TSP and IntelliDrive on transit evacuations, other issues should be investigated to further validate the model and improve its applicability.

1. *Improve existing TSP optimization model.* The traffic signal priority will be optimized while we consider maintaining the coordination with nearby signal controllers. More advanced TSP strategies will be investigated and applied in the model. Additionally, we will improve the TSP system to manage the bus dwell time at the pickup points so that a bus can progress in the coordination green band through the network.

2. *Apply the TSP optimization model to the actuated signal control.* Existing models and logics are based on fixed-time control. The drawback of the TSP implementation on

fixed-time control is that it cannot adjust the signal timing plan according to the changes in traffic conditions caused by TSP operations. Currently, it cannot adjust the signal timing plan and coordination for the approaching bus. In the future, IntelliDrive will provide more accurate and up-to-date traffic data to the actuated controller. It is necessary to develop TSP models and logics applicable on the actuated controller so that it can take full advantage of IntelliDrive on TSP optimization.

3. *Improve the existing TSP optimization and bus routing optimization algorithms.* After applying the TSP optimization model to the actuated signal control, the current TSP optimization algorithm will be revised in order to optimize the signal timing plan under the actuated control. Also, we will improve the efficiency of the current bus routing optimization algorithm so that it could be used in real time.

4. *Conduct field studies to validate the applicability of the proposed TSP system to real world conditions.* Measures of effectiveness from field experiments will be compared with the results from simulation. It is currently in discussion with transit agency to implement the proposed TSP system into the real bus management system.

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The people who participated directly in this project include the following:

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