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Integrated Special Event Traffic Management Strategies in Urban Transportation Network

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INTEGRATED SPECIAL EVENT TRAFFIC MANAGEMENT STRATEGIES IN URBAN TRANSPORTATION NETWORK

by

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ABSTRACT

INTEGRATED SPECIAL EVENT TRAFFIC MANAGEMENT STRATEGIES IN URBAN TRANSPORTATION NETWORK

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How to effectively optimize and control spreading traffic in urban network during the special event has emerged as one of the critical issues faced by many transportation professionals in the past several decades due to the surging demand and the often limited network capacity. The contribution of this dissertation is to develop a set of integrated mathematical programming models for unconventional traffic management of special events in urban transportation network. Traffic management strategies such as lane reorganization and reversal, turning restriction, lane-based signal timing, ramp closure, and uninterrupted flow intersection will be coordinated and concurrently optimized for best overall system performance. Considering the complexity of the proposed formulations and the concerns of computing efficiency, this study has also developed efficient solution heuristics that can yield sufficiently reliable solutions for real-world application. Case studies and extensive numerical analyses results validate the effectiveness and applicability of the proposed models.

To

my parents,

my wife,

and my son

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Chapter 1: Introduction

1.1 Background

Special event, as an occurrence that abnormally increases traffic demand (like an incident or construction and maintenance activities that typically restrict the roadway capacity), was defined by the National Highway Institute in 1998. Under this definition, special event can be categorized as frequent or infrequent. Frequent special event include such as sporting event, commencements, concerts, festivals, and conventions occurring at permanent multiuse venues (e.g., arenas, stadiums, racetracks, fairgrounds, amphitheaters, convention centers, etc.). Summer-long event series and seasonal tourist venues that temporarily increase traffic demand are also included. The size of these event is likely manageable, with predictable times of day and durations. The scope of impact is anticipated to be local or possibly regional. Infrequent special event include sporting game, bicycle races, firework displays, seasonal festivals, milestone celebrations at temporary venues, parades, fairs and other less frequent public event. The amount of traffic associated with infrequent event may be dramatically larger than for frequent event. Hence, the impact is likely regional or statewide rather than local. The duration of these types of event is also likely longer than that of the frequent event (e.g., several days versus several hours). Special event could result in a surge in travel demand and may require road closure to stage the event, thus impacting the entire transportation system operations. This includes freeway operations, arterial and street operations, transit operations, and pedestrian flows in the transportation network, causing high levels of congestion and creating a big challenge for transportation authorities. For instance, London, in 2003, caused tailbacks up to 10 miles on the highway A1 towards the stadium (Lei-lei et al., 2012). Similarly, the concert of Rihannain Johannesburg (South Africa) in October 2013 caused people to sit in traffic for as long as five hours, trying to reach the stadium (Kwoczek et al., 2014). Recently, on 24 September 2015, an overcrowding situation caused the death of, at minimum, 1,100 people who were suffocated or crushed to death during the annual Hajj pilgrimage in Mina, Mecca.

In response to the above challenges, special event traffic management refers to spreading traffic onto alternate routes to mitigate congestion with the use of pre-event publicity, dynamic message boards, or road closures. The process involves various issues, such as event type identification, message dissemination, and socioeconomic attributes of travelers, preparedness/response organizations, and expected response patterns (Sorensen et al., 1987). Responsible agencies usually need to predict the temporal/spatial evolution of the event impacts, decide the control area, issue and publicize the traffic management plan, estimate traffic demand as well as traveler response patterns, guide traffic to proper routes, and update traffic signals to efficiently move people out of the impacted zone. In view of all such complexities and the often limited capacity of transportation infrastructure, how to effectively manage traffic so as to best utilize available network capacity has emerged as one of the primary research issues in special event planning and management.

Pioneering studies on evacuation planning and traffic management focused on emergency evacuations where many researchers have made significant contributions (Gillis, 1990; Lambert and Wolshon, 2002; Wojtowicz and Wallace, 2010; Hua et al., 2013; Wolshon, 2001; Theodoulou and Wolshon, 2004; Xie et al., 2010; Ren et al., 2012; Chen and Xiao, 2008; Ng and Waller, 2010a,b; Xie et al., 2010; Ayfadopoulou et al., 2012; Sheffi et al., 1982; Southworth, 1991; Hobeika et al., 1994; Pidd et al., 1996; Urbina and Wolshon, 2003; Chalmet et al., 1982; Hamacher and Tufekci 1987; Miller-Hooks and Patterson 2004; Murray-Tuite and Wolshon 2013; Liu et al. 2008). However, previous research efforts on emergency evacuation are difficult to be applied to special event traffic management due to their different problem natures (e.g. objectives, demand distribution patterns, traveler behaviors, and management strategies).

Existing special event traffic management strategies are limited, primarily focused on demand control (e.g., shifted departure time), capacity enhancement (contraflow and arterial signal optimization), or a better match of the demand pattern and the available network capacity via traffic routing (Veneziano et al, 2007; Suzane et al 2009; Yuan et al, 2009; Jeffrey Wojtowicz et al, 2010; Liu et al, 2011; Shakibaei et al 2013). Although these popular traffic management strategies have been reported in the literature or, in some cases, even applied in actual operations, there exist some technical deficiencies that remain to be overcome. For examples,

- Most of the traffic management strategies used for special event management are traditional and may not be sufficiently effective to address non-recurrent congestion problems caused by special event. The potential and benefits of non-traditional strategies (e.g. lane reorganization, uninterrupted flow intersections, lane-based signal control) in special event traffic management have not been sufficiently investigated.
- There lacks an overall operational framework or guidelines that can effectively integrate different types of strategies for special event traffic management. If implemented concurrently, different traffic management strategies will apparently interact with each other and affect traffic flows in the same time-space network. A properly designed lane reorganization plan may reduce the need for contraflow operations, while an arterial with effective traffic signal-timing plans will certainly better accommodate traffic demand from traffic routing.

- Some unnecessary or unrealistic assumptions have been employed in the literature for design of traffic management strategies. For example, contraflow strategies should take into account the geometric features and their discrepancies among different arterial segments so as to avoid creating local bottlenecks.

1.2 Research Objectives

The primary objective of this dissertation is to develop an overall operational framework embedded with a set of integrated mathematical programming models for special event traffic management in urban transportation network. This research is expected to assist responsible agencies/operators in generating effective network-level traffic management plan under various scenarios of special event. More specifically, this research contributes to:

- Develop realistic representation of the spatial and temporal interactions among traffic flow distribution in the network due to time varying demands and congestions that often incur during special event;
- Develop mathematical optimization models with real world operational constraints to best trade-off, select, and integrate various strategies for special event traffic management under different network configurations (e.g. static and dynamic networks, grid network sand mixed freeway and urban corridors) and traffic scenarios;
- Design high-efficiency solution algorithms to solve the proposed models for large-scale and real-world applications; and
- Design an operational framework to apply the developed models to real-world cases, and provide guidelines to responsible transportation authorities.

1.3 Thesis Outline

Based on the proposed research objectives, this study proposes to organize the primary research activities into eight chapters. The core of those tasks and their interrelations are illustrated in Figure 1.1.

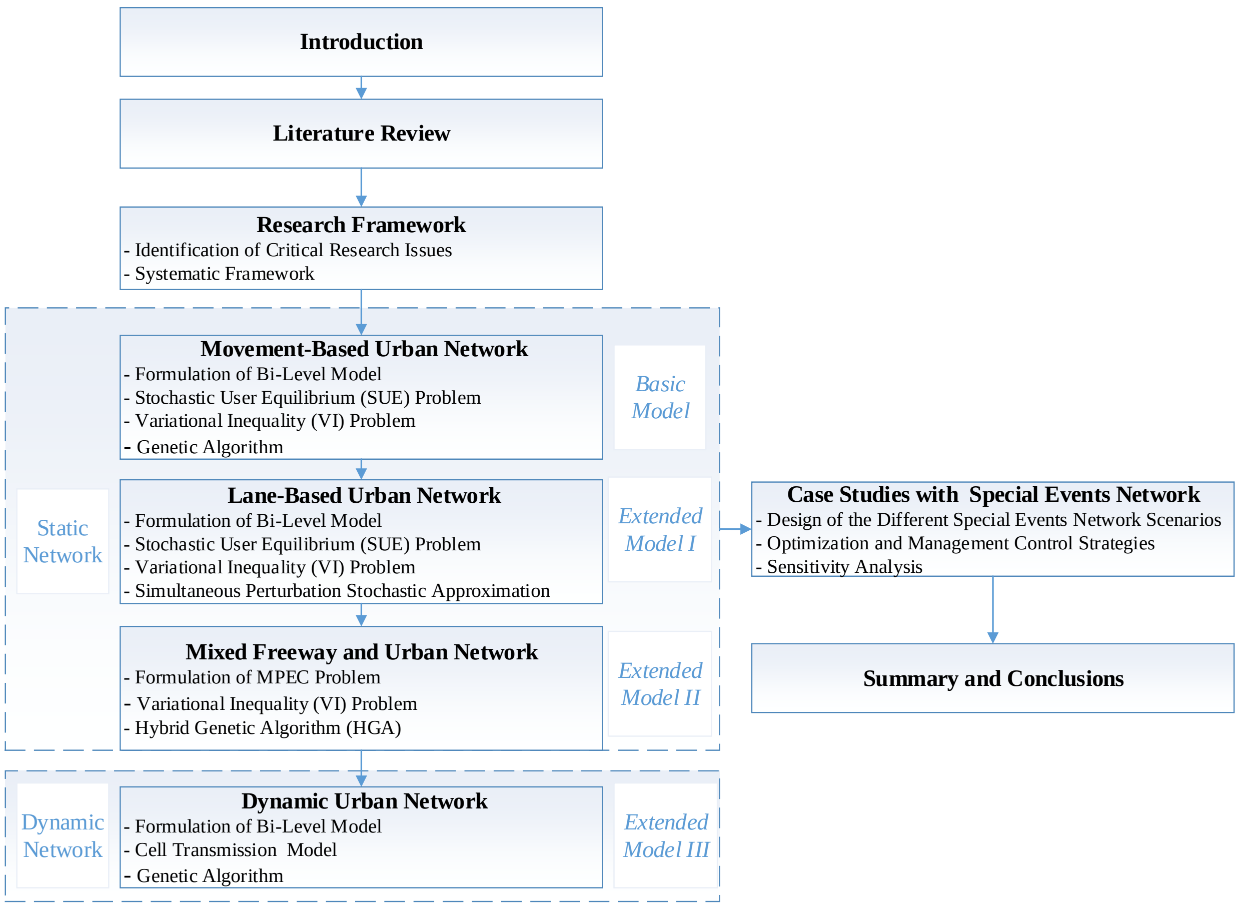


Figure 1. 1 Dissertation Organizations

The remaining chapters of this dissertation are proposed to be organized as follows:

- **Chapter 2** presents a comprehensive review of relevant research, including network traffic flow formulations, non-traditional traffic management strategies, traffic signal control models, and solution methods, freeway operations. The review focuses on identifying the advantages and limitations of those studies, along with their potential enhancements.

- **Chapter 3** illustrates the modeling framework of the proposed research, based on critical operational issues that need to be addressed in design of special event traffic management strategies. It briefly describes the functions of each principle modeling component and their operational interrelations, which provides the foundation for the identification of research tasks for this study.
- **Chapter 4** develops a movement-based network representation scheme and a base model formulation for special event traffic management in a simplified static urban transportation network. Traffic movement reorganization and restriction, signal timing optimization, and uninterrupted flow strategies are best selected and prioritized at critical road network segments and intersections for maximum network operational efficiency under the available budget. The proposed model, incorporating a parametric variational inequality (VI) to formulate the stochastic user equilibrium (SUE) behavior of travelers in route choice, is expected to provide effective solutions to the following critical questions that have long challenged transportation professionals for special event traffic management: 1) how many intersections should be implemented with the signals and interrupted flow controls; 2) what would be the optimal spatial distribution for those intersections in the target network; and 3) how to best design turning restriction, channelization, and signal timings in the network? In view of the large number of variables and constraints for the proposed model, this chapter will develop an efficient heuristic approach embedded with a diagonalization algorithm to yield the meta-optimal solutions. Extensive numerical analysis with the case in Washington DC will be performed to demonstrate the applicability and effectiveness of the proposed model.

- **Chapter 5** further extends the base model presented in Chapter 4 by proposing a new network representation scheme that can better capture the traffic flow interactions at the lane level. Such modeling features offer the capability to use more sophisticated and effective lane-based traffic management strategies (e.g. lane reorganization and reversal, cross elimination, lane-based signal, etc.) to further improve the overall network capacity and operational efficiency during special event. The extended model will feature a bi-level structure with equilibrium constraints. Considering the high-dimensionality of its decision variables, this chapter further develops a fast-convergent projection method algorithm based searching heuristic to solve the model to meta-optimality for real-world applications.
- **Chapter 6** presents formulations of optimal traffic management strategies for the mixed freeway and arterial corridor considering its critical role in improving highway system efficiency and mobility. Network flow formulations that capture interactions between the freeway and arterial are developed. Ramp control strategies and detour operations will be supplemented in the existing modeling framework to best coordinate the freeway system and the arterial system during special event management. A Hybrid Genetic Algorithm (HGA) will be developed to solve the proposed model. Case studies with a hypothetical construction work zone on mixed freeway network will be performed to demonstrate the effectiveness of the developed models.
- **Chapter 7** presents the mathematical model formulations for special event traffic management in a dynamic transportation network considering the time-varying traffic demand and network characteristics that often occur in a special event. The model features a bi-level structure with the upper level searching for the best traffic

management strategies by minimizing the total event clearance time, and the lower level handling routing assignment of the traffic demand with a single-destination user-optimal DTA problem. The cell transmission model (CTM) is adopted to mathematically represent dynamic traffic flow evolution and queuing in the network. To deal with the combinatorial complexity of the proposed model, this chapter will also develop heuristic solution algorithms.

- **Chapter 8** summarizes the contributions of this dissertation and the directions for future research.

Chapter 2: Literature Review

2.1 Introduction

In view of the large body of literature relevant to special or non-recurrent event traffic management strategies and network optimization models, this chapter will present a comprehensive review of these research efforts. The purpose is to identify the special characteristics, strengths, and deficiencies of existing studies and thus to define the primary direction for this dissertation.

To facilitate the presentation, this chapter has divided related traffic management strategies into three categories: geometric design strategies, signal control strategies, and traffic routing strategies. Network flow formulations that are employed in traffic management and optimization are also reviewed.

2.2 Traffic Management Strategies

2.2.1 Geometric Design Strategies

Geometric design strategies such as lane reversal, one-way street, turning restriction and cross elimination have demonstrated their effectiveness in enhancing transportation network capacity. However, how to select the most appropriate combination of those strategies in a special event network remains challenging to transportation professionals considering the complex interactions among those strategies and their impacts on conventional traffic control components.

In review of literature, commonly adopted geometric design strategies for network enhancement include lane reversal, turning restriction, one-way street operation, and cross elimination (Wolshon and Lambert, 2004).

2.2.1.1 Lane Reversal

Lane reversal, also termed contraflow or counter flow, has been used for several decades as a traffic control technique to accommodate frequent and predictable unbalanced traffic demand between two driving direction of a congested roadway section. Lots of lane reversal studies, for example, MacDorman (1965), Glickman (1970), Hemphill and Surti (1974), and Caudill and Kuo (1983), focused on its design, efficiency, feasibility and safety problems.

An update on the development of lane reversal techniques and applications as well as its current state of special event management (Lambert and Wolshon, 2002; Wojtowicz and Wallace, 2010; Hua et al., 2013), and emergency evacuation (Theodoulou and Wolshon, 2004; Williams et al., 2007; Ren et al., 2012) was provided. The key idea is to configure the lanes of a roadway to match available capacity with traffic demand. In evacuation cases, it has been suggested that the traffic direction of the inbound lanes of eligible roadway segments may be reversed for the overwhelming outbound traffic so as to increase the outbound capacity. Since late 1990s, lane reversal has been widely used in the states along the Atlantic and Gulf Coasts of the U.S. for hurricane evacuations (Urbina and Wolshon, 2003).

The use of contraflow traffic operations during evacuations increased significantly after Hurricane Floyd in 1999 when it was implemented for the first time on a significant scale (Murray-Tuite and Wolshon, 2013). Contraflow is a form of reversible traffic operation in which one or more travel lanes of a divided highway are used for the movement of traffic in the opposing direction (Aashto, 2001)(American Association of State Highway and Transportation Officials, 2004). It is a highly effective strategy because it can both immediately and significantly increase the directional capacity of a roadway without the time or cost required to plan, design, and construct additional lanes. It is also popular with the public because it is viewed as a logical utilization of the unused lane capacity of adjacent inbound lanes. Recently, contraflow is one of the most widely used traffic management techniques in states threatened by hurricanes and has been developed for use in coastal states from New Jersey to Florida on the Atlantic seaboard and from Florida west through Texas along the Gulf of Mexico (Wolshon, 2001). The effectiveness of contraflow during a live operation was quantified for the first time by Wolshon (2008) based on traffic counts recorded during the Hurricane Katrina evacuation of south Louisiana in 2005. The flow rates measured during this event were about 75% of the adjacent normally flowing lanes. Although no firm explanation for these lower rates has been determined, this reduced flow is consistent with modeling predictions (Post, 2000) and simulation studies (Lim and Wolshon, 2005; Theodoulou and Wolshon, 2004; Williams et al., 2007).

2.2.1.2 One way Street

An extreme case of the lane reversal is the one-way street strategy in which the conversion takes place in the entire roadway. Experimental studies have quantified the trip-serving capacity of the one-way street strategy (Dorroh and Kochevar, 1996; Vo et al., 2015; Chiu et al., 2007) however those results tend to be site-specific and generalization to other networks cannot be made. Gayah and Daganzo (2012) compared the trip-serving capacities of one-way and two-way networks based on macroscopic analyses. It was found that two-way networks can serve more trips per unit time than one-way networks when average trip lengths are short. Similar to the turning restriction strategy, one-way street is not always beneficial due to the resulting extra vehicle detour distance. Realizing this, some researchers have developed optimization models to select the most appropriate segments for one-way traffic organization (Tuydes, 2005; Feng et al., 2009; Dongfang et al., 2010).

2.2.1.3 Turning Restriction

Turning restriction is one of the most commonly used strategies to improve the capacity of signalized intersections in an urban evacuation network (Yu and Prevedouros, 2012). The resulting capacity increase is due to the reduced number of signal phases and less loss time. However, vehicles in prohibited movements are forced to detour, which may induce extra driving distances in the network. In the NCHRP Report 457 (Bonneson and Fontaine, 2001), proposed guidelines to identify the conditions for left-turn restriction at existing intersections; however where to implement turning restrictions was not discussed in the report. Some researchers in recent years have formulated discrete network design problems with a bi-level structure to optimize turning restriction settings in the transportation network (Long et al., 2010; Guang and Wu, 2013). Wang et al. (2012) considered different restricted movements and developed a system optimal cell transmission–based model to optimize the selection of the crossing movements to be eliminated to minimize the overall evacuation clearance time. Jahangiri et al. (2014) also developed a bi-level approach to determine the optimal movement restriction configuration and four-leg intersection selection during a no-notice evacuation. Other studies Cova and Johnson (2003) attempt to eliminate conflicts between movements at an intersection and convert signalized intersections into uninterrupted flow ones (also termed crossing elimination). (Luo and Liu, 2012; Luo et al., 2013) optimized the distribution of signal control and uninterrupted flow intersections with resource constraints in static and dynamic network settings. Integrated models (Xie et al., 2010; Xie and Turnquist, 2011) were also proposed to combine crossing elimination and lane reversal strategies during emergency evacuation.

2.2.1.4 Cross Elimination

Another traffic management strategy that has been suggested to facilitate the movement of traffic during urban evacuations is the elimination of certain turning and crossing maneuvers at intersections. Cova and Johnson (2003, 2012) first suggested using this measure as a lane-based routing strategy for emergency evacuations to reduce traffic control delays (e.g., delays due to traffic signals and stop signs) at intersections. The basic rationale of applying the crossing elimination for evacuation is to convert an intersection with interrupted flow situations to an uninterrupted flow facility by prohibiting some turning movements through blocking lane entries and limiting flow directions. Without the stop-and-go traffic control setting, the intersection capacity for those allowable traffic movements is significantly expanded. Based on an integer extension of the minimum cost flow problem, it was used to generate routing plans that trade total vehicle travel-distance against merging, while preventing traffic crossing-conflicts at intersections. These plans were then evaluated using capacity analysis and microscopic traffic simulation techniques. The results of these analyses showed up to a 40% reduction in travel time depending on the network configuration and hazard scenario. Cova and Johnsons general idea has recently been extended by several other researchers, such as Xie and colleagues (Xie et al., 2010; Xie and Turnquist, 2011).

The benefits from implementing the intersection crossing-elimination strategy for evacuation traffic management are threefold. First, it is a desirable control measure to increase the traffic throughput capacity at intersections so as to better serve the exceedingly high traffic demand under emergency conditions. Second, it channels traffic flow along certain routes and improves traffic safety under emergency situations. Third, in the case of a post-disaster evacuation, it may become a critical and necessary remedy measure for intersection traffic control when the traffic signal and communication system fails due to widespread power outages.

Such a system failure often occurs in the evacuation cases of no-notice disasters. In the aftermath of the 1985 Mexico City earthquake, for example, most of the traffic signals in the city network were not functional because of the loss of electric power, damage of traffic sensors, and communication interruption (Ardekani and Hobeika, 1988).

2.2.2 Signal Control Strategies

Traffic signal operation during the spreading traffic process plays a key role for special event when moving people away from dangerous places. Signal control has been widely accepted as an effective strategy to increase arterial capacity and to mitigate congestion during daily traffic scenarios. Despite the large body of literature related to signal control (Boillot,1992 and Papageorgiou et.al., 2003), most such researches have not focused on contending with non-current congestion in urban network of special event. Usually, researchers have employed special signal control strategies to address non-current congestion situations for normal traffic condition at high demand levels. Thus, this section will review only key models for special signal control strategies, including signal control strategies under abnormal operations and lane-based signal control strategies.

2.2.2.1 Signal Control Strategies under Abnormal Operations

For evacuation operations, Post (2000) proposed that an optimal signal time scheme could enhance the capacity of intersection of urban transportation network that provide access to/from evacuation routes and prevent bottlenecks at their access points. Various other documents associated with evacuation planning have also proposed to include arterial signal control as an integrated part of the overall evacuation control strategy (Perry and Lindell, 2003; Ballard and Borchardt, 2006).

Despite this wide recognition of the critical role of signal control in emergency evacuation, the development of spreading traffic signal-timing plans has received limited attention in the literature. The current researches for traffic management strategies are divided into two groups that are application of simplified controls strategies based on experience and application of standard signal optimization practices for normal traffic conditions with high demand, respectively.

Among the first group, Chen et al. (2007) applied the microscopic simulation software CORSIM for two evacuation corridors of Washington, D.C., and examined four different signal-timing plans: 1) Red Flash Plan, providing red flash phase to all approaches; 2) Yellow Flash Plan, providing a yellow flash phase to arterial and a red flash phase to side streets; 3) Minimal Green Plan, which uses the longest cycle length the controller allows while offering only minimal green phases to side streets; and 4) Ordinary Peak Hour Plan, which was designed based on normal afternoon peak hour traffic conditions. Although this study offered some insights into the effects of different timing plans, its analysis of plan selection under various evacuation scenarios is mostly qualitative.

Among the second group of practices, Sisiopiku et al. (2004) used the signal optimization software SYNCHRO to establish the optimal signal-timing plans for a small area in Birmingham, Alabama. They then used the CORSIM simulator to test different evacuation plans and evaluated the impacts of signal-timing optimization on the selected measurements of effectiveness. The results suggested that traffic signal optimization could significantly reduce average vehicle delays and improve evacuation time. McHale and Collura (2003) applied another signal optimization program, TRANSYT-7F, to generate the optimal signal-timing plan when assessing the impact of emergency vehicles preemption strategies in a CORSIM simulator.

In addition to modeling work that looked specifically at signal timing and coordination, another branch of recent modeling work has evolved to examine network signal control strategies. Work by Liu et al. (2007) involved the development of a model reference adaptive control framework for real-time traffic management under emergency evacuation. The idea of the system was to be able to dynamically control traffic flow under evacuation conditions in such a way that the overall performance of the system could be improved during the emergency by using prevailing traffic conditions to produce traffic control schemes in real-time. Simulation studies done in conjunction with the project showed it could significantly improve the performance evacuation traffic networks.

2.2.2.2 Lane-based Signal Time Control Strategies

Over the past decades, various signal optimal control strategies have been developed and studied by many research. In the context of signal settings optimization at isolated intersection, there will be broadly classified two streams: The first stream develops optimization models to determine optimal lane allocation, signal phase, and signal timings for conventional intersection. Early studies in this stream including Webster (1958), proposed one of first systematic mathematical framework for traffic signal design problem. In his studies, the signal cycle was divided into separate stages. The green times were allocated to the stages according to the ratio of arrival flow to saturation flow for the representative arm in each stage. A more general approach to the problem was developed by Allsop (1971a) in which the calculation of signal settings was formulated as a convex mathematical programming problem to minimize the total delay on all approaches to an isolated junction. An ad hoc procedure was derived to solve the problem. Allsop (1972) extended the approach to the determination of capacity-maximizing signal settings, and formulated the problem as a linear program that was solvable by any standard linear programming routine. These mathematical programming approaches were implemented in computer programs (Allsop, 1971b, 1975, 1981), and more recently to lane-based methods where lane allocations are simultaneously optimized (Wong and Wong, 2003; Wong and Heydecker, 2011).

For combined signal settings and assignment problems, Allsop (1974) was among the first to suggest that signal control could be explored to affect the distribution and assignment of traffic on an equilibrium network, and he provided a rigorous mathematical framework for the problem. An extensive literature is devoted to the optimization of signal settings at isolated junctions, in which the arrival pattern of traffic is assumed to be of the Poisson type. The combined lane marking and signal time setting design was first proposed by Lam et al. (1997). They enumerated all possible sets of lane marking from each approach, and then formulated a mixed integer program to maximize the sum of flow factors from all approaches, and finally solved the program by a heuristic solution procedure that consisted of three stages of green time allocations to traffic and pedestrians' movement. They showed that by including the lane marking design in the optimization procedure, substantial improvement in the junction performance could be achieved. However, the maximization of the sum of flow factors may not always lead to the maximization of the junction capacity. Moreover, the allocation of green times to pedestrian crossings was conducted at the later stage of the optimization heuristics, and is usually subject to lower priority. To overcome these difficulties, Wong and Wong, (2003) developed a lane-based optimization method that combined lane marking design and signal timing calculation for determining the capacity maximizing and cycle length minimizing signal timing settings for an isolated intersection, which was formulated as BMILP that was solved by any standard branch-and-bound algorithm. Wong and Wong (2002) extend the lane-based optimization method to solve the combined lane marking design and signal optimization in a traffic equilibrium network.

Wong and Heydecker, (2011) proposed a lane-based optimization method to further relax the numbers of approach lane in traffic arms as new integer variables which can then be optimized to give optimal lane arrangement in various arms of a junction to manage the given traffic demands more efficiently. All well-defined signal timings variables in the phase-based approach as well as the lane marking and lane flow variables in the lane-based approach together with their governing constraints are all preserved in the new formulation for the reserve capacity optimization of isolated signal-controlled junctions The present study extends the lane-based optimization method for determining a combined set of lane markings and signal settings to minimize the traffic delay at an isolated signal-controlled junction. In order to get the minimum total intersection delay at insolated junction in the lane-based optimization network, Wong and Lee, (2012) proposed a 2D convergence density criterion to formulate this problem.

The second stream of research recognizes the fact that the left turn significantly reduces the capacity of conventional intersections, because it often requires separate green phase allocation, during which only part of the intersection cross-section can be used to discharge vehicles (Newell, 1989). Researchers have therefore proposed a variety of ways to ban and re-route left-turning vehicles at such intersections, for example, median U-turns, jug handles, super streets and so on (Reid, 2004; Rodegerdts et al., 2004). These strategies increase the intersection capacity by eliminating the left turns and the need for left turn phases. Yan et al. (2014) operationalize the phase swap sorting strategy (Xuan et al. 2011) to use most, if not all, traffic lanes to discharge vehicles at the intersection cross-section to increase its capacity.

2.2.3 Traffic Routing/Detouring Strategies

While route choice depends upon different characteristics of drivers and the traffic situation, the most critical questions to be resolved by the modeler is the level of myopia and preplanning that drivers put into their routes choice process (Southworth, 1991). Based on the differences among the reviewed route strategies studies in control logic and model formulations, this section divides them into the following four groups: responsive strategies, predictive strategies, iterative strategies, and integrated strategies.

To contend with this vital operational issue, transportation professionals have proposed a variety of traffic diversion control and route guidance strategies, which may prioritize either system-optimal or user-optimal traffic conditions within the freeway corridor system. Responsive route strategies usually provide plans based on current measurement from the surveillance system, without using mathematical models in real time. Messmer and Papageorgiou (1994) have proposed sever types of simple responsive strategies. Extending simple responsive strategies, multivariable responsive strategies, as well as heuristics and advanced feedback control strategies, have been proposed by some researchers (Mammar et al, 1996; Dorge al., 1996; Hawas and Mahmassami 1995; Pavlis and Papageorgiou 1996, Wang and Papageorgiou 2000) to address the low sensitivity issues with respect to varying demands and driver compliance rates.

As an extension to responsive strategies, predictive strategies usually employ a dynamic network flow model to predict further conditions under the current route guidance setting, based on the current traffic state, control inputs, and predicted further travel times, delays, and demands in the transportation network (Morin, 1995; Messmer et al., 1998; Wang et al., 2002). Compared with responsive strategies alone, these methods are generally more robust and are preferable when the corridor network has long links. Although predictive strategies are more effective than those relying on responsive logic alone, more research and field experience are needed to verify their application under difference topological and traffic conditions, especially under non-current congestion.

Iterative strategies run a freeway network model in real time with a route guidance plan dynamically that adjusts at each time interval to ensure the successful achievement of the control goal. Therefore, iterative strategies are predictive in nature and may at achieveing either the system optimal or user optimal condition. Some researchers (Papageogiou 1990 c; Charbonnier et. al., 1991; Messmer and Papagoegiou 1995) considering the route diversion via variable message signs as the control measure proposed a macroscopic modeling framework to resolve the dynamic assignment and the routing guidance problem. Other similar studies focusing on this subject can be found in Lafortune et al., (1993); Wie et al., (1995) and Iftar (1995).

In the past two decades, some researchers began to realize the benefits of integrating route guidance strategies with other control measures to best the corridor operational condition. Several studies have documented the benefits of ramp metering with diversion over the scenario with no metering controls. Nsour et al., (1992) investigated the impacts of freeway ramp metering, with and without diversion, on traffic flow. The results suggested that, with proper ramp metering control and coordinated arterial signal timings, the level of service of traffic flow between freeway and surface streets. In the research on integrated optimal strategies, Moreno-Banos et al., 1993 presented an integrated control strategy addressing both rout guidance and ramp metering, based on a simplified traffic flow model. The same problem was also address by Elloumi et el., 1996 using a linear programming approach. More advance integrated control strategies have been developed to generate optimal route guidance schemes concurrently with other control measures (Cremer and Schoof, 1989; Chang et al., 1993; Papageoriou, 1995; Zhang and Hobeika, 1997; Wu and Chang, 1996b; Van den Berg et al., 2001; Kotsialos et al., 2002)

Traffic detour, as one of the important control strategies to identify the potentially best set of routing decisions so as to fully utilize the available capacity of the network during special events. Urbanik (2000) proposed the mechanism of traffic detouring as load balancing with spreading traffic being diverted from routes of excess demand to those of excess capacity. Such a balancing state is mainly achieved by optimizing some predefined performance measurements for the entire decentralization operation with the approximated network traffic demand. Ziliaskopoulos (2000) pointed out that most analytical formulations cannot adequately capture all constraints in existing street networks due to simplification, and thus become intractable for a realistic size of urban networks. Heuristic approaches, especially simulation-based, fail to guarantee optimality and convergence, and also lack insights into the nature of the problem. Thus, he proposed a simple linear formulation, based on the cell transmission model, for producing the system optimal dynamic traffic assignment to a single destination. Cova (2003) presented a lane-based routing evacuation model in a complex roadway network, intending to eliminate conflicts and reduce traffic delays at intersections. Cova's model was inspired by the extraordinarily efficient and rapid evacuation of Los Alamos, New Mexico, during the 2000 Cerro Grande Fire. He hypothesized that the efficiency of the Los Alamos evacuation plan stemmed from a lane-based routing approach that minimized traffic conflicts. Yuan (2006) simultaneous optimized the destination and route choices by solving a traffic assignment problem on a modified network structure. Chiu (2008) found drivers' route choice behaviors usually lead to selecting non optimal routes, which may result in significant degradation of evacuation effectiveness. He proposed an FIR (Feedback Information Routing) strategy by regularly providing frequently updated route information, using existing intelligent transportation system infrastructures such as detectors, cameras, and surveillance systems. Stepanov

(2009) formulated an integer programming for system optimal route assignment, using M/G/c/c state-dependent queueing models to cope with congestion and time delays. The formulations include multiple minimization objectives with respect to clearance time, total travelled distance, and blocking probabilities.

To contend with traffic routing/routing strategies of dynamic traffic network, some researchers also investigated optimal dynamic traffic assignment (DTA) model to solve the transportation network problem. Sattayhatewa and Ran (2000) employed an analytical DTA model to minimize the total spreading traffic time under a nuclear power plant failure. The output includes the optimal inflow rate into and exit flow rate from each link at each time interval. Liu et al. (2006) also applied the DTA method in Model Reference Adaptive Control (MRAC) framework for real time spreading traffic management. Yuan et al. (2006) formulated the spreading traffic routing problem with the simulation-DTA models embedded in the software package DYNASMARTP. Using mesoscopic simulation to capture vehicle movements over the network, the program can generate two types of routing plans for minimization of total travel cost: 1) static routing that dispatches vehicles to different routes only at their departures, and 2) dynamic routing where vehicles can be assigned to a new route based on the prevailing network conditions. Some other studies focused on spreading traffic and also employed DTA models to yield optimal traffic routing schemes concurrently with other control strategies. Some other evacuation studies have also applied DTA models to generate optimal traffic routing schemes concurrently with other control strategies, such as contraflow design (Tuydes and Ziliaskopoulos, 2004, 2006; Tuydes, 2005; Mahmassani and Sbayti, 2005), staged evacuation order (Tuydes and Ziliaskopoulos, 2005), and scheduling of the evacuation demand (Chiu, 2004; Chiu et al., 2006, Sbayti and Mahmassani, 2006).

2.3 Network Flow Formulations

2.3.1 Cell Transmission Model

The cell transmission model (CTM) developed by (Daganzo, 1994, 1995) is one of the widely used first order traffic flow models. It provides a convergent approximation to a simplified version of the LWR hydrodynamic model (Lighthill and Whitham, 1955; Richards, 1956), whereby the fundamental diagram of traffic flow and density is assumed to be a piecewise linear function. The model is capable of capturing the traffic propagation phenomena such as spill back, kinematic wave, and physical queue. CTM has been used for various dynamic problems in the last decade. To name a few, Lo and Szeto (2002), Szeto and Lo (2004) incorporated CTM into the user equilibrium dynamic traffic assignment problem using the variational inequality approach. Waller and Ziliaskopoulos (2006) efficiently solved the dynamic user optimal problem embedding CTM. Han et al. (2011), Ukkusuri et al. (2012) formulated the cell-based dynamic user equilibrium problem using complementarity theory. One limitation of CTM lies in its uniform cell based discretization structure. Yperman (2007) addressed the issue by presenting the link transmission model (LTM). Zhu and Ukkusuri (2014) proposed a link based dynamic network loading model which is equivalent to CTM. Other link based first order dynamic network loading models include the merge and diverge model (Jin and Zhang, 2003), multiclass model (Bliemer, 2007), continuous time model (Friesz et al., 2013). For a more comprehensive review, please refer to (Lebacque and Khoshyaran, 2002; Tampère et al., 2011).

Recently, some researcher (Chiu et al. 2007, Kalafatas and Peeta 2009, Kimms and Maassen 2011a, 2011b, Shen et al. 2007, Tuydes and Ziliaskopoulos 2004, 2006, Xie et al. 2010, Yue et al. 2008) have employed various CTM to optimize traffic management strategies or spreading traffic scheme. The seminal work of Ziliaskopoulos (2000) contains a general model for dynamic traffic assignment problems. Although all of the CTM-based traffic assignment or decentralization models take advantage of the same concept, major differences concerning level of detail in network representation, adaptability, computational requirements and especially in the field of planning scope exist. Chiu et al. (2007), Kalafatas and Peeta (2009), Shen et al. (2007), Tuydes and Ziliaskopoulos (2004, 2006), Xie et al. (2010) and Yue et al. (2008) predetermine all predecessors and successors of a cell so that the complete spreading traffic routing is known in advance. The remaining problem is "just" to calculate the explicit traffic flow from cell to cell over time. In contrast, Kimms and Maassen (2011a, 2011b) assume that the spreading traffic scheme is not known so that all routing decisions are part of the optimization process. Furthermore, the size of test networks massively differs, e.g. small networks in Chiu et al. (2007), Shen et al. (2007) and Xie et al. (2010), medium networks in Kimms and Maassen (2011a) and Tuydes and Ziliaskopoulos (2004) as well as large networks in Kalafatas and Peeta (2009), Kimms and Maassen (2011b), Tuydes and Ziliaskopoulos (2006) and Yue et al. (2008). Kalafatas and Peeta (2009) and Xie et al. (2010) decide to increase level of detail by using one cell per driving direction instead of one cell per street segment like the other authors. Thus, this approach shows some similarities to Bretschneider and Kimms (2011) and Cova and Johnson (2003).

2.3.2 Other Models

To improve the computing efficiency, other methods have been proposed in the literature by either linearizing the network flow formulations or employing the rolling solution techniques. Papageorgiou (1995) developed a linear optimal-control model to design integrated control strategies for traffic corridors, including both motorways and signal-controlled urban roads based on the store-and-forward modeling philosophy. Wu and Chang (1999) formulated a linear programming system for integrated corridor control in which the flow-density relation was approximated with a piece-wise linear function to facilitate the use of a successive linear programming algorithm for global optimality. Van den Berg et al. (2001) proposed a model predictive control approach for mixed urban and freeway networks, based on the enhanced macroscopic traffic flow models in which traffic flow evolution on ramps has been explicitly captured. Liu et al. (2011b) have proposed an integrated diversion control model to determine the best diversion control strategy (i.e., diversion rates and corresponding signal retiming plans at the detour route) that yields the maximum utilization of corridor capacity. Their control model has effectively integrated a set of macroscopic traffic flow models that can precisely model and predict the traffic evolution along the freeway mainline, arterial link, and on–off ramps.

Focused mainly on the spreading traffic network, Campos et al. (2000) presented a heuristic to identify k-optimal independent routes for spreading the areas surrounding a nuclear power plant. The objective was to maximize the sum of capacity/travel time ratios for those selected routes. Talebi and Smith (1985) modeled the stochastic evacuation problem with analytical queuing network models. In the extension work, Smith (1991) proposed a state-dependent queuing model for building decentralized. Assuming that drivers' arrivals follow a Poisson distribution, the model approximates the spreading traffic process with M/G/C/C state-dependent queues, which capture the nonlinear effects of increased traffic flows on the service rate along spreading traffic routes.

2.4 Summary

In summary, this chapter has provided a comprehensive review of existing research efforts in the design of various special event traffic management strategies. Some additional areas which have not been adequately addressed in existing literature are summarized below:

- Most previous studies focus on the emergency evacuation planning and management, which are not transferrable to special event traffic management due to the differences in problem nature (e.g. objectives, demand distribution patterns, traveler behaviors, and management strategies);
- Most of the traffic management strategies used for special event management are traditional and may not be sufficiently effective to address non-recurrent congestion problems caused by special event. The potential and benefits of non-traditional strategies (e.g. lane reorganization, uninterrupted flow intersections, lane-based signal control) in special event traffic management have not been sufficiently investigated;
- There lacks an overall operational framework with rigorous supporting models that can effectively integrate and trade-off different types of strategies for special event traffic management. If implemented concurrently, different traffic management strategies will apparently interact with each other and affect traffic flows in the same time-space network. For examples, a properly designed lane reorganization plan may reduce the need for contraflow operations, while an arterial with effective traffic signal-timing plans will certainly better accommodate traffic demand from traffic routing. Neglect of interactions between different types of traffic management strategies may not achieve the best operational performance;

- Some real-world operational constraints have been overlooked in the literature for design of traffic management strategies. For example, contraflow strategies should take into account the geometric features and their discrepancies among different arterial segments so as to avoid creating local bottlenecks. Conflict elimination strategies, though effective in reducing intersection delays, may cause a substantial increase in traveling distances due to the restriction of certain turning movements at intersections, especially in a large-scale network; and
- Existing literatures focus more on arterial networks but neglect the mixed freeways and arterial systems

In view of the aforementioned limitations in the existing literatures, this research aim to develop an overall operational framework embedded with a set of integrated mathematical programming models for special event traffic management in urban transportation network. The framework for the system will be presented in the next chapter, and the modeling details within the system modules will be illustrated in the following chapters.

Chapter 3: A Systematic Modeling Framework

3.1 Introduction

This chapter illustrates the modeling framework of the proposed research and the interrelations between its principle components. Also included are the critical research issues in the development of each modeling component and proposed primary research tasks to address those issues.

3.2 Key Research Issues and Primary Research Tasks

Some major research issues to be addressed in this research are listed below:

- Network representation, which efficiently and precisely captures the real-world operational constraints of the transportation network as well as the spatial and temporal interactions between traffic management and network flows.
- Demand estimation, which provides the estimated population to be impacted and estimates travelers' responses to traffic management strategies.
- Integrated traffic control and management, which develops mathematical programming models to identify the feasible traffic management decisions, control objectives, operational constraints, and interactions embedded in implementing different strategies.
- Optimal design, which applies some solution algorithms to solve the optimization formulations, and searches for the optimal parameters.

It should be noted that all aforementioned research issues are interrelated and each is indispensable for the proposed research. To address these critical issues, this dissertation has divided the research efforts into the following primary tasks:

Task 1: Perform a comprehensive review of relevant research for special events and related traffic management strategies, including geometric designs, traffic signal operations, network flow formulations, and optimization algorithms.

Task 2: Develop realistic representation of the spatial and temporal interactions among traffic flow distribution in the network. Depending on the scope and needs of applications, both movement-based and lane-based network representation schemes will be developed to capture the operational characteristics of urban transportation network with different levels of accuracy and flexibility.

Task 3: Develop mathematical optimization models with real world operational constraints to best trade-off, select, and integrate various strategies for special event traffic management under different network configurations (e.g. static and dynamic networks, grid network sand mixed freeway and urban corridors) and traffic scenarios. More specifically, Task 3 can be divided into four sub tasks:

- **Task 3-1:** Develop a base model formulation for special event traffic management in a simplified static urban transportation network. Traffic movement reorganization and restriction, signal timing optimization, and uninterrupted flow strategies are best selected and prioritized at critical road network segments and intersections for maximum network operational efficiency under the available budget;
- **Task 3-2:** Extends the base model in Task 3-1 by developing a new optimization model based on the lane-based network representation scheme, which offers the capability to use more sophisticated and effective lane-based traffic management strategies (e.g. lane reorganization and reversal, cross elimination, lane-based signal,

etc.) to further improve the overall network capacity and operational efficiency during special event;

- **Task 3-3:** Develop formulations of optimal traffic management strategies for the mixed urban freeway and arterial corridor considering its critical role in improving highway system efficiency and mobility. Ramp control strategies and detour operations will be supplemented in the existing modeling framework to best coordinate the freeway system and the arterial system during special event management;

- **Task 3-4:** Develop formulations for special event traffic management in a dynamic transportation network considering the time-varying traffic demand and network characteristics that often occur in a special event.

Task 4: Design heuristic algorithms for obtaining suboptimal but efficient and implementable solutions to the proposed models within a tolerable time window even for large-size networks.

Task 5: Validate the proposed models and demonstrate their operational effectiveness in special event traffic management using case studies. Sensitivity analyses will also be performed to provide guidelines to responsible transportation authorities for best application of the proposed models and strategies.

3.3 Model Framework

In view of the above research tasks, Figure 3.1 depicts the framework of the proposed dissertation, highlighting interrelations between principal modeling components. This study will focus only those modules to effectively improve the efficiency operation performance with the traffic management strategies for special events in the urban transportation network.

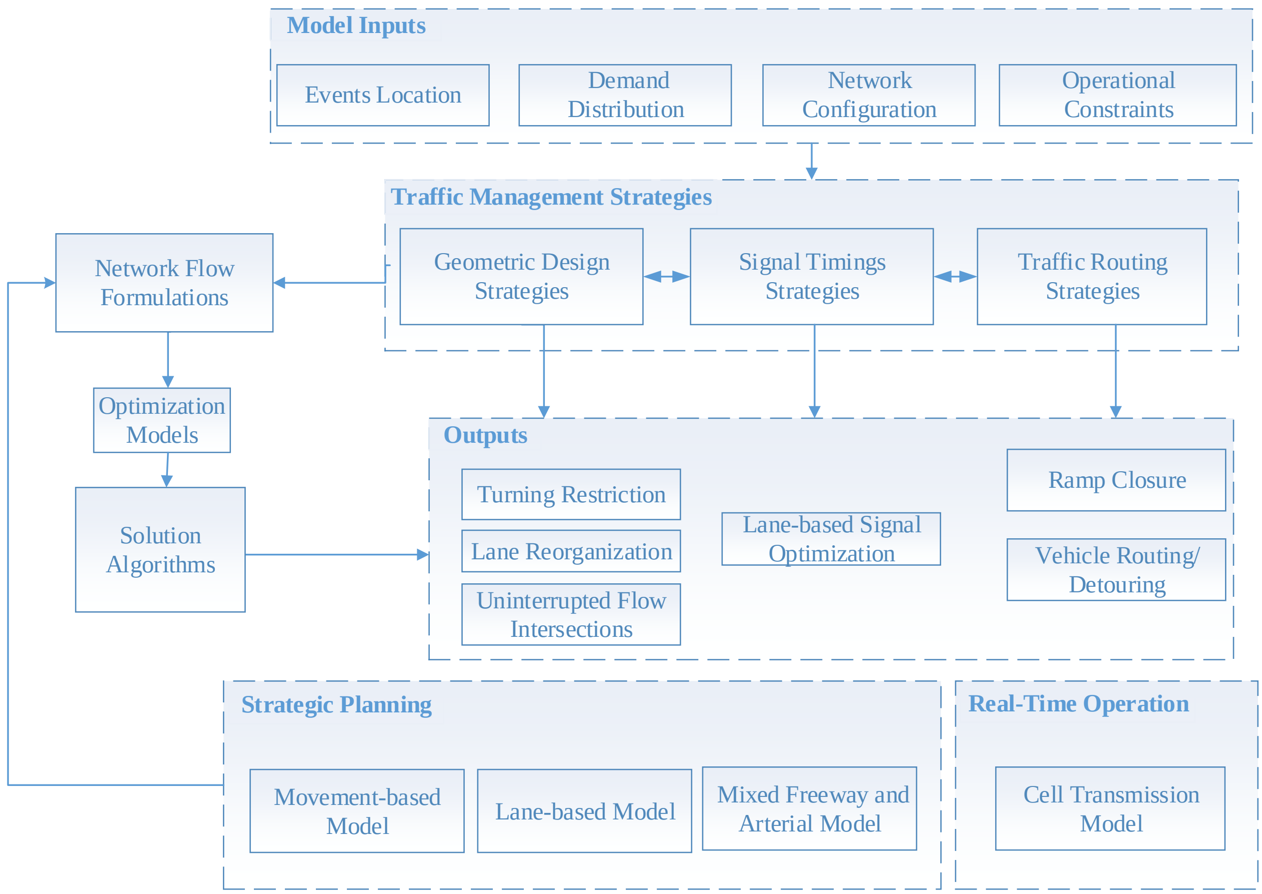


Figure 3. 1 A Modeling Framework of the Proposed Dissertation

Chapter 4: The Base Model: Movement-Based Special Event Management in Urban Transportation Network

4.1. Introduction

Due to the advantage over signals in expanding network capacity, the strategy of using uninterrupted flow (or crossing–elimination) intersection has been viewed as one of the most effective means for managing spreading traffic during the special events in urban transportation network. However, implementing such a strategy may demand a large amount of labor and recourse, and often need some spreading traffic to take additional detours. To optimize the selection of distribution of signalized and uninterrupted flow intersection in special events network, the main motivation of this chapter is to build a movement-based network representation scheme and a base model formulation for special events traffic management in a simplified static urban transportation network. Traffic movement reorganization and restriction, signal timing optimization, and uninterrupted flow intersection strategies are best selected and prioritized at critical road network segments and intersections for maximum network operational efficiency under the available budget.

In a review of the literature, early efforts tackling special events management strategies primarily focused on the network flow optimization problems that are designed to optimize various types of measurement of effectiveness (MOE), such as the spreading traffic time, the network clearance time, the maximum network flow, the total distance by decentralization, and the shortest paths, depending on the encountered special events situations and management requirements (Sheffi et al., 1981; Southworth, 1991; Hobeika et al., 1994; Pidd, 1996; Urbina and Wolshon, 2003). To represent the evolution of a spreading traffic process over time, a pioneering work by Chalmet et al. (1982) developed a time-space network flow model with the objective of minimizing the total clearance time, known as the quickest flow problem. Hamacher and Tufekci (1987) further extended the quickest flow problem by taking into account different priority levels for different parts of the special events network. Choi et al. (1988) formulated three dynamic network flow problems (i.e., maximum flow, minimum cost and quickest flow problems) for spreading traffic and introduced additional constraints to define link capacity as a function of the incoming flow rate. Miller-Hooks and Patterson (2004) proposed the time-dependent quickest flow problem in time varying capacitated special events networks, where link travel times and capacities vary with time. A more thorough and updated review of relevant studies can be found in Murray-Tuite and Wolshon (2013).

Despite their effectiveness in reducing intersection delays, those conflict-elimination strategies may result in a substantial increase in detours by the spreading traffic due to the restriction of certain turning movements at intersections, especially in a large-scale urban network of special events.

In addition, spreading traffic may be confused and panic if they are frequently blocked from making preferred turns at intersection or rerouted from their pre-planned routes during the special events situation. Most importantly, conflict-elimination at many intersections in a large network will be quite time-consuming and require a large amount of labor and resources (e.g. barricades or cones), which may not be implementable in real-world applications.

This chapter seeks to identify the optimal set of intersections in an urban network of special events for implementing traffic crossing-elimination and signal control strategies (see Figure 4.2), which can yield the maximum spreading traffic efficiency and the best utilization of available resources. A mathematical model, developed in this chapter, intends to figure out the following critical issues that have long challenged transportation authorities during traffic spreading planning, namely: 1) how many intersections should be implemented with signals and where are their most appropriate locations; 2) how many uninterrupted flow intersections should be implemented and what should be their optimal spatial distribution; and 3) how to properly plan turning restrictions, channelization, and signal plans at those intersections? Reliable answers or solutions to the aforementioned questions can also be used by responsible agencies in best allocate limited resources to the most appropriate control points for strategic planning of a special event. The remaindering sections are organized as follows.

Section 4.2 presents the network representation and formulation that realistically capture the temporal and spatial interactions of traffic over and special event, including the urban transportation network, mixed freeway segments, arterials, on/off ramps. An innovative formulation using movement-based network representation scheme is proposed for special event traffic management in a simplified static urban transportation network.

Based on aforementioned network formulation, Section 4.3 proposes a basic model to solve and optimize some critical problems and strategies that have long challenged transportation professional for special event traffic management. To yield the efficient solution of the static urban network that involve some traffic management strategies, including the turning restriction, lane channelization, appropriate location of signal intersection or uninterrupted flow intersection, and optimization of signal timing plans. The proposed model, incorporating a parametric variational inequality (VI) to formulate the stochastic user equilibrium (SUE) behavior of travers in route choice, is expect to accurately capture to the traffic characteristics and efficiently solve the complex traffic problems in the transportation network.

Section 4.4 develops an efficient algorithm that can yield sufficiently reliable solutions for applying the proposed models in practice with a bi-level model. In view of the large number of variables and constraints for the proposed model, A Genetic Algorithm (GA)-based heuristic approach embedded with a diagonalization algorithm is developed to yield meta-optimal solutions for up level and low level for special events in the urban transportation network.

Section 4.5 illustrates the case studies with a real world sub-network in Washington DC, performing to demonstrate the applicability and effectiveness of the proposed model.

The last section 4.6 summarizes research efforts that have been completed in this chapter. Figure 4.1 has demonstrated the logical relation between different sections in this chapter.

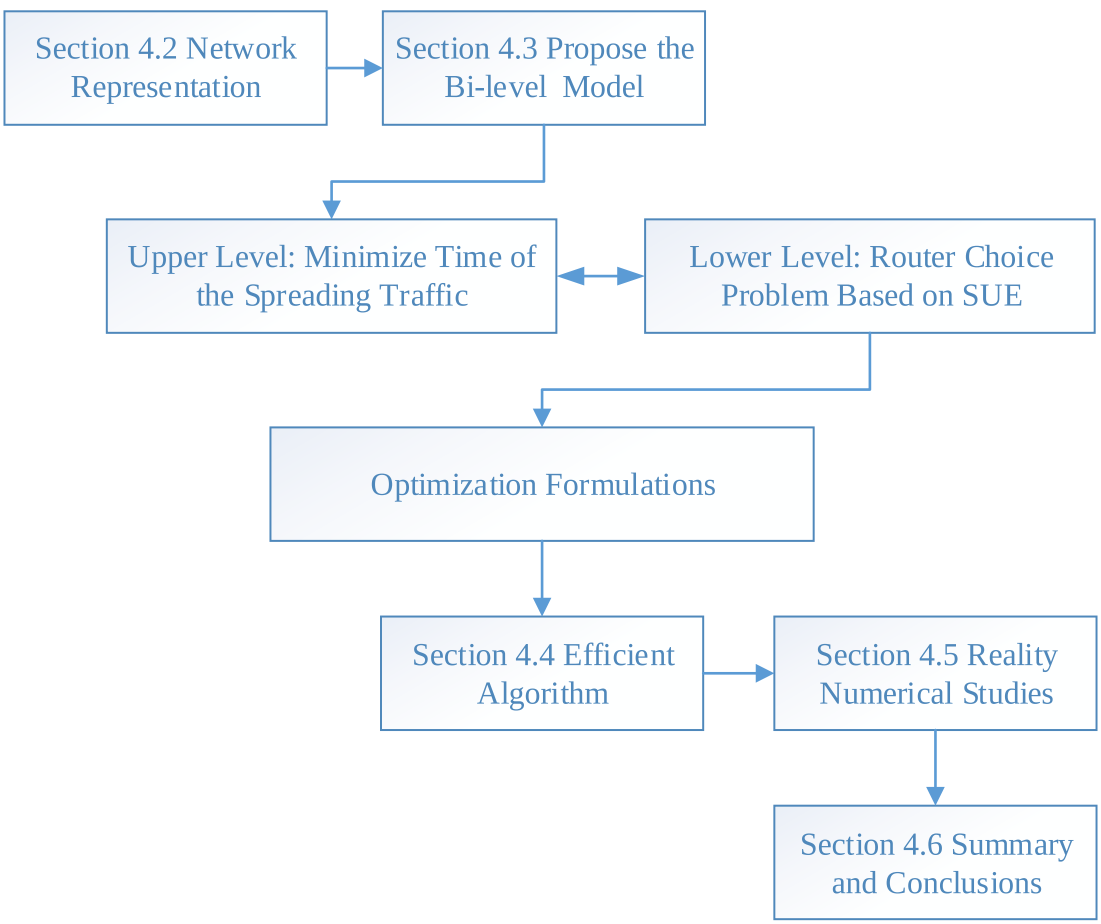


Figure 4. 1 Relations between Different Sections in Chapter 4

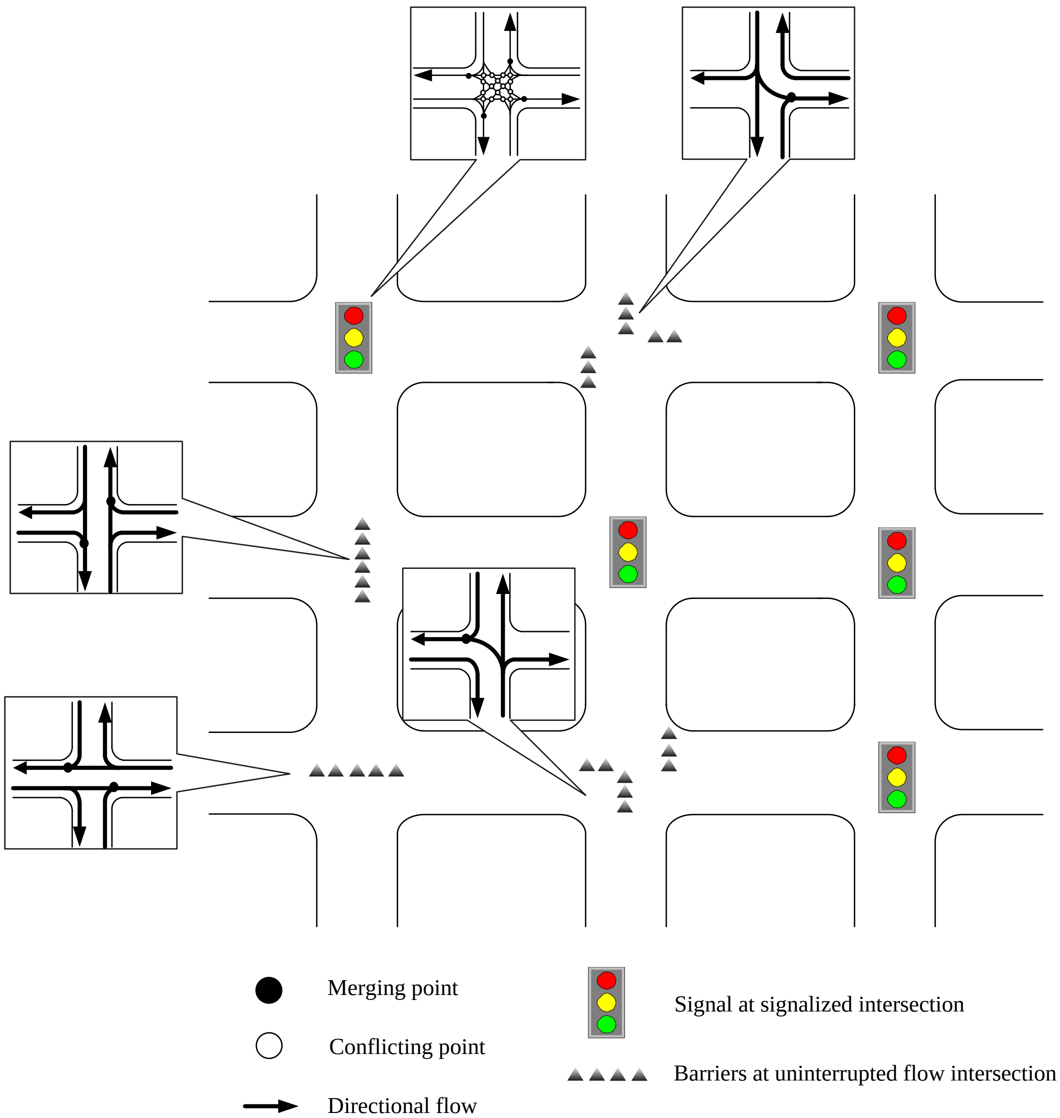


Figure 4. 2 Signal and Uninterrupted Flow Strategies in an Urban Network

4.2 Network Representation

To overcome the above modeling deficiencies as well as to ensure the computing efficiency, this section proposes movement-based model to capture the evolution process of traffic operation under special event in urban transportation network.

Let directed graph $\mathcal{G} = (\mathcal{N}, \mathcal{A})$ represent the urban transportation special event network comprising of the set of nodes denoted by $\mathcal{N}, \boldsymbol{i}, \boldsymbol{j} \in \mathcal{N}$ and the set of links joining two nodes denoted by $\mathcal{A}, a \in \mathcal{A}$. The traffic network manager aims to best select a set of candidate nodes for implementing signals and uninterrupted flow strategies, respectively. For any link $a \in \mathcal{A}$, denote v_a be the flows of on the link, n_a^- be the number of receiving lanes on the link, n_a^+ be the number of approach lanes into an intersection on the link, and c_a be the link capacity. Each node represents an intersection consisting of a set of turning arcs for possible movements. Let $\mathcal{T}_i$ be the set of arcs at node i, $\mathcal{T}_a^+$ and $\mathcal{T}_a^-$ represent the set of arcs originated from and destined to link a, and $\mathcal{T}$ be the set of all arcs in the network. Thus,

$$\mathcal{T}_i = \{w = (a_1, a_2)\}, \forall a_1 \in \mathcal{A}_i^-, a_2 \in \mathcal{A}_i^+, i \in \mathcal{N} \tag{4.1}$$

$$\mathcal{T} = \cup_{i \in \mathcal{N}} \mathcal{T}_i = \cup_{a \in \mathcal{A}} \mathcal{T}_a^+ = \cup_{a \in \mathcal{A}} \mathcal{T}_a^- \tag{4.2}$$

where w is a turning arc between link a_1 and link a_2; $\mathcal{A}_i^-$ represents the set of links going into node i, and $\mathcal{A}_i^+$ represents the set of links going out of node i. Let $v_w, w \in \mathcal{T}_i$ denote the turning flows from link a_1 to link a_2, and c_w be the potential capacity for turning arc w at node i. If a node is selected as a signalized intersection, all its comprising arcs are allowed to conflict with each other and presumed to be eliminated by a sequential of phases; while the conflicts among arcs comprising the uninterrupted flow intersection are prohibited.

In the network $\mathcal{G} = (\mathcal{N}, \mathcal{A})$, let $\mathcal{R} \subseteq \mathcal{N}$ represent the set of traffic spreading demand origin nodes, $\mathcal{S} \subseteq \mathcal{N}$ represent the set of traffic spreading destinations nodes, and (r, s) represents each OD pair, where $r \in \mathcal{R}$, $s \in \mathcal{S}$, between which drivers choose their routes. Let q_{rs} be the demand of traffic spreading between (r, s), and Z_{rs} represent the set of routes for special events between (r, s), and a route $z \in Z_{rs}$ may include a sequence of links and turning arcs. We define $\delta_{rs}^{az} = 1$ if a route z between (r, s) traverses link a; zero otherwise, and $\delta_{rs}^{wz} = 1$ if a route z between (r, s) passes turning arc w. The flow on route z between (r, s) is denoted by q_{rs}^z.

To facilitate the model presentation, the notations used hereafter are summarized in Table 4.1.

Table 4. 1 Notation of Key Model Parameters and Variables

Sets and Parameters	
$\boldsymbol{\mathcal{G}} = (\boldsymbol{\mathcal{N}}, \boldsymbol{\mathcal{A}})$	Directed graph represent the urban transportation network
$\boldsymbol{\mathcal{N}}$	The set of nodes denoted by $\mathcal{N}$
$\boldsymbol{\mathcal{A}}$	The set of links joining two nodes denoted by $\mathcal{A}$
$\boldsymbol{A_i^+}$	The set of upstream links to node i, $A_i^+ \subseteq \mathcal{A}$
$\boldsymbol{A_i^-}$	The set of downstream links from node i, $A_i^- \subseteq \mathcal{A}$
a	The link that connecting two nodes, $\forall\ a \in A_i^+$
a'	The downstream of link a, $\forall\ a' \in A_i^-$
a_k	The k^{th} link in one junction, $a_k \in A_i^+$
a_{k+p}	The downstream of the link a_k, , $a_{k+p} \in A_i^-$
n_a^+	The number of approach lanes into an intersection on the link a , $\forall\ a \in \mathcal{A}$
n_a^-	The number of receiving lanes on the link a , $\forall\ a \in \mathcal{A}$
w	The turning arc from link a to link a', $w = (a, a'), \forall\ a \in \mathcal{A}$
P_i	The set of phase at intersection $i, \forall p \in\ P_i$
p	The phase at intersection $i, \forall p \in\ P_i$
v_a	The traffic flow of link a
c_a	The capacity of link a
n_a	The number of lanes on link a

v_w	The turning flows rate for turning *w*
c_w	The capacity for turning *w*
$\mathcal{L}_a$	The set of lanes on link *a*
$\mathcal{R}$	The set of spreading traffic demand origin nodes, $\mathcal{R} \subseteq \mathcal{N}$
$\mathcal{S}$	The set of spreading traffic destinations nodes, $\mathcal{S} \subseteq \mathcal{N}$
(r, s)	The each OD pair
Z_{rs}	Set of routes for drivers between (r, s)
z	A router may include a sequence of links and turning
q_{rs}	Demand traffic flow of drivers between (r, s)
q_{rs}^z	The demand traffic flow on router *z* between *(r, s)*
B_i , B_j	The budget for uninterrupted flow and signal intersection, $i\,, j \in \mathcal{N}$

Binary Variable

x_i	Intersection *i* is implemented with uninterrupted flow, $x_i = 1;$ otherwise; $x_i = 0$
y_w	Permission of the movement on turning *w*, if permitted y_w *=1;* otherwise y_w *=0*
n_w	The number of lanes assigned to turning arc w, $\forall w \in \boldsymbol{\mathcal{T}}$
λ_i^p	The green time ratio for phase p at node i, $\forall p \in P_i, i \in \mathcal{N}$

Figure 4.3 illustrates an example urban transportation special events network composed by uninterrupted flow intersections, bi-directional roadway links, and signalized intersections. Within the intersection sub-network, arcs in dot and dash represent turning movements at signalized and uninterrupted flow intersections, respectively.

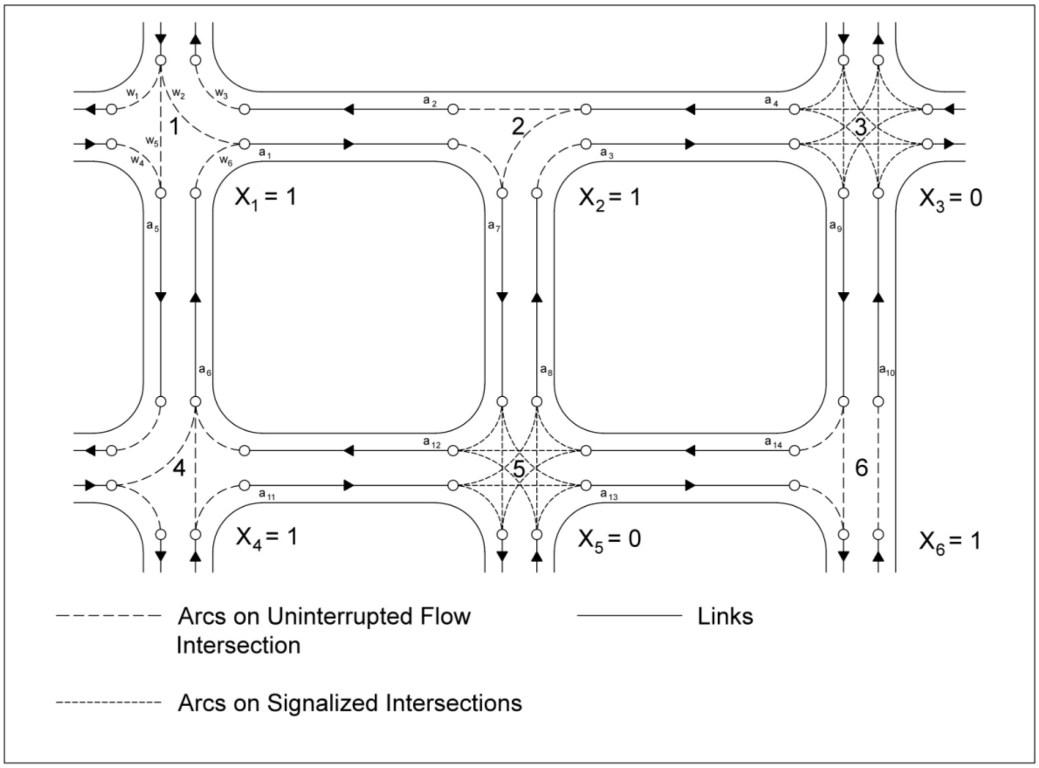


Figure 4. 3 Example Network Representation

4.3 The Network Design Problem

Given the network representation in Section 4.2, the proposed model aims to simultaneously determine the best distribution of signals and uninterrupted flow intersections as well as the corresponding turning restriction, lane channelization, and signal timing plans, expressed by the following set of decision variables:

$$x_i = \begin{cases} 1, \text{intersection } i \text{ is implemented with uninterrupted flow} \\ 0, \quad \text{otherwise} \end{cases}, \forall i \in \mathcal{N} \tag{4.3}$$

$$y_w = \begin{cases} 1, \quad \text{direction flow at arc } w \text{ is allowed} \\ 0, \text{direction flow at arc } w \text{ is prohibited} \end{cases}, \forall w \in \mathcal{T} \tag{4.4}$$

$$n_w = \text{the number of lanes assigned to turning arc } w, \ \forall w \in \mathcal{T} \tag{4.5}$$

$$\lambda_i^p = \text{the green time ratio for phase } p \text{ at node } i, \ \forall p \in P_i, i \in \mathcal{N} \tag{4.6}$$

Where P_i represents the set of phases at node i if it is signalized. Variables in (3) - (6) can be further grouped into the solution vector $\boldsymbol{\omega} = (\mathbf{x}, \mathbf{y}, \mathbf{n}, \boldsymbol{\lambda})$ with $\mathbf{x} = (x_i | i \in \mathcal{N})$, $\mathbf{y} = (y_w | w \in \mathcal{T})$, $\mathbf{n} = (n_w | w \in \mathcal{T})$, and $\boldsymbol{\lambda} = (\lambda_i^p | p \in P_i, i \in \mathcal{N})$. Let $\mathbf{v} = (\mathbf{v_a}, \mathbf{v_w}) = \{(v_a, a \in \mathcal{A}) \cup (v_w, w \in \mathcal{T})\}$ represent the flow pattern under the solution $\boldsymbol{\omega}$. One can estimate the costs by traffic spreading on link a and turning arc w with:

$$u_a(\mathbf{v}, \boldsymbol{\omega}) = t_a(\mathbf{v}, \boldsymbol{\omega}) \tag{4.7}$$

$$u_w(\mathbf{v}, \boldsymbol{\omega}) = t_w(\mathbf{v}, \boldsymbol{\omega}) \tag{4.8}$$

Where $t_a(\mathbf{v}, \boldsymbol{\omega})$ and $t_w(\mathbf{v}, \boldsymbol{\omega})$ are the travel time functions on a and w, respectively. In this study, the travel time performance function is described by two parts: running time on non-intersection links and delays at intersections (i.e. turning arcs).

One can estimate $t_a(\mathbf{v}, \boldsymbol{\omega})$ with the traditional BPR-form function, given by:

$$t_a(\mathbf{v}, \boldsymbol{\omega}) = t_a^0 \left[1 + \alpha_a \cdot \left(\frac{v_a}{c_a}\right)^{\beta_a}\right] \quad \forall a \in \mathcal{A} \tag{4.9}$$

The turning delay on arc w can be estimated with the following equation:

$$t_w(\mathbf{v}, \boldsymbol{\omega}) = t_w^0 \cdot \left\{1 + \alpha_w \cdot \left[\frac{v_w}{c_0 \cdot n_w \cdot \gamma_w \cdot [x_i y_w + (1 - x_i) \cdot \lambda_w]}\right]^{\beta_w}\right\} \ \forall w \in \mathcal{T}, i \in \mathcal{N} \tag{4.10}$$

In Equations (4.9) and (4.10), t_a^0 and t_w^0 are the free-flow travel time and turning time on a and w, respectively; α_a, β_a, α_w, and β_w are travel cost function parameters; c_0 is the lane capacity; n_w is an integer variable representing the number of lanes assigned to turning arc w; γ_w is the lane utilization factor; x_i is a binary variable deciding whether or not to implement uninterrupted flow at node i (1-Yes, 0-No); λ_w is the green time ratio for arc w and $\lambda_w = \lambda_i^p, \forall w \in \mathcal{T}_i^p, p \in P_i, i \in \mathcal{N}$ where $\mathcal{T}_i^p$ denotes the set of turning arcs in phase p at node i. Note that, the travel time on arc w depends on whether node i is selected as an uninterrupted flow or signalized intersection. If node i is selected to be a uninterrupted-flow location, turning time at its arcs will not be affected by other conflicting flows; otherwise, one needs to consider the green time ratio when calculating the turning capacity at arc w.

4.3.1 Route Choice for Traffic Spreading

Given a feasible solution $\boldsymbol{\omega} = (\mathbf{x}, \mathbf{y}, \mathbf{n}, \boldsymbol{\lambda})$ to the problem stated above, the drivers will be routing in the network derived from **s** without violating the turning restrictions and signal control constraints. The network flow distribution will therefore result from their route choice behavior. In this section, we adopt the stochastic user equilibrium (SUE) principle to capture the resulting network flow pattern. Based on the SUE principle, no traffic could unilaterally decrease his/her transportation disutility by changing routes between a certain OD pair.

Let C_{rs}^z represent random perceived travel time along the route z between the OD pair, so we can get the relation with the actual travel time c_{rs}^z along route z between OD pair as follow:

$$C_{rs}^z = c_{rs}^z - \frac{1}{\theta}\xi_{rs}^z, \forall r \in \mathcal{R}, s \in \mathcal{S};\ z \in Z_{rs} \tag{4.11}$$

Where θ is a positive unit scaling parameter. ξ_{rs}^z is the random term and associates with the route under consideration and can be considered to represent the unobservable factor of utility. In this paper, $\xi_{rs}^{z}$is assumed to be normally distributed, one would obtain the probit-based route choice model. However, the probit-based model does not entail a closed form expression of the route choice probability. Hence we consider the logit-based route choice model only. The logit-based model assumes that random that the random terms of the utility function associated with all routes are independently and identically distributed Gumbel random variables. The choice probability is then given by

$$P_{rs}^{z}(\mathbf{f}) = \frac{exp(-\theta c_{rs}^{z}(\mathbf{f}))}{\sum_{k\in Z_{rs}} exp(-\theta c_{rs}^{k}(\mathbf{f}))} \quad \forall r \in \mathcal{R}, s \in \mathcal{S}; z \in Z_{rs} \tag{4.12}$$

Where P_{rs}^{z} represents the probability of users choosing route z, $r \in \mathcal{R}, s \in \mathcal{S}; z \in Z_{rs}$, which is also the share of the users choosing route, the perceived travel time minimization principle implies that

$$P_{rs}^{z}(\mathbf{f}) = Prob\{C_{rs}^{z}(\mathbf{f}) \leq C_{rs}^{k}(\mathbf{f})\}, \forall z \in Z_{rs}; r \in \mathcal{R}, s \in \mathcal{S} \tag{4.13}$$

This choice probability has the following properties:

$$0 \leq P_{rs}^{z}(\mathbf{f}) \leq 1 \text{ and } \sum_{z\in Z_{rs}} P_{rs}^{z}(\mathbf{f}) = 1, \forall r \in \mathcal{R}, s \in \mathcal{S} \tag{4.14}$$

Then the route flow assignment is given by

$$\mathbf{f}_{rs}^{z} = q_{rs} \frac{exp(-\theta c_{rs}^{z}(\mathbf{f}))}{\sum_{k\in Z_{rs}} exp(-\theta c_{rs}^{k}(\mathbf{f}))} \quad \forall r \in \mathcal{R}, s \in \mathcal{S}; z \in Z_{rs} \tag{4.15}$$

It is well known (Fisk, 1980) that the above logit-based SUE model can formulated ad the following equivalent minimization problem:

$$\min_{\mathbf{f}\in\Lambda_f} \mathcal{Z}(\mathbf{f}) = \sum_{a\in\mathcal{A}} \int_0^{v_a} t_a(\omega)\, d\omega + \frac{1}{\theta} \sum_{r\in\mathcal{R},s\in\mathcal{S}} \sum_{z\in Z_{rs}} \sum_{a\in\mathcal{A}} f_{rs}^{z} \delta_{rs}^{az} \ln f_{rs}^{z} \delta_{rs}^{az}$$
$$+ \sum_{w\in\mathcal{T}} \int_0^{v_w} t_w(\omega)\, d\omega + \frac{1}{\theta} \sum_{r\in\mathcal{R},s\in\mathcal{S}} \sum_{z\in Z_{rs}} \sum_{w\in\mathcal{T}} f_{rs}^{z} \delta_{rs}^{wz} \ln f_{rs}^{z} \delta_{rs}^{wz} \tag{4.16}$$

Denote SUE route flow as $\mathbf{f}^{\mathbf{sue}} = (\mathrm{f}_a^{\mathrm{sue}}, \mathrm{f}_w^{\mathrm{sue}}) \in \boldsymbol{\Lambda}_{\boldsymbol{f}}$, and the corresponding SUE link flow $\mathbf{v}^{\mathbf{sue}} = (\mathbf{v}_{\mathbf{a}}^{\mathbf{sue}}, \mathbf{v}_{\mathbf{w}}^{\mathbf{sue}}) \in \boldsymbol{\Lambda}_{\mathbf{v}}$ and $\mathbf{g}(\mathbf{f})^T = (\mathrm{g_a}(\mathbf{f}), \mathrm{g_w}(\mathbf{f}))^T$.

Lemma 1. If the travel time function, $\mathrm{t}_a(\mathbf{v}, \boldsymbol{\omega})$ and $\mathrm{t_w}(\mathbf{v}, \boldsymbol{\omega})$ are separable functions and are monotonically increase with the flow $\mathbf{v}_a$ and $\mathbf{v}_\mathrm{w}$ respectively. The minimization of SUE problem is equivalent the following Variational Inequality (VI) Problem, find $\mathbf{f}^{sue} \in \boldsymbol{\Lambda}_{\mathbf{f}}$, so that

$$\sum_{a\in\mathcal{A}} \mathbf{g}_{\boldsymbol{a}}(\mathbf{f})^T \left(\mathbf{f}_{\boldsymbol{a}} - \mathrm{f}_a^{\mathrm{sue}}\right) + \sum_{w\in\mathcal{T}} \mathbf{g}_{\boldsymbol{w}}(\mathbf{f})^T \left(\mathbf{f}_{\boldsymbol{w}} - \mathrm{f}_{\mathrm{w}}^{\mathrm{sue}}\right) \geq 0 \tag{4.17}$$

$$\mathrm{g}_a(\mathbf{f}) = \sum_{r\in\mathcal{R}} \sum_{s\in\mathcal{S}} \sum_{z\in Z_{rs}} (c_{rs}^a(\mathrm{f}_a^{\mathrm{sue}}) + \frac{1}{\theta}\ln f_{rs}^z \delta_{rs}^{az}) \tag{4.17.a}$$

$$\mathrm{g}_w(\mathbf{f}) = \sum_{r\in\mathcal{R}} \sum_{s\in\mathcal{S}} \sum_{z\in Z_{rs}} (c_{rs}^w(\mathrm{f}_w^{\mathrm{sue}}) + \frac{1}{\theta}\ln f_{rs}^w \delta_{rs}^{wz}) \tag{4.17.b}$$

$$\forall\, \mathbf{f} \in \boldsymbol{\Lambda}_{\mathbf{f}} = \{\mathbf{f} | q_{rs} = \sum_{a\in\mathcal{A}} \sum_{z\in Z_{rs}} f_{rs}^z \delta_{rs}^{az} \quad \forall\, r \in \mathcal{R}, s \in \mathcal{S}$$

$$q_{rs} = \sum_{w\in\mathcal{T}} \sum_{z\in Z_{rs}} f_{rs}^z \delta_{rs}^{wz} \quad \forall\, r \in \mathcal{R}, s \in \mathcal{S}$$

$$f_{rs}^z \geq 0 \quad \forall\, r \in \mathcal{R}, s \in \mathcal{S}, z \in Z_{rs}\} \tag{4.17.c}$$

Proof. It suffers to probe that minimization problem (4.16) is equivalent to VI (4.17). With the assumption of monotonically increasing travel time function, the problem (4.16) of the minimizing a strictly convex function over a compact set guarantees the existence and uniqueness of a path flow $\mathbf{f}^{\mathbf{sue}} \in \boldsymbol{\Lambda}_{\mathbf{f}}$. In addition, the entropy type objective function ensures that the optimal is an achieved at an interior point. It is necessary condition for $\mathbf{f}^{\mathbf{sue}} \in \boldsymbol{\Lambda}_{\mathbf{f}}$ to the unique optimal solution to problem (4.16) is that

$$[\nabla_{\mathbf{f}} \mathcal{Z}(\mathbf{f}^{\mathrm{sue}})]^{\mathrm{T}}(\mathbf{f} - \mathbf{f}^{\mathbf{sue}}) \geq 0, \forall\, \mathbf{f} \in \boldsymbol{\Lambda}_{\mathbf{f}} \tag{4.18}$$

Using $\mathbf{v}_a = \sum_{r\in\mathcal{R}} \sum_{s\in\mathcal{S}} \sum_{z\in Z_{rs}} f_{rs}^z \delta_{rs}^{az}$ and $\mathbf{v}_w = \sum_{r\in\mathcal{R}} \sum_{s\in\mathcal{S}} \sum_{z\in Z_{rs}} y_w f_{rs}^z \delta_{rs}^{wz}$ substituting to (4.18) and then we can get following equation:

$$[\nabla_{\mathbf{f}_a}\mathcal{Z}(\mathbf{f}^{\text{sue}})]^T = \left[\dots, \frac{1}{\theta} + \frac{1}{\theta}\ln f_{rsz}^{sue}\,\delta_{rs}^{az} + \sum_{a\in\mathcal{A}} t_a(v_a)\delta_{rs}^{az}, \dots\right] \tag{4.19.a}$$

$$[\nabla_{\mathbf{f}_w}\mathcal{Z}(\mathbf{f}^{\text{sue}})]^T = \left[\dots, \frac{1}{\theta} + \frac{1}{\theta}\ln f_{rsz}^{sue}\,\delta_{rs}^{wz} + \sum_{w\in\mathcal{T}} t_w(v_w)\delta_{rs}^{wz}, \dots\right] \tag{4.19.b}$$

We use the (4.20.a) and (4.20.b), substituting to (4.19.a) and (4.19.b), respectively.

$$c_{rs}^{a}(\mathbf{v}_{\boldsymbol{a}}) = \sum_{a\in\mathcal{A}} t_a(v_a)\,\delta_{rs}^{az} \tag{4.20.a}$$

$$c_{rs}^{w}(\mathbf{v}_{\boldsymbol{w}}) = \sum_{w\in\mathcal{T}} t_w(v_w)\,\delta_{rs}^{wz} \tag{4.20.b}$$

We can get

$$[\nabla_{\mathbf{f}_a}\mathcal{Z}(\mathbf{f}^{\text{sue}})]^T = \left[\dots, \frac{1}{\theta} + \frac{1}{\theta}\ln f_{rsz}^{sue}\,\delta_{rs}^{az} + c_{rs}^{a}(\mathrm{f}_a^{\text{sue}}), \dots\right] \tag{4.21.a}$$

$$[\nabla_{\mathbf{f}_w}\mathcal{Z}(\mathbf{f}^{\text{sue}})]^T = \left[\dots, \frac{1}{\theta} + \frac{1}{\theta}\ln f_{rsz}^{sue}\,\delta_{rs}^{wz} + c_{rs}^{w}(\mathrm{f}_w^{\text{sue}}), \dots\right] \tag{4.21.b}$$

We can get this separable function optimal condition as following:

$$[\nabla_{\mathbf{f}_a}\mathcal{Z}(\mathbf{f}^{\text{sue}})]^T(\mathbf{f_a} - \mathbf{f^{sue}}) \geq 0 \tag{4.22.a}$$

$$[\nabla_{\mathbf{f}_w}\mathcal{Z}(\mathbf{f}^{\text{sue}})]^T(\mathbf{f_w} - \mathbf{f^{sue}}) \geq 0 \tag{4.22.b}$$

We use

$$[\nabla_{\mathbf{f}}\mathcal{Z}(\mathbf{f}^{\text{sue}})]^T = \begin{bmatrix}\nabla_{\mathbf{f}_a}\mathcal{Z}(\mathbf{f}^{\text{sue}})\\ \nabla_{\mathbf{f}_w}\mathcal{Z}(\mathbf{f}^{\text{sue}})\end{bmatrix}^T, \mathbf{f} = (\mathbf{f_a}, \mathbf{f_w})^T,$$

and substitute to (4.18). We can get the following equation:

$$[\nabla_{\mathbf{f}_a}\mathcal{Z}(\mathbf{f}^{\text{sue}}]^T(\mathbf{f_a} - \mathbf{f^{sue}}) + [\nabla_{\mathbf{f}_w}\mathcal{Z}(\mathbf{f}^{\text{sue}})]^T(\mathbf{f_w} - \mathbf{f^{sue}}) \geq 0 \tag{4.23}$$

In this section, we just calculate the first half of the equation (4.23) and the second half is same with first one.

We can get

$$\sum_{r\in\mathcal{R}}\sum_{s\in\mathcal{S}}\sum_{z\in Z_{rs}}\sum_{a\in\mathcal{A}}\left(\frac{1}{\theta}+\frac{1}{\theta}\ln\mathbf{f}_{\mathbf{rsz}}^{\mathbf{sue}}\delta_{rs}^{az}+c_{rs}^{a}(\mathbf{f}_{\mathbf{a}}^{\mathbf{sue}})\right)(\mathbf{f}_{\mathbf{a}}-\mathbf{f}_{\mathbf{a}}^{\mathbf{sue}})$$

$$=\frac{1}{\theta}\sum_{r\in\mathcal{R}}\sum_{s\in\mathcal{S}}\sum_{z\in Z_{rs}}\sum_{a\in\mathcal{A}}(\mathbf{f}_{\mathbf{rs}}^{\mathbf{z}}\delta_{rs}^{az}-\mathbf{f}_{\mathbf{rsz}}^{\mathbf{sue}}\delta_{rs}^{az})+\sum_{r\in\mathcal{R}}\sum_{s\in\mathcal{S}}\sum_{z\in Z_{rs}}\sum_{a\in\mathcal{A}}\left(\frac{1}{\theta}\ln f_{rsz}^{\text{sue}}\delta_{rs}^{az}+\right.$$

$$\left.c_{rs}^{a}(\mathbf{f}_{\mathbf{a}}^{\mathbf{sue}})\right)(\mathbf{f}_{\mathbf{a}}-\mathbf{f}_{\mathbf{a}}^{\mathbf{sue}})\geq 0 \quad (4.24)$$

In view of $\frac{1}{\theta}\sum_{r\in\mathcal{R}}\sum_{s\in\mathcal{S}}\sum_{z\in Z_{rs}}\sum_{a\in\mathcal{A}}(f_{rs}^{z}\delta_{rs}^{az}-f_{rsz}^{sue}\delta_{rs}^{az})=\frac{1}{\theta}\sum_{r\in\mathcal{R}}\sum_{s\in\mathcal{S}}(\mathrm{q_{rs}}-\mathrm{q_{rs}})=0.$

So we can have

$$\sum_{r\in\mathcal{R}}\sum_{s\in\mathcal{S}}\sum_{z\in Z_{rs}}\sum_{a\in\mathcal{A}}\left(\frac{1}{\theta}\ln f_{rsz}^{sue}\delta_{rs}^{az}+c_{rs}^{a}(\mathbf{f}_{\mathbf{a}}^{\mathbf{sue}})\right)(\mathbf{f}_{\mathbf{a}}-\mathbf{f}_{\mathbf{a}}^{\mathbf{sue}})\geq 0 \quad (4.25)$$

Similarly, we can have

$$\sum_{r\in\mathcal{R}}\sum_{s\in\mathcal{S}}\sum_{z\in Z_{rs}}\sum_{w\in\mathcal{T}}\left(\frac{1}{\theta}\ln f_{rsz}^{sue}\delta_{rs}^{wz}+c_{rs}^{w}(\mathbf{f}_{\mathbf{w}}^{\mathbf{sue}})\right)(\mathbf{f}_{\mathbf{w}}-\mathbf{f}_{\mathbf{w}}^{\mathbf{sue}})\geq 0 \quad (4.26)$$

Substituting (4.25) and (4.26) to (4.23), we can have VI (4.17). This completes the proof. ■

4.3.2 Model Formulation

The proposed model aims to achieve the minimal total traffic spreading time for the given urban transportation network. In this study, we assume a single-super-destination in the traffic network of special events, and travelers could be viewed as “safe” when they have reached the exit nodes, connected with the super destination via impedance free links. The total traffic spreading time can be represented with the summation of flows on links multiplied by their corresponding travel times, given by:

$$min f(\mathbf{v},\boldsymbol{\omega})=\sum_{\forall a\in\mathcal{A}}u_a(\mathbf{v},\boldsymbol{\omega})v_a+\sum_{\forall w\in\mathcal{T}}u_w(\mathbf{v},\boldsymbol{\omega})v_w \quad (4.27)$$

The objective function (4.27) minimizes the total traffic spreading time over the transportation network of special events.

$$y_w + \sum_{w' \in \chi_w} y_{w'} \leq 1 + M(1 - x_i) \quad \forall w, w' \in \mathcal{T}_i, i \in \mathcal{N} \tag{4.28}$$

Constraint (4.28) is developed for conflict elimination, where χ_w is the set of conflicting arcs (including both cross conflict and merging conflict) for arc w and M is a large enough positive number. If node i is set up as an uninterrupted flow intersection (i.e. $x_i = 1$), each pair of conflicting arcs should be eliminated at node i; otherwise there is no restriction on arc turning for a signalized intersection.

$$\sum_{w \in \mathcal{T}_a^+} n_w \leq n_a^+ \quad \forall a \in \mathcal{A} \tag{4.29}$$

Constraint (4.29) limits the number of lanes assigned to any arc w to be less than the total number of approach lanes on the link it is originated from.

$$n_w \leq y_w n_a^+ \quad \forall w \in \mathcal{T}_a^+, a \in \mathcal{A} \tag{4.30}$$

$$n_w \leq y_w n_a^- \quad \forall w \in \mathcal{T}_a^-, a \in \mathcal{A} \tag{4.31}$$

Constraints (4.30) and (4.31) indicate that if an arc turning is blocked, the number of lanes assigned to it should be 0; otherwise it should not exceed the number of approach and receiving lanes.

$$\lambda_i^p \geq \lambda_{min} \;\; \forall p \in P_i, i \in \mathcal{N} \tag{4.32}$$

$$\sum_{p \in P_i} \lambda_i^p \leq 1 + Mx_i \;\; \forall i \in \mathcal{N} \tag{4.33}$$

Constraints (4.32) and (4.33) limit the green time ratio to be within reasonable range.

$$B \geq \sum_{i \in \mathcal{N}} B_i x_i \tag{4.34}$$

Due to the limited management resources, constraint (4.34) requires that the total cost for setting uninterrupted flow intersections less than the given budget, where B and B_i represent the total budget and the cost to set up uninterrupted flow operation at node i, respectively.

$$v_a \leq c_a \quad \forall a \in \mathcal{A} \tag{4.35}$$

$$v_w \leq c_0 \cdot n_w \cdot \gamma_w \cdot [x_i y_w + (1 - x_i) \cdot \lambda_w] \quad \forall w \in \mathcal{T}_i \,, i \in \mathcal{N} \tag{4.36}$$

Constraints (4.35) and (4.36) restrict that the flow on a link or an arc cannot exceed its capacity.

$$\sum_{a\in\mathcal{A}} \mathbf{g}_{\boldsymbol{a}}(\mathbf{f})^{\boldsymbol{T}} \, (\mathbf{f}_{\boldsymbol{a}} - \mathbf{f}_a^{\text{sue}}) + \sum_{w\in\mathcal{T}} \mathbf{g}_{\boldsymbol{w}}(\mathbf{f})^{\boldsymbol{T}} \, (\mathbf{f}_{\boldsymbol{w}} - \mathbf{f}_{\text{w}}^{\text{sue}}) \geq 0, \forall \, \mathbf{f} \in \boldsymbol{\Lambda}_{\mathbf{f}} \tag{4.37}$$

The parametric VI (4.37) captures the interaction between the decisions of event clearance planner and the network flow patterns. All decision variables should be subject to non-negative constraints.

4.4 Solution Approach

The proposed problem is NP-hard and difficult to solve due to its non-convexity and non-differential characteristics. Considering the computational complexity underlying the proposed formulation, in this section we develop a Genetic Algorithm (GA) based heuristic that can yield viable and approximate-optimal solutions in a reasonable time period. Specifics about the GA are illustrated as follows:

4.4.1. GA Coding

An essential step in the GA search for the proposed optimization problem lies in efficient coding of chromosomes that can capture the characteristics of the solution structure. In this study, a randomly generated binary string of $\{(\bar{x}_1, \bar{x}_2, \bar{x}_i \dots \bar{x}_{|\mathcal{N}|}), (\bar{y}_1, \bar{y}_2, \bar{y}_w \dots \bar{y}_{|\mathcal{T}|})\}$ can be used to code the decisions of signalized and uninterrupted flow intersection locations and turning restriction plans. Each $\bar{x}_i$ indicates whether a node i is selected as a signalized intersection or uninterrupted flow intersection, and each $\bar{y}_w$ indicates if turning at arc w is allowed or not.

For arcs originated from link a, to generate lane assignment plans that satisfy constraints (4.29)-(4.31), a total number of $|\mathcal{T}_{\mathrm{a}}^{+}|-1$ fractions $(\pi_w^+, w = 1 \cdots |\mathcal{T}_{\mathrm{a}}^{+}|-1)$ are generated from decomposed binary strings by converting the binary string to a decimal number and dividing the number by the maximum possible decimal number represented by the binary string. Equations (4.38) and (4.39) are then employed to obtain the number of lanes assigned to each arc:

$$n_w^+ = min\{\lfloor n_a^+ \cdot \bar{y}_w \cdot \pi_w^+ \cdot \prod_{k=1}^{w}(1-\pi_{k-1}^+)\rfloor, n_{a'}^-\}, w = 1 \cdots |\mathcal{T}_a^+|-1 \quad (4.38)$$

$$n_w^+ = min\left\{\left(n_a^+ - \sum_{k=1}^{|\mathcal{T}_{\mathrm{a}}^+|-1} n_k^+\right) \cdot \bar{y}_w, n_{a'}^-\right\}, w = |\mathcal{T}_{\mathrm{a}}^+| \quad (4.39)$$

Where a' represents the link receiving arc w and $\lfloor . \rfloor$is the floor brackets round number to lower integer.

To make sure constraints (4.32)-(4.33) are satisfied, a number of $|P_i|-1$ fractions $(\pi_i^p, p = 1 \cdots |P_i|-1)$ are used to code green time ratios, given by:

$$\lambda_i^p = \lambda_{min} + (1 - |P_i| \cdot \lambda_{min}) \cdot \pi_i^p \cdot \prod_{k=1}^{p}\left(1-\pi_i^{k-1}\right), p = 1 \cdots |P_i|-1 \quad (4.40)$$

$$\lambda_i^p = \lambda_{min} + (1 - |P_i| \cdot \lambda_{min}) \cdot \prod_{k=1}^{p}\left(1-\pi_i^{k-1}\right), p = |P_i| \quad (4.41)$$

4.4.2. Infeasibility Handling

Note that the candidate solutions generated may still violate conflict elimination constraints and capacity constraints. To deal with this problem, we penalize solutions violating constraints by including them as penalty terms in an evaluation function, given by:

$$F(\mathbf{v},\boldsymbol{\omega}) = f(\mathbf{v},\boldsymbol{\omega}) + \sum_{a\in\mathcal{A}} M_a \cdot (max\{v_a - c_a, 0\})^2$$
$$+ \sum_{i\in\mathcal{N}} \sum_{w\in\mathcal{T}_i} M_w \cdot (max\{v_w - c_0 \cdot n_w \cdot \gamma_w \cdot [x_i y_w + (1 - x_i) \cdot \lambda_w], 0\})^2$$
$$+ \sum_{i\in\mathcal{N}} \sum_{w,w'\in\mathcal{T}_i} M_w \cdot x_i \cdot \left(max\left\{y_w + \sum_{\mathbf{w}'\in\chi_w} y_{\mathbf{w}'} - 1, 0\right\}\right)^2 \quad (4.42)$$

where $F(\mathbf{v},\boldsymbol{\omega})$ is the revised evaluation function; M_a, M_w are large positive penalty coefficients.

4.4.3. Network Flow Assignment

The network flow calculated by the diagonalization algorithm is embedded into the GA for objective function evaluation. Note that the impedance of a link or an arc in the network is associated with its flow. Therefore, the vector of cost functions of links and arcs will in general have asymmetric Jacobian matrix, and the assignment problem is an asymmetric network assignment problem (Dafermos, 1980; Dafermos and Nagurney, 1984), which does not have an equivalent optimization formulation. One approach, most commonly used to solve asymmetric network assignment problems, is the well-known diagonalization method (Florian, 1979; Abdulaal and LeBlanc, 1979; Mahamassani and Mouskos, 1988).

In this study, the diagonalization method is used to solve the VI problem (4.37) to obtain the SUE flow pattern corresponding to a design decision. At each iteration, the vector cost function is diagonalized at the current solution, yielding a normal SUE problem, which can be solved by Frank–Wolfe method. An extreme point can be obtained easily if the Frank–Wolfe method is used to solve the network equilibrium problem. The diagonalization algorithm converges when the Jacobian matrix of the cost functions is diagonally dominant (Dafermos, 1983). Details of the diagonalization algorithm can be found elsewhere and is not the focus of this paper.

4.4.4. Crossover and Mutation

The initial populations of the GA are generated randomly following the aforementioned coding scheme and chromosomes are further selected to ensure all of them satisfy the constraint (4.34). Then, one-point crossover and mutation are used to generate new solution populations with the probability of p_{cross} and $p_{mutation}$.

4.4.5. Fitness Evaluation

For a chromosome k in generation n, one can calculate its fitness value with the following equation:

$$eval(\mathbf{v}_k^n, \boldsymbol{\omega}_k^n) = \frac{F_{max}^n - F(\mathbf{v}_k^n, \boldsymbol{\omega}_k^n) + \varepsilon}{F_{max}^n - F_{min}^n + \varepsilon} \quad (4.43)$$

where F_{max}^n and F_{min}^n denote the maximum and minimum evaluation function values in generation n, respectively; $F(\mathbf{v}_k^n, \boldsymbol{\omega}_k^n)$ is the evaluation value corresponding to the k^{th} chromosome in generation n; ε is a positive value between 0 and 1 which functions to: 1) prevent (4.43) from zero division; and 2) adjust the selection behavior between fitness proportional selection and pure random selection (Gen and Cheng, 2000).

4.4.6. Evolution and Stopping Criteria

Based on the fitness values of chromosomes, a binary tournament method is used to generate new populations. The GA stops to evolve until the following criteria are met:

(1) $\left|\frac{F_{min}^n - F_{min}^{n+1}}{F_{min}^n}\right| < \zeta$, i.e., the difference between the minimum evaluation values between two adjacent generations is less than a threshold ζ; or

(2) A pre-set maximal number of generations (n_{max}) are reached.

4.5 Numerical Studies

4.5.1 An Illustrative Example

An illustrative example is presented in this part to evaluate the effectiveness of the proposed algorithm. The hypothetical network shown in Figure 4.4 consists of 48 bi-directional links and 14 nodes in which 2 nodes are exits for the network linking to a super destination via impedance free links. The other nodes are represented as intersections and decentralization origins. Note that nodes 1, 4, 13, and 16 represent two-leg intersections where traffic conflicts are naturally eliminated, and the exit nodes 8 and 9 are traffic-spreading destinations therefore should be excluded from the intersection list for implementation of signals or uninterrupted flow strategies. For the sake of simplicity, all road segments consist of two receiving lanes and four approach lanes, all links have the free flow speed of 60km/h, and all turning arcs have the free flow speed of 30km/h. Other information regarding the hypothetical special event network is summarized in Table 4.1.

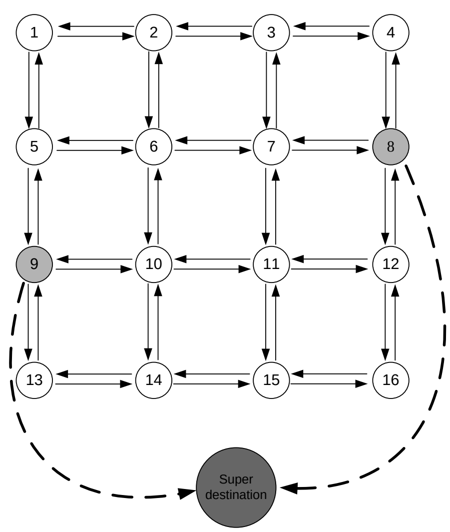


Figure 4. 4 The Hypothetical Traffic Spreading Network of Special Events

Table 4. 2 Data for the Hypothetical Sample Network

Links	Length (m)	Capacity (PCU)	Links	Length (m)	Capacity (PCU)	Links	Length (m)	Capacity (PCU)
1,2 2,1	330	2800	11,12 12,11	370	3100	6,10 10,6	430	4000
2,3 3,2	500	2100	13,14 14,13	370	3200	10,14 14,10	550	3600
3,4 4,3	280	3000	14,15 15,14	400	2100	3,7 7,3	260	2400
5,6 6,5	290	3000	15,16 16,15	330	2400	7,11 11,7	420	2800
6,7 7,6	400	3200	1,5 5,1	300	2700	11,15 15,11	500	3200
7,8 8,7	450	2700 3300	5,9 9,5	370	3800 2300	4,8 8,4	500	3800 2700
9,10 10,9	600	2800 3700	9,13 13,9	360	2300 3500	8,12 12,8	330	3200
10,11 11,10	500	3400	2,6 6,2	280	3500	12,16 16,12	400	2100

Other parameters are set as follows: 1) α_a, β_a, α_w, and β_w are set to be 0.15, 4.0, 1.5, and 2.5, respectively; 2) c_0 is set at 1900pcphpl; 3) γ_w is set to be 0.95; 4) M_a and M_w are set to be 10,000 veh-hours; 5) p_{cross} and $p_{mutation}$ are set at 0.2 and 0.01; 6) The population size is set as 50 and n_{max} is set at 200; and 7) ε and ζ are set to be 0.12 and 0.1%, respectively.

4.5.2 Performance of the Proposed Algorithm

In this section, we compare the performance of the proposed algorithm with two other solution algorithms as described below:

1) An enumeration approach (EA) to yield the optimal solution;
2) A computer program embedded with a LINGO solver (LINGO);

All algorithms are implemented in C++ on a work station with an Intel Core i7-3770S 3.9GHz Turbo CPU and 32GB RAM. The performances of three algorithms are compared in terms of objective function values, optimal solutions, and computational time under the following scenarios:

1) Three levels of available budgets a), b), and c) that allow the maximum number of uninterrupted flow intersections to be 2, 4, and 6, respectively; and
2) Three levels of total spreading traffic demand over the network (i, ii, iii): 5,000 veh, 10,000 veh, and 15,000 veh.

Comparison results are summarized in Table 4.3 through Table 4.5. It can be observed in Table 4.3 that the EA can find the global optimal solution using a significantly longer time for budget levels a) and b); however for budget level c), the EA fails to yield a solution after running for more than 120 days (2880 hours). The computer program with a LINGO solver ends up with local optima in a relatively shorter time period and the GA yields acceptable solutions in a much faster way.

Table 4. 3 Comparison of Three Algorithms (Objective Values and Computational Times)

Budget Plans	Demand Level	Evaluation Results					
		EA		LINGO		The proposed algorithm	
		Min. Obj. (veh-hr)	Time (hr)	Min. Obj. (veh-hr)	Time (hr)	Min. Obj. (veh-hr)	Time (hr)
a	i	163.81	940.85	177.82	228.3	166.15	86.2
	ii	360.31	924.71	377.04	247.6	361.48	92.2
	iii	713.23	1005.26	739.69	239.2	716.34	78.5
b	i	110.51	2232.33	122.57	287.1	113.23	85.4
	ii	282.88	2421.48	312.45	287.6	285.21	73.5
	iii	482.10	2430.79	503.50	296.3	486.77	99.7
c	i	-	-	99.61	238.9	82.10	72.1
	ii	-	-	184.82	245.1	163.04	94.6
	iii	-	-	351.36	254.3	328.40	79.4

Note: "-" means that the EA fails to find the optimal solution

Compared with the LINGO-based approach, the GA can provide more consistent results with the EA (indicated in Table 4.4 and Table 4.5), which result in closer objective function values to the global optimal (see Table 4.3). For all scenarios under budget plans a) and b), the GA yields the same location solutions with the EA for the test problem. The slightly higher objective function values are probably due to the UE-based network flows, minor difference in turning restrictions and green time ratios, and the sensitivity of certain algorithm parameters to different demand levels. Despite the global optimality provided by the EA, it takes up to 2500 hours to solve this model in a relatively small-scale test network, which makes the EA not suitable for large-scale applications. The computational time of the proposed algorithm is significantly less than the EA and is reasonable for planning-level applications. Most importantly, its computational time seems not sensitive to the variation of budget plans and demand levels as the EA and the LINGO do. Such findings indicate that the proposed algorithm is a good substitute for the EA to solve large-scale network problems.

Table 4. 4 Comparison of Three Algorithms (Distribution of Signal and Uninterrupted Flow Intersections)

Budget Plans	Demand Level	Uninterrupted Flow Intersection Locations (Node IDs)		
		EA	LINGO	The proposed algorithm
a	i	6,7	7,10	6,7
	ii	6,10	6,11	6,10
	iii	6,10	7,10	6,10
b	i	5,6,7,10	5,6,7,11	5,6,7,10
	ii	2,5,7,10	3,5,7,11	2,5,7,10
	iii	2,7,10,14	2,7,10,12	2,7,10,14
c	i	-	2,4,5,7,11,14	2,5,6,7,10,14
	ii	-	2,4,5,7,10,14	2,5,6,7,10,14
	iii	-	5,6,7,10,11,12	2,5,6,7,10,14

Note: “-” means that the EA fails to find the optimal solution

4.5.3 A Large-scale Case Study

This section presents the application of the proposed model and solution algorithm in a sub-network in downtown Washington DC, including 62 intersections (see Figure 4. 4). Directional links in bold denote arterials and others are secondary roads. In case of being threatened by a hypothetical chemical exposure, people are required to spread out of this area. Spreading traffic

Table 4. 5 Comparison of Three Algorithms under Budget Plan b) and Demand Level III

Algorithms	Node List	Control Type	Turning Movements											
			EB			WB			NB			SB		
			L	T	R	L	T	R	L	T	R	L	T	R
EA	2	U	-	0	1	1	1	-	0	-	1	-	-	-
	3	S	-	.47	.79	.21	.68	-	.32	-	.53	-	-	-
	5	S	-	-	-	.57	-	.57	-	.43	.57	0	.43	-
	6	S	0	.09	.09	.41	.41	0	.24	.24	.24	.26	.26	.26
	7	U	1	1	1	0	0	1	0	0	1	0	0	1
	10	U	0	0	1	0	0	1	0	1	1	0	1	1
	11	S	.12	.46	.46	.12	.46	.46	.24	.18	.18	.24	.18	.18
	12	S	.25	-	.49	-	-	-	.24	.75	-	-	.51	.76
	14	U	1	1	-	-	0	1	-	-	-	0	-	1
	15	S	.25	.63	-	-	.38	.75	-	-	-	.37	-	.62
GA	2	U	-	0	1	1	1	-	0	-	1	-	-	-
	3	S	-	.44	.75	.25	.69	-	.31	-	.56	-	-	-
	5	S	-	-	-	.56	-	.56	-	.44	.44	0	.44	-
	6	S	0	.10	.10	.36	.36	0	.27	.27	.27	.27	.27	.27
	7	U	0	1	1	0	1	1	0	0	1	0	0	1
	10	U	0	0	1	0	1	1	1	0	1	0	0	1
	11	S	.15	.45	.45	.15	.45	.45	.19	.21	.21	.19	.21	.21
	12	S	.21	-	.47	-	-	-	.26	.79	-	-	.53	.74
	14	U	1	1	-	-	0	1	-	-	-	0	-	1
	15	S	.20	.62	-	-	.42	.80	-	-	-	.38	-	.58
LINGO	2	U	-	0	1	1	1	-	0	-	1	-	-	-
	3	S	-	.54	.85	.15	.70	-	.31	-	.46	-	-	-
	5	S	-	-	-	.51	-	.51	-	.49	.51	0	.49	-
	6	S	0	.14	.14	.41	.41	0	.29	.29	.29	.16	.16	.16
	7	U	0	1	1	0	1	1	0	0	1	0	0	1
	10	U	0	0	1	0	0	1	0	1	1	0	1	1
	11	S	.12	.39	.39	.12	.39	.39	.22	.27	.27	.22	.27	.27
	12	U	0	0	1	-	-	-	1	1	-	-	0	1
	14	S	.36	.62	-	-	.26	.64	-	-	-	.38	-	.75
	15	S	.41	.75	-	-	.34	.59	-	-	-	.25	-	.66

Note: U – Uninterrupted flow, S – Signalized, 0 – turning blocked, 1 – turning allowed

are identified to be finish when they arrived any of the nodes on the boundaries of the network at K St NW, 6 St NW, Constitution Ave NW, and 23 St NW. The total spreading traffic demand is 10,000 vph, which is uniformly distributed to all nodes in the network.

This study has designed 3 scenarios to evaluate the effectiveness of the proposed model. Assuming that an average of $5,000 is the cost to implement one uninterrupted flow intersection, the three budget plans of $50,000 for Plan-A, $75,000 for Plan-B, and $100,000 for Plan-C will allow for converting the maximum of 10, 15, and 20 intersections, respectively, to uninterrupted flow points.

The effectiveness of the proposed model will be compared with two alternative management strategies (denoted as "S-1" and "S-2"). "S-1" does not convert signalized intersections to uninterrupted flow intersections in the network. "S-2" is a commonly adopted strategy by authorities during the spreading traffic practice. It usually implements uninterrupted flow at intersections between major decentralized arterials and secondary roads to prevent the minor street movements from interrupting the major spreading directions. For example, flows on the secondary roads are not allowed to go through or make a left at those intersections, but may make the right turns.

To make a fair comparison between the proposed model and the alternative strategies, we further apply the developed optimization approach to fine-tune the plans for "S-1" and "S-2". In this way, the importance for planning locations of signalized and uninterrupted flow intersection can be identified from the comparison.

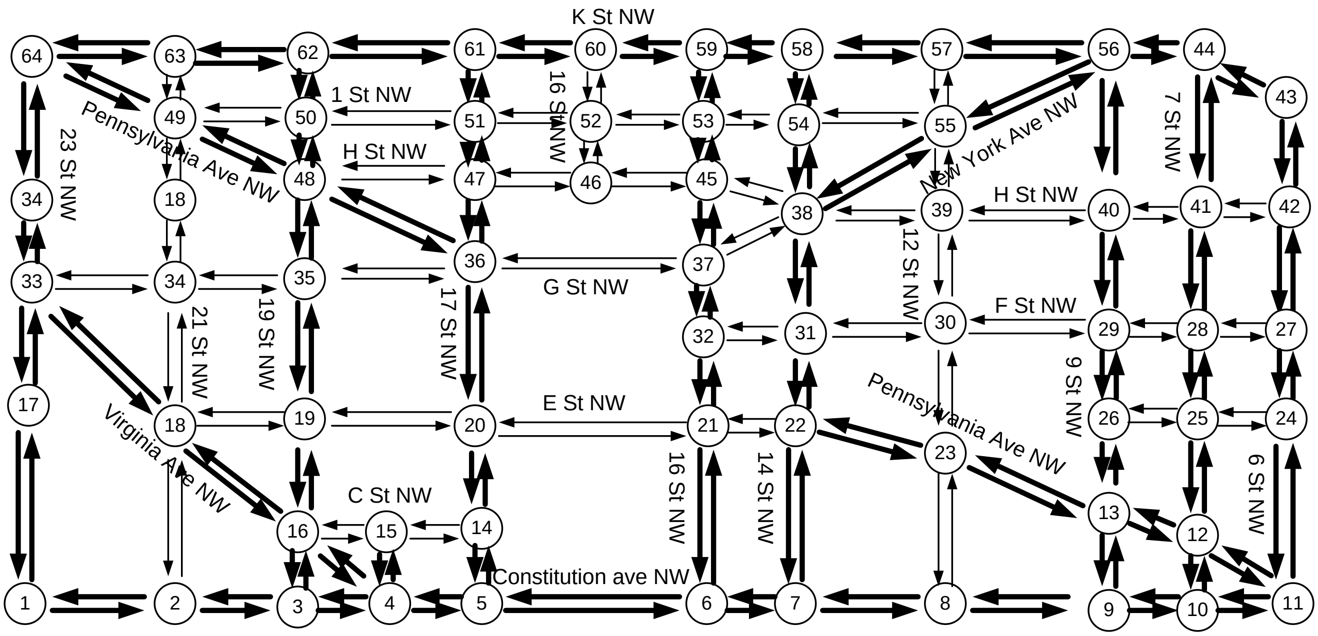


Figure 4. 5 The Case Study Network

The proposed model is implemented on the same computer workstation. Table 4.5 summarizes the comparison results between the proposed model and alternatives, including the locations of uninterrupted flow intersections and the total event clearance time. Figure 4.6 shows the evolution of the total event clearance time change with respect to the GA evolution. One can observe that the GA converges fast to near optimal within the first 50 generations (about 45-50 hours) and the entire optimization process takes around 180-200 hours to finish for the case study network.

As shown in Table 4.6, compared with the “S-1” strategy (all signalized intersections), the proposed model yields -49.5%, -58.5%, and -63.9% less total event clearance time in the study network under budget levels A, B, and C, respectively. Such results indicate that implementation of uninterrupted flow intersections helps to improve the special event network performance substantially. Furthermore, one can identify significant discrepancies in the locations of uninterrupted flow intersections generated by the proposed model and the “S-2” strategy. Such discrepancy results in their differences in the total event clearance time (the proposed model yields -12.7%, -15.9%, and -18.7% less total event clearance time compared with "S-2" under budget levels A, B, and C). Such findings show that the locations selected under the budget constraints for uninterrupted flow and signalized intersections play a key role in determining the efficiency for traffic management of special events network. The proposed model outperforms the "S-1" and "S-2" in terms of total event clearance time under all scenarios, which demonstrates the effectiveness of the proposed model in prioritizing resources at the most appropriate control points during the special events. It is also interesting to find that some intersections are always selected to implement uninterrupted flow strategies by the proposed model (e.g. nodes 13, 14, 19, 29, 37, 54) under various budget levels. Such information is valuable to transportation authorities for their identification of critical intersections over the network and for making preparations in advance of any potential a special event.

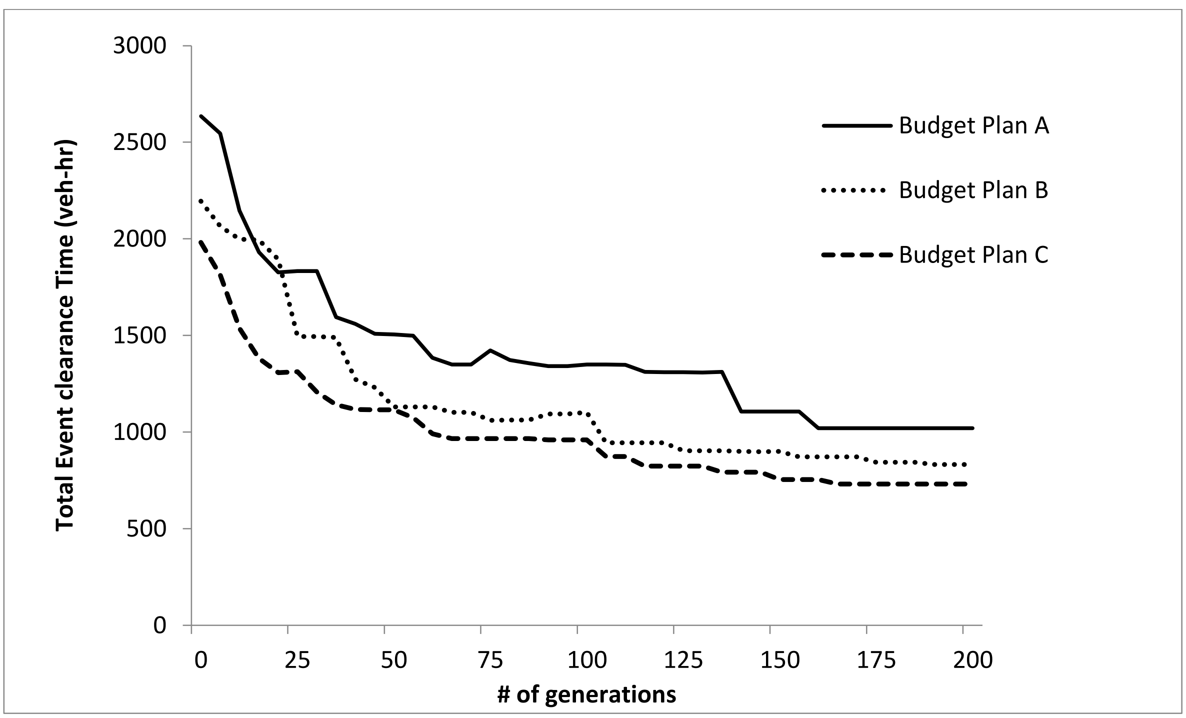


Figure 4. 6 GA Evolution Process for the Case Study

Table 4. 6 Comparison of Decentralization Strategies and Network Performance under Various Scenarios

Budget Plans	Uninterrupted Flow Intersection Locations (Node IDs)			Total Event Clearance Time (veh-hrs)			Reduction Percentage	
	The proposed model	S-1	S-2	The proposed Model	S-1	S-2	S-1	S-2
A	13,14,19,21,29 31,37,47,51,54	N/A	15,16,21,26,28 31,36,37,44,50	1021	2023	1169	-49.5%	-12.7%
B	13,14,19,20,29 36,37,38,47,48 49,51,52,54,55	N/A	15,16,21,28,29 32,35,36,37,40 44,49,51,53,54	833	2023	991	-58.8%	-15.9%
C	13,14,16,19,20 29,31,34,36,37 38,40,45,46,48 49,51,52,53,54	N/A	14,15,16,21,26 28,29,31,32,35 36,37,38,40,44 49,50,51,53,54	731	2023	899	-63.9%	-18.7%

To investigate the impact of the number of interrupted flow intersections on the spreading traffic performance, this study has also performed sensitivity analyses under different demand levels (I-5,000vph, II-10,000vph, and III-20,000vph). As shown in Figure 4.7, the more intersections are set to be uninterrupted flow; the lower the total event clearance time can be achieved in the network for all test demand levels. Such findings are in agreement with those from Cova and Johnson (2003), which confirm the notion that the implementing uninterrupted flow intersections can effectively expand the special event network capacity and thus improve the operational efficiency. However, the marginal benefit from increasing the number of uninterrupted flow intersections reveals a decreasing trend, especially for low decentralization demand conditions, which indicate that there may exist an optimal allocation of signalized and interrupted flow intersections in a given network to maintain the best decentralization efficiency. The static network flow model developed in this chapter, incapable of modeling queue dynamics and flow interactions, may not be sufficient to capture such a phenomenon, which leaves the room to be explored in our future studies.

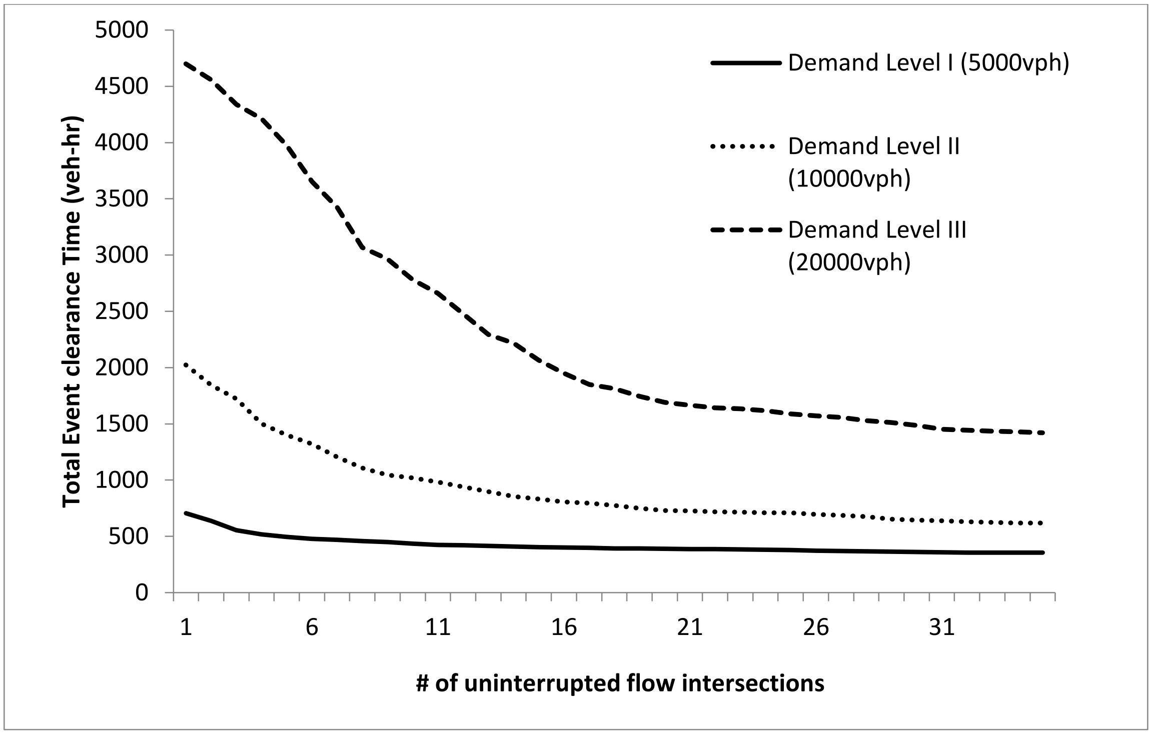


Figure 4. 7 The Total Event Clearance Time under Various Numbers of Uninterrupted Flow Intersections and Spreading Traffic Demand Levels

4.6 Conclusion and Future Research

This study has addressed an important issue of under budget constraints how to optimally convert some signalized intersections in the special event network into uninterrupted flow control points. A mathematical program with equilibrium constraints incorporating a parametric variational inequality was developed to formulate the proposed network design problem with the objective of minimizing the total event clearance time over the network. Disutility functions for both links and turning arcs were proposed to reflect the preference of a driver in route choices. To deal with the combinatorial complexity in combined location selection and turning restriction designs, this study has designed a heuristic solution framework based on the genetic algorithm. The proposed algorithm was found to be capable of yielding acceptable solutions to the problem in terms of both computational time and accuracy compared with the enumeration method and a LINGO-based program. The algorithm was further applied to solve a larger scale problem in a sub-network in Washington DC for effectiveness assessment.

The experimental results confirm that the decision of where to implement uninterrupted flow and signalized intersections significantly affect the resulting efficiency of traffic management of special events network, especially under budget constraints. The proposed model has demonstrated its effectiveness in prioritizing resources to the most appropriate control points for the decentralization operations. In addition, the location decisions from the proposed model are sufficiently stable for planning-level applications, especially for predictable special events.

Note that although the operational efficiency of the spreading traffic monotonically increases with the number of interrupted flow intersections in the network, its marginal benefit reveals a decreasing trend (shown in Figure 4.7). Hence, transportation authorities are suggested to implement a proper number of uninterrupted flow intersections to maintain cost-benefit spreading traffic efficiency even without the budget constraints. Future work along the line will be extending the model into a dynamic setting and introduction of stochastic elements into the network flow patterns to accommodate the dynamic process of spreading traffic.

Chapter 5: The Extended Model I: Lane-Based Special Event Management in Urban Transportation Network

5.1 Introduction

Considering the uninterrupted flow and signal intersection strategies proposed in chapter 4, this chapter further extends this base model to reduce the spreading traffic time by representing a new network representation scheme that can better capture the traffic flow interactions at the lane level. Although the uninterrupted flow and signal intersection for urban transportation network of special events problem effectiveness decrease the intersection delays and decentralization time in the Chapter 4, an another key special events management strategy which is the lane reorganization scheme should be employed to address these complex issues and improve the operation efficiency during special events on urban transportation network.

Under the special events decentralization condition, where all intersections are implemented the signalized in the traffic network, the total of traffic spreading time may have more delay, since the red time of signal plan would waste much time in each intersection if we move traveler away from the actual occurrence. If all intersections are uninterrupted flow, it could be costly for the government to set the lane function of every intersection even though the decentralized time should be decreased. Based on this, this chapter first identifies the optimal set of the intersections in special events network for setting the uninterrupted flow and signal control strategies. Then we get the maximum traffic spreading efficiency and the best utilization of the available resources. A bi-level program model will contribute to solve the above problem by answering the following critical questions that have long challenged transportation authorities for emergency planning. The upper level problem is to minimize the total decentralization time when the special events incurred of urban transportation network. The lower level problem is to capture the driver's route choice behavior and obtain the optimal traffic detour route for any given network based on the Stochastic User Equilibrium (SUE) principle.

The proposed modeling features offer the capability to use more sophisticated and effective lane-based traffic management strategies (e.g. lane reorganization. Turn restriction, reversal, cross elimination, and lane-based signal, etc.) to further improve the overall network capacity and operational efficiency during special event. Considering the high-dimensionality of its decision variables, this chapter further develops a fast-convergent projection method algorithm based searching heuristic to address the following critical issues:

1) How to determine the appropriate location of the uninterrupted flow intersection and signal intersection for the urban transportation network of special events;

   The appropriate distribution of uninterrupted flow intersection and signal intersection could be yield the minimum the travel time during traffic spreading of the special events. If the intersections of entire urban transportation network are implemented the uninterrupted flow intersection, it will increase detours from the original to destination. In contrary, if the all of the intersections are implemented the signal light, the travel time will be increased from traveler's original to destination.

2) How many uninterrupted flow intersection and signal intersection should be implemented;

   The proper number of the uninterrupted flow intersection and signal intersection should be decrease the travel cost and then sufficiently effective to improve the operational efficiency during the complex urban transportation network of special events.

3) How to optimize the channelization strategies for lane marking, lane reversal, turning restrictions, and lane base signal time including cycle length and green time in urban

transportation network. To enhance the traffic throughput and improve the efficiency operation of special events of urban transportation network, the optimization strategies should be consider the lane channelization that can effective improve the capacity of lane and mitigate the congestion and reduce the travel delay time during special event in urban the traffic network.

To address the aforementioned critical issues in the model development, the reminder of this chapter is organized as follows. The section 5.2 introduces detailed definition in the model formulation and network representation. The mathematical model for planning of the uninterrupted flow and signal intersection will be solved in the section 5.3. Section 5.4 designs the solution method of the specific algorithm for the special events. In section 5.5, numerical examples are given to assess the proposed model and solution algorithm. Conclusion remarks are summarized in section 5.6.

5.2. Network Representation

As illustrated in Figure 5. 1, the special event network $\mathcal{G} = (\mathcal{N}, \mathcal{A})$ is comprised of the set of nodes denoted by $\mathcal{N}, i \in \mathcal{N}$ and the set of the links connecting two adjacent nodes denoted by $\mathcal{A}, a = (i, i') \in \mathcal{A}$. Each node i consists of a set of arms denoted by $\mathcal{J}_i; j, m \in \mathcal{J}_i$. And each arm j in the node consists of a set of turning movements denoted by $W_i, w = (j, m) \in W_i$, $w =$ 1,2,3,4 represent U-Turning, Left-Turning, Through and Right-Turning on arm j, respectively (in Figure 5.1). Let $\mathcal{L}_j, l \in \mathcal{L}_j$ represent the set of approach lanes on arm j. For any link $a \in \mathcal{A}$, denote v_a be the flows of on the link, $n_{ij}$and n'_{ij} be the number of the approach and exit lanes on the arm j at node i, and c_a be the link capacity. For arbitrary turning $w \in W_i$, let v_w denote the turning flows from arm j to arm m, and c_w be the potential capacity for turning w, and n_w is an integer variable representing the number of lanes assigned to turning w. Let q_{ijw} represent the flow of turning movement w on arm j at node i, and q_{ijwl} present the flow of turning movement w via lane l on arm j at node i.

For an arbitrary node $i \in \mathcal{N}$, denote x_i be implemented with signal control or uninterrupted flow intersection. If any node i is implemented with the uninterrupted flow intersection, $x_i = 1$;otherwise, $x_i = 0$, the node i is implemented with signal control intersection. For any lane $l \in \mathcal{L}_j$, denote y_{ijwl} be the permission of turning w via lane l on arm j at node i. Then, turning restriction can be easily realized by setting the prohibited movement not permitted via any lane on the arm. The binary variable y_{ijw} represents the permission of turning w on arm j at node i (1- Yes, 0- No). Figure 5. 2 illustrates an example network operated with different type of traffic management strategies.

In the network $\mathcal{G} = (\mathcal{N}, \mathcal{A})$, let $\mathcal{R} \subseteq \mathcal{N}$ be the set of spreading traffic demand origin nodes, $\mathcal{S} \subseteq \mathcal{N}$ be the set of decentralization destinations nodes, and (r, s) be each OD pair, where $r \in \mathcal{R}$, $s \in \mathcal{S}$, between which spread choose their routes. Let q_{rs} be the demand of spreading traffic between (r, s) and Z_{rs} be the set of routes for travers between (r, s) . A route $z \in Z_{rs}$ includes sequence of links and turning movements. We define $\delta_{rs}^{az} = 1$ if a route z between (r, s) traverses link a; otherwise, $\delta_{rs}^{az} = 0$. if a route z between (r, s) passes turning $\delta_{rs}^{wz} = 1$; otherwise $\delta_{rs}^{wz} = 0$ .The flow on route z between (r, s) is denoted by f_{rs}^{z}.

To facilitate the model presentation, the notations used hereafter are summarized in Table 5.1.

Table 5. 1 Notation of Key Model Parameters and Variables

Sets and Parameters	
$\boldsymbol{\mathcal{G} = (\mathcal{N}, \mathcal{A})}$	Directed graph represent the special events network
$\boldsymbol{\mathcal{N}}$	The set of nodes denoted by $\mathcal{N}$

$\mathcal{A}$	The set of links joining two nodes denoted by $\mathcal{A}$
A_i^+	The set of upstream links to node i, $A_i^+ \subseteq \mathcal{A}$
A_i^-	The set of downstream links from node i, $A_i^- \subseteq \mathcal{A}$
A_a^+ , A_a^-	The set of upstream and downstream of link a, $A_a^+ \subseteq \mathcal{A}, A_a^- \subseteq \mathcal{A}$
a	The link that connecting two nodes, $\forall\, a \in \mathcal{A}$
a'	The downstream of link a, $\forall\, a \in A_a^+, a' \in A_a^-$
a_k	The k^{th} link in one junction, $a_k \in A_a^+$
a_{k+p}	The downstream of the link a_k, , $a_{k+p} \in A_a^-$
p	The positive integer, $p=1,2,3....$
k	The numbering for the link a
v_a	The traffic flow of link a
c_a	The capacity of link a
α_a	The number of approach lanes on link a
ε_a	The number of exit lanes on link a
n_a	The number of lanes on link a
W_a	The set of turning on link a
W_a^l	The set of turning on link a via lane l
w	The turning from link a to link a', $w=(a, a')$
w_p	The turning from link a_k to link a_{k+p}, $w_p = (a_k, a_{k+p})$
w_p^l	The turning from link a_k to link a_{k+p} via lane l, $w_p^l = (a_k, a_{k+p}, l)$
v_w	The turning flows rate for turning w
c_w	The capacity for turning w
$\mathcal{L}_a$	Represent a set of lanes on link a
l	The numbering for lanes on the link a
$\mathcal{R}$	Set of decentralization demand origin nodes, $\mathcal{R} \subseteq \mathcal{N}$
$\mathcal{S}$	Set of decentralization destinations nodes, $\mathcal{S} \subseteq \mathcal{N}$
(r, s)	Represent each OD pair
Z_{rs}	Set of routes for drivers between (r, s)
z	A router may include a sequence of links and turning
q_{rs}	Demand traffic flow of drivers between (r, s)
q_{rs}^z	The demand traffic flow on router z between (r, s)
C_i	Signal cycle length of the node i

$C_{max}(C_{min})$	Minimum (Maximum) cycle length
g_w	Green time on turning *w*
G_i	The sum of the green time for all signal phase at node *i*
L_i	Total lost time per cycle at node *i*
S_a^l	Saturation flow of lane *l* in link *a*
η_a^l	The degree of saturation at lane *l* in link *a*
ρ_a^l	The maximum acceptable degree of saturation on lane *l* at link *a*
θ_w	Start of the green for turning *w*
$\emptyset_w$	Green time ratio for turning *w*
Θ_a^l	Start of the green in link a for approach traffic lane *l*
Φ_a^l	Green time ratio in link a for approach traffic lane *l*
$B_i\ ,B_j$	The budget for uninterrupted flow and signal intersection, $i\ ,j \in\ \mathcal{N}$
z_w	The number of lanes assigned to turning *w*
Binary Variable	
x_i	Intersection *i* is implemented with uninterrupted flow, $x_i\ = 1;$ otherwise; $x_i\ = 0$
y_w	Permission of the movement on turning *w*, if permitted y_w *=1;* otherwise y_w *=0*
δ_w^l	A binary variable, if the turning *w* via lane *l*, $\delta_w^l\ = 1$; otherwise $\delta_w^l\ = 0$
δ_{rs}^{az}	A router *z* between *(r,s)* traverses link *a*, if true $\delta_{rs}^{az}\ = 1$;otherwise $\delta_{rs}^{az}\ = 0$
δ_{rs}^{wz}	A router *z* between *(r,s)* pass turning *w*, if true $\delta_{rs}^{wz}\ = 1$;otherwise $\delta_{rs}^{wz}\ = 0$

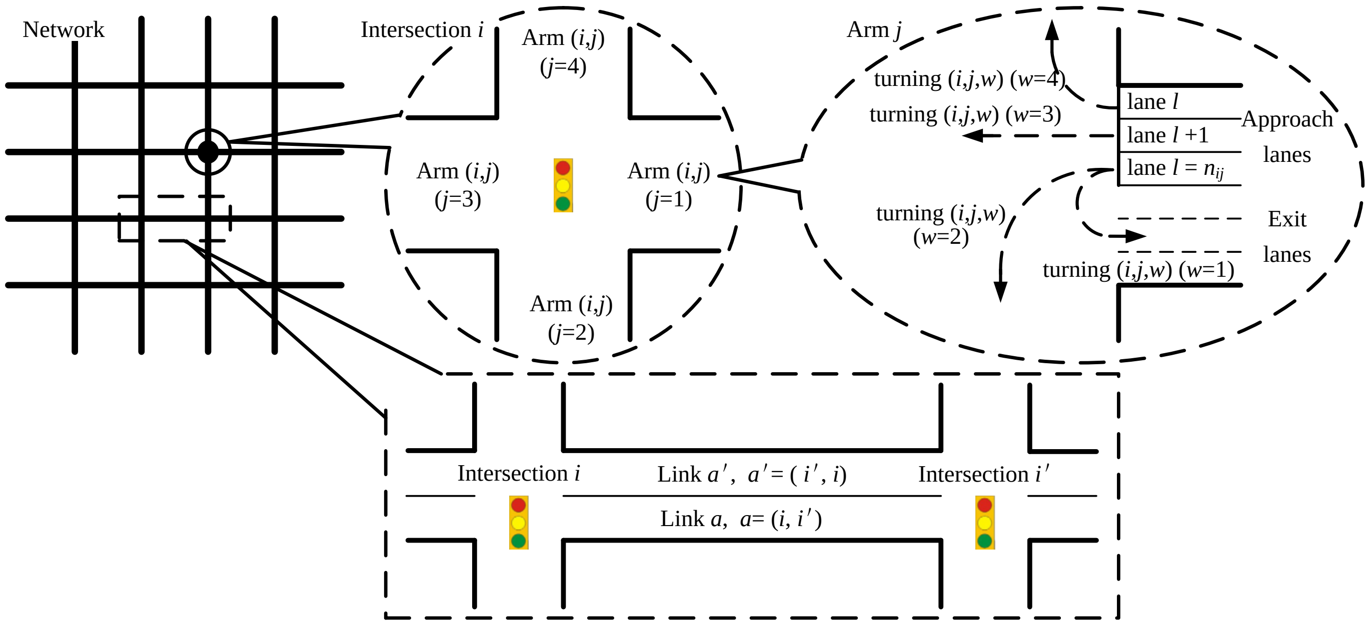


Figure 5. 1The Lane Marking of Intersection in Road Network

5.3 The Optimization Network Model

5.3.1 Decision Variables

Given the network representation in Section 5.2, the proposed model aims to simultaneously determine the best locations and number of the uninterrupted flow and signal control intersection as well as the corresponding turning restriction and lane channelization plans, expressed by the following set of decision variables:

$$\boldsymbol{x}_i = \begin{cases} 1, & \text{intersection } i \text{ is implemented with uninterrupted flow} \\ 0, & \text{intersection } i \text{ is implemented with signal} \end{cases}, \forall i \in \mathcal{N}$$

$$\boldsymbol{y}_{ijwl} = \begin{cases} 1, & \text{the turning } w \text{ is permissed on lane } l \text{ on arm } j \text{ at intersection } i \\ 0, & \text{the turning } w \text{ is prohibited on lane } l \text{ on arm } j \text{ at intersection } i \end{cases}, \forall i \in \mathcal{N}; j \in \mathcal{J}_i; l \in \mathcal{L}_j; w \in W_i$$

$\boldsymbol{\xi}_i$ = reciprocal of signal cycle length at intersection i (1/s), $\forall i \in \mathcal{N}$

$\mathbf{\Theta}_{ijl}$ = start of green for lane l on arm j at intersection i, $\forall\, i \in \mathcal{N}; j \in \mathcal{J}_i; l \in \mathcal{L}_j$

$\boldsymbol{\Phi}_{ijl}$ = green split for lane l on arm j at intersection i, $\forall\, i \in \mathcal{N}; j \in \mathcal{J}_i; l \in \mathcal{L}_j$

$\boldsymbol{\Omega}_{(jw,mw')}$ = an order of the signal phase for a pair of conflicting traffic movements on node i, $\Omega_{(jw,mw')} = 1$, movement jw follows movement mw', otherwise, movement mw' follows movement jw. $\forall\, j, m \in \mathcal{J}_i, m \neq j; w, w' \in W_i$

These variables are the feasible network design solution vector $\mathbf{s} = (\mathbf{X}, \mathbf{Y}, \boldsymbol{\xi}, \boldsymbol{\Theta}, \boldsymbol{\Phi}, \boldsymbol{\Omega})$ with $\mathbf{X} = (x_i | i \in \mathcal{N})$, $\mathbf{Y} = \left(y_{ijwl} \middle| i \in \mathcal{N}; j \in \mathcal{J}_i; l \in \mathcal{L}_j; w \in W_i\right)$, $\boldsymbol{\xi} = (\xi_i | i \in \mathcal{N})$, $\boldsymbol{\Theta} = \left(\Theta_{ijl} \middle| i \in \mathcal{N}; j \in \mathcal{J}_i; l \in \mathcal{L}_j\right)$, $\boldsymbol{\Phi} = \left(\Phi_{ijl} \middle| i \in \mathcal{N}; j \in \mathcal{J}_i; l \in \mathcal{L}_j\right)$, $\boldsymbol{\Omega} = (\Omega_{(jw,j'w')} | j \in \mathcal{J}_i; w, w' \in W_i)$.

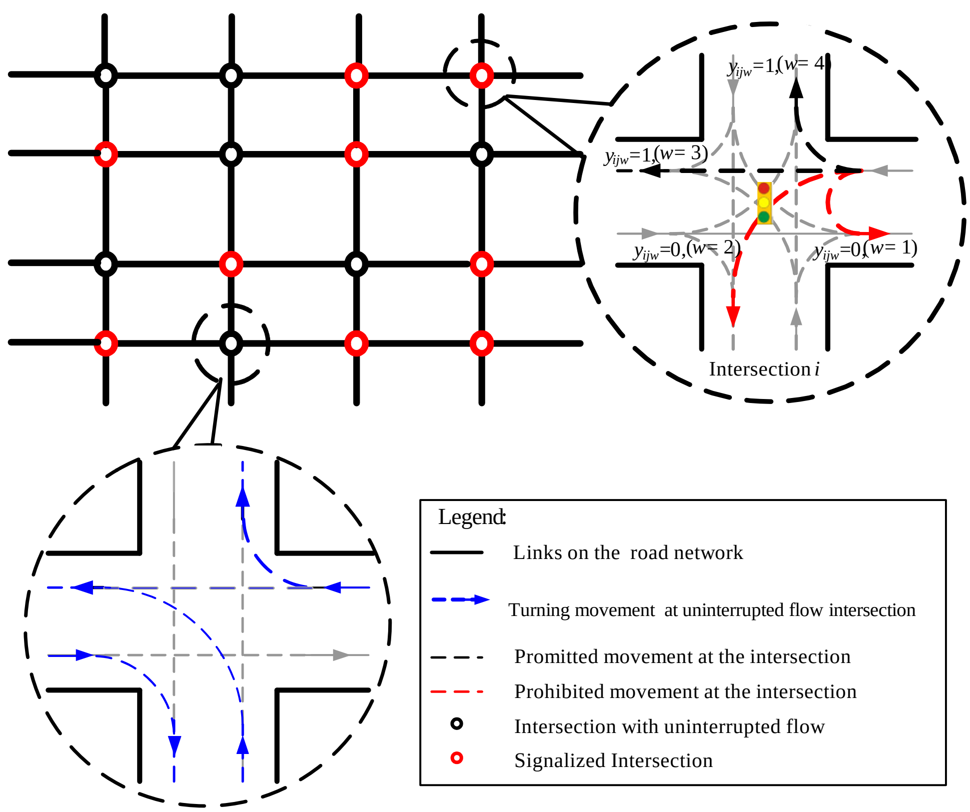


Figure 5. 2 Traffic Management Strategies in a Network

5.3.2 Upper-level Problem

In this paper, we assume a single super destination in the special events network, and spreading traffic would perceive safety when they reach the exit nodes connected with the super destination via impedance free links. The total event clearance time can be represented with the summation of flows on links multiplied by their corresponding travel times, as follow:

$$min\, f(\mathbf{v},\mathbf{s}) = \sum_{a\in\mathcal{A}} u_a\,(\mathbf{v},\mathbf{s}) v_a + \sum_{w\in W_i} u_w\,(\mathbf{v},\mathbf{s}) v_w \quad (5.1)$$

The flow conservation constraint

$$q_{ijw} = \sum_{l=1}^{n_{ij}} q_{ijwl}\,,\ \forall\, i \in \mathcal{N}; j \in \mathcal{J}_i; w \in W_i \quad (5.2)$$

Constraint (5.2) indicates that the sum of the flows of a movement on different lanes shou ld be equal to the total assigned flow of that movement.

The lane assignment constraints

$$y_{ijwl} + \sum_{w'\in\chi_{w_i}} y_{ijw'l} \le 1 + M(1 - x_i)\,,\ \ \forall\, i \in \mathcal{N}; j \in \mathcal{J}_i; w, w' \in W_i; l \in \mathcal{L}_j \quad (5.3)$$

Constraint (5.3) is developed for cross elimination, where χ_{w_i} is a conflicting matrix for turning w at any node i and M is a large enough positive number. In the special event network, if node i is implemented with an uninterrupted flow intersection (i.e. $x_i = 1$), each pair of conflicting turnings should be eliminated at node i; otherwise, there is no restriction on turning for a signalized intersection. There are many approach and exit lanes in any arm j.

$$\sum_{w\in W_i} y_{ijwl} \ge 1\,, \forall\, j \in \mathcal{J}_i;\ l \in \mathcal{L}_j;\ i \in \mathcal{N} \quad (5.4)$$

Constraint (5.4) allows each approach lane to carry at least one turning or through movement.

$$n'_{im}\ \ge \sum_{l\in\mathcal{L}_j} y_{ijwl}\,, \forall\, w = (j, m) \in W_i; j, m \in \mathcal{J}_i, m \ne j; i \in \mathcal{N} \quad (5.5)$$

Constraint (5.5) sets the minimum number of exit lanes strategy. For a turning w from arm j to the adjacent arm m at intersection i, the number of the exit lane in the arm j should be at least as many as the total number of lanes assigned to such a turning movement from the arm j.

$$1 - y_{ijwl} \geq y_{ijw'(l+1)}, \forall i \in \mathcal{N};\ j \in \mathcal{J}_i; w \in \{1,2,3\};\ w' \in \{w+1, \dots, 4\}; l \in \{1, \dots, n_{ij} - 1\} \quad (5.6)$$

Constraint (5.6) prevents internal conflicts among lanes on an arm. We will set the permitted movements across adjacent approach lanes. For any adjacent traffic lanes, l (right-hand) and $l + 1$(left-hand) lanes from arm j to m is permitted on lane l, then all other traffic turns should be prohibited on lane $l + 1$ to eliminate the intersection conflicts within a junction.

$$My_{ijw} \geq \sum_{l \in \mathcal{L}_j} y_{ijwl} \geq y_{ijw}, \forall\ i \in \mathcal{N}; j \in \mathcal{J}_i; w \in W_i \quad (5.7)$$

Constraint (5.7) sets the turning restriction strategy. If a movement at the intersection is prohibited mean that the number of lanes permitted for the prohibited movements should be equal to zero; otherwise, the movement should be permitted in least one lane, where M is an arbitrary large positive constant number.

$$v_a \leq c_a, \forall\ a \in \mathcal{A} \quad (5.8)$$

$$v_w \leq c_w, \forall\ ; w \in W_i \quad (5.9)$$

Constraints (5.8) and (5.9) restrict that the flow on a link or a turning cannot exceed its capacity in any intersection. Where c_w is the capacity of turning w.

The signal time constraints

$$\frac{(1-x_i)}{C_{max}} \leq \xi_i \leq \frac{(1-x_i)}{C_{min}}, \forall\ i \in \mathcal{N} \quad (5.10)$$

Constraint (5.10) limits the common cycle lengths C_i for the any intersection i in the network to be within C_{min} and C_{max}, which present the minimum and maximum cycle lengths.

Instead of defining the cycle length directly as the control variable, its reciprocal, $\xi_i = 1/C_i$, is used to preserve the linearity in the mathematical formulation (Wong and Wong, 2003; Wong and Heydecker, 2011).

$$1 - x_i \geq \theta_{ijw} \geq 0, \forall \; i \in \mathcal{N}; j \in \mathcal{J}_i; w \in W_i \tag{5.11}$$

Constraint (5.11) confines the start of the green to be within a fraction between 0 and 1 of the cycle length at any intersection i. Where the θ_{ijw} is the start of green for turning w on arm j at intersection i.

$$1 - x_i \geq \phi_{ijw} \geq 0, \forall \; i \in \mathcal{N}; j \in \mathcal{J}_i; w \in W_i \tag{5.12}$$

Constraint (5.12) indicates that the green split of a movement is confined between 0 and 1 of the cycle length.

$$M(1 - x_i)y_{ijw} \geq \phi_{ijw} \geq -M(1 - x_i)y_{ijw}, \forall \; i \in \mathcal{N}; j \in \mathcal{J}_i; w \in W_i \tag{5.13}$$

Constraint (5.13) sets that the green split of a movement should be equal to zero if the movement is prohibited. Where ϕ_{ijw} represents the duration of green and the green time for turning w on arm j at intersection i. If a lane is shared by more than one movement, these movements must receive the identical signal indication to avoid ambiguity.

$$M\big(1 - (1 - x_i)y_{ijwl}\big) \geq \Theta_{ijl} - \theta_{ijw} \geq -M\big(1 - (1 - x_i)y_{ijwl}\big), \forall \; i \in \mathcal{N}; j \in \mathcal{J}_i; w \in W_i; l \in \mathcal{L}_j \tag{5.14}$$

$$M\big(1 - (1 - x_i)y_{ijwl}\big) \geq \Phi_{ijl} - \phi_{ijw} \geq -M\big(1 - (1 - x_i)y_{ijwl}\big), \forall \; i \in \mathcal{N}; j \in \mathcal{J}_i; w \in W_i; l \in \mathcal{L}_j \tag{5.15}$$

Considering the lane l from link a, if the movement w is permitted on this lane, the following two constraints (5.14)-(5.15) can be established to fulfill the above condition. Where M is an arbitrary large positive constant number. If a movement w is permitted on lane l, then the lane marking $y_{ijwl} = 1$, and hence the values on both sides the above two inequalities become zero.

$$\Omega_{(jw,mw')} + \Omega_{(mw',jw)} = (1 - x_i), \forall\ i \in \mathcal{N}; j, m \in \mathcal{J}_i, m \neq j; w, w' \in W_i \tag{5.16}$$

Constraint (5.16) sets the order of signal phase display for a pair of conflicting traffic movements at intersection i, which is governed by a successor function (Heydecker, 1992).

$$(1 - x_i)(\theta_{mw'} + \Omega_{(jw,mw')}) \geq \theta_{jw} + \phi_{ijw} + \omega_{(jw,mw')}\xi_i, \forall\ i \in \mathcal{N};\ j, m \in \mathcal{J}_i, m \neq j; w, w' \in W_i \tag{5.17}$$

Constraint (5.17) limits the start of greens for any pair of conflicting traffic movements considering the minimum clearance time and movement prohibition, where $\omega_{(jw,mw')}$ represents the clearance time for a pair of conflicting traffic movements.

5.3.3 Lower Level Problem

The lower level problem specifies the destination distribution and router assignment of the traffic demand. Given the feasible network design solution vector $\mathbf{s}$. Let $\mathbf{v} = (\mathbf{v}_a, \mathbf{v}_w) = \{(v_a, a \in \mathcal{A}) \cup (v_w, w \in W_i)\}$ be the flow pattern under the solution $\mathbf{s}$. We can estimate the costs by drivers on link a and turning w with

$$u_a(\mathbf{v}, \mathbf{s}) = t_a(\mathbf{v}, \mathbf{s}) \tag{5.18}$$

$$u_w(\mathbf{v}, \mathbf{s}) = t_w(\mathbf{v}, \mathbf{s})\ , \tag{5.19}$$

where the $t_a(\mathbf{v}, \mathbf{s})$ and $t_w(\mathbf{v}, \mathbf{s})$are the travel time on link a and turning w, respectively

We can estimate $t_a(\mathbf{v}, \mathbf{s})$ with the BPR-form function, given by:

$$t_a(\mathbf{v}, \mathbf{s}) = t_a^0 \left[1 + \omega_a \cdot \left(\frac{v_a}{c_a}\right)^{\beta_a}\right],\ \ \forall a \in \mathcal{A} \tag{5.20}$$

Further, the turning time on turning w can be calculated by following equation:

$$t_w(\mathbf{v}, \mathbf{s}) = t_w^0 \left[1 + \omega_w \cdot \left(\frac{v_w}{c_w}\right)^{\beta_w}\right], \forall\ w\ \in W_i \tag{5.21}$$

In Equations (5.20) and (5.21), t_a^0 and t_w^0 are the free-flow travel time and turning time on link a and turning w, respectively; ω_a, β_a, ω_w, and β_w are travel cost function parameters; c_0 is the lane capacity; γ_w is the lane utilization factor ; x_i is a binary variable deciding whether or not to implement uninterrupted flow at node i (1-Yes, 0-No).

$$c_w = [x_i + (1 - x_i)\phi_{ijw}]S_{ijal} \sum_{l\in\mathcal{L}_j} y_{ijwl}\gamma_w \tag{5.22}$$

$$S_{ijal} = \frac{\overline{S}_{ijal}}{1+1.5\sum_{j\in\mathcal{J}_i} f_{ijwl}/r_{ijwl}}, \forall\ i \in \mathcal{N}; w \in W_i; l \in \mathcal{L}_j \tag{5.23}$$

$$f_{ijwl} = \frac{q_{ijwl}}{\sum_{m\in\mathcal{J}_i} q_{imwl}}, \forall i \in \mathcal{N}; j \in \mathcal{J}_i; w \in W_i; l \in \mathcal{L}_j \tag{5.24}$$

Equation (5.22) is the capacity of turning w. Let ϕ_{ijw} be the green split on turning w at node i, if the intersection is signalized. Equation (5.23) S_{ijal} is the saturation flow of lane l on link a at node i, r_{ijwl} and f_{ijwl} are respectively, the radius of the turning trajectory (=∞ for straight-ahead movement) and the proportion of flow in equation (5.24), during turning w via lane l, and $\overline{S}_{ijal}$ is the saturation flow of the lane for straight-ahead movement only when the lane is shared by straight-head movement and a turning movement, the expression reduces to the form in Kimber et al. (1986) for a mix lane. Moreover, if it is used exclusively for one turning movement the expression also reduces to the formula in Kimber et al. For straight-ahead movement only, the saturation flow become $\overline{S}_{ijal}$ by default. Equation (5.23) is derived based on the weighted average radius of curvature for different turning movement.

5.3.4 Route Choice

Given a feasible solution $\mathbf{s} = (\mathbf{X}, \mathbf{Y}, \boldsymbol{\xi}, \boldsymbol{\Theta}, \boldsymbol{\Phi}, \boldsymbol{\Omega})$ to the problem stated above, travelers will be routing in the network derived from **s** without violating the turning restrictions and signal control constraints. The network flow distribution will therefore result from their route choice behavior. We consider the stochastic user equilibrium (SUE) principle to capture the resulted network flow pattern. Based on the SUE model, no traveler could unilaterally decrease his/her transportation disutility by changing routes between a certain OD pair.

Let C_{rs}^{z} represent random perceived travel time along the route z between the OD pair, so we can get the relation with the actual travel time c_{rs}^{z} along route z between OD pair as follow:

$$C_{rs}^{z} = c_{rs}^{z} - \frac{1}{\theta}\xi_{rs}^{z}, \forall r \in \mathcal{R}, s \in \mathcal{S};\ z \in Z_{rs} \tag{5.25}$$

Where θ is a positive unit scaling parameter. $\xi_{rs}^{z}$is the random term and associates with the route under consideration and can be considered to represent the unobservable factor of utility. In this paper, ξ_{rs}^{z} is assumed to be normally distributed, one would obtain the probit-based route choice model. However, the probit-based model does not entail a closed form expression of the route choice probability. Hence we consider the logit-based route choice model only. The logit-based model assumes that random that the random terms of the utility function associated with all routes are independently and identically distributed Gumbel random variables. The choice probability is then given by

$$P_{rs}^{z}(\mathbf{f}) = \frac{exp(-\theta c_{rs}^{z}(\mathbf{f}))}{\sum_{k\in Z_{rs}} exp(-\theta c_{rs}^{k}(\mathbf{f}))} \quad \forall r \in \mathcal{R}, s \in \mathcal{S}; z \in Z_{rs} \tag{5.26}$$

Where P_{rs}^{z} represents the probability of users choosing route z, $r \in \mathcal{R}, s \in \mathcal{S}; z \in Z_{rs}$, which is also the share of the users choosing route, the perceived travel time minimization principle implies that

$$P_{rs}^{z}(\mathbf{f}) = Prob\{C_{rs}^{z}(\mathbf{f}) \leq C_{rs}^{k}(\mathbf{f}), \forall z \in Z_{rs}; r \in \mathcal{R}, s \in \mathcal{S} \tag{5.27}$$

This choice probability has the following properties:

$$0 \leq P_{rs}^{z}(\mathbf{f}) \leq 1 \text{ and } \sum_{z\in Z_{rs}} P_{rs}^{z}(\mathbf{f}) = 1, \forall r \in \mathcal{R}, s \in \mathcal{S} \tag{5.28}$$

Then the route flow assignment is given by

$$\mathbf{f}_{rs}^{z} = q_{rs}\frac{exp(-\theta c_{rs}^{z}(\mathbf{f}))}{\sum_{k\in Z_{rs}} exp(-\theta c_{rs}^{k}(\mathbf{f}))} \quad \forall r \in \mathcal{R}, s \in \mathcal{S}; z \in Z_{rs} \tag{5.29}$$

It is well known (Fisk,1980) that the above logit-based SUE model can formulated ad the following equivalent minimization problem:

$$\min_{\mathbf{f}\in\mathbf{\Lambda}_f} \mathcal{Z}(\mathbf{f}) = \sum_{a\in\mathcal{A}} \int_0^{v_a} t_a(\omega)\, d\omega + \frac{1}{\theta}\sum_{r\in\mathcal{R},s\in\mathcal{S}} \sum_{z\in Z_{rs}} \sum_{a\in\mathcal{A}} f_{rs}^{z}\delta_{rs}^{az} \ln f_{rs}^{z}\delta_{rs}^{az}$$

$$+ \sum_{w\in\mathcal{T}} \int_0^{v_w} t_w(\omega)\, d\omega + \frac{1}{\theta}\sum_{r\in\mathcal{R},s\in\mathcal{S}} \sum_{z\in Z_{rs}} \sum_{w\in W_i} f_{rs}^{z}\delta_{rs}^{wz} \ln f_{rs}^{z}\delta_{rs}^{wz} \qquad (5.30)$$

Denote SUE route flow as $\mathbf{f^{sue}} = (\mathbf{f}_a^{\text{sue}}, \mathbf{f}_w^{\text{sue}}) \in \mathbf{\Lambda}_f$, and the corresponding SUE link flow $\mathbf{v^{sue}} = (\mathbf{v_a^{sue}}, \mathbf{v_w^{sue}}) \in \mathbf{\Lambda_v}$ and $\mathbf{g}(\mathbf{f})^T = (\mathrm{g_a}(\mathbf{f}), \mathrm{g_w}(\mathbf{f}))^T$.

Lemma 1. If the travel time function, $\mathrm{t}_a(\mathbf{v_a})$ and $\mathrm{t_w}(\mathbf{v_w})$ are separable functions and are monotonically increase with the flow $\mathbf{v}_a$ and $\mathbf{v}_{\mathrm{w}}$ respectively. The minimization of SUE problem is equivalent the following Variational Inequality (VI) Problem, find $\mathbf{f}^{sue} \in \boldsymbol{\Lambda}_{\mathbf{f}}$, so that

$$\sum_{a\in\mathcal{A}} \mathbf{g}_a(\mathbf{f})^T \left(\mathbf{f}_a - \mathbf{f}_a^{\text{sue}}\right) + \sum_{w\in W_i} \mathbf{g}_w(\mathbf{f})^T \left(\mathbf{f}_w - \mathbf{f}_{\mathrm{w}}^{\text{sue}}\right) \geq 0 \qquad (5.31)$$

$$\mathrm{g}_a(\mathbf{f}) = \sum_{r\in\mathcal{R}} \sum_{s\in\mathcal{S}} \sum_{z\in Z_{rs}} (c_{rs}^{a}(\mathrm{f}_a^{\text{sue}}) + \frac{1}{\theta}\ln f_{rs}^{z}\delta_{rs}^{az}) \qquad (5.31.a)$$

$$\mathrm{g}_w(\mathbf{f}) = \sum_{r\in\mathcal{R}} \sum_{s\in\mathcal{S}} \sum_{z\in Z_{rs}} (c_{rs}^{w}(\mathrm{f}_w^{\text{sue}}) + \frac{1}{\theta}\ln f_{rs}^{w}\delta_{rs}^{wz}) \qquad (5.31.b)$$

$$\forall\, \mathbf{f} \in \boldsymbol{\Lambda}_{\mathbf{f}} = \{\mathbf{f} | q_{rs} = \sum_{a\in\mathcal{A}} \sum_{z\in Z_{rs}} f_{rs}^{z}\delta_{rs}^{az} \quad \forall\, r \in \mathcal{R}, s \in \mathcal{S}$$

$$q_{rs} = \sum_{w\in W_i} \sum_{z\in Z_{rs}} f_{rs}^{z}\delta_{rs}^{wz} \quad \forall\, r \in \mathcal{R}, s \in \mathcal{S}$$

$$f_{rs}^{z} \geq 0 \quad \forall\, r \in \mathcal{R}, s \in \mathcal{S}, z \in Z_{rs} \qquad \} \qquad (5.31.c)$$

Proof. It suffers to probe that minimization problem (5.30) is equivalent to VI (5.31). With the assumption of monotonically increasing travel time function, the problem (5.30) of the minimizing a strictly convex function over a compact set guarantees the existence and uniqueness of a path flow $\mathbf{f^{sue}} \in \mathbf{\Lambda_f}$. In addition, the entropy type objective function ensures that the optimal is an achieved at an interior point. It is necessary condition for $\mathbf{f}^{\mathbf{sue}} \in \mathbf{\Lambda_f}$ to the unique optimal solution to problem (5.30) is that

$$[\nabla_{\mathbf{f}} \mathcal{Z}(\mathbf{f}^{\text{sue}})]^{\text{T}}(\mathbf{f} - \mathbf{f}^{\mathbf{sue}}) \geq 0, \forall\, \mathbf{f} \in \mathbf{\Lambda_f} \tag{5.32}$$

Using $\mathbf{v}_a = \sum_{r\in\mathcal{R}} \sum_{s\in\mathcal{S}} \sum_{z\in Z_{rs}} f_{rs}^{z}\, \delta_{rs}^{az}$ and $\mathbf{v}_w = \sum_{r\in\mathcal{R}} \sum_{s\in\mathcal{S}} \sum_{z\in Z_{rs}} y_w f_{rs}^{z}\, \delta_{rs}^{wz}$ substituting to (5.32) and then we can get following equation:

$$[\nabla_{\mathbf{f}_a} \mathcal{Z}(\mathbf{f}^{\text{sue}})]^T = \left[\dots, \frac{1}{\theta} + \frac{1}{\theta} \ln f_{rsz}^{sue} \delta_{rs}^{az} + \sum_{a\in\mathcal{A}} t_a(v_a) \delta_{rs}^{az}, \dots\right] \tag{5.33.a}$$

$$[\nabla_{\mathbf{f}_w} \mathcal{Z}(\mathbf{f}^{\text{sue}})]^T = \left[\dots, \frac{1}{\theta} + \frac{1}{\theta} \ln f_{rsz}^{sue} \delta_{rs}^{wz} + \sum_{w\, \in W_i} t_w(v_w) \delta_{rs}^{wz}, \dots\right] \tag{5.33.b}$$

We use the (5.34.a) and (5.34.b), substituting to (5.33.a) and (5.33.b), respectively.

$$c_{rs}^{a}(\mathbf{v}) = \sum_{a\in\mathcal{A}} t_a(v_a)\, \delta_{rs}^{az} \tag{5.34.a}$$

$$c_{rs}^{w}(\mathbf{v}) = \sum_{w\, \in W_i} t_w(v_w)\, \delta_{rs}^{wz} \tag{5.34.b}$$

We can get

$$[\nabla_{\mathbf{f}_a} \mathcal{Z}(\mathbf{f}^{\text{sue}})]^T = \left[\dots, \frac{1}{\theta} + \frac{1}{\theta} \ln f_{rsz}^{sue} \delta_{rs}^{az} + c_{rs}^{a}(\mathbf{f}_{\boldsymbol{a}}^{\mathbf{sue}}), \dots\right] \tag{5.35.a}$$

$$[\nabla_{\mathbf{f}_w} \mathcal{Z}(\mathbf{f}^{\text{sue}})]^T = \left[\dots, \frac{1}{\theta} + \frac{1}{\theta} \ln f_{rsz}^{sue} \delta_{rs}^{wz} + c_{rs}^{w}(\mathbf{f}_{\boldsymbol{w}}^{\mathbf{sue}}), \dots\right] \tag{5.35.b}$$

We can get this separable function optimal condition as following:

$$[\nabla_{\mathbf{f}_a} \mathcal{Z}(\mathbf{f}^{\text{sue}})]^T(\mathbf{f_a} - \mathbf{f}^{\mathbf{sue}}) \geq 0 \tag{5.36.a}$$

$$[\nabla_{\mathbf{f}_w} \mathcal{Z}(\mathbf{f}^{\text{sue}})]^T(\mathbf{f_w} - \mathbf{f}^{\mathbf{sue}}) \geq 0 \tag{5.36.b}$$

We use

$$[\nabla_{\mathbf{f}} \mathcal{Z}(\mathbf{f}^{\text{sue}})]^T = \begin{bmatrix} \nabla_{\mathbf{f}_a} \mathcal{Z}(\mathbf{f}^{\text{sue}}) \\ \nabla_{\mathbf{f}_w} \mathcal{Z}(\mathbf{f}^{\text{sue}}) \end{bmatrix}^T, \mathbf{f} = (\mathbf{f_a}, \mathbf{f_w})^T,$$

and substitute to (5.32). We can get the following equation:

$$[\nabla_{\mathbf{f}_a}\mathcal{Z}(\mathbf{f}^{\mathrm{sue}}]^T(\mathbf{f_a}-\mathbf{f^{sue}})+[\nabla_{\mathbf{f}_w}\mathcal{Z}(\mathbf{f}^{\mathrm{sue}})]^T(\mathbf{f_w}-\mathbf{f^{sue}})\geq 0 \tag{5.37}$$

In this section, we just calculate the first half of the equation (5.37) and the second half is same with first one. We can get

$$\sum_{r\in\mathcal{R}}\sum_{s\in\mathcal{S}}\sum_{z\in Z_{rs}}\sum_{a\in\mathcal{A}}\left(\frac{1}{\theta}+\frac{1}{\theta}\ln f_{rsz}^{sue}\delta_{rs}^{az}+c_{rs}^{a}(\mathbf{f_a^{sue}})\right)(\mathbf{f_a}-\mathbf{f_a^{sue}})=$$

$$\frac{1}{\theta}\sum_{r\in\mathcal{R}}\sum_{s\in\mathcal{S}}\sum_{z\in Z_{rs}}\sum_{a\in\mathcal{A}}(f_{rs}^{z}\delta_{rs}^{az}-f_{rsz}^{\ sue}\delta_{rs}^{az})$$

$$+\sum_{r\in\mathcal{R}}\sum_{s\in\mathcal{S}}\sum_{z\in Z_{rs}}\sum_{a\in\mathcal{A}}\left(\frac{1}{\theta}\ln f_{rsz}^{\ sue}\delta_{rs}^{az}+c_{rs}^{a}(\mathbf{f_a^{sue}})\right)(\mathbf{f_a}-\mathbf{f_a^{sue}})\geq 0 \tag{5.38}$$

In view of $\frac{1}{\theta}\sum_{r\in\mathcal{R}}\sum_{s\in\mathcal{S}}\sum_{z\in Z_{rs}}\sum_{a\in\mathcal{A}}(f_{rs}^{z}\delta_{rs}^{az}-f_{rsz}^{\ sue}\delta_{rs}^{az})=\frac{1}{\theta}\sum_{r\in\mathcal{R}}\sum_{s\in\mathcal{S}}(\mathrm{q_{rs}}-\mathrm{q_{rs}})=0.$

So we can have

$$\sum_{r\in\mathcal{R}}\sum_{s\in\mathcal{S}}\sum_{z\in Z_{rs}}\sum_{a\in\mathcal{A}}\left(\frac{1}{\theta}\ln f_{rsz}^{sue}\delta_{rs}^{az}+c_{rs}^{a}(\mathbf{f_a^{sue}})\right)(\mathbf{f_a}-\mathbf{f_a^{sue}})\geq 0 \tag{5.39}$$

Similarly, we can have

$$\sum_{r\in\mathcal{R}}\sum_{s\in\mathcal{S}}\sum_{z\in Z_{rs}}\sum_{w\in W_i}\left(\frac{1}{\theta}\ln f_{rsz}^{sue}\delta_{rs}^{wz}+c_{rs}^{w}(\mathbf{f_w^{sue}})\right)(\mathbf{f_w}-\mathbf{f_w^{sue}})\geq 0 \tag{5.40}$$

Substituting (5.39) and (5.40) to (5.37), we can have VI (5.31). This completes the proof. ■

5.4 Solution Approach

The proposed optimization model has a bi-level structure with a mix-integer-non-linear-programming problem at the upper-level and a parametric variational inequality at the lower-level. It has been proved to be NP-hard (Johnson et., 1978) and the UFSI problem is difficult to solve due to its non-convexity and non-differential characteristics of the parameter VI problem.

In this section, we have been explored a hybrid genetic algorithm (HGA) based heuristic method to yield viable and approximate optimal solutions to the bi-model in a reasonable time period.

To deal with the combinatorial complexity in combined location selection and turning restriction designs, this problem is a bi-lever programming model with the genetic algorithm to solve the upper-level and using the projection method algorithm to deal with the parametric variational inequality problem at the lower-level. To penalize solutions violating capacity constraints, we define the following event clearance function $\mathrm{F}(\mathbf{v},\mathbf{s})$:

$$F(\mathbf{v},\mathbf{s}) = Z(\mathbf{v},\mathbf{s}) + \sum_{a\in\mathcal{A}} M_a \left(max\{(v_a - c_a, 0\}\right)^2 + \sum_{i\in\mathcal{N}} \sum_{w\in W_i} M_w \left(max\{(v_w - x_i c_w^1 + (1 - x_i)c_w^0, 0\}\right)^2 + \sum_{i\in\mathcal{N}} \sum_{w,w'\in W_i} M_w x_i \left(max\{(y_{ijwl} + \sum_{w'\in\chi_w} y_{ijw'l} - 1,0\}\right)^2 \quad (5.41)$$

Where M_a , M_w are the large positive penalty coefficients.

5.4.1 Hybrid Genetic Algorithm

<u>Step 0. Initialization</u>

Randomly determine an initial population consisting of λ distinct chromosomes, denote the population by $\mathcal{S}^n = \{\mathbf{s}_m^n | m = 1,2,3,\dots,\lambda\}$, are generated satisfying constraints (5.2)-(5.17), n represents the index of GA generation; m represents the index of chromosome; $\mathbf{s}_m^n$ is used to represent chromosome m in iteration n. Let the number of iterations $n = 0$. The procedure of the algorithm flow is demonstrated in Figure 5.3

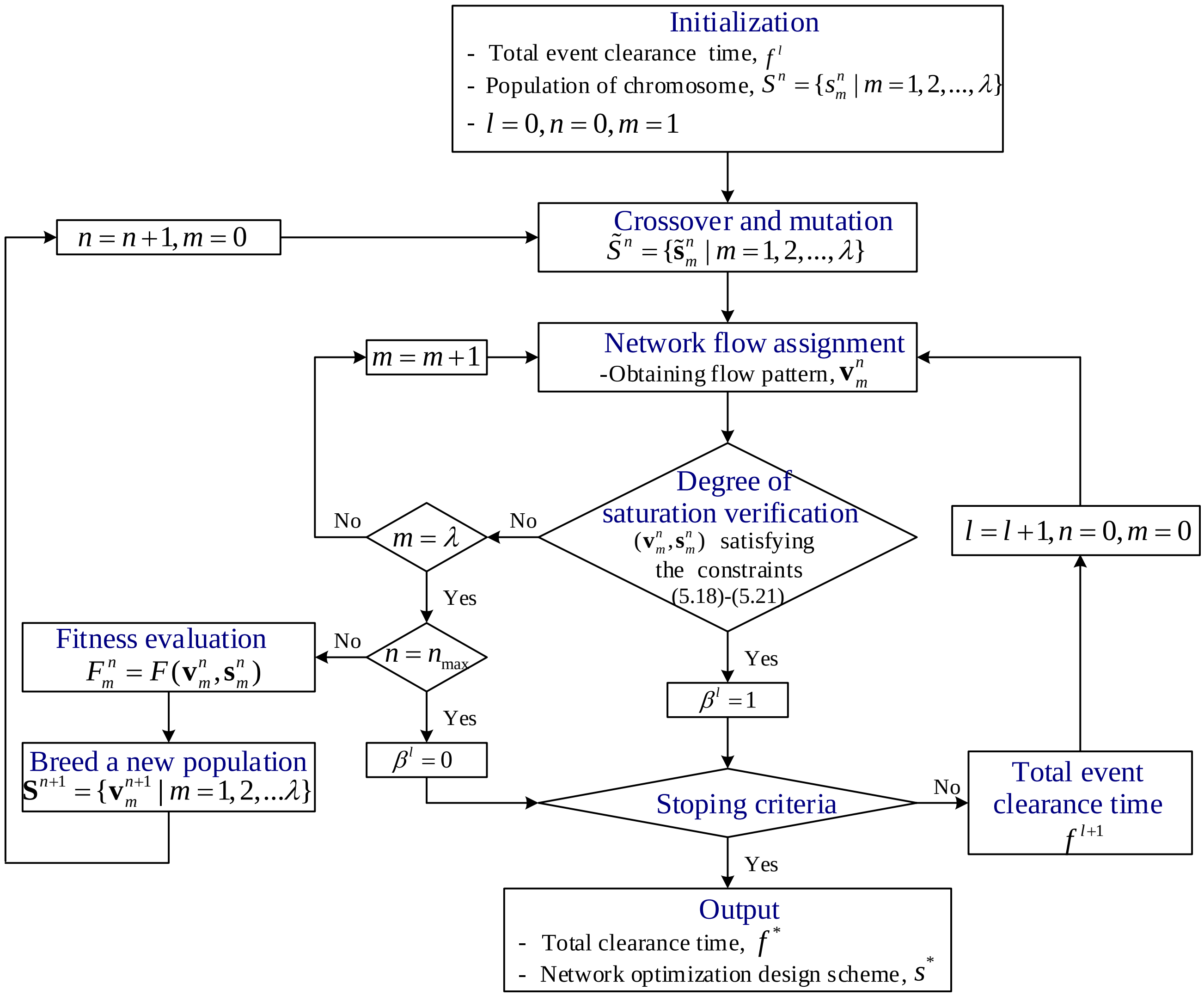


Figure 5. 3 Procedure of the Heuristic Algorithm

<u>Step 1. Crossover and Mutation</u>

The initial population of the genetic algorithm (GA) is generated randomly following the aforementioned coding scheme and chromosomes are further to ensure all of them satisfy the constraint (5.2)-(5.17). Then, one-point crossover and mutation are used to generate new solution populations with the probability of p_{cross} and p_{mt}.

<u>Step 2. Fitness Evaluation</u>

Two sub-steps are executed to calculate fitness of each chromosome in population S^n as follows.

Step 2.1 Network Flow Assignment

The network flow calculated by the projection methods algorithm is embedded in the hybrid genetic algorithm (GA) for the objective function evaluation. Note that the impedance of a link or turning in the network is associate with its flow. Therefore, the vector of disutility function of the links and turnings will in general have asymmetric Jacobian matric, and the assignment problem is an asymmetric network assignment problem (Dafermos,1980; Dafermos and Nagurney,1984), which does not have an equivalent optimization formation. One approach, most commonly used to solve asymmetric network assignment problems, is the well-known diagonalization method (Florian,1979; Abdulaal and LeBlanc,1979;Mahamassani and Mouskos,1988). In this paper, the projection method is used to solve the variation inequality VI (5.31) to obtain the SUE flow pattern $\mathbf{v}_m^n$ corresponding to the design decision $\mathbf{s}_m^n$.

Step 2.2 Fitness Normalization

Giving $\mathbf{v}_m^n$ and $\mathbf{s}_m^n(m = 1,2,3, \dots, \lambda)$, the evaluation value of chromosomes m in generation n, F_m^n=$F(\mathbf{v}_m^n, \mathbf{s}_m^n)$, can be calculated by Eq.(5.41). Then the fitness of each chromosome can be then computed by normalizing its evaluation value with Eq.(5.42).

$$\widetilde{F_m^n}(\mathbf{v}_m^n, \mathbf{s}_m^n) = \frac{F_{max}^n - F(\mathbf{v}_m^n, \mathbf{s}_m^n) + \varepsilon}{F_{max}^n - F_{min}^n + \varepsilon} \tag{5.42}$$

Where F_{max}^n and F_{min}^n denote the maximum and minimum evaluation function value in generation n, respectively; F($\mathbf{v}_m^n, \mathbf{s}_m^n$) is the evaluation value corresponding to the m^{th} chromosome in generation n; ε is the positive value between 0 and 1which function to prevent (5.42) from zero division and adjust the selection behavior between fitness proportional selection and pure random (Gen and Cheng, 2000).

Step 3. Breed a New Population

Generate the new population $\mathcal{S}^{n+1}$ of size λ by using a binary tournament selection method (Gen and Cheng, 1997) according to the fitness of each chromosome calculated with Equation (5.42). Set $n = n + 1$ and go to Step 1

Step 4. Evaluation and Stop Criteria

Based on the fitness value of chromosomes, a binary tournament method is used to generation new populations. The genetic algorithm (GA) stops to evolve until the following criteria:

$$\left|\frac{F_{min}^{n+1} - F_{min}^{n}}{F_{min}^{n}}\right| \leq \varsigma \tag{5.43}$$

Such as the difference between the minimum evaluation values between two adjacent generations is less than a threshold ς.

The projection method algorithm used in Step 2.1 is described in the following:

The non-smooth nature of the route travel time function riders solution methods based on derivative information rather difficult. So we develop a solution methods to solve this VI (Eq. 5.31) problem with the projection methods.

$$[\partial \mathcal{Z}(\mathbf{f}^{\text{sue}})/\partial \mathbf{f}]^{\mathrm{T}}(\mathbf{f} - \mathbf{f}^{\mathbf{sue}}) \geq 0, \forall\, \mathbf{f} \in \mathbf{\Lambda}_{\mathbf{f}} \tag{5.44}$$

Where, $\mathbf{\Gamma}(\mathbf{f}) = [\nabla_{\mathbf{f}} \mathcal{Z}(\mathbf{f}^{\text{sue}})]^T = \begin{bmatrix} \nabla_{\mathbf{f}_a} \mathcal{Z}(\mathbf{f}^{\text{sue}}) \\ \nabla_{\mathbf{f}_w} \mathcal{Z}(\mathbf{f}^{\text{sue}}) \end{bmatrix}^T, \mathbf{f} = (\mathbf{f}_\mathbf{a}, \mathbf{f}_\mathbf{w})^T$.

So the Eq. (5.31) can be rewritten the general VI problem as follow:

$$F(\mathbf{x}^*)^T(\mathbf{x} - \mathbf{x}^*) \geq 0 \tag{5.45}$$

$$\mathbf{x} = \begin{pmatrix} \mathbf{f} \\ \boldsymbol{\lambda} \end{pmatrix}, \; \boldsymbol{F}(\mathbf{x}) = \begin{pmatrix} \mathbf{\Gamma}(\mathbf{f}) - \boldsymbol{M}^T \boldsymbol{\lambda} \\ \boldsymbol{M}\mathbf{f} - \boldsymbol{q} \end{pmatrix} \tag{5.46}$$

In this projection method, we will denote the set K and the residual error function for the problem under consideration as:

$$\mathbf{e}(\mathbf{x},\boldsymbol{\beta}) = \mathbf{x} - \mathrm{P_K}\{\mathbf{x} - \boldsymbol{\beta} F(\mathbf{x})\} = \begin{pmatrix} \mathbf{f} - \mathrm{P_K}\{\mathbf{f} - \boldsymbol{\beta}[\boldsymbol{\Gamma}(\mathbf{f}) - \boldsymbol{M}^{\boldsymbol{T}}\boldsymbol{\lambda}]\} \\ \boldsymbol{\beta}(\boldsymbol{M}\mathbf{f} - \boldsymbol{q}) \end{pmatrix} \tag{5.47}$$

Where β is a set of given penalty parameter and $\mathrm{P_K}\{*\}$ the projection on K. it can be proved readily that if $\mathbf{e}(\mathbf{x}, \beta) = 0$, the VIP depressed in (5.45) and (5.46) is solved. Furthermore, we define $\mathbf{r}(\mathbf{x}, \beta)$ as:

$$\mathbf{r}(\mathbf{x},\boldsymbol{\beta}) = r(\mathbf{f},\boldsymbol{\lambda},\boldsymbol{\beta}) = \begin{pmatrix} \mathbf{f} - \mathrm{P_K}\{\mathbf{f} - \boldsymbol{\beta}[\boldsymbol{\Gamma}(\mathbf{f}) - \boldsymbol{M}^{\boldsymbol{T}}(\boldsymbol{\lambda} - \boldsymbol{\beta}(\boldsymbol{M}\mathbf{f} - \boldsymbol{q}))]\} \\ \boldsymbol{\beta}(\boldsymbol{M}\mathbf{f} - \boldsymbol{q}) \end{pmatrix} \tag{5.48}$$

Likewise, it can be verified that solved the VIP (5.45) and (5.46) is equivalent to finding a zero point of $\mathbf{r}(\mathbf{x}, \beta)$.

The detailed projection algorithm step are the following:

Step 2.1.0 Given an initial arbitrary point $\mathbf{x} = (\mathbf{f}^{\mathbf{0}}, \boldsymbol{\lambda}^{\mathbf{0}})$ and positive constants $\beta < 4c, \varepsilon > 0$, set $k = 0$;

Step 2.1.1 Compute $\tilde{\mathbf{x}} = (\tilde{\mathbf{f}}^{\mathbf{0}}, \tilde{\boldsymbol{\lambda}}^{\mathbf{0}})^{\boldsymbol{T}}$ by:

$$\tilde{\mathbf{f}}^{\mathbf{k}} = \mathrm{P_K}\{\mathbf{f}^{k} - \boldsymbol{\beta}\left[\boldsymbol{\Gamma}\left(\mathbf{f}^{k}\right) - \boldsymbol{M}^{\boldsymbol{T}}\left(\boldsymbol{\lambda}^{k} - \boldsymbol{\beta}\left(\boldsymbol{M}\mathbf{f}^{k} - \boldsymbol{q}\right)\right)\right]\} \tag{5.49}$$

$$\tilde{\boldsymbol{\lambda}}^{\mathbf{k}} = \boldsymbol{\lambda}^{k} - \boldsymbol{\beta}(\boldsymbol{M}\tilde{\mathbf{f}}^{\mathbf{k}} - \boldsymbol{q}) \tag{5.50}$$

Step 2.1.2 Compute $\mathbf{x}^{\boldsymbol{k}+\mathbf{1}} = (\mathbf{f}^{\mathbf{k}}, \boldsymbol{\lambda}^{\mathbf{k}})^{\boldsymbol{T}}$

$$\mathbf{x}^{\boldsymbol{k}+\mathbf{1}} = \mathbf{x}^{\boldsymbol{k}} - \boldsymbol{\theta}_{\boldsymbol{k}}\boldsymbol{\alpha}_{\boldsymbol{k}}\mathbf{e}(\mathbf{x},\boldsymbol{\beta}) \tag{5.51}$$

$$\mathbf{x}^{\boldsymbol{k}+\mathbf{1}} = \mathbf{x}^{\boldsymbol{k}} - \boldsymbol{\theta}_{\boldsymbol{k}}\boldsymbol{\alpha}_{\boldsymbol{k}}(\mathbf{x}^{\boldsymbol{k}} - \mathrm{P_K}\{\mathbf{x}^{\boldsymbol{k}} - \boldsymbol{\beta} F(\mathbf{x}^{\boldsymbol{k}})\}) \tag{5.52}$$

$$\tilde{\mathbf{x}}^{k} = \mathbf{P}_{\mathrm{K}}\{\mathbf{x}^{k} - \boldsymbol{\beta}\boldsymbol{F}(\mathbf{x}^{k})\} \tag{5.53}$$

$$\mathbf{x}^{k+1} = \mathbf{x}^{k} - \boldsymbol{\theta}_k \boldsymbol{\alpha}_k (\mathbf{x}^{k} - \tilde{\mathbf{x}}^{k}) \tag{5.54}$$

Where

$$\boldsymbol{\alpha}_k = (\mathbf{1} - \frac{\boldsymbol{\beta}}{\mathbf{4c}}),\ \boldsymbol{\theta}_k \in (\mathbf{0}, \mathbf{2}) \tag{5.55}$$

Step 2.1.3 If

$$||\mathbf{x}^{k+1} - \mathbf{x}^{k}||_2 / ||\mathbf{x}^{k}||_1 \leq \varepsilon\ , \tag{5.56}$$

where ε is the a small positive value, then stop and according to $\mathbf{v}_a = \sum_{r\in\mathcal{R}} \sum_{s\in\mathcal{S}} \sum_{z\in Z_{rs}} f_{rs}^{z}\, \delta_{rs}^{az}$ and $\mathbf{v}_w = \sum_{r\in\mathcal{R}} \sum_{s\in\mathcal{S}} \sum_{z\in Z_{rs}} y_w f_{rs}^{z}\, \delta_{rs}^{wz}$ and let $\mathbf{f}_m^n = \mathbf{x}^{k+1}$; Else set $k = k + 1$ and go to Step 2.1.1.

5.5 Numerical Studies

5.5.1 An Illustrative Example

An illustrative example is presented in this section to evaluate the effectiveness of the proposed algorithm. The hypothetical network show in Figure 5.4 consists of the 80 bi-directional links and 29 nodes in which 2 nodes are exits for the network linking to a supper destination via impedance free links and 1node is represented as intersection and decentralization origins. Note that nodes, all of the intersections have four-leg intersection where traffic conflicts are naturally avoid, the node 7 is the original location of the special events spreading traffic and the exit node 9 and 18 are decentralization destinations therefore should be excluded from the intersection list for implementation of signal or uninterrupted flow strategies. For the sake of simplicity, all road segments consist of three lanes, all links have the free flow speed of 60 km/h, and all turnings have the free flow speed of 35km/h, respectively.

Other parameters are set as follows: (1) in the BPR function, some parameters such as ω_a, β_a, ω_w, and β_w are set to be 0.15, 4.0, 20, and 2.5; (2) c_{max} and c_{min} are set to be 120s and 60s if intersections are controlled by signal light and the clearance time for any pair of conflict traffic movement is set to be 4s; (3) γ_w^0, γ_w^1 are the lanes utilization factor which were set to be 0.9 and 0.95 respectively; (4) length of each link is 500m; (5) c_0 is set to be 1,900 pcphl; (6) M_a and M_w are the large positive penalty coefficients which were set to be 5,0000 veh-hours, respectively.

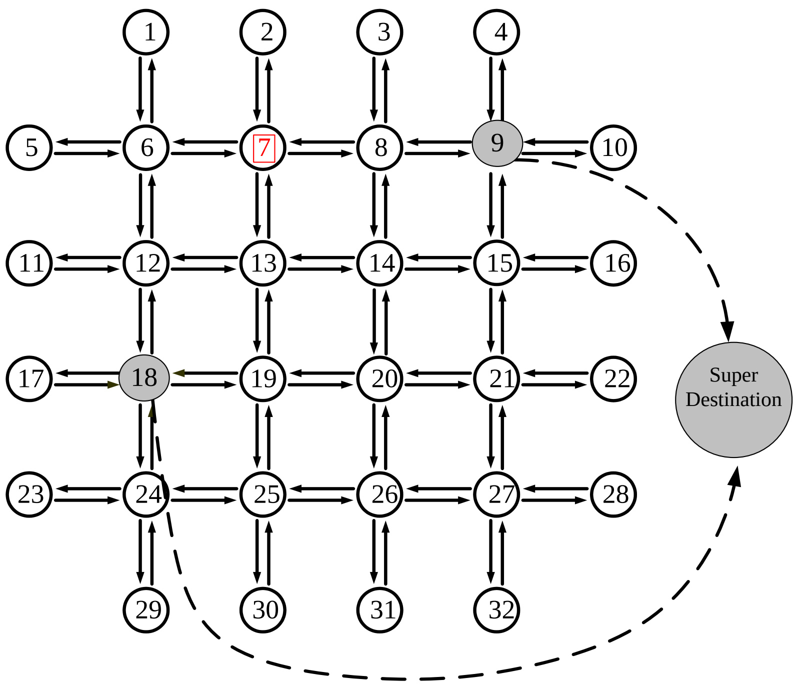


Figure 5. 4 The Hypothetical Special Events Network

5.5.2 The Optimal Schemes for the Network Example

In this section, we explore the projection method algorithm to yield the optimal result of the network example. Figure 5.3 illustrates the optimized schemes for the proposed model, which included the location of the uninterrupted flow and signal intersections, lane marking channelized, turning restraints, and the signal time length and the green times when the intersections were implemented signalized intersection in Table 5.2

Table 5. 2 Signal Timings of Proposed Model

Intersection	Phase 1		Phase 2		Phase 3	
(Node IDs)	Movements	Green Time	Movements	Green time	Movements	Green time
6	EB-T+R, SB-T+R	39.55 (s)	NB-T+R SB-T+R	72.45 (s)	-	-
7	O	-	O	-	O	-
8	U	-	U	-	U	-
9	D	-	D	-	D	-
12	U	-	U	-	U	-
13	U	-	U	-	U	-
14	U	-	U	-	U	-
15	U	-	U	-	U	-
18	D	-	D	-	D	-
19	U	-	U	-	-	-
20	WB-R NB-T+R EB-L+R	72.44 (s)	SB-L+T+R	39.56 (s)	-	-
21	EB-L+T NB-T+R	72.44 (s)	SB-R WB-T+R	39.56 (s)	-	-
24	WB-L+T+R	72.45 (s)	EB-L+R, NB-T	39.55 (s)	-	-
25	WB-L	38.12 (s)	EB-T+R	47.07 (s)	SB-L+T	22.81 (s)
26	EB-L+T	62.13 (s)	NB-T+R	49.87 (s)	-	-
27	WB-T, NB-L+R	39.55 (s)	SB-L+T+R	72.45 (s)	-	-

Note: L, T, and R represent left-turn, through movement, and right-turn, respectively; U represent uninterrupted flow intersection, and O represent the original location of the spreading traffic and D represent the destination of the decentralization.

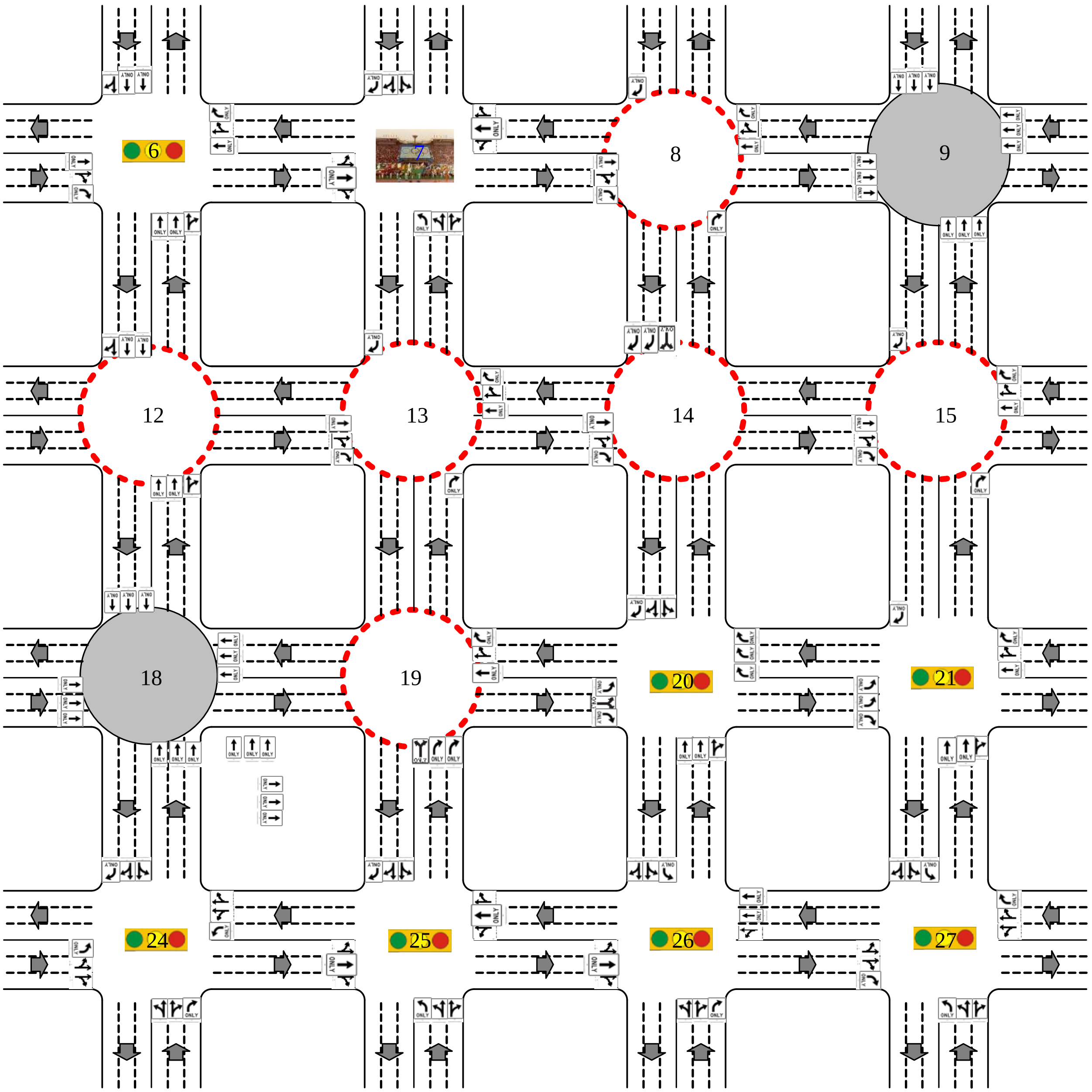


Figure 5. 5 Detailed Layout Schemes for Proposed Mode

5.5.3 Performance of the Proposed Algorithm

In this section, we compare the performance of the proposed model with other three strategies in the same network and we used hybrid genetic algorithm based on projection methods to search the optimal solution for these four models (Figure 5.6) as described below:

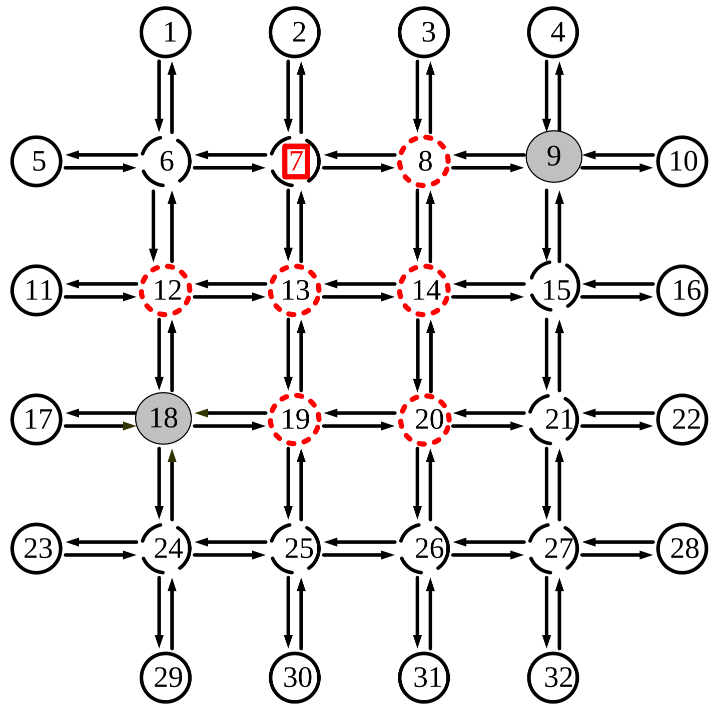
Strategies 1: Proposed model that consider the uninterrupted flow intersection and signalized control management which include green time and the lane marking channelized when the intersection was implemented the signalized intersections.

Strategies 2: All of the intersections are implemented the uninterrupted flow intersection

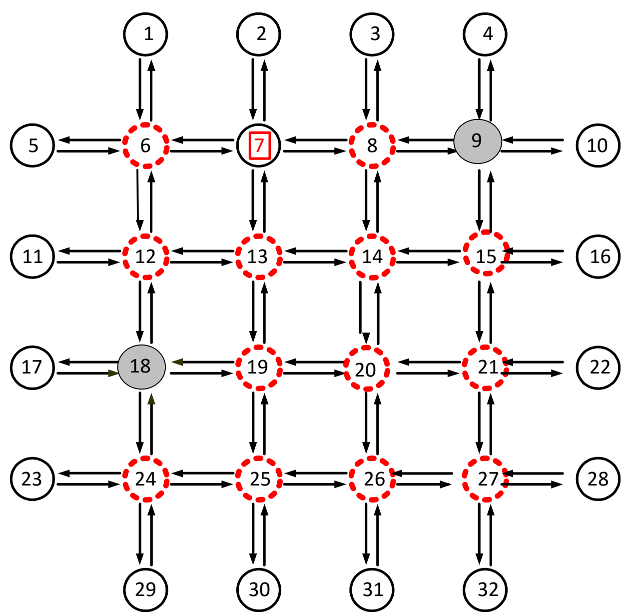
Strategies 3: All of the intersections are implemented the signalized intersection

Strategies 4: Considering the location of the uninterrupted flow and signal intersection, and turning restrictions proposed in Chapter 4.

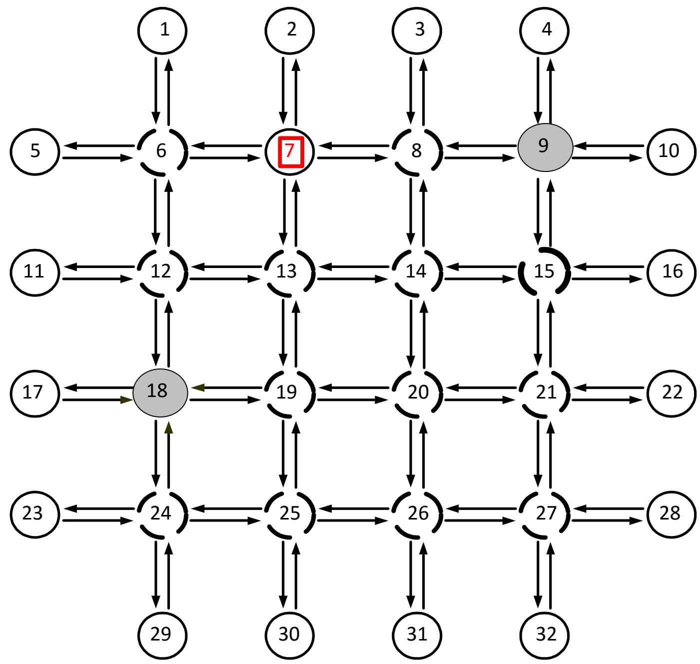
All algorithms are implemented in C++ on a work station with an Intel Core i7-3770S Ivy Bridge 3.9GHz Turbo CPU and 32G RAM. The performances of the three algorithms are compared in terms of objective function values, optimal solution, and computational time under the following scenarios. With the limit budget that allow the maximum number of the uninterrupted flow intersection to be 6. We assume the total spreading traffic demand over the network 10,000veh. Comparing with the four strategies, we find the optimal solution as listed in Table 5.3.



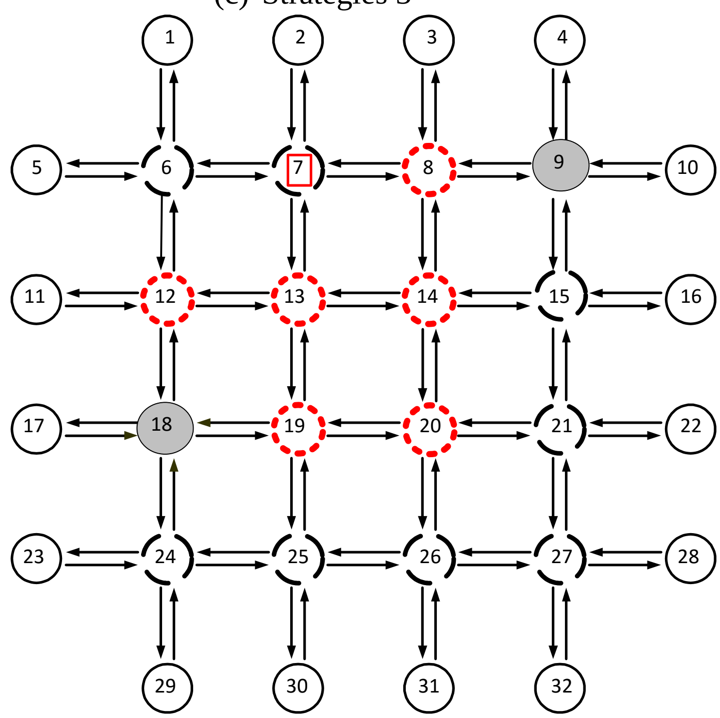
(a) Strategies 1



(b) Strategies 2



(c) Strategies 3



(d) Strategies 4

Permitted direction of the segment
The destination of the special event
The original of the special event
Signalized intersection locations
Uninterrupted flow intersection locations

Figure 5. 6 Optimization Schemes of Layout for the Two Design Methods

Table 5. 3 Performance Comparison of Different Strategies

Performance indices		Strategy 1	Strategy 2	Strategy 3	Strategy 4
Minimum total event clearance time f (veh-hrs)		1,492	1,542	1,563	1,526
Operator time (min)		710.5	693.7	701.6	790.3
The original decentralization of the network		7	7	7	7
The destination of the special event network		9,18	9,18	9,18	9,18
Intersections types	Uninterrupted flow intersection locations	8, 12, 13, 14,15,19	All	/	8, 12, 13, 14,15,20
	Signalized intersection locations	6,20,21,24, 25,26,27	/	All	6,19,21,24, 25,26,27
Signal cycle length (s)		120	**/**	120	**NA**
The duration of the green time (s)		62.6	/	53.8	**NA**
Average travel distance (m)		3780	3996	3654	3840

5. 6 Conclusion and Future Research

This paper develops an integrated optimization model in consideration of several traffic management strategies such as the location of the uninterrupted flow and signalized intersection, changing lane marking, and turning restriction. A bi-level programming model is formulated to simultaneously optimize lanes markings and signal time setting. We solve it by hybrid genetic algorithm (HGA) based on the heuristic method. A mathematical program with equilibrium constraints incorporating a parametric variational inequality was developed to formulate the proposed network design problem aimed to minimize the total event clearance time of the special events over the network. Disutility functions for both links and turnings were proposed to reflect the preference of a decentralization in route choices. To deal with the combinatorial complexity in combined location selection and turning restraints designs, this study uses a hybrid genetic algorithm (HGA). The proposed algorithm was found to be capable of yielding acceptable solutions to the problem in terms of both computational time and compared with the enumeration method and the Liu's algorithm based the program.

In the paper, we find that the decision of implementing uninterrupted flow and signalized intersections play a crucial role during the traffic management of special events in a limited budget. Our model solves two problems: (1) what are the most appropriate locations and how many intersections implement the signal light and uninterrupted flow; (2) The optimal channelization plans for lane marking and signal time including cycle length and green time at any network for the special events.

Future work along the line will be extending the model into a dynamic setting and introduction of stochastic elements into the network flow patterns to accommodate the dynamic process of signal control and uninterrupted flow intersection location management. In the future research, we will apply and consider the factor of pedestrians and different type traveler vehicles during the spreading traffic in the real-world special events network of urban transportation network.

Chapter 6: The Extended Model II: Special Event Management for Mixed Freeways and Arterials

6.1 Introduction

Construction work zones was denoted as an area occupied for three or more days for the purpose of constructing, reconstructing, rehabilitating, or performing preventive maintenance (Mahoney, K. M, et al. 2007). With the rapid highway system expansion in the past decades, construction of additional capacity has diminished. However, the construction work zones are considered as a bottleneck lead to serious traffic jam, large travel time delay, and pollutions of air. Distribution of traffic jam caused by construction work zones from freeway to an urban transportation area has received much attention in past decades.

The frequency of traffic congestion and growing length of queue will increase, since some mitigation strategies, including full road closure, lane closure, lane constriction, lane construction, lead to the large travel delay, and the traffic congestion. Therefore, due to these disadvantages dealing with traffic congestion strategies, the freeway traffic management and control have become an important strategy to enhance the effective freeway performance in the urban traffic network. How to effectively mitigate the traffic congestion and appropriate guide the travelers to select the optimal route for the traffic detour during the construction work zoned occupied on freeway, has drawn growing interest from researchers, engineers and governments that challenged with continuous management of freeways, assuring their adequate performance in the near term and far into the future.

A key challenge for the transportation agencies is to improve the efficiency of freeway operation and commercial vehicle movement while ensuring any traffic accidents appeared on the urban transportation network. In a review of the literature, early efforts tackling freeway traffic accident control and management strategies primarily focus on how to enhance the capacity or decrease the traffic delay when traffic incident occurred freeway employing following methods, including detour operation and route guidance, arterial traffic control strategies, and signal timing planning.

In this study we consider the integrated strategies, including location of ramp closure, route detour, lane making reorganization, and signal timing planning, because this integrated strategies is effective operation on the entire urban transportation network. To improve the computing efficiency, other optimization algorithm has been investigated in the literature by either linearizing the network flow formulations or employing the rolling solution techniques. Papageorgiou (1995) developed a linear optimal-control model to design integrated control strategies for traffic corridors, including both motorways and signal-controlled urban roads based on the store-and-forward modeling philosophy. Wu and Chang (1999) formulated a linear programming system for integrated corridor control in which the flow-density relation was approximated with a piecewise linear function to facilitate the use of a successive linear programming algorithm for global optimality. Van den Berg et al. (2001) proposed a model predictive control approach for mixed urban and freeway networks, based on the enhanced macroscopic traffic flow models in which traffic flow evolution on ramps has been explicitly captured. Liu. et al. (2013) have proposed an integrated diversion control model to determine the best diversion control strategy (i.e., diversion rates and corresponding signal retiming plans at the detour route) that yields the maximum utilization of corridor capacity. Their control model has effectively integrated a set of macroscopic traffic flow models that can precisely model and predict the traffic evolution along the freeway mainline, arterial link, and on off ramps. Despite the promising progress from those integrated In response to above research needs, this paper proposes a new method for spread traffic control strategies of multi-segments corridor, in which multiple detour routes comprising several on/off ramp closure.

The proposed model is designed to have the following operation features: (1) determining the appropriate location of on-ramp, off-ramp closure on the freeway; (2) selecting a set of critical upstream off-ramp and downstream on-ramps for use in the detour operations within each control interval (i.e., the control boundaries); (3) optimizing the appreciate distribution of uninterrupted flow intersection and signal intersection for each intersection on surface street; (4) resetting the signal timings to prevent the formation of local bottlenecks caused by detour traffic; (5) redesigning the lane marking function, including left turn restricted, lane prohibit, and lane reversal for surface street to ensure maximize throughput and minimize the traffic delay at bottlenecks due to by detour traffic on urban transportation network.

The section 5.2 introduces detailed definition in the model formulation and network representation. The mathematical model for planning of the uninterrupted flow and signal intersection will be solved in the section 5.3. Section 5.4 designs the solution method of the specific algorithm for the special events. In section 5.5, numerical examples are given to assess the proposed model and solution algorithm. Conclusion remarks are summarized in section 5.6.

The remainder of this chapter is organized as follows. The next section 6.2, will present a detail definition in the model formulation and network representation. The mathematical model for mixed freeway traffic management of construction work zone in urban transportation network in the section 6.3. Section 6.4 designs the solution algorithm approach to address the proposed model. In section 6.5, numerical tests with a hypothetical mixed freeway network have demonstrated the formulated model and solution algorithm for construction work zone in urban transportation network.

6.2 Network Representation

In this section, Let a direct graph, $G=(N,A)$ be comprised of the set of nodes denoted by $N=N_u \times N_f$. N_u represents the set of urban road nodes; N_f represents the set of freeway sections, $r \in N$ and the set of the links connecting two adjacent nodes denoted by $A=A_u \times A_f, a=(r,r') \in A$. Each node $r \in N$ consists of a set of arms denoted by $I_r; i, j \in I_r$. And the o_{r_i} represents the original arm in the node r and $d_{r'_i}$ is the destination arm in the node r' . Each arm i in the node consists of a set of turning movements denoted by $W, w=(i,j) \in W, w=1,2,3,4$ represent U-Turning, Left-Turning, Through, and Right-Turning on arm i , respectively. For any arm $i \in I_r$, let denote $y_{r,r',i}$ be the permission of turning from the upstream nodes r to downstream node r' at the arm i . Then, turning restriction can be easily realized by setting the prohibited movement not permitted via downstream on the arm. The binary variable $y_{r,r',i}$ is used to represent the permission of turning w toward arm i at node r (1- Yes, 0- No).

6.2.1 Notations

Indices:

r	Index of nodes r , $\forall r \in N = N_u \times N_f$
a	Index of link a , $\forall a=(r,r') \in A = A_u \times A_f$
μ	Index of on ramps
v	Index of off ramps
p	Index of signal phase p , $\forall p \in p_r$
i	Index of arms

Sets:

G Directed graph represent the mixed traffic network, $G=(N,A)$

N Set of nodes r, $\forall r \in N = N_f \times N_u$

N_f Set of nodes of freeway network, $N_f \subseteq N$

N_u Set of nodes of urban road network, $N_u \subseteq N$

A Set of link a joining two adjacent nodes, $\forall a \in A = A_f \times A_u$

A_u Set of link for urban road network, $A_u \subseteq A$

A_f Set of link for the freeway, $A_f \subseteq A$

I_r Set of arm i on node r, $\forall r \in N = N_f \times N_u$

W_r Set of turning movement w on node r, $W_r = \{L, T, R\}, \forall r \in N = N_f \times N_u$

Γ_r^+, Γ_r^- Set of nodes upstream and downstream to node r,

$\Gamma_\mu^+, \Gamma_\mu^-$ Set of on ramp upstream and downstream of the incident location

Γ_v^-, Γ_v^- Set of off ramp upstream and downstream of the incident location

o_{r_i} Set of origins arm i of node r, $\forall i \in I_r, r \in \Gamma_r^+$

d_{r_i} Set of the destination arm i of node r, $\forall i \in I_r, r \in \Gamma_r^-$

O_r Set of origins of intersection r, $\forall r \in \Gamma_r^+$

D_r Set of destination of intersection r, $\forall r \in \Gamma_r^-$

Parameters and Variables

$a = (r, r')$ The link from intersection r to its downstream intersection r', $\forall r \in \Gamma_r^+, r' \in \Gamma_r^-$

$a' = (r', r)$ The link from intersection r' to its downstream intersection r, $\forall r' \in \Gamma_r^+, r \in \Gamma_r^-$

L_a The length of link a in number of vehicles

n_a The number of lanes of link a

v_a The traffic flow of link a, $\forall a \in A = A_u \times A_f$

c_a The capacity of link a, $\forall a \in A = A_u \times A_f$

α_a The number of approach lanes on link a, $\forall a \in A$

ε_a The number of exit lanes on link a, $\forall a \in A$

w The turning from arm i to arm j, $w=(i,j),\ \forall i\in I_r, j\in I_{r'}$

v_w The turning flows for turning w

c_w The capacity for turning w

z A router may include a sequence of links and turning

q_{od} Demand traffic flow between (o,d)

f_{od}^z The demand traffic flow on router z between (o,d)

C_r Signal cycle length of the intersection $r,\ \forall r\in N$

C_r^{max} Maximum cycle length at node $r,\ \forall r\in N$

C_r^{min} Minimum cycle length at node $r,\ \forall r\in N$

g_r^w Green time on turning w at node $r,\ \forall r\in N$

G_r The sum of the green time for all signal phase at node $r,\ \forall r\in N$

L_r Total lost time per cycle at node $r,\ \forall r\in N$

S_a^l Saturation flow of lane l in link $a,\ \forall r\in N,\ \forall a\in A$

Decision Variables:

X_r^μ The on ramp was closed or not at section r on freeway (1-Yes, 0-No), $\forall r\in N_u, r'\in N_f$

X_r^ν The off ramp was opened or not at section r on freeway (1-Yes, 0-No), $\forall r\in N_f, r'\in N_u$

y_w^l Permission of the turning w via lane l, (1-Yes, 0-No)

x_r The intersection r on urban network is implemented with signal control or not, (1-Yes,0-No)

$\gamma_{r,r'}^\mu$ The traffic detour from section r on freeway to intersection r' of urban network, (1-Yes, 0-No)

$\theta_{r,r'}^\mu$ The fraction of traffic detour from section r on freeway to intersection r' of urban network

ξ_r^u Reciprocal of signal cycle length at intersection $r,\ \forall i\in N_u$

λ_r^p The g/C ratio for phase p at intersection r on urban network, $r\in N_u, p\in P_r^u$

6.3 Mixed Network Design Problem

6.3.1 Freeway and Ramp

From this figure, we have $L_m^f = kL_n^u$, L_m^f is the length of segment of freeway, $\forall m \in N_f$; L_n^u is the length of segment between two intersection on urban street, $\forall n \in N_u$;

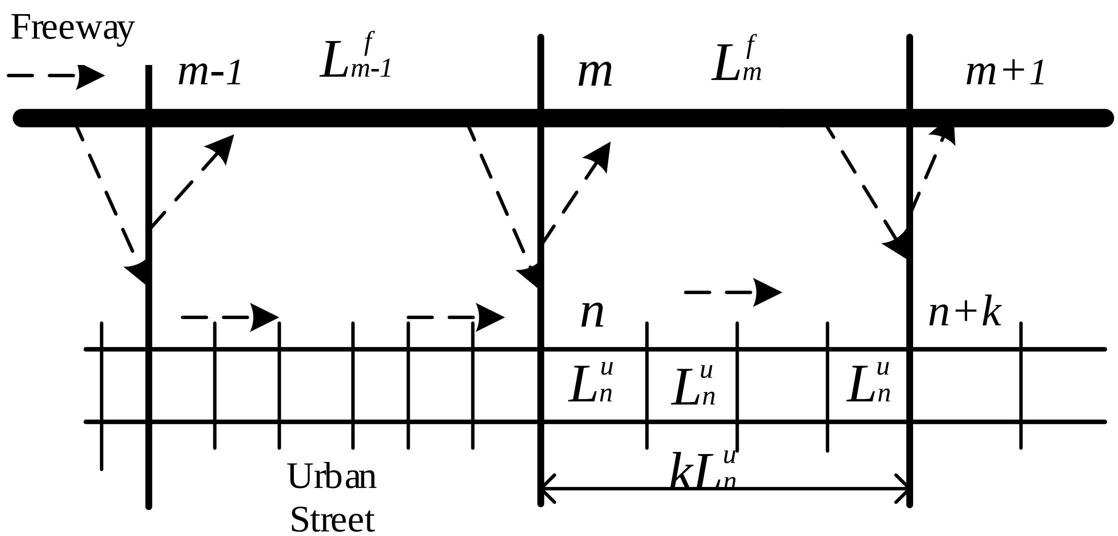


Figure 6. 1 The Relationship of Freeway Section and Urban Network Intersection

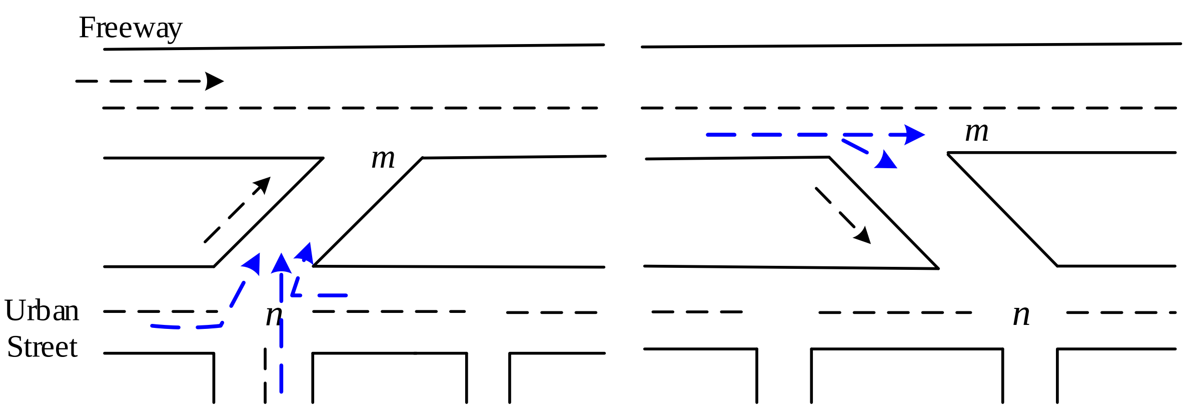


Figure 6. 2 Layout of an On-ramp and an Off-ramp

6.3.1.1 On Ramp

For arbitrary node $r \in N_u, r' \in N_f$, Let $y_{r,r',i}$ be a binary variable prohibited the turning movement or not from urban node r to freeway node (on ramp) r' at arm i (1-Yes, 0-No). Denote $X_r^{\mu} = \bigcap_{i \in I_r} y_{r,r',i}$ be closed or not on ramp at section r on the freeway. $X_r^{\mu} = \bigcap_{i \in I_r} y_{r,r',i} = 1$ represents all turning movement from node $r \in N_u$ to section $r' \in N_f$ was prohibited, it means that the on ramp μ was closed on node $r \in N_u$. otherwise, $X_r^{\mu} = 0$ means that the on ramp of section r was opened on the freeway. $\Pi_{r \in N_\mu} X_r^{\mu} = 1$, all on-ramps are closed, where on ramp is close $X_r^{\mu} = 1$ on freeway. $1 - \Pi_{r \in N_u}(1 - X_r^{\mu}) = 0$, all of on ramps is opened; otherwise, $1 - \Pi_{r \in N_u}(1 - X_r^{\mu}) = 1$, at last one onramp is closed from first ramp to r^{th} ramp. $\Pi_{r=1}^{k}(1 - X_r^{\mu}) > \Pi_{r=1}^{k+1}(1 - X_r^{\mu})$ the on ramp of $(k+1)^{th}$ node is closed.

Proof: If $\Pi_{r=1}^{k}(1 - X_r^{\mu}) = 1$, $(1 - X_{k+1}^{\mu})\Pi_{r=1}^{k}(1 - X_r^{\mu}) = 0, (1 - X_{k+1}^{\mu}) = 0$, and then, we can get the $X_{k+1}^{\mu} = 1$, so on ramp of $(k+1)^{th}$ node is closed. ■

6.3.1.2 On Ramp Constraints

$$\Pi_{r=1}^{k} X_r^{\mu} > 2 - \Pi_{j=1}^{r-1}(1 - X_j^{\mu}) - \Pi_{k=1}^{n}(1 - X_k^{\mu}) \tag{6.1}$$

There are the from r^{th} on ramp to k^{th} on ramp closed. k on- ramps were closed on the freeway.

6.3.1.3 Off Ramp

For arbitrary node $r \in N_u, r' \in N_f$, Let $y_{r',r,i}$ be a binary variable permitted the turning movement or not from freeway node (off-ramp) r' to urban node r at arm i (1-Yes, 0-No). Denote

$X_r^v = \bigcup_{i \in I_r} y_{r',r,i}$ be opened or not off ramp v at section r on the freeway. $X_r^v = \bigcup_{i \in I_r} y_{r',r,i} = 1$ represents at last one turning movement from node $r \in N_f$ to section $r' \in N_u$ was permitted, it means that the off ramp v was opened on node $r \in N_f$; otherwise, $X_r^v = 0$ means that the off ramp v of section r was closed on the freeway. $\Pi_{r \in N_f} X_r^v = 1$, all off ramps are opened, where, $X_r^v = 1$ off ramp is opened on freeway and $X_r^v = 0$ off ramp is closed. $1 - \Pi_{r \in N_f}(1 - X_r^v) = 0$ all of off ramps are closed; otherwise, $1 - \Pi_{r \in N_f}(1 - X_r^v) = 1$ at last one off ramp is opened from first ramp to r^{th} ramp.

Proof: If $\Pi_{r \in N_f}(1 - X_r^v) = 1,\ (1 - X_{r+1}^v)\Pi_{r \in N_v}(1 - X_r^v) = 0,$ the off ramp of intersection k is opened. $\Pi_{r \in N_f} X_r^v = 1$ all onramps are closed, where $X_r^v = 1$ on ramp is close on freeway.■

6.3.1.4 Off Ramp Constraints

$$\Pi_{r=1}^{k}(1 - X_r^v) > 2 - \Pi_{j=1}^{r-1} X_j^v - \Pi_{k=1}^{n} X_k^v \tag{6.2}$$

There are the from r^{th} off ramp to k^{th} off ramp closed. k off ramps were closed on the freeway.

6.3.2 Traffic Equilibrium with Traffic Detour Effects

The travel time on each link is assumed to follow the equation developed by the U.S. Bureau of Public Road (BPR) (1964). For the urban network, the travel time is given by:

$$t_a^u(v_a^u) = T_a^0[1 + \alpha_a^u(\frac{v_a^u}{C_a^u})^{\beta_a^u}], \forall a \in A_u \tag{6.3}$$

$$t_a^f(v_a^f) = T_a^0[1 + \alpha_a^f(\frac{v_a^f}{C_a^f})^{\beta_a^f}], \forall a \in A_f \tag{6.4}$$

$$t_a^{\mu}(v_a^{\mu}) = T_a^0[1+\alpha_a^f(\frac{v_a^{\mu}}{c_0\sum_{l\in L} y_w^l \zeta_a^{\mu}})^{\beta_a^{\mu}}], \forall a \in A_{on} \quad (6.5)$$

$$t_a^{\nu}(v_a^{\nu}) = T_a^0[1+\alpha_a^f(\frac{v_a^{\nu}}{c_0\sum_{l\in L} y_w^l \zeta_a^{\nu}})^{\beta_a^{\nu}}], \forall a \in A_{off} \quad (6.6)$$

$$t_w^u(v_w^u) = T_w^0[1+\alpha_w^u(\frac{v_w^u}{\sum_{l\in L_r} y_{rw}^l[x_r+(1-x_r)\phi_r]S_r\zeta_w^l})^{\beta_w^u}] \quad (6.7)$$

Where the $t_a^u(v_a^u)$ is the travel time of the urban road network on link a depends on its own flow v_a^u; $t_a^f(v_a^f)$ is the travel time of the freeway segment of link a depends on its own flow v_a^f; $t_a^{\mu}(v_a^{\mu})$ is the travel time of on-ramps of link a depends on its own flow v_a^{μ}; $t_a^{\nu}(v_a^{\nu})$ is the travel time of off-ramps of link a depends on its own flow v_a^{ν}; $t_w^u(v_w^u)$ is the travel time of turning movement w at urban road network depends on its own flow v_w^u.

Where $\mathbf{t}(\mathbf{v}) = \{t_a^u(v_a^u), t_a^f(v_a^f), t_a^{\mu}(v_a^{\mu}), t_a^{\nu}(v_a^{\nu}), t_w^u(v_w^u)\}$ is the vector of the travel time of freeway segment and urban road network. As a result, there is symmetrical flow interaction with its own related flow, respectively. To check the property of the Jacobian of the link cost functions $\mathbf{t}(\mathbf{v})$, we get all partial derivative are positive. It is evident that $\partial\mathbf{t}(\mathbf{v})/\partial v_a^f > 0$, the whole the Jacobian of links and turnings, the whole Jacobian of link cost functions, $\nabla\mathbf{t}(\mathbf{v})$ is positive.

6.3.2.1 The Equilibrium Condition at Urban Street

$$f_{o,d}^{u_a,k}[\frac{1}{\theta}(ln\frac{f_{o,d}^{u_a,k}}{q_{o,d}^{u_a}}+1)+c_{o,d}^{u,k}-u_{od}^u]=0 \quad (6.8)$$

$$\frac{1}{\theta}(ln\frac{f_{o,d}^{u_a,k}}{q_{o,d}^{u_a}}+1)+c_{o,d}^{u,k}-u_{od}^u \geq 0 \quad (6.9)$$

$$c_{o,d}^{u,k} = \sum_{a \in A_u} (t_a^u(v) + d_a^u)\delta_{od}^{u_a k} \quad (6.10)$$

$$d_a^u(v_a^u - C_a^u) = 0; d_a^u \geq 0 \quad (6.11)$$

6.3.2.2 The Equilibrium Condition on Freeway

$$f_{o,d}^{f,k}[\frac{1}{\theta}(ln\frac{f_{o,d}^{f,k}}{q_{o,d}^{f}} + 1) + c_{o,d}^{f,k} - u_{od}^{f}] = 0 \quad (6.12)$$

$$\frac{1}{\theta}(ln\frac{f_{o,d}^{f,k}}{q_{o,d}^{f}} + 1) + c_{o,d}^{f,k} - u_{od}^{f} \geq 0 \quad (6.13)$$

$$c_{o,d}^{f,k} = \sum_{a \in A_f} (t_a^f(v) + d_a^f)\delta_{od}^{ak} \quad (6.14)$$

$$d_a^f(v_a^f - C_a^f) = 0; d_a^f \geq 0 \quad (6.15)$$

6.3.2.3 The Equilibrium Condition with on Ramps

$$f_{o,d}^{\mu,k}[\frac{1}{\theta}(ln\frac{f_{o,d}^{\mu,k}}{q_{o,d}^{\mu}} + 1) + c_{o,d}^{\mu,k} - u_{od}^{\mu}] = 0 \quad (6.16)$$

$$\frac{1}{\theta}(ln\frac{f_{o,d}^{\mu,k}}{q_{o,d}^{\mu}} + 1) + c_{o,d}^{\mu,k} - u_{od}^{\mu} \geq 0 \quad (6.17)$$

$$c_{o,d}^{\mu,k} = \sum_{a \in A_\mu} (t_a^\mu(v) + d_a^\mu)\delta_{od}^{ak} \quad (6.18)$$

$$d_a^\mu(v_a^\mu - C_a^\mu) = 0; d_a^\mu \geq 0 \quad (6.19)$$

6.3.2.4 The Equilibrium Condition with off Ramps

$$f_{o,d}^{v,k}[\frac{1}{\theta}(ln\frac{f_{o,d}^{v,k}}{q_{o,d}^{v}} + 1) + c_{o,d}^{v,k} - u_{od}^{v}] = 0 \quad (6.20)$$

$$\frac{1}{\theta}(ln\frac{f_{o,d}^{v,k}}{q_{o,d}^{v}} + 1) + c_{o,d}^{v,k} - u_{o,d}^{v} \geq 0 \quad (6.21)$$

$$c_{o,d}^{v,k} = \sum_{a \in A_v} (t_a^v(v) + d_a^v)\delta_{od}^{ak} \tag{6.22}$$

$$d_a^v(v_a^v - C_a^v) = 0; d_a^v \geq 0 \tag{6.23}$$

6.3.2.5 The Equilibrium Condition of Turning Movement

$$f_{o,d}^{u_w,k}[\frac{1}{\theta}(ln\frac{f_{o,d}^{u_w,k}}{q_{o,d}^{u_w}}+1)+c_{o,d}^{u_wk}-u_{od}^{u_w}]=0 \tag{6.24}$$

$$\frac{1}{\theta}(ln\frac{f_{o,d}^{u_w,k}}{q_{o,d}^{u_w}}+1)+c_{o,d}^{uk}-u_{od}^{u_w}\geq 0 \tag{6.25}$$

$$c_{o,d}^{uk} = \sum_{w \in W} (t_w^u(v) + d_w^u)\delta_{a,od}^{wk} \tag{6.26}$$

$$d_w^u(v_w^u - C_w^u) = 0; d_w^u \geq 0 \tag{6.27}$$

To simply the formula, we reformulate the aforementioned equilibrium conditions as vectors format:

$$\mathbf{f}[\frac{\mathbf{1}}{\boldsymbol{\theta}}(\mathbf{ln}\frac{\mathbf{f}}{\mathbf{q}}+\mathbf{I})+\mathbf{c}_{\mathbf{o,d}}^{\mathbf{k}}-\mathbf{u}_{\mathbf{od}}]=\mathbf{0} \tag{6.28}$$

$$\frac{\mathbf{1}}{\boldsymbol{\theta}}(\mathbf{ln}\frac{\mathbf{f}}{\mathbf{q}}+\mathbf{I})+\mathbf{c}_{\mathbf{o,d}}^{\mathbf{k}}-\mathbf{u}_{\mathbf{od}}]\geq\mathbf{0} \tag{6.29}$$

$$\mathbf{c}_{\mathbf{o,d}}^{\mathbf{k}} = \sum_{\mathbf{w} \in \mathbf{W}} (\mathbf{t}(\mathbf{v}) + \mathbf{d})\boldsymbol{\delta}^{\mathbf{k}} \tag{6.30}$$

$$\mathbf{d}(\mathbf{v}-\mathbf{C}) = \mathbf{0}; \mathbf{d} \geq \mathbf{0} \tag{6.31}$$

$\mathbf{f} = \{f_{o,d}^{u_a,k}, f_{o,d}^{f,k}, f_{o,d}^{\mu,k}, f_{o,d}^{v,k}, f_{o,d}^{u_w,k}\}$ presents the vector of the route and turning movement flow; $\mathbf{q} = \{q_{o,d}^{u_a}, q_{o,d}^{f}, q_{o,d}^{\mu}, q_{o,d}^{v}, q_{o,d}^{u_w}\}$ presents the vector of demand from origin node to destination node; $\mathbf{c}_{\mathbf{o,d}}^{\mathbf{k}} = \{c_{o,d}^{u_a,k}, c_{o,d}^{f,k}, c_{o,d}^{\mu,k}, c_{o,d}^{v,k}, c_{o,d}^{u_w,k}\}$ presents the vector of the link travel time for freeway and urban network; $\mathbf{d} = \{d_a^u, d_a^f, d_a^\mu, d_a^v, d_w^u\}$ presents the vector of extra waiting time for each path;

$\mathbf{C}=\{C_a^u, C_a^f, C_a^{\mu}, C_a^{v}, C_w^u\}$ is the capacity of the each link for freeway and urban road network; $\mathbf{u_{od}}=\{u_{od}^{u_a}, u_{od}^{f}, u_{od}^{\mu}, u_{od}^{v}, u_{od}^{u_w}\}$ is vector constraint of the Lagrange multiplier for the $\sum \mathbf{f}=\mathbf{q}$; $\mathbf{I}$ is the unit vector.

Let $S_{o,d}^k$ be the satisfaction function, defined as the expected minimum perceived travel cost from o to d.

$$S_{o,d} = E[min_{k\in P_w}\{c_{o,d}^k\}] \tag{6.32}$$

The SUE formulation can be applied to a variety of route choice models which can meet certain conditions imposed on the satisfaction function. For the general logit model, the satisfaction can be formulated by:

$$S_{o,d} = -\frac{1}{\theta} ln \sum_k exp(-\theta c_{o,d}^k) \tag{6.33}$$

The partial derivative of the satisfaction function with respect to route travel cost is the route choice probability, given by:

$$\frac{\partial S_{o,d}}{\partial c_{o,d}^k} = P_{o,d}^k \tag{6.34}$$

For the logit SUE model, substituting Eq. (6.32) into Eq. (6.33), we have:

$$P_{o,d}^k = \frac{\partial S_{o,d}}{\partial c_{o,d}^k} = \frac{exp(-\theta c_{o,d}^k)}{\sum_l exp(-\theta c_{o,d}^l)} \tag{6.35}$$

Then, the path flow and link flow are, respectively, given by: $f_{o,d}^k = q_{o,d} P_{o,d}^k$.

6.3.3 Equilibrium Properties

Proposition 1: The travel demand $f^* = (f_{o,d}^{u_a,k^*}, f_{o,d}^{f,k^*}, f_{o,d}^{\mu,k^*}, f_{o,d}^{v,k^*}, f_{o,d}^{u_w,k^*})$ in a mixed network reaches the equilibrium state if and only if the solution of the following Variational Inequality (VI) problem:

$$\sum_{o,d}\sum_{k\in P_u}(c_{o,d}^{u_a,k^*}+\frac{1}{\theta}(lnf_{o,d}^{u_a,k^*}-lnq_{o,d}^{u_a})-S(c_{o,d}^{k}))(f_{o,d}^{u_a,k}-f_{o,d}^{u_a,k^*})$$

$$+\sum_{o,d}\sum_{k\in P_f}(c_{o,d}^{f,k^*}+\frac{1}{\theta}(lnf_{o,d}^{f,k^*}-lnq_{o,d}^{f})-S(c_{o,d}^{k}))(f_{o,d}^{f,k}-f_{o,d}^{f,k^*})$$

$$+\sum_{o,d}\sum_{k\in P_{on}}(c_{o,d}^{u,k^*}+\frac{1}{\theta}(lnf_{o,d}^{u,k^*}-lnq_{o,d}^{u})-S(c_{o,d}^{k}))(f_{o,d}^{u,k}-f_{o,d}^{u,k^*}) \quad (6.36)$$

$$+\sum_{o,d}\sum_{k\in P_{off}}(c_{o,d}^{v,k^*}+\frac{1}{\theta}(lnf_{o,d}^{v,k^*}-lnq_{o,d}^{v})-S(c_{o,d}^{k}))(f_{o,d}^{v,k}-f_{o,d}^{v,k^*})$$

$$+\sum_{o,d}\sum_{k\in P_W}(c_{o,d}^{u_w,k^*}+\frac{1}{\theta}(lnf_{o,d}^{u_w,k^*}-lnq_{o,d}^{u_w})-S(c_{o,d}^{k}))(f_{o,d}^{u_w,k}-f_{o,d}^{u_w,k^*})\geq 0, \forall\ \mathrm{f}\in\Omega(\mathrm{f})$$

To simply the formula, we reformulate the Variational Inequality (VI) problem Eq. 6.36 as following:

$$\sum_{\mathbf{o,d}}\sum_{\mathbf{k}}(\mathbf{c_{o,d}^{k}}+\frac{\mathbf{1}}{\boldsymbol{\theta}}(\mathbf{lnf}^*-\mathbf{lnq})-S(\mathbf{c_{o,d}^{k}}))(\mathbf{f}-\mathbf{f}^*)\geq\mathbf{0} \quad (6.37)$$

$$\boldsymbol{\Omega}(\mathbf{f})=\{\mathbf{f}\mid\mathbf{v}=\sum_{\mathrm{od}}\mathbf{q}_{\mathrm{od}}\boldsymbol{\delta}_{\mathrm{od}}^{\mathrm{T}},\mathbf{q}_{\mathrm{od}}=\sum_{\mathrm{z}}\mathbf{q}_{\mathrm{od}}^{\mathrm{z}},\ \mathbf{f}=\mathbf{q}\mathbf{P}^{\mathrm{T}}\} \quad (6.38)$$

Where $\Omega(\mathrm{f})$ is the feasible set of traffic demand $\mathrm{f} = (f_{o,d}^{u_a,k^*}, f_{o,d}^{f,k^*}, f_{o,d}^{\mu,k^*}, f_{o,d}^{v,k^*}, f_{o,d}^{u_w,k^*})$.

Proof

Necessity: Base on the freeway equilibrium condition, we have:

$$f_{o,d}^{f,k}[\frac{1}{\theta}(ln\frac{f_{o,d}^{u_a,k^*}}{q_{o,d}^{u_a}}+1)+c_{o,d}^{f,k^*}-u_{od}]\geq 0 \tag{6.39}$$

$$f_{o,d}^{f,k^*}[\frac{1}{\theta}(ln\frac{f_{o,d}^{u_a,k^*}}{q_{o,d}^{u_a}}+1)+c_{o,d}^{f,k^*}-u_{od}]=0 \tag{6.40}$$

$$\frac{1}{\theta}(ln\frac{f_{o,d}^{u_a,k^*}}{q_{o,d}^{u_a}}+1)+c_{o,d}^{f,k^*}-u_{od}](f_{o,d}^{f,k}-f_{o,d}^{f,k^*})\geq 0 \tag{6.41}$$

$$\sum_{o,d}\sum_{k\in P_u}(ln\frac{f_{o,d}^{u_a,k^*}}{q_{o,d}^{u_a}})+c_{o,d}^{u,k^*}-u_{od}](f_{o,d}^{u,k}-f_{o,d}^{u,k^*})\geq 0 \tag{6.42}$$

In here, using same method, we can get the above Variational Inequality (VI) problem.

$$\sum_{o,d}\sum_{k\in P_f}(ln\frac{f_{o,d}^{u_a,k^*}}{q_{o,d}^{f}})+c_{o,d}^{f,k^*}-u_{od}](f_{o,d}^{f,k}-f_{o,d}^{f,k^*})\geq 0 \tag{6.43}$$

$$\sum_{o,d}\sum_{k\in P_{on}}(ln\frac{f_{o,d}^{u_a,k^*}}{q_{o,d}^{\mu}})+c_{o,d}^{\mu,k^*}-u_{od}](f_{o,d}^{\mu,k}-f_{o,d}^{\mu,k^*})\geq 0 \tag{6.44}$$

$$\sum_{o,d}\sum_{k\in P_{off}}(ln\frac{f_{o,d}^{u_a,k^*}}{q_{o,d}^{v}})+c_{o,d}^{v,k^*}-u_{od}](f_{o,d}^{v,k}-f_{o,d}^{v,k^*})\geq 0 \tag{6.45}$$

$$\sum_{o,d}\sum_{k\in P_W}(ln\frac{f_{o,d}^{w,k^*}}{q_{o,d}^{w}})+c_{o,d}^{w,k^*}-u_{od}](f_{o,d}^{w,k}-f_{o,d}^{w,k^*})\geq 0 \tag{6.46}$$

Sufficiency:

We need to prove that any solution to VI satisfies SUE conditions (6.38).

$$\sum_{o,d}\sum_{k\in P_u}(ln\frac{f_{o,d}^{u_a,k^*}}{q_{o,d}^{u_a}})+c_{o,d}^{u,k^*}-u_{od}](f_{o,d}^{u,k}-f_{o,d}^{u,k^*})\geq 0 \tag{6.47}$$

$$\sum_{o,d}\sum_{k\in P_u} f_{o,d}^{u_a,k}[(ln\frac{f_{o,d}^{u_a,k^*}}{q_{o,d}^{u_a}})+c_{o,d}^{u,k}-u_{od}]\geq\sum_{o,d}\sum_{k\in P_u} f_{o,d}^{u,k^*}[(ln\frac{f_{o,d}^{u_a,k^*}}{q_{o,d}^{u_a}})+c_{o,d}^{u,k^*}-u_{od}] \quad (6.48)$$

$$\sum_{o,d}\sum_{k\in P_u} f_{o,d}^{u_a,k}[\frac{1}{\theta}(ln\frac{f_{o,d}^{u_a,k}}{q_{o,d}^{u_a}}+1)+c_{o,d}^{u,k}-u_{od}]\geq\sum_{o,d}\sum_{k\in P_u} f_{o,d}^{u_a,k^*}[\frac{1}{\theta}(ln\frac{f_{o,d}^{u_a,k^*}}{q_{o,d}^{u_a}}+1)+c_{o,d}^{u,k^*}-u_{od}] \quad (6.49)$$

the foregoing equation means that $f^*=(f_{o,d}^{u_a,k^*}, f_{o,d}^{f,k^*}, f_{o,d}^{\mu,k^*}, f_{o,d}^{v,k^*}, f_{o,d}^{u_w,k^*})$ is an optimal solution to the following mathematical programming problem:

$$min\, f(v,s)=\sum_{o,d}\sum_{k\in P_u} f_{o,d}^{u_a,k}[\frac{1}{\theta}(ln\frac{f_{o,d}^{u_a,k}}{q_{o,d}^{u_a}}+1)+c_{o,d}^{u,k}-u_{od}]$$

$$+\sum_{o,d}\sum_{k\in P_f} f_{o,d}^{f,k}[\frac{1}{\theta}(ln\frac{f_{o,d}^{f,k}}{q_{o,d}^{f}}+1)+c_{o,d}^{f,k}-u_{od}]+\sum_{o,d}\sum_{k\in P_\mu} f_{o,d}^{\mu,k}[\frac{1}{\theta}(ln\frac{f_{o,d}^{\mu,k}}{q_{o,d}^{\mu}}+1)+c_{o,d}^{\mu,k}-u_{od}] \quad (6.50)$$

$$+\sum_{o,d}\sum_{k\in P_v} f_{o,d}^{v,k}[\frac{1}{\theta}(ln\frac{f_{o,d}^{v,k}}{q_{o,d}^{v}}+1)+c_{o,d}^{v,k}-u_{od}]+\sum_{o,d}\sum_{k\in P_w} f_{o,d}^{w,k}[\frac{1}{\theta}(ln\frac{f_{o,d}^{w,k}}{q_{o,d}^{w}}+1)+c_{o,d}^{w,k}-u_{od}]$$

subject to Constraints (6.38) . This completes the proof of Proposition 1.■

6.4 Urban Network Formulation

The proposed model intend to achieve minimize the total travel time for mixed freeway and arterial network. In order to optimize the travel time, the traffic management strategies including on/off ramps closure, traffic detour strategies, and arterial signal times strategies for spreading traffic plays a role in the transportation network of special events. The traffic management problem is to find an optimal appropriate on/off ramps closure, pre-plane traffic detouring strategies, and arterial signal time schemes under the construct zone or full freeway closure conditions. In this study, we employed a mathematical program with equilibrium constraints (MPEC) as following:

$$min\, f(v,s) = \sum_{a \in A_u} t_a^u(v_a^u)v_a^u + \sum_{a \in A_f} t_a^f(v_a^f)v_a^f + \sum_{a \in A_{on}} t_a^\mu(v_a^\mu)v_a^\mu + \sum_{a \in A_{off}} t_a^v(v_a^v)v_a^v + \sum_{w \in W_i} t_w^u(v_w^u)v_w^u \qquad (6.51)$$

6.4.1 The Flow Conservation Constraint:

$$q_{od}^w = \sum_{l=1}^{n_{r,i}} q_{od}^{wl}, \forall r \in N; i \in I_r; w \in W_r \qquad (6.52)$$

Constraint (6.52) indicates that the sum of the flows of a movement on different lanes should be equal to the total assigned flow of that movement.

6.4.2The Lane Assignment Constraints:

$$y_w^l + \sum_{w' \in Xw_r} y_{w'}^l \le 1 + M(1 - x_r), \forall r \in N_u; w, w' \in W_r; l \in L_i; i \in I_r \qquad (6.53)$$

Constraint (6.53) is developed for cross elimination, where X_{w_r} is a conflicting matrix for turning w at any node r and M is a large enough positive number. In the special event network, if node r is implemented with an uninterrupted flow intersection (i.e. $x_r = 1$), each pair of conflicting turnings should be eliminated at node r; otherwise there is no restriction on turning for a signalized intersection.

$$\sum_{w \in W_r} y_w^l \ge 0, \forall r \in N_u; i \in I_r; l \in L_i \qquad (6.54)$$

There are many approach and exit lanes in any arm i. If all of turning w are prohibited at node r, the $\sum_{w \in W_r} y_w^l = 0$, in another word, the road are closed at node r in constraint (6.54). Otherwise, constraint (6.52) allows each approach lane to carry at least one turning or through movement.

$$n'_{ri} \ge \sum_{l \in L_i} y_{ri}^{wl}, \forall r \in N; i \in I_r, w = (i, j) \in W_r \qquad (6.55)$$

Constraint (6.55) sets the minimum number of exit lanes strategy. For a turning w from arm i to the adjacent arm j at intersection r, the number of the exit lane in the arm i should be at least as many as the total number of lanes assigned to such a turning movement from the arm i.

$$1 - y_{ri}^{wl} \geq y_{ij}^{w'}, \forall r \in N; i \in I_r; w \in \{1,2,3\}; w' \in \{w+1,...,4\}; l \in \{1,...,n_{ri}-1\} \qquad (6.56)$$

Constraint (6.56) prevents internal conflicts among lanes on an arm. We will set the permitted movements across adjacent approach lanes. For any adjacent traffic lanes, l (right-hand) and $l+1$ (left-hand) lanes from arm i to j is permitted on lane l, then all other traffic turns should be prohibited on lane $l+1$ to eliminate the intersection conflicts within a junction.

$$My_{ij}^{w} \geq \sum_{l \in L_j} y_{ri}^{wl} \geq y_{ij}^{w}, \forall r \in N; i \in I_i; w \in W_r \qquad (6.57)$$

Constraint (6.57) sets the turning restriction strategy. If a movement at the intersection is prohibited mean that the number of lanes permitted for the prohibited movements should be equal to zero; otherwise, the movement should be permitted in least one lane, where M is an arbitrary large positive constant number.

$$v_a \leq c_a, a \in A \qquad (6.58)$$

$$v_w \leq c_w, w \in W_r \qquad (6.59)$$

Constraints (6.58) and (6.59) restrict that the flow on a link or a turning cannot exceed its capacity in any intersection. Where c_w is the capacity of turning w.

6.4.3The Signal Time Constraints:

$$\frac{1}{c_{min}} \geq \xi_r \geq \frac{1}{c_{max}}, \forall r \in N_u \tag{6.60}$$

Constraint (6.60) limits the common cycle lengths C_r for the any intersection r in the network to be within C_{min} and C_{max}, which presents the minimum and maximum cycle lengths. Instead of defining the cycle length directly as the control variable, its reciprocal, $\xi_r = 1/C_r$, is used to preserve the linearity in the mathematical formulation (Wong and Wong, 2003; Wong and Heydecker, 2011).

$$1 \geq \theta_w \geq 0, \forall r \in N_u; w \in W_r \tag{6.61}$$

Constraint (6.61) confines the start of the green to be within a fraction between 0 and 1 of the cycle length at any intersection r. Where the θ_{ri}^{w} is the start of green for turning w on arm i at intersection r.

$$1 \geq \phi_w \geq 0, \forall r \in N_u; w \in W_r \tag{6.62}$$

Constraint (6.62) indicates that the green split of a movement is confined between 0 and 1 of the cycle length.

$$My_w\phi_w \geq \phi_w \geq -My_w, \forall r \in N_u; w \in W_r \tag{6.63}$$

Constraint (6.63) sets that the green split of a movement should be equal to zero if the movement is prohibited. Where ϕ_{ij}^{w} represented the duration of green and the green time for turning w on arm i at intersection r. If a lane is shared by more than one movement, these movements must receive the identical signal indication to avoid ambiguity.

$$M(1-y_{wl}) \geq \Theta_w^l - \theta_w \geq -M(1-y_w^l), \forall r \in N_u; w \in W_r; l \in L_i \tag{6.64}$$

$$M(1-y_w^l) \geq \Phi_w^l - \phi_w \geq -M(1-y_w^l), \forall r \in N_u; w \in W_r; l \in L_i \tag{6.65}$$

Considering the lane l from link a if the movement w is permitted on this lane, the following two constraints (6.64)-(6.65) can be established to fulfill the above condition. Where M is an arbitrary large positive constant number. If a movement w is permitted on lane l, then the lane marking $y_{ri}^{wl} = 1$, and hence the values on both sides the above two inequalities become zero.

$$\Omega_{(iw,jw')} + \Omega_{(jw',iw)} = 1, \forall i,j \in I_r, j \neq i; w,w' \in W_r \tag{6.66}$$

Constraint (6.66) sets the order of signal phase display for a pair of conflicting traffic movements at intersection r ,which is governed by a successor function (Heydecker, 1992).

$$\theta_{jw'} + \Omega_{(iw,jw')} \geq \theta_{jw} + \phi_w + \omega_{(iw,jw')}\xi_r, \forall i,j \in I_r, j \neq i; w,w' \in W_r \tag{6.67}$$

Constraint (6.67) limits the start of greens for any pair of conflicting traffic movements considering the minimum clearance time and movement prohibition, where $\omega_{(iw,jw')}$ represents the clearance time for a pair of conflicting traffic movements.

6.5 Solution Algorithm

The proposed optimal model has a bi-level structure with a min-integer-nonlinear-programming at the upper-level and a stochastic user equilibrium problem (SUE) model at the lower-level. It has been proved to be NP-hard (Johnson et., 1978) and the mixed freeway and urban network problem is difficult to solve due to its non-convexity and non-differential characteristics of the parameter VI problem. In this section, we have been explored a hybrid genetic algorithm (HGA) based heuristic method to yield viable and approximate optimal solutions to the bi-level model in a reasonable time period.

To deal with the combinatorial complexity in combined location selection and turning restriction designs, this problem is a bi-lever programming model with the genetic algorithm to solve the upper-level and using the projection method algorithm to deal with the parametric variational inequality problem at the lower-level. To penalize solutions violating capacity constraints, we define the following event clearance function $F(v,s)$:

$$F(\mathbf{v},\mathbf{s}) = f(\mathbf{v},\mathbf{s}) + \sum_{a\in\mathcal{A}} M_a \cdot (max\{v_a - c_a, 0\})^2$$

$$+\sum_{i\in\mathcal{N}}\sum_{w\in\mathcal{T}_i} M_w \cdot (max\{v_w - c_0 \cdot n_w \cdot \gamma_w \cdot [x_i y_w + (1-x_i)\cdot\lambda_w], 0\})^2$$

$$+\sum_{i\in\mathcal{N}}\sum_{w,w'\in\mathcal{T}_i} M_w \cdot x_i \cdot \left(max\left\{y_w + \sum_{\mathbf{w'}\in\chi_w} y_{\mathbf{w'}} - 1, 0\right\}\right)^2 \tag{6.68}$$

6.5.1 Hybrid Genetic Algorithm

Step 0. Initiation

Randomly determine an initial an initial population consisting of λ distinct chromosomes are generated satisfying constraints (6.52)-(6.59). Denote the population by $S^n = s_m^n \mid m = 1, 2, ..., ,$ of which bit string s_m^n is used to represent chromosome m in iteration n Let the number of iterations $n = 0$.

Step 1. Crossover and Mutation

The initial population of the genetic algorithm (GA) is generated randomly following the aforementioned coding scheme and chromosomes are further to ensure all of them satisfy the constraint (6.52)-(6.59). Then, one-point crossover and mutation are used to generate new solution populations with the probability of p_{cross} and p_{mut}

Step 2. Fitness Evaluation

Two sub-steps are executed to calculate fitness of each chromosome in population S^n as follows.

Step 2.1. Network Flow Assignment

The network flow calculated by the heuristic algorithm is embedded in the hybrid genetic algorithm (GA) for the objective function evaluation. Note that the impedance of a link or turning in the network is associate with its flow. Therefore, the vector of disutility function of the links and turnings will in general have asymmetric Jacobian matric, and the assignment problem is an asymmetric network assignment problem (Dafermos,1980; Dafermos and Nagurney,1984), which does not have an equivalent optimization formation. One approach, most commonly used to solve asymmetric network assignment problems, is the well-known diagonalization method (Florian,1979; Abdulaal and LeBlanc,1979;Mahamassani and Mouskos,1988). In this paper, the projection method is used to solve the variation inequality VI (6.36) to obtain the SUE flow pattern v_m^n corresponding to the design decision s_m^n.

Step 2.2 Fitness Normalization

Giving v_m^n and $s_m^n (m=1,2,3,...,\lambda)$, the evaluation value of chromosomes m in generation n, $F_m^n = F(v_m^n, s_m^n)$, can be calculated by Eq.(6.36). Then the fitness of each chromosome can be then computed by normalizing its evaluation value with Eq.(6.69).

$$F_m^n(v_m^n, s_m^n) = \frac{F_{max}^n - F(v_m^n, s_m^n) + \varepsilon}{F_{max}^n - F_{min}^n + \varepsilon} \tag{6.69}$$

Where F_{max}^{n} and F_{min}^{n} denote the maximum and minimum evaluation function value in generation n, respectively; $F(v_m^n, s_m^n)$ is the evaluation value corresponding to the m^{th} chromosome in generation n; ε is the positive value between 0 and 1 which function to prevent (6.69) from zero division and adjust the selection behavior between fitness proportional selection and pure random (Gen and Cheng, 2000)

Step 3. Bread a new population

Generate the new population $S^{(n+1)}$ of size λ by using a binary tournament selection method (Gen and Cheng, 1997) according to the fitness of each chromosome calculated with Equation (6.69). Set $n = n+1$ and go to Step 1

Step 4. Evaluation and stop criteria

Based on the fitness value of chromosomes, a binary tournament method is used to generation new populations. The genetic algorithm (GA) stops to evolve until the following criteria:

$$\left| \frac{(F_{min}^{(n+1)} - F_{min}^{n})}{F_{min}^{n}} \right| \leq \varsigma \tag{6.70}$$

Such as the difference between the minimum evaluation values between two adjacent generations is less than a threshold ς.

The non-smooth nature of the route travel time function riders solution methods based on derivative information rather difficult. So we develop a solution methods to solve this VI problem with the hybrid genetic algorithm methods.

6.6 Case Study

To illustrate the applicability of the mixed freeway model, this study has employed a hypothetical mixed freeway and urban transportation network which includes 8 freeway exits and 8 freeway entrances in the freeway network, and 16 nodes in the arterial street network for the numerical tests. Basic layout of the mixed freeway network is given in Figure 6.3.

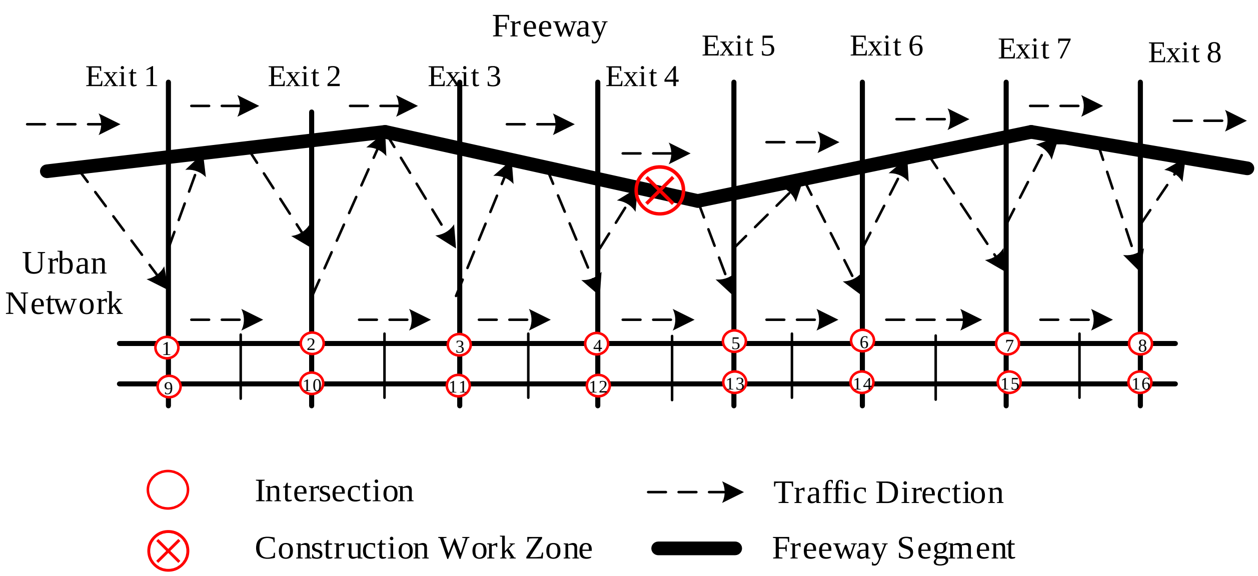


Figure 6. 3 A Hypothetical Mixed Freeway Network for Case Study

Assuming that a construction work zone occurs on the freeway mainline section (between exit 4 and exit 5), which was full closed for upstream on ramp of the construction work zone by traffic agencies. The proposed optimization model will determine a set of critical off-ramps and on-ramps for detour operations, and implement the appropriate location of uninterrupted flow intersection or signal intersection, and reset the signal timing at all related intersections implemented by signal intersection in the urban network. The key data used for model inputs is summarized as follows:

The traffic demand related

- Freeway entry volumes: 3000vph;
- Normal urban street network entry volumes:1000vph, 500vph for arterial, side streets respectively;
- Normal exit rate at each off-ramp is 5% for the entire control area;

The model related

- Update time steps for arterial (δt) and the freeway (δT) are set to be 1s and 5s, respectively;
- Each freeway segment is set to be 800ft;
- Jam density ρ^{jam} set to be 210veh/mile/lane, and the minimum density ρ^{min} to be 20veh/mile/lane;
- Discharge capacity: freeway (2200vplph), arterial link (1800vplph), ramp (1900vplph);
- Average vehicle length is set to be 24 ft to compute the storage capacity of arterial links;
- Freeway segment will be closed at the construction work zones;
- The velocity of the urban street set to be 30mph

Geometric related:

- All of lanes are closed during the construction work zone;
- The maximum number of full lanes at the arterial: 4;
- The number of lanes at on-ramps and off-ramps:1;

Geometric related:

- Maximum and minimum cycle length for the arterial intersections:(120s), (60s);

Optimization algorithm related

- The population size of Genetic Algorithm (GA) is set at 100;
- The maximum number of generation is set of 200;

- The crossover probability is set at 0.6;
- The mutation probability is set at 0.02;

6.6.1 Experimental Analysis and Results

Since the base version of the integrated management strategies could be effectively improve the operation efficiency of mixed freeway special event in urban transportation network. This section will evaluate the proposed model with emphasizes on following aspects:

- Demonstrate the impacts of the difference location on/off ramp closed on control area generated from the proposed model and the system measure of effectiveness (MOEs).
- Perform sensitivity analysis of the proposed model to different levels of driver detour rates.

6.5.1.1 The impact of different location of on/off ramps closed on control area generated from the proposed model and the system measure of effectiveness (MOEs)

Table 6.1 presents the variation of the control boundaries generated form the proposed model with the assignment traffic from different location off ramps for mixed freeway network. Comparison between the results yield the following findings:

- With the different detour traffic location of off-ramps from the upstream to the downstream on-ramps of construction work zone, the generated traffic management strategies and optimization route are difference of the location of signal intersection and uninterrupted flow intersection, signal timing planning;
- The number of the diversion flow back to freeway through construction work zone downstream on-ramps is less than that construction work zone upstream off-ramps. Since some detour traffic arrive the destination or choice the arterial corridor to their destination within minimum travel time after exiting freeway.

- Depending on the traffic conditions and mixed freeway network structure, the exits a critical control area beyond which the time spent by total detour traffic no longer decrease. For example, although the study network covers an 8-exits stretch, only 3 upstream exits and 3 downstream exits are used to generate the minimal total travel time. (see Table 6.3)

This section has also investigated the distribution of diversion traffic flow over different upstream off-ramps and downstream on-ramps of construction work zone within the control area under various detour rates. The comparison results, as shown in Table 6.1 and Table 6.3, have indicated that:

- The diversion flows are not event distributed over the on-ramps. An upstream off-ramps closer to the construction work zone location has carried most diversion flows, and on-ramps closer to the work zone location has also received more detour flows. This is reasonable as traffic prefers to reduce the extra travel distances caused by the detour operations, and comes back to the freeway as soon as possible to best use the high capacity at work zone-downstream freeway links; and
- Traffic agencies shall preplan the integrated diversion flow strategies that distribute the detour traffic at proper location of upstream off-rams and downstream on-ramps of work zone to reduce the travel time and effectively improve the efficiency operational performance. Meanwhile, traffic operators should schedule the scheme to obtain a proper detour rates to guide the drivers detour at appropriate location of upstream off-ramps and to reduce the travel delay with diversion flow freeway to urban street network.
- Regarding with the lane channelization, the traffic operators should redesign the distribution of signal intersection and uninterrupted flow intersection, lane marking

function to effectively decentralize the sudden increase traffic demand for special evets occurred.

Table 6. 1 Optimal Integrated Traffic Management Strategies for Construction Work Zone

Off-ramp (Construction work zone) Upstream				On-ramp (Construction work zone) Downstream				Urban Street Network		Optimal Route
								Signal Intersection	Uninterrupted Flow Intersection	
1	2	3	4	5	6	7	8			
1				1				1, 3,5,11	2,4,8,9,10,12	1-2-3-4-5
1					1			1,3,6, 11,12	2,4,5,9,10,13,14	1-9-10-12-13-14-6
1						1		1,3,6,7,11,12,15	2,4, 5,9,10,13,14	1-9-10-2-3-4-5-6-7
1							1	3,4,6,7,8,9,11,14,16	1,2,5,7,10,12,13,15	1-2-10-11-12-13-5-6-7-8
	1			1				1,2, 3,5,12	4,9,10,11,13	2-3-4-5
	1				1			1,2,3,10,12,13	4,5,6,9,11,14	2-3-4-5-6
	1					1		1,2,3,5,7,10,12,13	4,5,9,11,14,15	2-3-4-5-6-7
	1						1	1,3,6,7,8,9,10,12,15	4, 5,11,13,14,16	2-3-4-5-13-14-15-16-8
		1		1				1,2,3,4,5,9	10,11,12,13	3-11-12-13-5
		1			1			1,2,3,6,9,10,12,13	4,5,11,14	3-4-5-6
		1				1		1,2,3,4,9,11,14,15	5,6,10,12,13	3-4-5-6-7
		1					1	1,2,3,5,7,8,9,11,14,16	4,6,10,12,13,14,15,	3-4-12-13-14-15-7-8
			1	1				1,2,3,4,5,9,10,11,	12,13	4-12-13-5
			1		1			1,2,3,4,5,6,9,10,11	12,13,14	4-12-13-14-6
			1			1		1,2,3,4,7,9,10,11,13	5,6,12	4-5-6-7
			1				1	1,2,3,4,5,6,8,9,10,11,16	7,12,13,14,15,	4-12-13-14-15-7-8

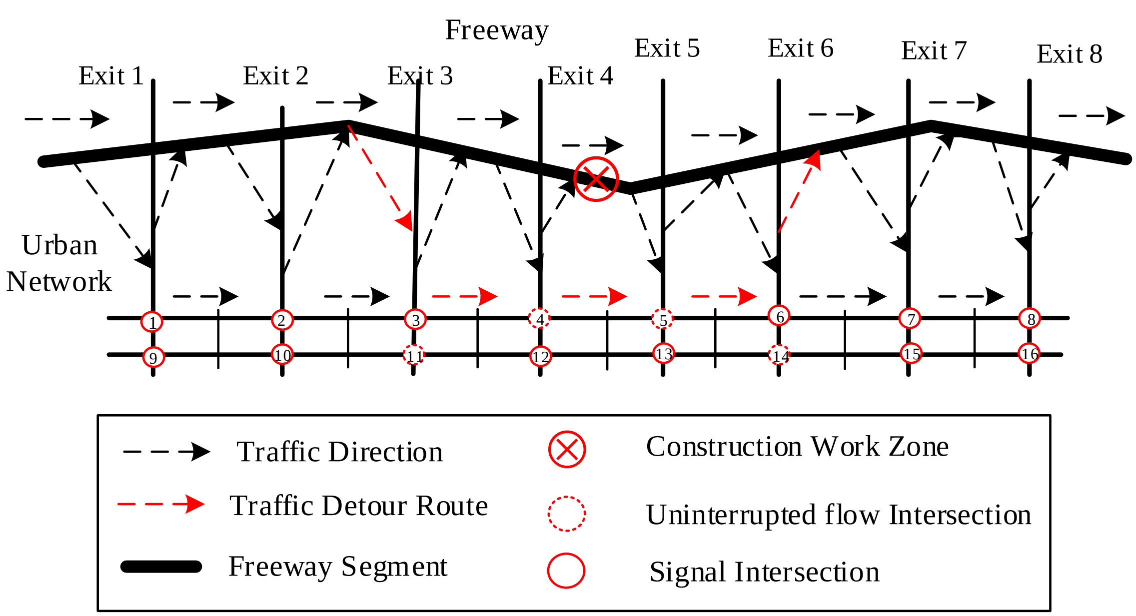


Figure 6. 4 Optimal Traffic Management Strategies for Mixed Freeway Network

Table 6. 2 Optimized Signal Timing Planning of Proposed Model

Intersection (Node IDs)	Phase 1		Phase 2		Phase 3	
	Movements	Green Time	Movements	Green time	Movements	Green time
1	EB-T+R, NB- R	49.12 (s)	SB-L+T+R	36.07 (s)	WB-L+T+R	38.81 (s)
2	SB-T+R, NB-T+R	39.55 (s)	EB-T+R, WB-T+R	72.45 (s)	-	-
3	EB-R, SB-T+R	75.28 (s)	WB-T+R	36.72(s)	-	-
4	U	-	U	-	U	-
5	U	-	U	-	U	-
6	EB-L+T+R, WB-R	75.28 (s)	NB-T+R, SB-T +R	36.72 (s)	-	-
7	EB-T+R, SB-L+R	62.08(s)	NB-L+R, WB-T+R	49.92 (s)	-	-
8	NB-T+R, SB-T+R	49.12 (s)	WB-L+T+R	38.81(s)	EB-L+T+R	36.07 (s)
9	SB-T+R, NB-T+R	49.12 (s)	WB-L+T+R	36.07 (s)	EB-L+T+R	38.81(s)
10	EB-T+R, SB-T+R	49.92(s)	NB-L+R, WB-T+R	62.08 (s)	-	-
11	U	-	U	-	-	-
12	SB-L+T, NB-R	49.12 (s)	WB-L+T+R	36.07 (s)	EB-L+T+R	38.81(s)
13	SB-L+T+R, NB-R	36.72 (s)	EB-T+R, WB-T+R	75.28 (s)	-	-
14	**U**	**-**	**U**	**-**	**U**	**-**
15	NB-T+R, SB-T+R	62.08 (s)	EB-T+R, WB-T+R	49.92 (s)	-	-
16	SB-L+T, NB-R	49.12 (s)	EB-L+T+R	36.07 (s)	WB-L+T+R	38.81(s)

Note: L, T, and R represent left-turn, through movement, and right-turn, respectively; U represents uninterrupted flow intersection.

Table 6.2 demonstrates the optimized signal timings for proposed model generated results Figure 6.5, and detailed lane configuration plans for mixed freeway network. To decrease the total travel time and enhance the capacity of the entire urban network, the proposed model optimized the appropriate location of signal and uninterrupted flow intersection of urban street network, and the signal timing planning, turning restriction. The intersection 4, 5, 11,and 14 are uninterrupted flow intersection which are no traffic conflict to reduce the wait red time during signal intersection and to guarantee the travel time minimized under the limit budget.

The proposed model yield the integrated traffic management strategies, with lane channelization, the appropriate location of the uninterrupted flow intersection and signal intersection, for construction work zone of mixed freeway network.

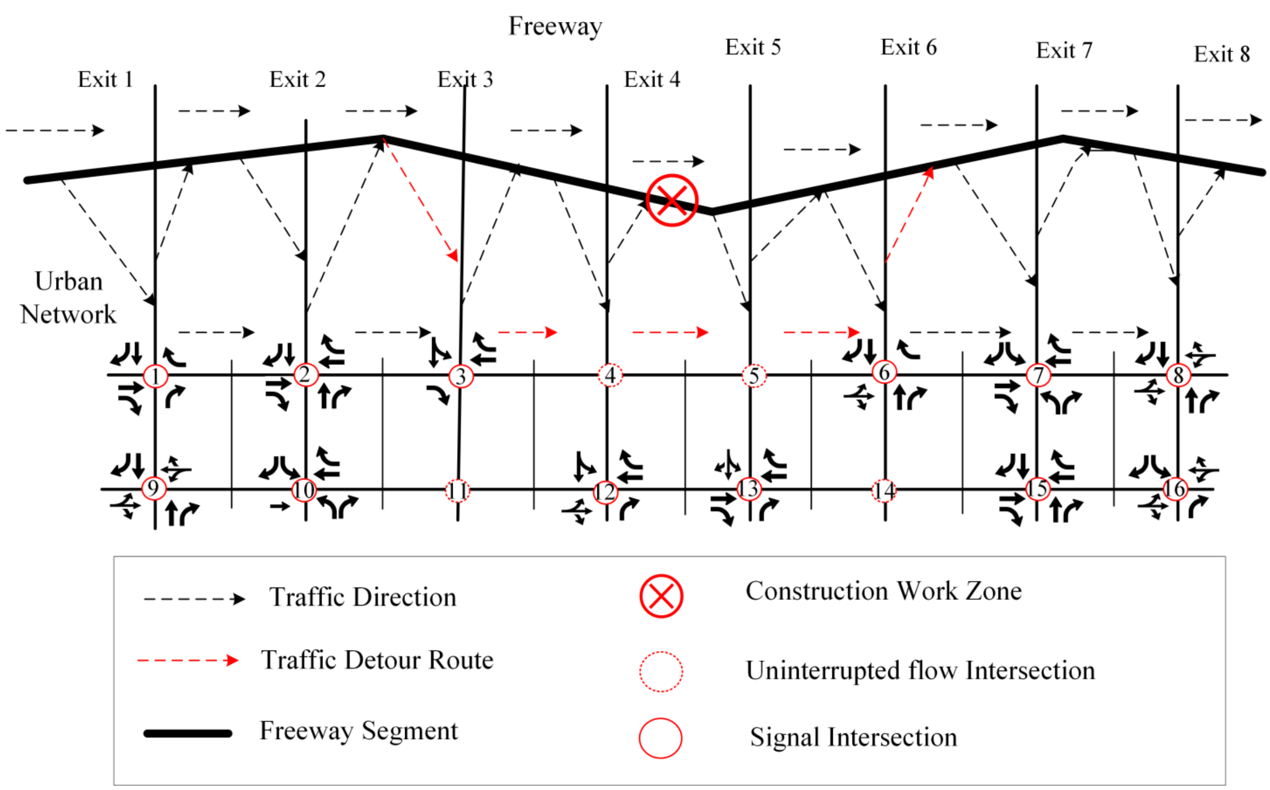


Figure 6. 5 Optimal Traffic Management Strategies with Lane Reorganization

6.6.2 The Sensitive Analysis for the Proposed Integrate Model

The promising performance of the proposed model is conditioned on a 100% level of detour traffic on the construction work zone of mixed freeway network. However, during the real-world operations, the driver behavioral patterns of spreading traffic usually subject to time-varying fluctuations. To address above critical issues, this section has evaluated the performance of the proposed traffic management model under different level of detour traffic rates. The traffic management objective is reset to minimize the total travel time spent by detour traffic.

In this section, we formulate the detour traffic from upstream off-ramps to downstream on-ramps of construction work zone. Let $\sum_{i=1}^{4}(\frac{v_i^n}{\alpha_i}+\frac{v_i^{de}}{\beta_i})=\sum_{i=1}^{4}(\alpha_i v^{ne}+\beta_i v^{de})=v^{off}$ represent the totally exit traffic volume through all off-ramps i. First part is the normal exit traffic volume and α_i, v^{ne} are the normal exit rate and traffic volume, respectively. And the second part is the totally traffic detour volume through all off-ramps i and β_i, v^{de} is the traffic detour rates and traffic volume, respectively. Where, $v_i^n=\alpha_i v^{ne}, v_i^{de}=\beta_i v^{de}$ are the normal exit and traffic detour volume from off-ramp i, respectively, and $i=1,2,3,4$ represents the index of off-ramp on upstream of construction work zone. $\sum_{i=1}^{4}\beta_i=1$, all of traffic must be detour on upstream of the construction work zone due to freeway segment closed. Let $\sum_{i=5}^{8}v_i^{on}\gamma_i=v^{on}$ represent the totally traffic through all on-ramps$i$. Where, v_i^{on} is the entrance traffic detour volume from on-ramps i, and $i=5,6,7,8$ represents the index of on-ramp on downstream of construction work zone. $\sum_{i=5}^{8}\gamma_i\leq 1$, presents some traffic arrive their destination. Table 6.3 has summarized the sensitivity of the proposed model performance to detour traffic rates in the upstream of construction work zone.

Table 6. 3 Traffic Assignment for Each Off-ramp and On-ramp

Off-ramp (Construction work zone) upstream				**On-ramp (Construction work zone) downstream**				**Urban street network**		Average detour route delay time (minutes)
								Signal Intersection	Uninterrupted Flow Intersection	
1	2	3	4	5	6	7	8			
5%	15%	35%	45%	50%	30%	15%	5%	1,2,3,5, 7,11,15,16	4,6,8,9, 10,12,13,14	23.6
5%	15%	35%	45%	40%	50%	5%	5%	1,2,3,5,8, 9,10,12,15	4,5,6,7, 11,13,14,16	21.3
5%	25%	50%	20%	40%	50%	5%	5%	1,4,7,8,9 10,12,15,16	2,3,5,6, 7,11,13,14	26.4
5%	25%	50%	20%	50%	30%	15%	5%	1,4,5,7, 9,10,12,15	2,3,6,8, 11,13,14,16	24.7

As illustrated in Table 6.3, the performance of the proposed model has different traffic management strategies, since the input of the detour traffic rates at each off-ramps upstream of the construction work zone. In this case, the proposed model generated the minimized average travel time spent by detour traffic is 21.3 minutes, with the detour traffic rates at 5%, 15%, 35%, 45%, and divert traffic on-ramps rate at 40%, 50%, 5%, 5%, respectively.

6.7 Conclusions

This study proposed an integrated management strategy for full freeway construction work zone that is capable of concurrently optimizing strategies, including the appropriate location of off-ramps and on-ramps closure, the traffic detour rates, the location of signal and uninterrupted flow intersection, turning restriction, a signal time based lane, over multiple roadway segments between the freeway and its neighboring arterial network. To capture various operational complexities due to the interactions between multiple traffic detours, this study has investigated the mixed freeway model to address the complex and critical issues and scheme the integrated guidance preplan to traffic agencies to effectively improve the operation efficiency. Preliminary numerical tests with a hypothetical mixed freeway network have confirmed the conclusion as follows:

1. The proposed mixed freeway model offers the flexibility for the traffic operation to determine the appropriate location of off-ramp closed and on-ramp opened, which can help to effectively guide the traffic detour and achieve the best operation efficiency;
2. The proposed model can yield integrated strategies that includes signal intersection and uninterrupted flow intersection implemented with the appropriate location, signal timing based lane marking reset, lane channelized, which can mitigate the traffic congestion on

constriction work zone and guide drivers to choose the optimal routes to reduce travel delay in the complex mixed freeway network;

3. The traffic agencies should pre-plan the integrated diversion flow strategies, including the lane organization, the types of intersection, the appropriate location of off-ramps and on-ramps, and proper detour rates, to improve the efficiency of operational performance.

Despite the effectiveness of this study in overcoming several critical issues for the real-time traffic detour management for mixed freeway network under construction work zone, a more efficient and reliable solution for implementing such a system in network-wide applications remains essential. Further studies along this line include:

(1) Development of robust solution algorithms for the proposed model when available control inputs are missing or contain some errors. The performance of the proposed traffic management model for mixed freeway traffic detours model is conditioned on the quality and availability of input data from the surveillance system. However, the availability and accuracy of the existing surveillance system always suffer from the hardware quality deficiency. Neglecting the impact of the data quality in the model formulations may degrade both operational efficiency and reliability in real-world applications. To contend with such deficiencies embedded in the existing models, one needs to develop a robust algorithm to account for measurement errors in system inputs so that it can yield control strategies less sensitive to the data measurement errors.

(2) Development of an intelligent interface with advanced surveillance systems. For real-time implementation of the proposed traffic detours management model for mixed freeway, it requires real-time realization of the control input data from various sources of the surveillance system. Many advanced detection technologies developed in recent years in the traffic control field have featured their capabilities in capturing the evolution of traffic flows at each individual movement

or vehicle level, which offers the promise for a real-time control system to significantly reduce the cost in data processing and parameter estimation. Hence, to effectively operate an integrated real-time corridor control system, one should certainly develop an intelligent interface to take advantage of those features embedded in the emerging advanced detection technologies.

Chapter 7: The Extended Model III: Dynamic Traffic Management

7.1 Introduction

The main motivation of this Chapter is to present the mathematical model formulations for special events traffic management in a dynamic transportation network considering the time-varying traffic demand and network characteristics that often occur in special events. The proposed model features a bi-level structure with the upper level searching for the best traffic management strategies by minimizing the total event clearance time, and the lower level handling routing assignment of the traffic demand with a single-destination user-optimal DTA problem. The cell transmission model (CTM) is employed to mathematically represent dynamic traffic flow evolution and queuing in the network. To deal with the combinatorial complexity of the proposed model, this chapter will also develop heuristic solution algorithms. To contend with those critical issues, many researchers have attempted to develop methodologies, guidelines, and tools to plan and operate the spreading traffic process more effectively and efficiently.

In review of the literature, dynamic traffic assignment-simulation models have also been applied in traffic management modeling. Sattayhatewa and Ran (2000) have developed an analytical DTA model to minimize the total decentralization time under a nuclear power plant failure. Liu et al. (2007) also applied the DTA approach in a Model Reference Adaptive Control framework for real-time spreading traffic management. Yuan et al. (2006) formulated the spreading traffic routing problem with the simulation-DTA models embedded in the software package DYNASMART-P. Georgia et al. (2012) have developed a DTA model based the spreading traffic planning for the Central Business District in order to minimize the risk of potential casualties and injures. Luca et al. (2012) proposed an ant colony optimization algorithm and solved the asymmetric traffic assignment problem for the special events in urban transportation network. Many tools have been developed for spreading traffic routing and assignment, such as NETVAC (Sheffi et al., 1981), DYNEV (KLD Associates, 1984), and MASSVAC (Hobeika and Jamei, 1985), DynaSmart (Murray-Tuite and Mahmassani, 2004), DynusT (Chiu et al., 2005), and DynaMIT (Balakrishna et al., 2008). Microscopic traffic simulation based packages such as CORSIM (Lim and Wolshon, 2005), Paramics (Chen and Zhan, 2004), VISSIM (Elmitiny et al., 2007), and TRANSIMS (Naghawi and Wolshon, 2010) were also employed for operational planning. Some other studies have applied dynamic traffic assignment models to generate optimal traffic routing schemes (Sattayhatewa and Ran, 2000; Liu et al., 2007; Georgia and Iraklis, 2012; Luca and Mariano, 2012) concurrently with other control strategies, such as contra-flow design (Mahmassani and Sbayti, 2005; Tuydes, and Ziliaskopoulos, 2006), staged evacuation (Liu et al., 2006), and scheduling of the evacuation demand (Chiu, 2004; Sbayti and Mahmassani, 2006). A more thorough and updated review of relevant studies can be found in Murray-Tuite and Wolshon (2013).

Traffic signal operation plays a key role in effective spreading traffic management. In this regard, McHale and Collura (2003) applied TRANSYT-7F to generate an optimal signal-timing plan when assessing the impact of emergency vehicles' preemption strategies in a CORSIM simulator. Chen et al. (2005) applied the microscopic simulation software CORSIM for two decentralization corridors of Washington, D.C., and examined the influence of different signal-timing plans on the spreading traffic. Most literature either assumed oversimplified signal plans at intersections or applied standard signal optimization practices for normal traffic conditions, but with a high demand. To remedy this deficiency, Liu et al. (2008) have developed a critical intersection based model to maximize the efficiency of the primary spreading arterial, but not to incur excessive waiting time and queues on its side streets. However, their model is only applicable in a single corridor with the assumption that there are only two phases at the critical intersections. Liu and Chang (2011) developed an arterial signal optimization model for oversaturated intersections experiencing spillback and blockages under severe congestion.

Although proper signal control coupled with optimized routing plans may improve the overall spreading traffic efficiency, operating too many signals at intersections during the special event has been found to incur the unacceptable level of delays and induce aggressive driving maneuvers due to the frustration and excessive waiting time (Lajunen et al., 1999; Hamdar et al., 2008). Realizing such a critical issue, researchers in recent years have proposed to convert a signalized junction into an uninterrupted flow facility by properly setting cross-elimination or turning restriction plans at entries (Long et al., 2010). Cova and Johnson (2003) proposed an innovative lane-based network routing strategy, which converts an intersection with interrupted flow conditions to an uninterrupted flow facility. They showed that removing the stop-and-go traffic control setting had significantly expanded the intersection capacity. Cova's work has been further extended by combining the crossing-conflict elimination and the contra flow design, which have been practically shown to be an efficient strategy to better use the network capacity under spreading traffic situation (Kalafatas and Peeta, 2008; Xie, and Turnquist, 2011; Xie et al., 2010).

Such uninterrupted flow facilities, though effective in expanding the special event network capacity, may require a large amount of personnel and resources that often exceed the available resources. Most importantly, it may result in a substantial increase in traffic detours due to certain turning movement restrictions, especially in a large-scale special events network. In addition, drivers may be confused and panic if they are frequently blocked from making preferred turns at a junction or rerouted from their pre-planned routes during an emergency situation. In response to such concerns, Liu and Luo (2012) developed a bi-level model to best locate the set of intersections for implementing uninterrupted flow and signal control strategies in a static special events network with resource constraints. Their model is useful to prioritize the limited traffic management resources to the most appropriate control points. In a static special events network, their findings indicate that the decentralization performance (total events clearance time) improved monotonically with more uninterrupted flow intersections implemented. However, previous research efforts on special events are difficult to be applied to special event traffic management due to their different problem natures (e.g. objectives, demand distribution patterns, traveler behaviors, and management strategies).

7. 2. Research Motivation and Objectives

A static representation of the network conditions, though effective to diffuse traffic patterns across space with the assignment of traffic flows to approximate Stochastic User Equilibrium (SUE), do not directly reflect the dynamic flow patterns in a realistic special events network (e.g., explicit consideration of queuing on network links and time-varying spreading traffic demand), which may hinder their real-world applications. Therefore, findings held well under such modeling paradigms may not be accurate and reliable to support decision making.

In response to the above concern, this Chapter seeks to examine the problem of selecting and distributing signal control and uninterrupted flow strategies in dynamic special events network settings. More specifically, the following critical issues will be investigated: 1) Will the results in a static network still hold in a dynamic setting? 2) Does an optimal distribution between signal and uninterrupted flow strategies exist in a dynamic network and what is it? And 3) How to best plan turning restriction and signal timings at those intersections?

A network optimization model featuring a bi-level scheme is adopted in this paper to address the above questions. The upper level searches for the best spatial distribution of signalized and uninterrupted flow intersections in the network with the objectives of minimizing the total event clearance time. The lower level problem handles routing assignment of the spreading traffic demand.

The remaining of this Chapter is organized as follows. The next section details the representation of the special events network dynamics. The optimization model is formulated in Section 7.4. Specific algorithmic design of the solution method is elaborated in Section 7.5. Section 7.6 demonstrates the evaluation results with respect to the model performance and its applicability in a test special event network. Section 7.7 summarizes research findings and potential applications of the proposed model.

7. 3 The Network Flow Formulations

7. 3.1 Network Representation

In this study, the transportation network can be represented as a cell-based directed graph $G = (S, A)$ where S and A represent the set of cells and connectors. Let S_r, S_s represent the sets of source cells and sink cells in the network, thus the set of ordinary cells is given by $S \backslash (S_r \cup S_s)$. Cells in the network are joined by different sets of connectors including the set of road-section cell connectors (A_R), intersection cell connectors (A_I), and sink cell connectors (A_S). In the cell-based network, let $N = N_S \cup N_U$ represent the set of intersections where N_S and N_U are the sets of signalized intersections and uninterrupted flow intersections, respectively. Each intersection $n \in N$ can be further depicted as a sub-network ($G_n \subset G$) consisting of a set of cells ($S_n \subset S$) and connectors ($A_n \subset A$).

Figure 7.1 illustrates how different sub-networks are connected and interact, in which part A describes an example section composed of an uninterrupted flow intersection, a bi-directional road section, and a signalized intersection.

At a signalized intersection sub-network, any pair composed by an upstream cell and a downstream cell is always connected via a connector, and flows can go through the connectors only when they are at their right-ways according to the current signal status. At an uninterrupted flow intersection, movements between cells are allowed only if connectors joined them, which is determined by the turning restriction plans. The road segment sub-network is used to connect two intersections and propagate traffic demand in the network. The sink cells (not shown in Figure 7.1) are located at the exits of the network, which are assumed to connect with traffic detour destinations. Part B in Figure 7.1 lists several examples of possible turning restrictions at uninterrupted flow intersections with 3 and 4 legs.

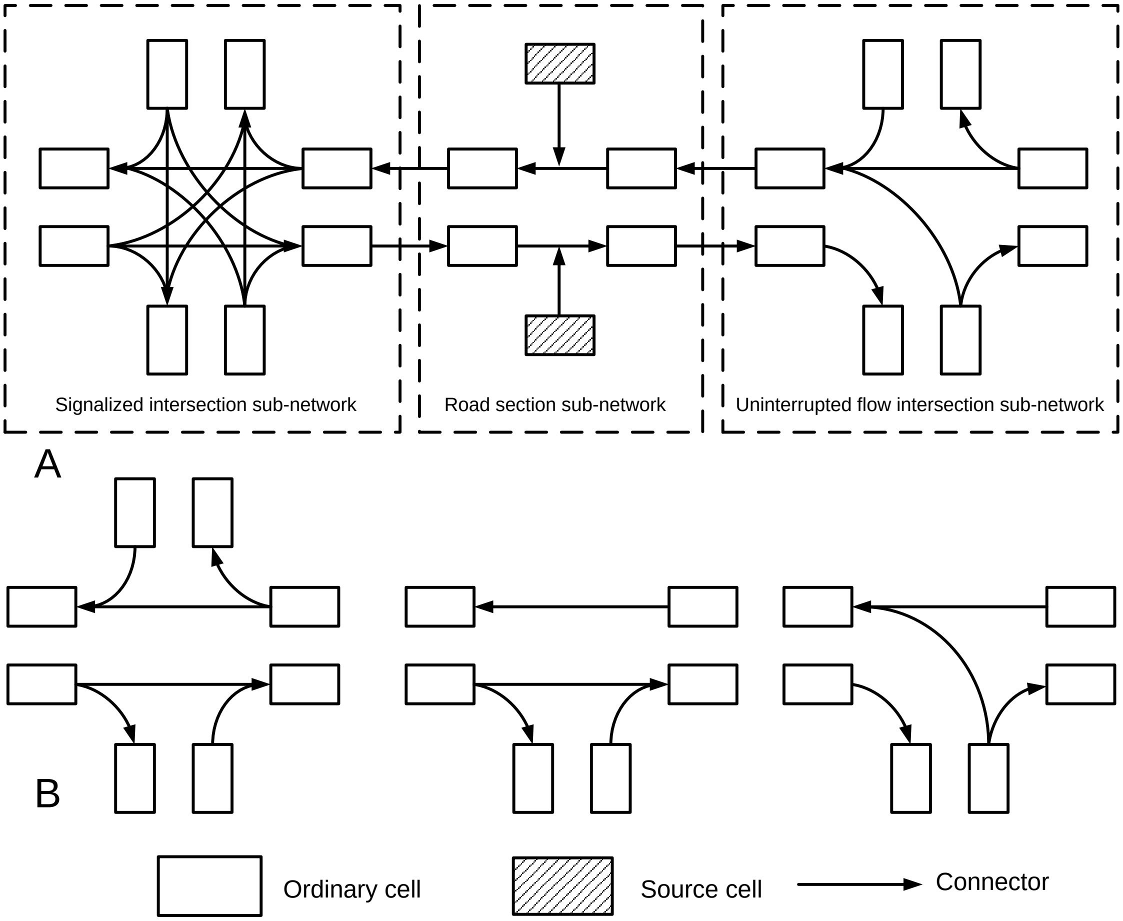


Figure 7. 1 Network Representation

7.3.2 Notations

To facilitate model presentation, notations used hereafter are summarized in Table 7.1.

Table 7. 1 Notation of Key Model Parameters and Variables

Sets	
G	The cell-based transportation network, $G = (S, A)$
S	Set of cells
A	Set of cell connectors
S_r	Set of source cells
S_s	Set of sink cells
A_R	Set of road-section cell connectors
A_I	Set of intersection cell connectors
A_S	Set of sink cell connectors
$N, n \in N$	Set of intersections in the network, $N = N_S \cup N_U$
N_S, N_U	Set of signalized and uninterrupted flow intersections
G_n	The sub-network of intersection n

S_n	Set of cells at intersection n
A_n	Set of connectors at intersection n
P_n	The set of phases at the signalized intersection n if it is signalized, $p \in P_n$
A_n^p	The set of cell connectors on which flow are allowed to move during phase p at intersection n
Γ_i^+	Set of cells upstream to cell i
Γ_i^-	Set of cells downstream to cell i
Parameters and variables	
$(i,j) \in A$	A connector from cell i to cell j
$T, t \in T$	Events clearance time window and the time step.
CT	Network clearance time.
D	The total spreading traffic demand loaded into the network
D_i	The total demand at source cell i at initialization, $i \in S_r$
d_i^t	Demand to source cell i at time step t, $i \in S_r, t \in T$
f_{ij}^t	The number of vehicles on connector (i,j) at time step t
f_i^t	The number of vehicles in cell i at the beginning of time step t, $i \in S, t \in T$
π_i^0	The initial number of vehicles in cell i
V_i	Free flow speed at cell $i, \forall i \in S \backslash S_s$
N_i^t	The number of vehicles can be accommodated at cell i at time step t, $\forall i \in S \backslash S_s, t \in T$
R_i^t	The receiving capacity of downstream cell i at time step t, $i \in S \backslash S_r, t \in T$
S_i^t	The sending capacity of upstream cell i at time step t, $i \in S \backslash S_s, t \in T$
Q_i^t	The number of vehicles that can flow into/out of cell i during time interval t, $\forall i \in S \backslash S_s, t \in T$
Q_{ij}^t	The number of vehicles that can flow out of connector (i,j) during time interval t, $\forall (i,j) \in A_I, t \in T$
λ_{ij}^t	The g/C ratio for turning movement on connector (i,j) during time interval t, $\forall (i,j) \in A_I, t \in T$
w_i^t	Backward shock-wave propagation speed at cell i during time interval t, $\forall i \in S \backslash S_s, t \in T$
Decision variables	
$x_n, n \in N$	A binary variable, 1 if n is set as an uninterrupted flow intersection; 0 otherwise
λ_n^p	The g/C ratio for phase p at intersection n
y_{ij}	A binary variable, 1 if flow on connector (i,j) is allowed; 0, otherwise $(i,j) \in A_I$

7. 4 The Optimization Model

The proposed network optimization model features a bi-level scheme with the upper level describing the decision of the authorities for minimizing the events clearance time. The lower-level problem models the behavior of spreading traffic in choosing optimal routes with respect to locations of signalized/uninterrupted flow intersections and the turning restriction plans.

7. 4.1 The Upper-level Problem

In the upper-level model, the objective function is to minimize the frequently used events clearance time, given by:

$$Min\ z(\boldsymbol{\omega}) = max\{t \in T | f_{ij}^{t} > 0, \forall (i,j) \in A_S\} \tag{7.1}$$

where the solution vector $\boldsymbol{\omega} = (\mathbf{x}, \mathbf{y}, \boldsymbol{\lambda})$ with $\mathbf{x} = (x_n | n \in N)$, $\mathbf{y} = (y_{ij} | (i,j) \in A_I)$, and $\boldsymbol{\lambda} = (\lambda_n^p | p \in P_n, n \in N)$. Note that selection of system objectives depends on the characteristics of the emergency event and does not affect the proposed modeling framework.

If intersection n is implemented as uninterrupted flow, turning restriction constraints are applied to prohibit traffic movement conflicts, given by:

$$y_{ij} + \sum_{(k,l)\in\Gamma_n^{(i,j)}} y_{kl} \leq 1 + M(1 - x_n),\ \forall n \in N, (i,j) \in A_n \tag{7.2}$$

where y_{ij} is a binary decision variable (1 if flow on connector (i,j) is allowed; 0, otherwise); $\Gamma_n^{(i,j)}$ is the set of the conflicting connectors with (i,j) at sub-network G_n; M is a sufficiently large positive number and x_n is a binary decision variable determining whether intersection n is an uninterrupted flow one (1-yes, 0-no).

7.4.2 The Lower-level Model

Given the decisions from the upper-level model, the lower-level model can be formulated as a single-destination user-optimal DTA problem (Xie et al., 2010) with the objective formulated as:

$$argmin\ \ z(f) = \sum_{(i,j)\in A_S} \sum_{t\in T} f_{ij}^{t}\, \mathcal{L}_t \tag{7.3}$$

$$\mathcal{L}_t - \mathcal{L}_{t-1} > (\mathcal{L}_T - \mathcal{L}_t)D \quad \forall t \in T \tag{7.4}$$

where $\mathcal{L}_t$ is a series of problem-specific increasing positive numbers in which the difference between two consecutive cost coefficients rapidly decreases over t (Waller and Ukkusuri, 2009). A linear programming formulation for the user optimal dynamic traffic assignment. Networks and Spatial Economics, in review.); D is the total demand of special events in the urban transportation network.

The lower level cell transmission based DTA problem shall include flow conservation and propagation constraints,

$$f_i^t - f_i^{t-1} + \sum_{j \in \Gamma_i^-} f_{ij}^{t-1} - \sum_{j \in \Gamma_j^+} f_{ji}^{t-1} = 0, \forall\, i \in S \backslash (S_r \cup S_s), t \in T \tag{7.5}$$

Equation (7.5) is the flow conservation equation for both general cells and sink cells.

$$f_i^t - f_i^{t-1} + \sum_{j \in \Gamma_i^-} f_{ij}^{t-1} - d_i^t = 0, \forall\, i \in S_r, t \in T \tag{7.6}$$

Equation (7.6) is the flow conservation equation for source cells.

$$\sum_{j \in \Gamma_i^+} f_{ji}^t \leq Q_i^t \; \forall\, i \in S \backslash S_r, t \in T \tag{7.7}$$

$$\sum_{j \in \Gamma_i^+} f_{ji}^t \leq N_i^t - f_i^t \; \forall\, i \in S \backslash S_r, t \in T \tag{7.8}$$

$$\sum_{j \in \Gamma_i^+} f_{ji}^t \leq \frac{w_i^t}{V_i}(N_i^t - f_i^t) \; \forall\, i \in S \backslash S_r, t \in T \tag{7.9}$$

Equations (7.7)-(7.9) present the relaxed flow propagation constraints related to the receiving capacity of any downstream cells.

$$\sum_{j \in \Gamma_i^-} f_{ij}^t \leq Q_i^t \quad \forall i \in S \backslash S_s, t \in T \tag{7.10}$$

$$\sum_{j \in \Gamma_i^-} f_{ij}^t \leq N_i^t \quad \forall i \in S \backslash S_s, t \in T \tag{7.11}$$

$$\sum_{j\in\Gamma_i^-} f_{ij}^t \le f_i^t \quad \forall i \in S\backslash S_s, t \in T \tag{7.12}$$

Equations (7.10)-(7.12) present the relaxed flow propagation constraints related to the sending capacity of any upstream cells.

$$f_{ij}^t \le Q_{ij}^t \cdot \left[\lambda_{ij}^t \cdot (1 - x_n) + x_n\right], \forall (i,j) \in A_n, n \in N, t \in T \tag{7.13}$$

Equation (7.13) presents the flow capacity constraints for connectors, which can model the reduced capacity of turning movements if the intersection is signalized.

$$f_{ij}^t \le M y_{ij} \quad \forall (i,j) \in A_I, t \in T \tag{7.14}$$

Equation (7.14) applies the turning restriction to relevant connectors.

The signal operational constraints,

$$\lambda_{ij}^t = \lambda_n^p \quad \forall\, (i,j) \in A_n^p, p \in P_n, n \in N, t \in T \tag{7.15}$$

Equation (7.15) maps the relation between connector flow *g/C* ratios and phase *g/C* ratios.

$$\lambda_n^p \ge \lambda_{min} \ \forall p \in P_n, n \in N \tag{7.16}$$

$$\sum_{p\in P_n} \lambda_n^p \le 1 + M x_n \quad \forall n \in N \tag{7.17}$$

Equations (7.16) and (7.17) limit the *g/C* ratio to be within reasonable range where λ_{min} is the minimum *g/C* ratio. The Equation (7.17) means that If the intersection n is set up as an uninterrupted flow intersection (i.e. $x_n = 1$), there is no restriction for an uninterrupted flow intersection n; otherwise, the great ratio for phase of each signalized intersection must be within reasonable range.

The network initialization constraints:

$$f_i^0 = \pi_i^0 \quad \forall i \in S \backslash S_r \tag{7.18}$$

$$f_i^0 = D_i \quad \forall i \in S_r \tag{7.19}$$

$$f_{ij}^0 = 0 \quad \forall (i,j) \in A \tag{7.20}$$

Equations (7.18)-(7.20) set the state of the network at initialization.

The network clearance constraint:

$$\sum_{i \in S_s} f_i^{T+1} = \sum_{i \in S_r} D_i \tag{7.21}$$

Equation (7.21) is used to guarantee that the network is completely cleared at the end of the decentralization analysis period T so that the DTA model will have a feasible solution.

The other general constraints:

$$f_{ij}^t \geq 0 \quad \forall (i,j) \in A, t \in T \tag{7.22}$$

$$f_i^t \geq 0 \quad \forall\, i \in S, t \in T \tag{7.23}$$

Equations (7.22) and (7.23) are non-negative constraints for connectors and cells.

7. 5 Solution Approach

Genetic algorithm (GA) based heuristics have been successfully demonstrated to yield viable and meta-optimal solutions to a series of bi-level optimization problems in a reasonable time period (Sarma and Adeli, 2001; Teklu et al., 2007). Considering the computational complexity underlying the proposed formulation, in this section we develop a genetic algorithm (GA) based heuristic to solve the problem.

To penalize candidate solutions that may violate cross-elimination constraint (7.2). We first relax Equation (7.2) and include it in a revised evaluation function with a penalty term, given by:

$$Z(\boldsymbol{\omega}) = z(\boldsymbol{\omega}) + \sum_{n\in N}\sum_{(i,j),(k,l)\in A_n} M\cdot x_n\cdot\left(max\left\{y_{ij}+\sum_{(k,l)\in\Gamma_n^{(i,j)}} y_{kl}-1,0\right\}\right)^2 \quad (7.24)$$

where $Z(\boldsymbol{\omega})$ is the output, in terms of clearance time, corresponding to candidate solution ω; $Z(\boldsymbol{\omega})$ is used in the evolution of GA to maintain the population size. Candidates with lower values have larger chances to be selected in the next generation.

7.5.1 Coding of GA Chromosomes

An essential step in the GA search for the proposed optimization problem lies in an efficient coding of chromosomes that can capture the characteristics of the solution structure. In external module, we generate vectors of binary variables $\{X^1, X^2, X^3 \dots X^n\}$ $\forall n\in N$ indicating the type of intersection n; while for the solution to turning restrictions, we use vectors of binary strings $\{l_1, l_2, l_3 \dots l_n\}$ $\forall n\in N$, where l_n is a binary string indicating the state of the turning restrictions applied at intersection n. If $X^n = 0$ (i.e., intersection n is a signalized one), then the string l_n is set to consist of all ones, indicating that no turning restrictions are implemented at intersection n. To make sure constraints (7.16)-(7.17) are satisfied, a number of $|P_n|-1$ fractions ($\mu_n^p, p = 1\cdots|P_n|-1$) are used to code g/C ratios at intersection n, given by:

$$\lambda_n^p = \lambda_{min} + (1-|P_n|\cdot\lambda_{min})\cdot\mu_n^p\cdot\prod_{k=1}^{p}(1-\mu_n^{k-1}),\ p = 1\cdots|P_n|-1 \quad (7.25)$$

$$\lambda_n^p = \lambda_{min} + (1-|P_n|\cdot\lambda_{min})\cdot\prod_{k=1}^{p}(1-\mu_n^{k-1}), p = |P_n| \quad (7.26)$$

7.5.2 Crossover and Mutation

The initial populations of the GA are generated randomly following the aforementioned coding scheme. Then, one-point crossover and mutation are used to generate new solution populations with the probability of p_{cross} and $p_{mutation}$.

7.5.3 Fitness Evaluation

For a chromosome h in generation m, one can calculate its fitness value with the following equation:

$$eval(\omega_h^m) = \frac{Z_{max}^m - Z(\omega_h^m) + \varepsilon}{Z_{max}^m - Z_{min}^m + \varepsilon} \qquad (7.27)$$

where Z_{max}^m and Z_{min}^m denote the maximum and minimum evaluation function values in generation m, respectively; $Z(\omega_h^m)$ is the evaluation value corresponding to the h th chromosome in generation m; ε is a positive value between 0 and 1 which functions to: 1) prevent Equation (7.27) from zero division; and 2) adjust the selection behavior between fitness proportional selection and pure random selection.

7.5.4 Evolution and Stopping Criteria

Based on the fitness values of chromosomes, a binary tournament method is used to generate new populations. The GA stops to evolve until the following criteria are met:

(1) $\left|\frac{Z_{min}^m - Z_{min}^{m+1}}{Z_{min}^m}\right| < \zeta$, i.e., the difference in average minimum evaluation values between any 10 adjacent generations is less than a threshold ζ; or

(2) A pre-set maximal number of generations (m_{max}) is reached.

7. 6. Numerical Example

This study employs the following example to illustrate the application of the proposed model.

7.6.1 The Test Network

Figure 7.2 shows the layout of the test network, which consists of 26 intersections (nodes), 82 links, 6 demand origins, and 2 exits (901 and 902). Exits are assumed to be connected with a super destination via impedance free connectors. This assumption facilitates the replication of travelers' choice behavior by enabling the route choice and destination choice simultaneously, and has been widely applied in previous studies (Sheffi, 1985)

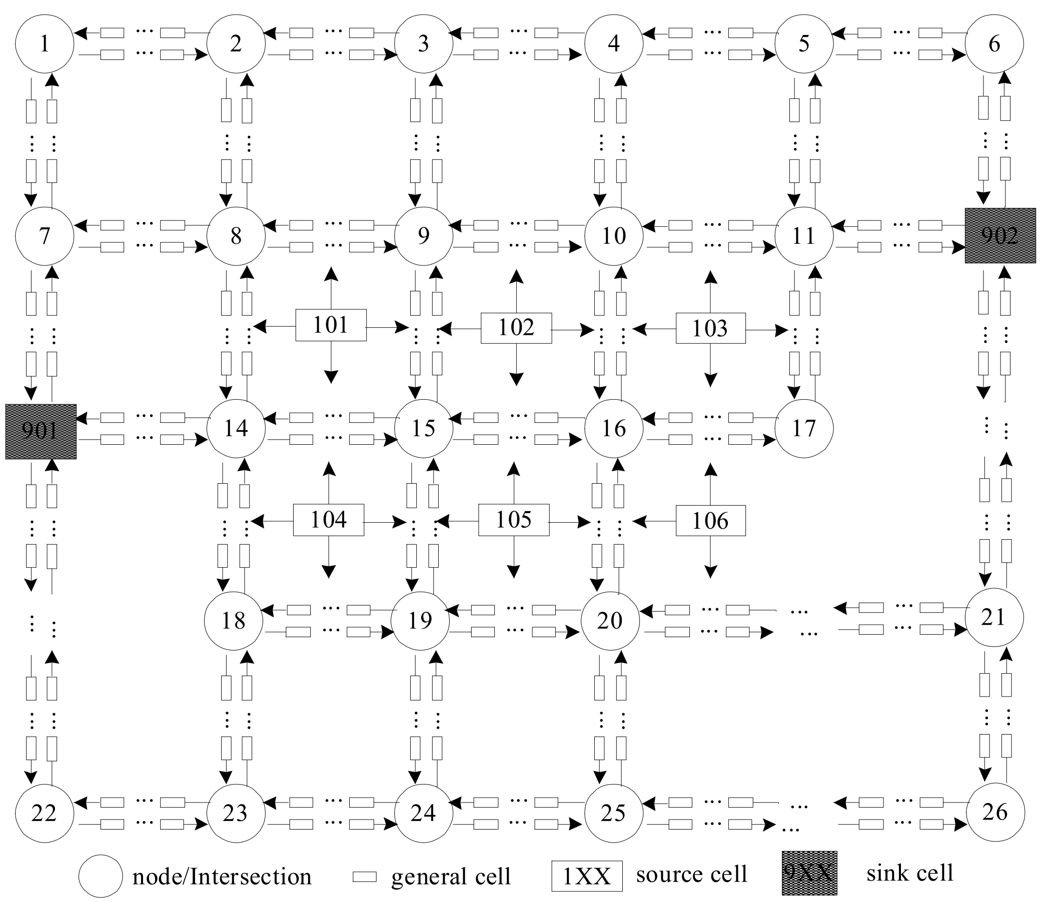


Figure 7. 2 Cell-based Representation of the Test Network

Table 7.2 summarizes the lengths and capacities of all roadway segments in the network. We assume 30 mph free-flow speed for all segments in the network, then we can convert the test network into a total of 346 cells with the system updating time step set as 10s. The jam density is set as 180 vpmpl, and the backward shockwave propagation speed is set as 30 mph.

In the test network, nodes 1, 6, 17, 22 and 26 represent two-leg intersections. They should be excluded from the candidate intersection list for distributing signal or uninterrupted flow strategies in this example.

In the numerical example, we adopted a relatively large pre-set spreading traffic time window (5 hours) to ensure that the test network can be completely cleared at the end of the decentralization analysis period. Other key model parameters are specified as: 1) M is set to be 10,000 seconds; 2) p_{cross} and $p_{mutation}$ are set at 0.4 and 0.02; 3) The population size is set to be 100; 4) m_{max} is set at 100; and 5) ε and ζ are set to be 0.1 and 0.01%, respectively.

It should be noted that the parameters used in the GA are tuned from extensive numerical experimentation to fit best with the case study network. They may need to go through the recalibration and updating process for use at other networks.

Table 7. 2 Length and Capacity of Road Segments for the Test Network

Links	Length (ft)	Capacity (vph)	Links	Length (ft)	Capacity (vph)	Links	Length (ft)	Capacity (vph)
1,2 2,1	1083	3600	14,15 15,14	1575	1900	7,13 13,7	787	3600
2,3 3,2	1804	3600	15,16 16,15	1673	1900	13,22 22,13	5184	3600
3,4	1640	3600	16,17	984	1900	2,8	951	1900

4,3			17,16			8,2		
4,5 4,4	951	3600	18,19 19,18	1148	1900	8,14 14,8	886	1900
5,6 6,5	984	3600	19,20 20,19	1739	1900	14,18 18,14	3281	1900
7,8 8,7	1214	3600	20,21 21,20	1837	1900	18,23 23,18	1575	1900
8,9 9,8	1608	3600	22,23 23,22	3707	3600	3,9 9,3	919	3600
9,10 10,9	1673	3600	23,24 24,23	1378	3600	9,15 15,9	886	3600
10,11 11,10	984	3600	24,25 25,24	1575	3600	15,19 19,15	3281	3600
11,12 12,11	820	3600	25,26 26,25	1837	3600	19,24 24,19	1542	3600
13,14 14,13	1115	1900	1,7 7,1	951	3600	4,10 10,4	919	1900
10,16 16,10	886	1900	16,20 20,16	3543	1900	20,25 25,20	1476	1900
5,11 11,5	1017	1900	11,17 17,11	755	1900	6,12 12,6	919	1900
12,21 21,12	4396	3600	21,26 26,21	1345	3600			

7.6.2 Evaluation Scenarios

Evaluation of the model performance is conducted under three demand levels: Level I, Level II, and Level III with the total spreading traffic demand set as 5000, 7500, and 10000 vehicles.

The performance of the proposed model will be compared with three alternative traffic management strategies (denoted as “S-1”, “S-2”, and “S-3”). “S-1” keeps all intersections signalized in the network; “S-2” implements interrupted flow strategies at all intersections in the network; and “S-3” is a commonly adopted strategy by authorities during the decentralization. It usually implements uninterrupted flow strategies at intersections between major spreading traffic arterials and secondary roads to prevent the minor street movements from interrupting the major traffic detour directions (e.g. flows on the secondary roads are not allowed to go through or make a left turn). When applying strategy “S-3”, uninterrupted flow strategies will be implemented at 3, 4, 7, 8, 11, 14, 18, 21, 24 and 25. To make a fair comparison between the proposed model and other strategies, we further apply the proposed turning restriction and g/C ratio optimization to fine-tune the plans in “S-1” through “S-3”.

7.6.3 Evaluation Results

The proposed model and algorithm are implemented in C++ on a work station with an Intel Core i7-3770S 3.9GHz Turbo CPU and 32GB RAM. Figure 7.3 illustrates the convergence of GA under different levels of demands. The computation time for three demand levels takes no more than 17.8 hours.

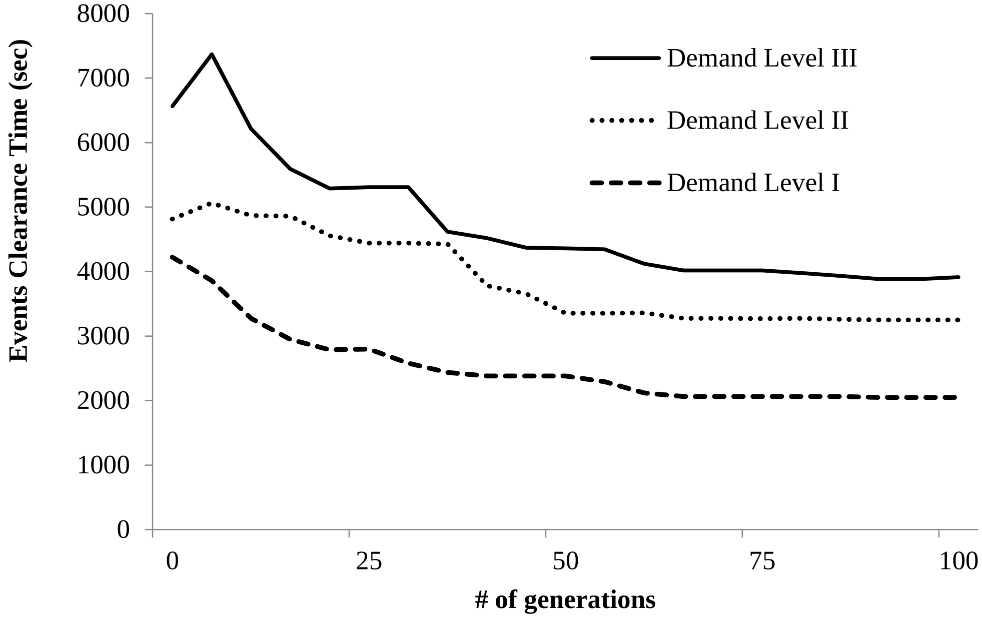


Figure 7. 3 Convergence of the GA under Various Demand Levels

Figures 7.4 to 7.6 show the optimal distribution of signalized and uninterrupted flow intersections in the network that yields the minimum network clearance time under all three demand levels. Note that there are significant discrepancies in the distribution of uninterrupted flow and signal intersections under different demand levels between the proposed model and the commonly adopted "S-3" in which nodes 3, 4, 7, 8, 11, 14, 18, 21, 24 and 25 are set as uninterrupted flow strategies. Such discrepancies have resulted in their differences in the events clearance time (see Table 7.3).

Table 7. 3 Comparison of Network Clearance Time between Different Strategies

Demand Level	Events Clearance Time (sec)			
	The proposed model	S-1	S-2	S-3
I	2047	2611 (+28%)	2828 (+38%)	2351 (+15%)
II	3250	4327 (+33%)	4102 (+26%)	3867 (+19%)
III	3912	6141 (+57%)	5173 (+32%)	4706 (+20%)

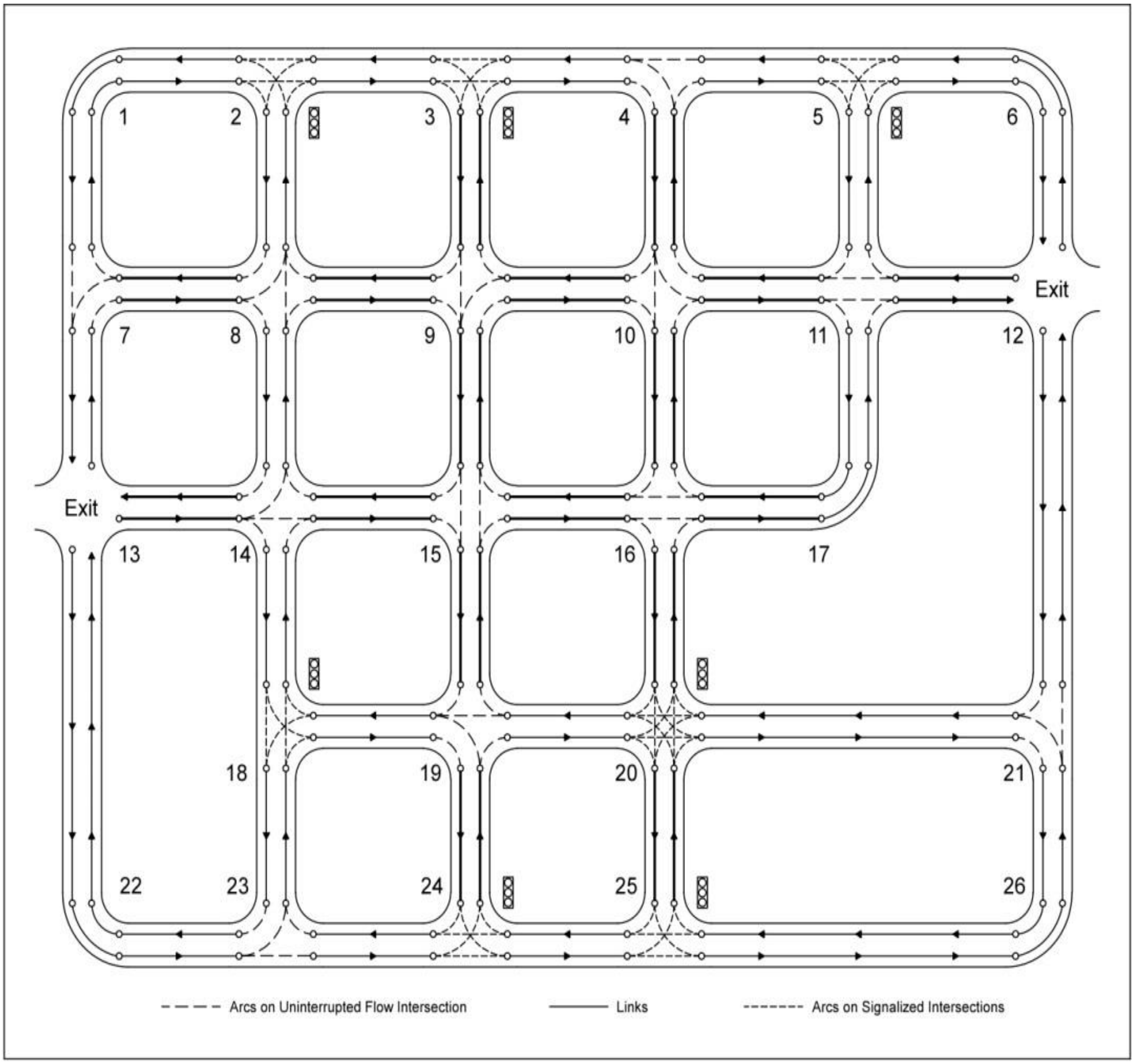


Figure 7. 4 Optimal Distribution of Signalized and Uninterrupted Flow Intersections under Demand Level I

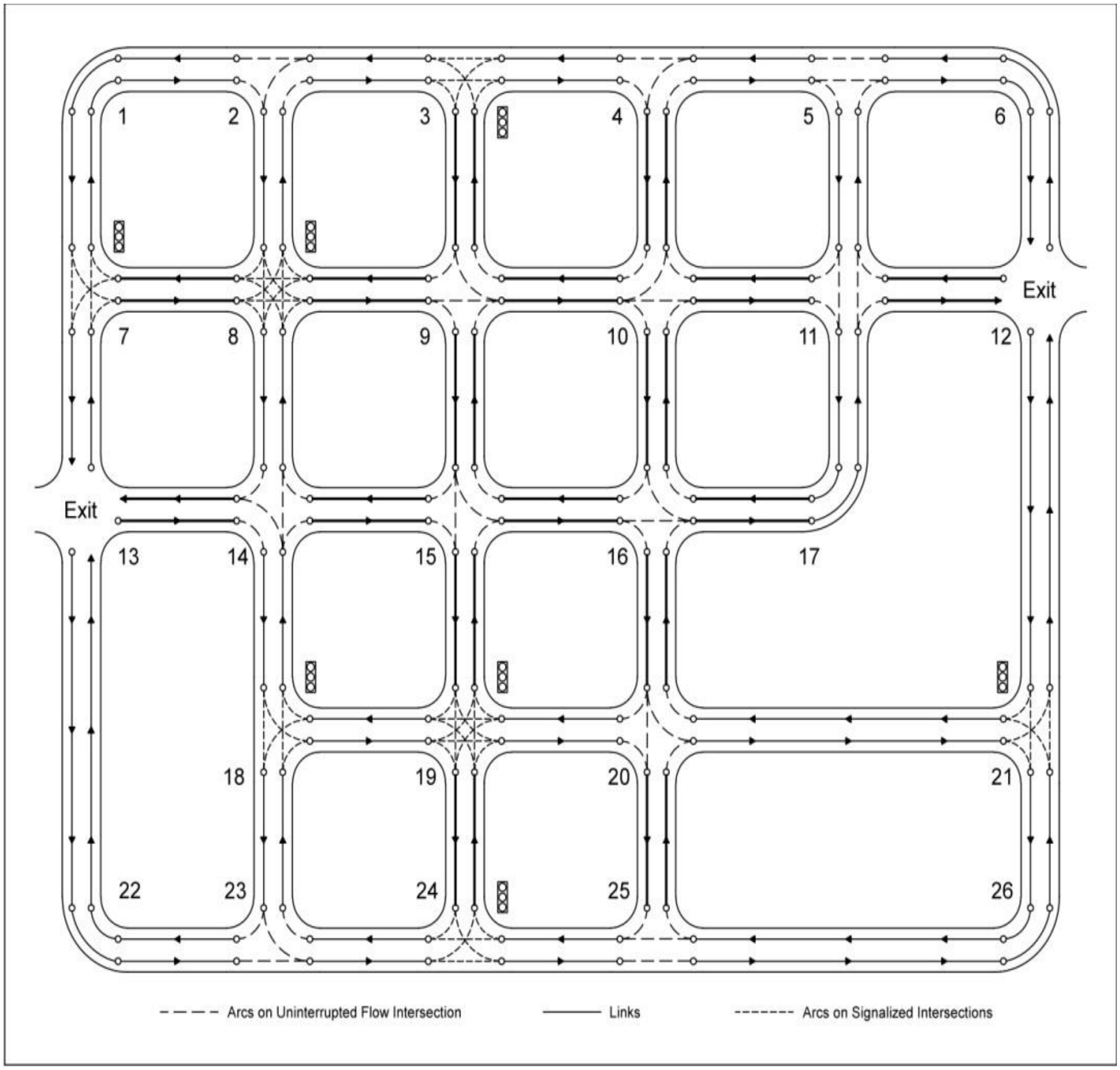


Figure 7. 5 Optimal Distribution of Signalized and Uninterrupted Flow Intersections under Demand Level II

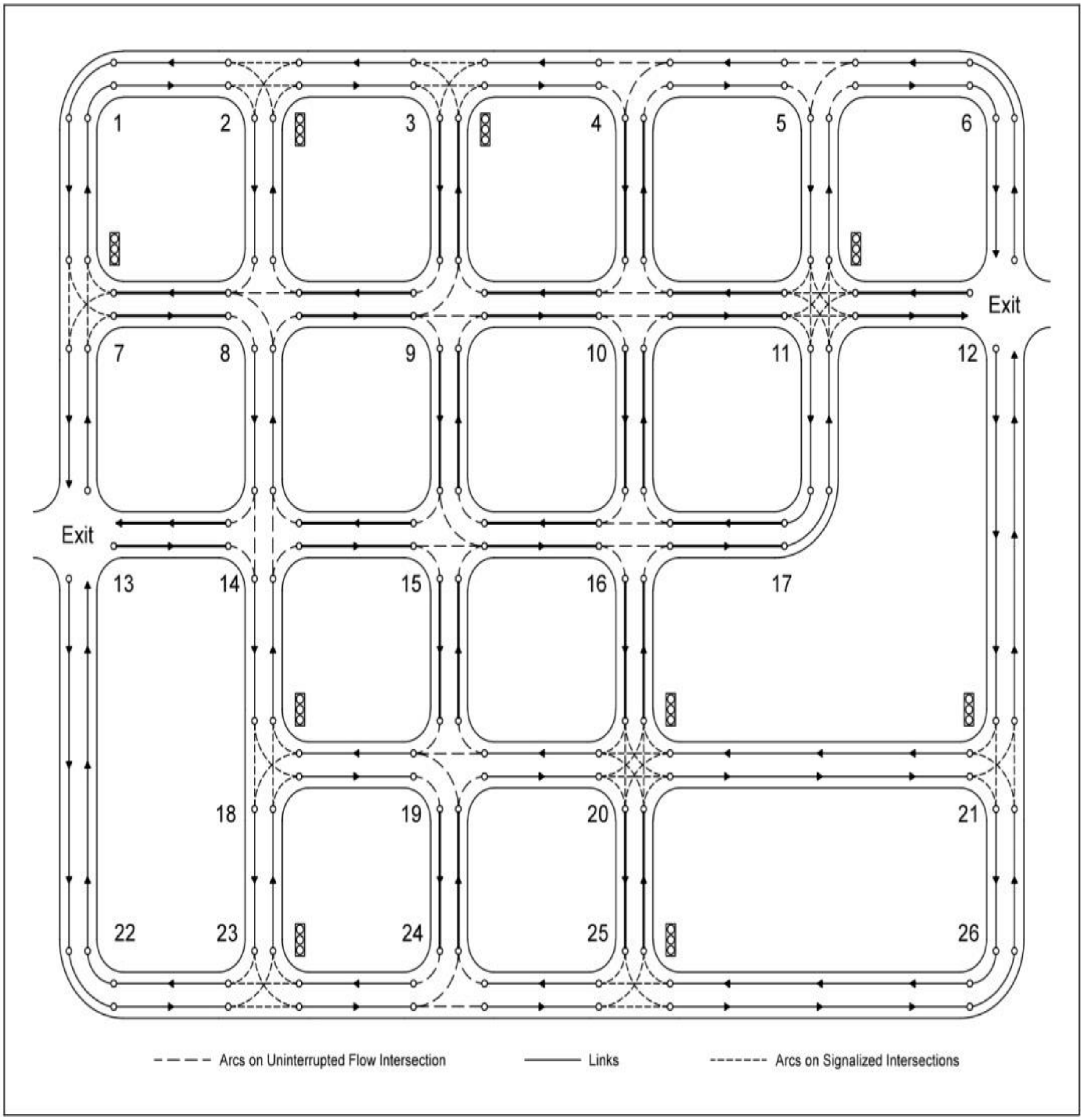


Figure 7. 6 Optimal Distribution of Signalized and Uninterrupted Flow Intersections under Demand Level III

Figures 7.7-7.9 further illustrate the time-varying cumulative arrival percentages of diversions under different strategies and demand levels. One can observe that the proposed model outperforms all other strategies in terms of events clearance time under all demand levels, which demonstrates the effectiveness of the proposed model and the importance of optimal selection and distribution of uninterrupted flow and signalized intersections of traffic management of special events in urban transportation network. In addition, the proposed model yields higher savings of network clearance time at high demand scenarios (see Table 3), which implies that the proper distribution of signals and uninterrupted flow intersections affects the spreading traffic performance more when the demand level is high.

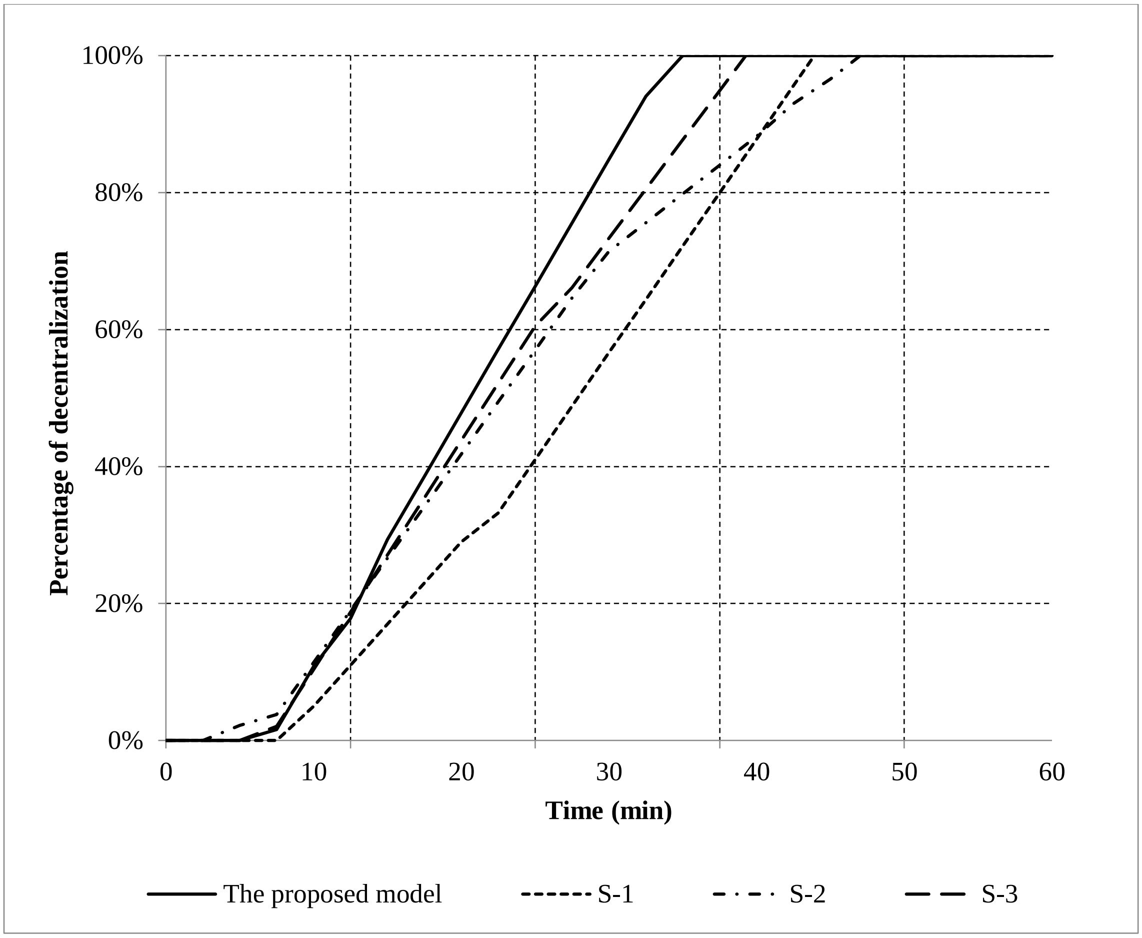


Figure 7. 7 Performance of Different Strategies under Demand Level I

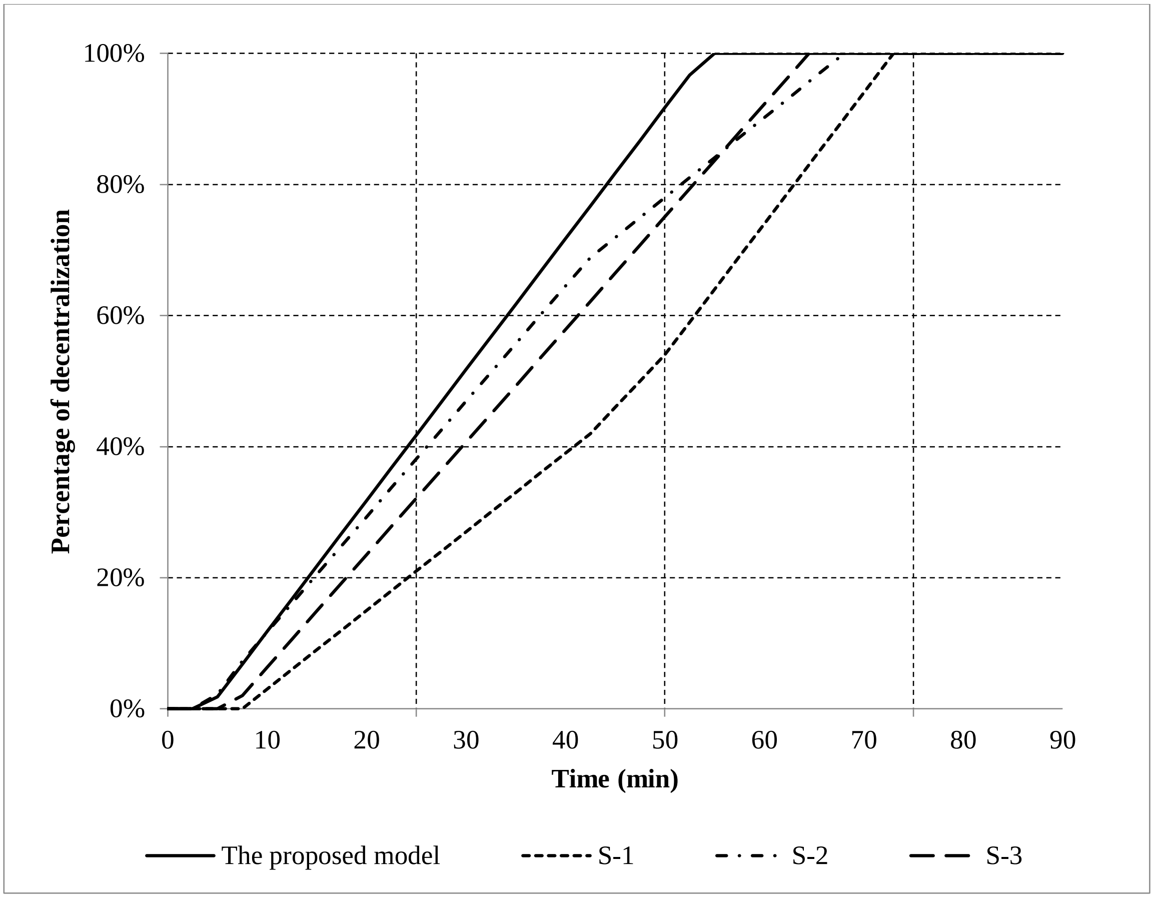


Figure 7. 8 Performance of Different Strategies under Demand Level II

Also indicated in Figures 7.4-7.6 is that certain intersections (i.e., 9, 10, 14, 15, and 16) are always selected to implement uninterrupted flow strategies by the proposed model under various demand levels. These intersections tend to locate within the impacted area of the special events network where the spreading traffic demand is generated. Setting uninterrupted flow intersections there makes more sense because it facilitates fast access of the spreading traffic demand to the traffic detour routes; while intersections outside the impacted area are more likely to be set as signalized ones to reduce detour of spreading traffic on their way to destination. Such information is critical for transportation authorities to best plan and allocate necessary resources to the most appropriate locations in a timely manner.

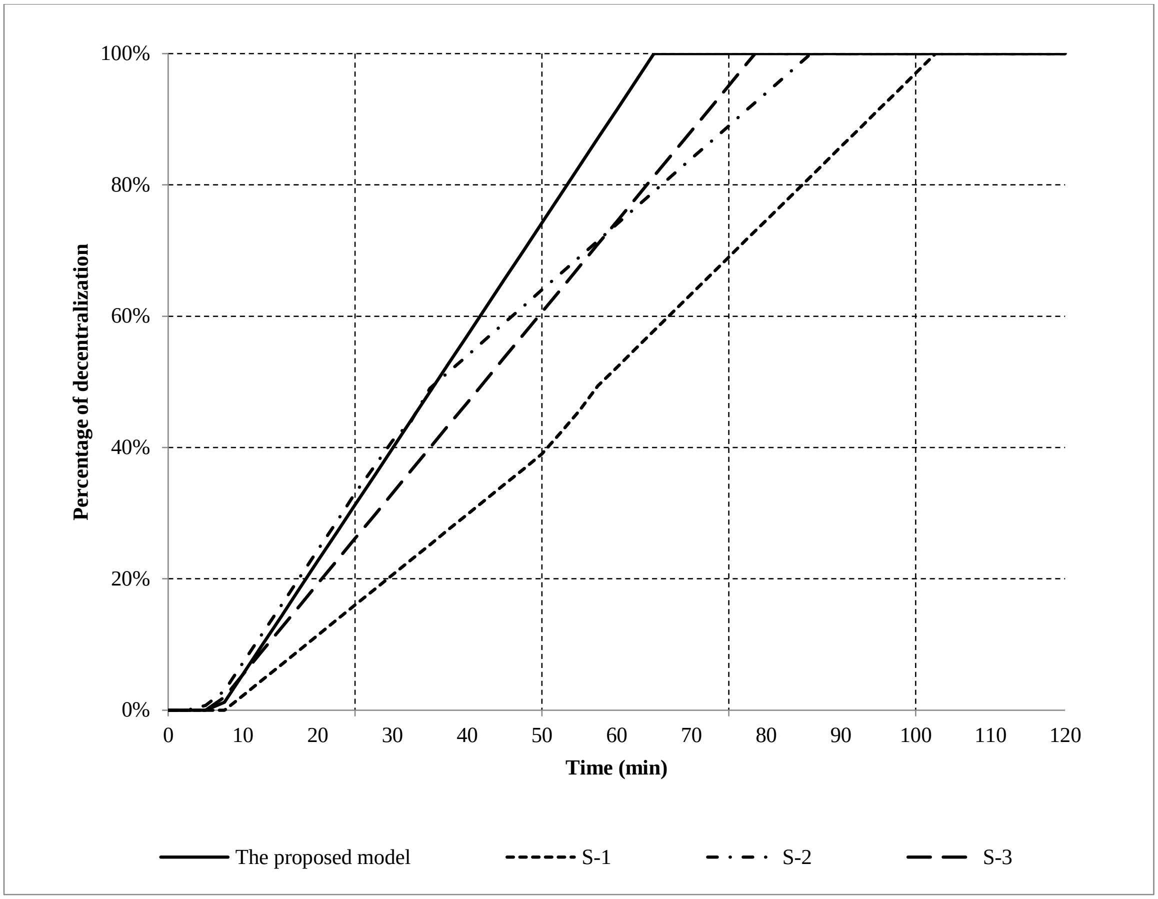


Figure 7. 9 Performance of Different Strategies under Demand Level III

From Figures 7.4-7.9, it is noted that there seems to be an optimal distribution of uninterrupted flow and signalized intersections to yield the best decentralization performance in a dynamic special events network. This is inconsistent with findings reached in a static network setting. Figure 7.10 shows the impact of the number of uninterrupted flow intersections on decentralization performance on the same test network, under the same demand levels, but with a static setting. One can observe that the performance of spreading traffic (in terms of total events clearance time) can always be improved by increasing the number of uninterrupted flow intersections in the network under all demand levels. Such a discrepancy indicates that the findings regarding the impact of uninterrupted flow operations in a static network no longer hold when moved to a dynamic context. Converting all signalized intersections to uninterrupted flow facilities (e.g. the strategy "S-2") may not always help to improve the decentralization performance. Transportation authorities shall be able to find the best distribution of uninterrupted flow and signal strategies during the dynamic process of spreading traffic management to achieve expected operational performance.

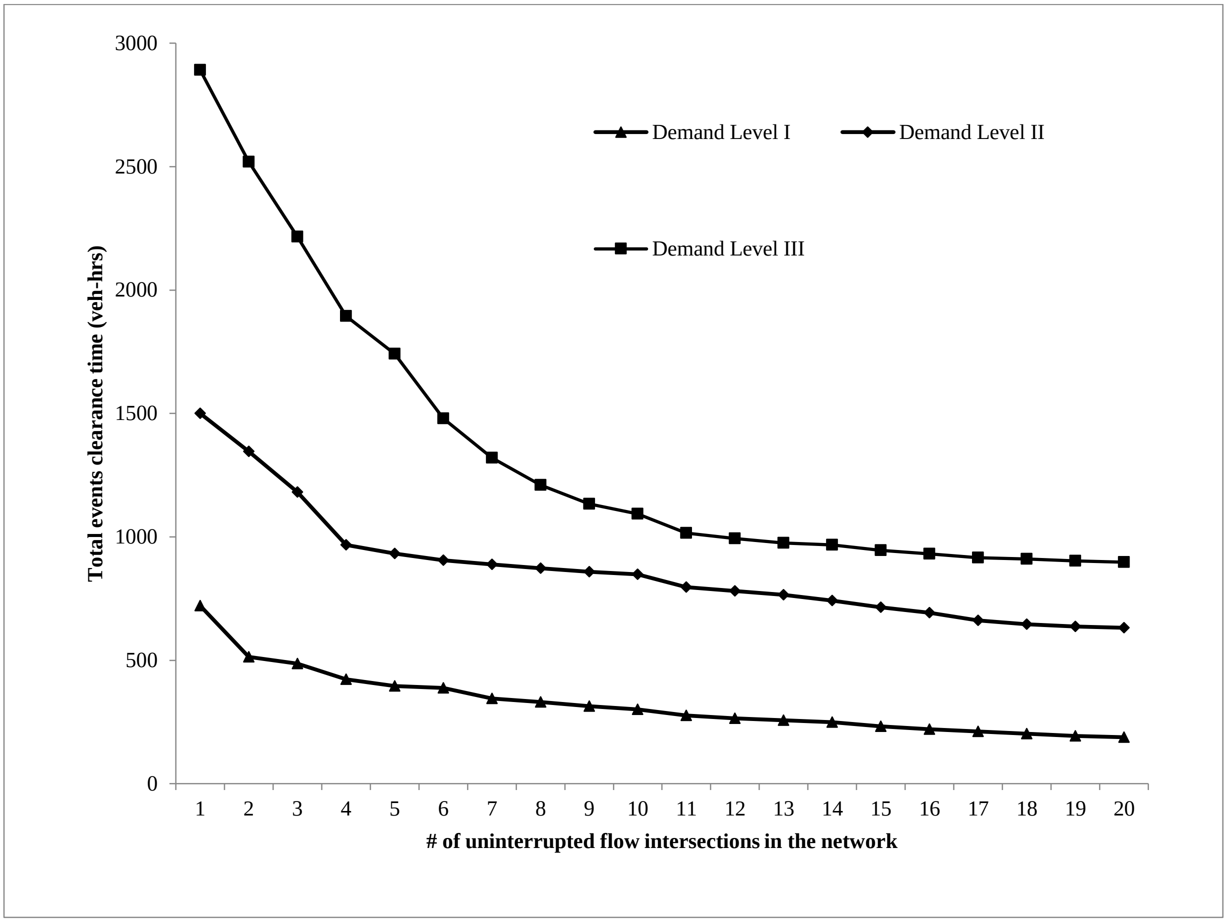


Figure 7. 10 Impact of the Number of Uninterrupted Flow Intersections on System Performance in a Special Events Network

7.7. Conclusions

This research examines the problem of selecting and distributing signal control and uninterrupted flow strategies in a dynamic special events network with a bi-level network optimization model. The upper level model searches for the best distribution of signalized and uninterrupted flow intersections in the network with the objectives of minimizing the total events clearance time. The lower level problem handles routing assignment of the spreading traffic demand. The cell transmission model (CTM) is adopted to mathematically represent dynamic traffic flow evolution and queuing in a special events network. To deal with the combinatorial complexity of the proposed model, we develop a heuristic approach that can yield meta-optimal solutions.

In a static special event network, previous research has demonstrated that the total event clearance time can be reduced by increasing the number of uninterrupted flow intersections in the network, especially during high demand conditions. In this study, such a finding has been shown not to hold any more in a dynamic special events network, in which the best distribution of uninterrupted flow and signalized intersections exists to yield the minimum event clearance time.

Intersections located within the demand generating area (i.e., the impacted area) are more likely to be selected by the model as uninterrupted flow ones to facilitate fast access of decentralization to the spreading traffic routes; while signals tend to locate outside the impact area to reduce detours of spreading traffic to destination. It can also be observed that the proposed model outperforms other existing practices under all demand levels in terms of reducing events clearance time, which demonstrates its effectiveness. The savings in clearance time are higher at high demand levels, indicating that proper distribution of uninterrupted flow and signalized intersections is more critical under high demand scenarios.

Future work along the line will be extending the model to incorporate more details in traffic management strategies, for example, lane marking optimization and explicit formulation of signal operations.

Chapter 8: Conclusions and Future Research

8.1 Research Summary and Contributions

This dissertation has investigated a set of integrated mathematical programming models for unconventional traffic management of special events and addressed several critical issues on optimization management strategies in urban transportation network. Grounded on real-world operation constraints, this study has developed an integrated traffic management and control system that enables traffic agencies to exert effective control strategies, including lane reorganization and reversal, lane-based signal timing, ramp closure, uninterrupted flow intersection will be coordinated and concurrently optimized for best overall system performance of special events in urban transportation network. The key features and capabilities of such a traffic management system are proposed in Chapter 1.

Chapter 2 has provided a comprehensive review of the relevant studies on formulation of traffic flow network, unconventional traffic management strategies, lane-base signal control models, discrete network design methods, and freeway operations. Not only has the review identified the lock of work on how to optimize the travel delay for traffic management of special events in urban transportation network in the literature, but it has also discovered the advantages and limitations of those studies, along with their potential enhancements.

In the responses to the identified research needs, Chapter 3 has demonstrated the model framework of proposed research, based on critical operational issues that need to be addressed in design of the special events traffic management strategies. This traffic management framework consists of two levels, including urban road level and freeway level, for the integrated management strategies of special events. It briefly depicts the features of each principle modeling component and their operational interrelations, which provides the foundation for the identification of research tasks for this study. The focus of the urban network level management strategies, including location of signal intersection or uninterrupted flow intersection determined, lane channelized, lane-based signal timing reset, and turn movement restricted, are enhancing the capacity utilization of the urban street to minimize the total spreading traffic time for special events in urban transportation network. Serving as a supplemental component, the mixed freeway level management strategies that have not only some traffic management strategies with urban network level, but also includes the appropriate location off-ramps closure, and on-ramps opened, and the optimal traffic detour through urban network to effectively enhance the throughput of traffic and improve the operational performance efficiency.

The key mathematical formulations for the integrated traffic management strategies are detailed in the Chapters 4, which proposes a movement-based network representation scheme and a base model formulation for special events traffic management in a simplified static urban transportation network. It starts with the development of innovative formulation with the conflict elimination (cross elimination) for the uninterrupted flow intersection and considered the travel delay on the arc that connected two different arms at one intersection during spreading traffic for traffic management of special events. Traffic movement reorganization and restriction, signal timing optimization, and uninterrupted flow strategies are best selected and prioritized at critical road network segments and intersections for maximum network operational efficiency under the available budget. Chapter 4 incorporated a parametric Variational Inequality (VI) problem to capture the Stochastic User Equilibrium (SUE) behavior of travels during route choice and expected to provide effective solutions to the following critical questions that have long challenged transportation professionals for special event traffic management. 1) How many intersections should be implemented with the signals and interrupted flow controls; 2) What would be the optimal spatial distribution for those intersections in the target network; 3) How to best design turning restriction, lane channelization, and signal timings in the special event network? In view of the large number of variables and constraints for the proposed model, this chapter will develop an efficient heuristic approach embedded with a diagonalization algorithm to yield the meta-optimal solutions. Extensive numerical analysis with the case in Washington DC will be performed to demonstrate the applicability and effectiveness of the proposed model.

Chapter 5 has further extended the movement-base model presented in previous chapter by proposing a new network representation scheme that can better capture the traffic flow interaction at the lane level. Such modeling features offer the capability to use more sophisticated and effective lane-based traffic management strategies (e.g. lane reorganization and reversal, cross elimination, lane-based signal, etc.) to further improve the overall network capacity and operational efficiency during special event. The extended model will feature a bi-level structure with equilibrium constraints. Considering the computational complexity underlying the proposed formulation, the Hybrid Genetic Algorithm (HGA) was proposed based heuristic that can yield viable and approximate optimal solutions in a reasonable time period.

Chapter 6 presents formulations of optimal traffic management strategies for construction work zone in the mixed freeway and arterial corridor considering its key role in improving the freeway system efficiency and mobility. To capture the interactions between the freeway and arterial are developed. The Network flow formulations has two levels, which are the formulation of freeway system level and urban street network level, respectively. For the freeway level, ramp control strategies and detour operations will be supplemented in the existing modeling framework to optimize the diversion flow from freeway to urban street network. For the urban network, integrated traffic management strategies, including lane reorganization, location of signal intersection and uninterrupted flow intersection, signal timing resetting, will be enhance the capacity and mitigate the traffic congestion caused by increase demand diverted from freeway. The mixed freeway problem is the NP-hard and difficult to solve due to its non-convexity and non-differential characteristics. Considering the computational complexity and high-dimensionality of the decision variables underlying the proposed formulation, this Chapter investigated a Hybrid Genetic Algorithm to solve the model to meta-optimality for real world application. To demonstrate the applicability of the proposed problem, the case study has employed a hypothetical mixed freeway and urban transportation network with 8 freeway exits and 8 freeway entrances, and 30 nodes in the arterial street network. Based on the proposed model, this Chapter obtained the optimization traffic management strategies for construction work zone and effectively improve the operational efficiency of mixed freeway and urban network.

Chapter 7 investigates the mathematical model formulations for special event traffic management in a dynamic transportation network considering the time-varying traffic demand and network characteristics that often occur in a special event. The model features a bi-level structure with the upper level searching for the best traffic management strategies by minimizing the total event clearance time, and the lower level handling routing assignment of the traffic demand with a single-destination user-optimal DTA problem. The cell transmission model (CTM) is adopted to mathematically represent dynamic traffic flow evolution and queuing in the network. To deal with the combinatorial complexity of the proposed model, this Chapter will also develop heuristic solution algorithms. The hypothetical traffic network that consists of 26 intersections, 82 links, 6 demand origins, and 2 exits is adopted to simulate the traffic environment during the special event occurred in the urban transportation network. Finally, the result of the test numerical experiments have shown that the distributed signal intersection and uninterrupted flow intersection and enhanced signal model are effectively mitigate the traffic congestion and reduce the travel delay, respectively, and thus consequently improve the overall arterial network performance.

The main motivation of this dissertation is develop an overall operation framework embedded with a set of integrated mathematical programming model for the special events traffic management strategies in urban transportation network. In summary, this research has made the following key contributions:

- Develop realistic representation of the spatial and temporal interactions among traffic flow distribution in the network due to time varying demands and congestions that often incur during special event;
- Develop mathematical optimization models with real world operational constraints to best trade-off, select, and integrate various strategies for special event traffic management under different network configurations (e.g. static and dynamic networks, and mixed freeway and urban corridors) and traffic scenarios;
- Propose the integrated traffic management strategies that are lane channelization, uninterrupted flow intersection, signal intersection, turning restriction to enhance the capacity of the urban street and mitigate the traffic congestion caused by sudden increase traffic volume in the urban transportation network;
- Design high-efficiency solution algorithms to solve the proposed models for large-scale and real-world applications. Considering the computational complexity underlying the proposed model, the Hybrid Genetic Algorithm was employed in this dissertation to

solve the proposed problem and generated the optimization strategies for the traffic agencies to effectively guide the detour traffic during special events in the urban transportation network.

- Develop an optimization traffic management strategies for the mixed freeway network to produce the distribution of the closure off-ramp and on-ramp that can effectively improve the diversion traffic efficiency from upstream of off-ramps of construction work zone on freeway network.
- Design an arterial signal timing plan to optimize signal control strategies that can prevent the formation of local bottlenecks and further improve the operational efficiency of the entire urban transportation network.
- Design an operational framework to apply the developed models to real-world cases, and provide guidelines to responsible transportation authorities.

8.2 Potential Future Research

Despite the effectiveness of this dissertation in overcome several critical issues for the real-world traffic management strategies of special events in the urban transportation network, a more efficient and reliable plan for implementing such a traffic system in large-scale network application remains essential. The potential further researches along this line are listed below:

1. Development of pedestrians considered modes for integrated traffic management strategies. This study has focused on effective decentralization to mitigate the traffic congestion caused by special events that abnormally increases traffic demand in the limitation throughput capacity of urban transportation network. For the integrated traffic management strategies of special events, the proposed models have ignored the impactor of pedestrians and the conflict between pedestrians and spreading vehicles that caused the travel delay when traffic agencies redesign the signal time occurred special events. The pedestrians play a key role for the spreading traffic process.
2. Development of the efficient operation modes for integrated traffic management strategies. This research has addressed the spreading traffic operation problem during special events network with only the urban transportation network and passenger cars. However, it is likely that some people need transferred not have any access to vehicles. Hence, they must reach special bus pick up points to get out of the decentralization zone. This type of multi-mode spreading traffic operations contains several following critical issues to be studies: (1) how to select the appropriate pickup location; (2) how to optimize pedestrian's phase of signal time and routing when they need to reach the pickup points or metro stations? (3) how to eliminate the conflict between bus and passenger-car flows?

3. Development of efficiency and sustained green transportation system. The study has investigated the integrated traffic management strategies and get the reasonable results for the critical issues of the special events in urban transportation network. However, this paper ignore the impact of traditional transportation system to environment in the real world. The sustained transportation is hot topic and have received more attention in past decade, considering the influence factors of environment, including fuel consumption, emission, and air polluted.

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CURRICULUM VITAE

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Place of birth: China

EDUCATION

- Ph.D., University of Wisconsin at Milwaukee, May 2016

  Major: Engineering (Urban Transportation network management and optimization)

- M.Sc., Beijing University of Aeronautics and Astronautics, China , Dec. 2012

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DISSERTATION TITLE:

Integrated Special Event Traffic Management Strategies in Urban Transportation Network

RESEARCH INTEREST

- Transportation Network Modelling
- Location Problem
- Network Optimization and Management
- Freeway Incident Evacuation Management and Planning
- Traffic Flow Theory
- Traffic Network Analysis

WORKING PAPER:

1. **Li, P.,** Zhao, J., Liu, Y.*, Optimal Solution for Lane-based Model of Special Events Traffic Management.
2. **Li, P.,** Liu, Y.*, Strategic Planning of Short-Term Urban Full Freeway Closure Due to Construction Zones.

PUBLICATION:

1. Zhao, J., **Li, P*.,** "An Extended Car-Following Model with Consideration of Speed Guidance at Intersections," Physic A: Statistical Mechanics and its Applications, Accepted for publication. (IF 1.73)
2. Zhao, J., **Li, P.,** Ma, W.J. *, Integrated Design of Location and Signal Timing for Mid-block Crosswalk to Achieve Tradeoff between Vehicles and Pedestrians, (Journal of Transportation Engineering), Accepted for publication. (IF 0.87)
3. (2015) Zhao, J.*, **Li, P.,** Zhou, X., "Capacity Estimation Model for Signalized Intersections under the Impact of Access Point," PLoS One. 2016, 11 (1). (IF 4.41)
4. (2015) Liu, Y.*, **Li, P.**, "Traffic management in a dynamic evacuation network: trade-off between signal and cross-elimination strategies," Transportation Research Part C, REVISED. (IF 3.402)
5. (2015) Liu, Y.*, **Li, P.,** "Optimal conversion of an evacuation network to signalized and uninterrupted flow intersections," Transportation Research Part B, REVISED (IF 4.116)

6. (2015) Zhao, J., Liu, Y.*, **Li, P.,** Yang, X., "A network enhancement model with integrated lane reorganization and traffic control strategies," Journal of Advanced Transportation, Accepted for publication (IF 1.606)

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INTERNATIONAL CONFERENCE

1. (2014) Liu, Y., Liu, D., Yu, J., Li, X., **Li, P.,** "Optimal conversion of an evacuation network to signalized and uninterrupted flow intersections," 93rd TRB Annual Meeting Proceedings CDROM (paper # 14-2261), Washington D.C., January 12-16, 2014. (Refereed)

2. (2014) Zhao, J., Liu, Y., **Li, P.,** Ma, W., Yang, X., "Network Enhancement Model with Integrated Lane Reorganization and Traffic Control Strategies," 93rd TRB Annual

Meeting Proceedings CDROM (paper # 14-2047), Washington D.C., January 12-16, 2014. (Refereed)

3. (2013) Liu, Y. *, Yu, J., **Li, P.**, Wehner, K. , "A generalized integrated corridor diversion control model for freeway incident management," 2013 Mid-Continent Transportation Research Symposium, Ames, Iowa, August 15-16, 2013. (Refereed)
4. (2013) **Li, P.** , Liu, Y. *, "A Lane-based Network Enhancement Model for Special Event and Emergency Traffic Management," invited to present at INFORMS 2013 Annual Meeting, Minneapolis, Minnesota, October 6–9, 2013. (Invited)
5. (2012) Tang, Z., **Li, P.,** Liu, Y. Jiang, W., Phase Design of Road Crossing with Consideration of Right Turning Vehicle," in Remote Sensing, Environment and Transportation Engineering (RSETE), 2012 2nd International Conference on vol., no., pp.1-4.

AWARDS

1. UWM Chancellor Award, by University of Wisconsin-Milwaukee, 2013-2016
2. Martin Bruening Award, by Wisconsin ITE, 2014
3. Beihang GuangHua Outstanding Research Award, by Beihang University, 2012
4. Award of Outstanding Graduate Scholarship, by Huaibei Normal University, 2010
5. National Mathematical Contest in Modeling, Second Prize. by China Society for Industrial and Applied Mathematics, 2009

INVITED PAPER REVIEW

1. PLOS One (13 papers)
2. IEEE Transactions On Intelligent Transportation Systems (4 papers)
3. Transportation Research Part C (2 papers)

4. ASCE Journal of Urban Planning and Development (4 papers)
5. Transportation Research Board Annual Meeting (6 papers)
6. Journal of Advanced Transportation (2 papers)