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Final Report

**PRIMARY EMERGENCY ROUTES FOR
TRANSPORTATION SECURITY**

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Primary Emergency Routes for Transportation Security

Introduction

Evacuation is called for when a natural or man-made extreme event (e.g. hurricane, flooding, hazmat release, or dirty bomb) strikes a populated area exposing the population to immediate or foreseeable life-threatening danger. After the identification of the boundaries of the affected or threatened area, an associated evacuation zone is defined. All civilians in the evacuation zone have to be relocated individually, or with the guidance of a responsible agency (such as an emergency management agency) to a safer location, the safety zone.

The evacuation process is an extremely complicated and difficult task where the agency addresses the efficient utilization and coordination of roadway capacities, traffic management equipment, public transportation vehicles, and various emergency response resources. For disasters which have a sufficient lead time (i.e. a short-notice disaster such as a hurricane or flooding), evacuation management agencies determine alternate evacuation routes a priori based upon the expected spatial-temporal impacts of the disaster. Citizens are then given advisories on which major roadways to use for evacuation. In the event that an unexpected disaster occurs (i.e. a no-

notice disaster), such as a dam burst or a biochemical attack, evacuating a large population becomes more challenging due to the short lead time and highly unpredictable pedestrian and vehicular traffic flows. In this case, evacuees may crowd roadways and significantly cripple the entire transportation system rendering it inoperable.

Evacuation operations can be significantly more efficient if strategic network improvements enable the fastest routing of evacuee population to the safety zone. The evacuation planning process, which seeks to determine where additional capacity is necessary in the network to enhance performance under evacuation, can be viewed as a combination of a dynamic traffic assignment problem and a network design problem. Both these problems are known for their significant computational complexity, especially in the context of large-scale problems. The proposed research focused on the mechanism to identify the best network design options for deployment (contra-flow operations and lane additions) and traffic signal control strategies, as well as on reducing the computational complexity of the associated solution methods.

Findings

The study findings can be separated into methodological contributions and insights/guidelines for emergency planning/management agencies. In terms of the methodological aspects, the study models the effects of reduced left/right turn capacities and identifies directional priorities for flow assignments at intersections. Further, the proposed approach allows the simultaneous modeling and evaluation of contra-flow

operations, new lane construction, shelter design and allocation, contra-flow corridors, and the effect of parking restriction policies on critical links. In doing so, it proposes an integrated formulation which is computationally efficient.

A key insight for evacuation related planning is that there is a critical level of resource allocation beyond which benefits are trivial (in terms of network clearance time). It enables the determination of an adequate budget for capacity

addition for the transportation-related response to terror threats/attacks. Another insight is that the additional capacity needs to be allocated at potential locations of bottlenecks in terms of traffic flow. From an operational standpoint, the study suggests that the evacuation is more effective when there are multiple destinations

identified in the safety zone. That is, by directing drivers to different locations in the safety zone, the possibility of congestion bottlenecks is reduced due to the more uniform spatial distribution of the traffic flow. The study also indicates that the network clearance time is linearly related to the evacuation population size.

Implementation

The procedures developed as part of this study enable evacuation-related planning agencies to generate pre-determined plans for contra-flow operations, prioritize locations for capacity enhancements through lanes additions, identify optimal flow directions at intersections under

evacuation scenarios, and determine the locations and capacities for security-related shelters. The study provides the relevant planning/management agency with a tool to enhance evacuation performance.

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PRIMARY EMERGENCY ROUTES FOR TRANSPORTATION SECURITY

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16. Abstract Security threats and natural disasters (such as hurricanes and cyclones) are events that have historically led to large scale evacuations. Evacuation operations are strongly characterized by traffic volumes that substantially exceed the network capacity, and consequently, the potential for severely degraded network performance. The efficient management of evacuations entails long-term planning and real-time operational paradigms that are, ideally, integrated. This study focuses primarily on the planning aspects of evacuation, while providing important insights for operations. Identifying capacity as a key element to efficient evacuation, the evacuation planning seeks to determine links where additional capacity is desired, as well as the amount of additional capacity. The study proposes contra-flow mechanisms and lane additions as the means to add capacity. Hence, the evacuation planning seeks to "improve" the network through strategic capacity addition so as to enhance performance during evacuation operations. The study formulates the capacity addition problem as a network design problem. The cell transmission model is used to propagate traffic flow. It forms the backbone of the problem formulation, which combines a dynamic traffic assignment component (network traffic routing) with a network design component (network capacity addition). The computational burden of the basic evacuation network design problem leads to the development of an improved formulation by exploiting a special property of the cell transmission model. Computational experiments are conducted using the improved formulation. Insights for practical implementation are obtained by analyzing the effect of resource allocation level, population size, and the spatial distribution of demand.			
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CHAPTER 1. INTRODUCTION

1.1 Background and motivation

Evacuation is called for when a natural or man-made extreme event (e.g. hurricane, flooding, hazmat release, or dirty bomb) strikes a populated area exposing the population to immediate or foreseeable life-threatening danger. After the identification of the boundaries of the affected or threatened area, an associated evacuation zone is defined. All civilians in the evacuation zone have to be relocated individually, or with the guidance of a responsible agency (such as an emergency management agency) to a safer location, the safety zone.

The evacuation process is an extremely complicated and difficult task where the agency addresses the efficient utilization and coordination of roadway capacities, traffic management equipment, public transportation vehicles, and various emergency response resources. For disasters which have a sufficient lead time (i.e. a short-notice disaster such as a hurricane or flooding), evacuation management agencies determine alternate evacuation routes a priori based upon the expected spatial-temporal impacts of the disaster. Citizens are then given advisories on which major roadways to use for evacuation. In the event that an unexpected disaster occurs (i.e. a no-notice disaster), such as a dam burst or a bio-chemical attack, evacuating a large population becomes

more challenging due to the short lead time and highly unpredictable pedestrian and vehicular traffic flows. In this case, evacuees may crowd roadways and significantly cripple the entire transportation system rendering it inoperable.

The recent events associated with Hurricane Katrina and its aftermath, as well as Hurricane Rita, is illustrative of the need to better understand the intricacies and multiple facets of evacuation so that large-scale response to potential massive disasters is integrative, effective and efficient. The central challenging objective is routing people to the safety zone as soon as possible. An efficient routing plan is valuable because evacuations result in traffic volumes that exceed the available network capacity (Cova and Johnson, 2002).

An evacuation plan entails identifying the set of routes which enable the fastest evacuation out of the evacuation zone. Dynamic traffic assignment (Peeta and Ziliaskopoulos, 2001), which explicitly incorporates the time-dependency of traffic flows, can be used to determine a routing plan.

A key impediment to the performance of an evacuation plan is the capacity of the traffic facilities (links) in the network. Kwon and Pitt (2004) highlight the significance of capacity addition to urban networks for enhancing network performance under evacuation. Traditionally, capacity is added to a traffic network through the construction of new lanes as part of a long-term planning process. For short-term events requiring evacuation, contra-flow operations are an attractive low budget capacity relocation option. Contra-flow options have been widely suggested for evacuation purposes as “the

only way out” (Wolshon, 2005). It is a low budget network re-design strategy that best fits the needs of the spatial restrictions of the dense urban metropolitan environment.

Traffic control at intersections under evacuation is a challenging issue as most traffic delays during an evacuation occur at intersections (Southworth, 1991). Cova and Johnson (2002) proposed a lane-based evacuation strategy for eliminating intersecting flows and minimizing merging flows. They organized routing in terms of non-intersecting lanes which can either merge or diverge.

In summary, evacuation operations can be significantly more efficient if strategic network improvements enable the fastest routing of evacuee population to the safety zone. The evacuation planning process, which seeks to determine where additional capacity is necessary in the network to enhance performance under evacuation, can be viewed as a combination of a dynamic traffic assignment problem and a network design problem. Both these problems are known for their significant computational complexity, especially in the context of large-scale problems. The proposed research focuses on the mechanism to identify the best network design options for deployment, as well as on reducing the computational complexity of the associated solution methods.

1.2 Study objectives

The study seeks to develop a methodology to address the strategic planning problem of capacity addition at a network-level for evacuation planning. The proposed methodology should enable decision-makers to select in a time-efficient manner an

effective set of network design options for evacuation-related operations. The specific objectives are:

1. Development of a model to address the evacuation network design problem. The mathematical formulation should identify, in a planning context, the best network design options (contra-flow operations and lane addition) that optimize evacuation under resource limitations.
2. Enhancement of the formulation to address the evacuation network design problem in a computationally more efficient manner. The problem-specific structure of the formulation will be analyzed to develop a modified formulation that enables the application of faster algorithms.
3. Sensitivity analysis of the evacuation planning models to derive insights for the decision-makers. This is done by analyzing the models for different levels of capacity addition, population size, and spatial distribution.

1.3 Organization of the research

The remainder of the research is organized as follows. Chapter 2 provides an overview of the relevant literature in evacuation planning, network design problems, the cell transmission model and its transportation planning applications. Chapter 3 defines the problem of network design for evacuation planning and formulates it. In Chapter 4, a key property of the cell transmission model is identified, and the related propositions are introduced. The problem is mathematically re-formulated, according to these

propositions, to have its computational time significantly decreased. The complexity of the formulation is identified and the identified network structure is discussed. In Chapter 5 some implementations issues are highlighted, the test network is described, and sensitivity analysis is performed. Key insights for transportation planners and emergency management agencies are identified. Chapter 6 summarizes the research and its contributions, and provides future research directions.

CHAPTER 2. LITERATURE REVIEW

This chapter provides a brief review of the methodological aspects relevant to the problem addressed in this study. Section 2.1 discusses the literature and characteristics related to evacuation planning. Section 2.2 describes the cell transition model, which is used as the traffic flow simulator for the study. Section 2.3 discusses aspects related to evacuation for network design. Section 2.4 discusses some algorithmic issues. Section 2.5 summarizes the issues and identifies the characteristics of the proposed approach.

2.1 Evacuation planning

Evacuation planning is typically associated with well-defined scenarios such as a deliberate disaster in a nuclear power plant or the evacuation of a low lying coastal zone under a hurricane threat. This necessitates the identification of a physical area around the nuclear power plant or the coastal area, labeled the zone or footprint, from which people must be evacuated. The zone or footprint for a potential evacuation scenario is called the evacuation planning zone or evacuation zone (CA DOT, 2002). All affected civilians have to be routed from the evacuation zone to the safety zone, as shown in Figure 2.1. In the figure, the area enclosed within the red-colored square is the evacuation zone and the

area enclosed between the red-colored and green-colored squares represents the safety zone identified for the specific scenario.

The total evacuation time includes four components: initial warning time, individual's evacuation preparation time, network clearance time, and evacuation verification time. The focus of evacuation planning from a transportation perspective is network clearance time, which represents the time needed for the evacuation volume to clear the network (Sheffi et al., 1981). The objective of minimizing the total time that evacuees are present in the evacuation zone is equivalent to requiring the minimization of the average time that an evacuee spends in the evacuation zone (Jarvis et al., 1982). This represents a system optimal dynamic traffic assignment problem (Peeta and Ziliaskopoulos, 2001).

Campos et al. (1999) seek k-optimal independent paths for vehicle routing in emergency evacuation planning. The proposed algorithm identifies paths such that a greater number of vehicles can be sent in minimum time to the safety zone. However, the paths are not time-dependent, and no planning is considered for capacity additions to the network.

The evacuation routing problem is characterized significantly by time dependencies in traffic flow and the related dynamic phenomena (queue formation and dissipation, spillbacks, etc.). As discussed in Chapter 1, this entails the need for dynamic traffic assignment models. In Section 2.2, the cell transmission model (CTM) will be introduced as the backbone for capturing dynamic traffic flows.

2.2 *The cell transmission model*

The cell transmission model is a simple approach for modeling traffic flow consistent with the hydrodynamic theory (Daganzo, 1994). As illustrated in Figure 2.2, the modeling elements for a traffic network are the cell and the cell connector. The cell is a homogeneous section of a road. Its length is equal to the distance traveled at light traffic conditions in one time interval. If the free flow speed is 70 mph and the time interval is 10 seconds then the length of this cell is approximately 1026 feet. The cell connectors link sequential cells and are responsible for advancing the flow to the next cell(s). The CTM linearly approximates the fundamental flow-density relation (Figure 2.3) at the cell level (Figure 2.4).

In the CTM, a road is divided into homogeneous cells, numbered consecutively from the upstream end of the road. Moreover, because cells represent link flow, flow variability inside the links can be captured, which is not easily possible if traffic is propagated by using link exit functions (Ziliaskopoulos, 2000). The cell transmission model is macroscopic and flow propagation obeys the aggregate characteristics of traffic flow. Therefore, the location of vehicles within a cell is not known, and the acceleration/deceleration of vehicles cannot be captured realistically.

Consider a long highway link with no entrances and exits which is modeled with sequential ordinary cells. Under light traffic, all vehicles in a cell can be assumed to advance to the next cell at each tick of the clock:

$$x_{i+1}^{t+1} = x_i^t \tag{2.1}$$

where x_i^t is the number of vehicles in cell $i \in C$ in time interval $t \in T$. It is assumed that this equation holds true for all traffic flows unless queuing occurs. Queuing is modeled by introducing two parameters:

- (i) Q_i^t , the maximum flow from cell $i-1$ to i during time interval $t \in T$ (when the clock advances from t to $t+1$), which is the equivalent of flow capacity.
- (ii) N_i^t , the maximum number of vehicles that can be present in cell $i \in C$ in time interval $t \in T$, which is the equivalent of maximum density.

The measurement unit of the two variables is “vehicles”, and not “vehicles/hour” or “vehicles/mile”. The amount of empty space in cell $i \in C$ in time interval $t \in T$ is $N_i^t - x_i^t$. Then, the number of vehicles y_i^t that can flow into $i \in C$ in time interval $t \in T$ is given by:

$$y_i^t = \min \{x_{i-1}^t, Q_i^t, N_i^t - x_i^t\} \quad (2.2)$$

The CTM is based on a recursion where the cell occupancy at time $t+1$ equals its occupancy in time interval $t \in T$, plus the inflow and minus the outflow:

$$x_{i+1}^t = x_i^t + y_i^t - y_{i+1}^t \quad (2.3)$$

The cell transmission model was extended for network flow (Daganzo, 1995), and the single destination system optimum dynamic traffic assignment formulation on the cell transmission basis was introduced by Ziliaskopoulos (2000). Since then, the cell transmission based network formulation has been used for transportation planning schemes like traffic signal coordination (Lo, 2000), lane addition in user-optimum traffic

assignment (Ukkusuri et al., 2004), and contra-flow operations (Tuydes and Ziliaskopoulos, 2005).

2.3 Network design

Capacity addition to a network under a budget constraint has been addressed under the label of network design (Fulkerson, 1958). A “project cost” is associated with each candidate capacity addition project, and the summation of the costs of all selected projects must satisfy the total budget constraint. However, the formulation considers a static network, which is unable to capture the traffic dynamics of essence to evacuation. Consideration of link performance functions to recognize congestion effects leads to a quadratic formulation. Queue spillbacks cannot be modeled even with this modification. Further, the formulation can only address the lane addition option.

Viswanath and Peeta (2003) formulated the Multi-commodity Maximal Covering Network Design Problem (MMCNDP) for identifying critical routes for earthquake response and seismically retrofitting bridges. The underlying concept is the identification of critical links, which are enhanced under a budget constraint so as to sustain seismic action. The key contribution is the synchronous optimization for both travel times and coverage in a single framework. The traffic assignment is static and link capacity is not considered as a constraint, as the focus is on enabling emergency personnel to reach the affected areas rather than on civilian evacuation.

Wolshon (2005) proposes various contra-flow options for evacuation. He describes three options as shown in Figure 2.5: (1) one opposite lane, (2) one opposite

lane and the shoulder of the direction of interest, and (3) all of the opposing lanes without any shoulders.

Kwon and Pitt (2004) analyze the significance of capacity additions to the urban network. They compare different evacuation strategies with contra-flow using the DYNASMART (Jayakrishnan et al., 1995) simulator to analyze various capacity configurations. However, they limit capacity changes only to freeway facilities.

Tuydes and Ziliaskopoulos (2004) formulate the single destination network re-design problem, accounting for contra-flow operations using the CTM. The concept of coupled cells is introduced, where capacity is shared between cells involving flows in opposite directions. The capacity is split according to a continuous variable, the lane reversibility factor. This makes the formulation computationally efficient, since it retains the linearity of the system optimal formulation. However, as discussed hereafter, the approach ignores the reduction in capacity due to reversed-flow lanes.

Reversed-flow lanes under the contra-flow option results in a significant capacity reduction for those lanes when routing flows in the opposite direction (Wolshon, 2005). This is because flow interactions occur between the two opposing physically non-separated flows. Also, drivers routed in the contra-flow lanes are unfamiliar with contra-flow driving (signage faced opposite, no known exit-turns).

Existing models typically use linear variables to address evacuation. Contra-flow options are lane-based discrete network design strategies. Since they involve option-specific planning characteristics, it is difficult to represent them using linear variables with adequate realism. That is, since lane-reversal is discrete in nature, the continuous

characteristic of linear variables cannot handle these discrete options. Further, linear variables cannot realistically capture option-specific budget and trained personnel constraints. For example, if one lane is reversed, it may require the same budget investment for island removal or signage addition as when three lanes are reversed. Another key realism issue for existing models is that they do not adequately model the problem of crossing flows at intersections. In reality, crossing flows under evacuation can lead to gridlock. This entails the need for explicit constraints (and practical deployment) to handle intersecting flow by preempting flow in some directions (by modifying signal plans or through law enforcement personnel present at intersections). By not doing so, existing models overestimate network performance under evacuation.

2.4 *Algorithmic aspects*

Li et al. (2003) introduce a computationally efficient algorithm. A minimum-cost flow sub-structure is recognized and the Dantzig-Wolfe decomposition method is used. Dantzig-Wolfe decomposition relies on the fact that generating columns is computationally more efficient than solving the original problem. However, the minimum-cost flow structure is identified as a sub-structure only, while the constraint responsible for the backward wave propagation (related to traffic flow modeling realism) is not analyzed further as part of the network structure. Thereby, the backward wave propagation is assumed to occur at free-flow speeds, which is not realistic. Also, source cells do not have an exact network representation and the destination cells are connected directly to a super-destination, precluding robust cell representation. The cell capacity

and cell connector capacity constraints are not discussed, though they are required for a precise statement of the minimum-cost flow problem. Finally, the formulation for multiple destinations ignores the first-in, first-out (FIFO) issue.

2.5 *Discussion*

The overview of the literature indicates that there is a strong need for a computationally efficient approach to capture the dynamic traffic phenomena of the evacuee routing. The cell transmission model allows a linear formulation for dynamic traffic assignment. However, computational efficiency can be achieved only when specific properties of the formulation are exploited. In this study, we propose a computationally efficient approach for evaluation planning as illustrated in Chapters 3 and 4. The proposed formulation allows for multiple capacity addition strategies, flow priorities at intersections, and shelter allocation studies.

Figure 2.1 Evacuation and safety zones.

Figure 2.2 Cell types: intermediate cells (i), (ii), (iii); source cell (iv), sink or destination cell (v), (Ziliaskopoulos, 2000).

Figure 2.3 Fundamental traffic flow-density relationship (Lighthill and Whitham, 1955; Richards, 1956).

Figure 2.4 Linear approximation of the fundamental flow-density relationship (Daganzo, 1994).

Figure 2.5. Freeway contra-flow use configurations (Wolshon, 2005).

CHAPTER 3. METHODOLOGY

Chapter 3 introduces the evacuation problem addressed in the research. Section 3.1 describes the problem generically. Section 3.2 provides a mathematical statement of the problem as well as the notation for the formulation. Section 3.3 introduces the formulation for the Evacuation Network Design Problem (ENDP). Section 3.4 discusses relevant computational aspects. Section 3.5 analyzes the problem complexity and relevant computational aspects. The chapter concludes with a summary in Section 3.6.

3.1 *Problem description*

The evacuation network design problem (ENDP) is formulated here. It seeks to identify the links whose capacities ought to be augmented, through contra-flow mechanism or new lane construction, so as to minimize the total time spent in the network over all evacuees subject to budget constraints on costs and personnel. It further assumes that cross-directional flows are not permitted under evacuation. Hence, the broader goal is to identify critical links vis-à-vis evacuation under specific security threats.

Figure 3.1 illustrates the methodological components of the ENDP. There are two key components: (i) the routing of the evacuees to the network, and (ii) the determination

of where capacity has to be added under a specific system-wide objective. The first component is addressed using traffic assignment, specifically dynamic traffic assignment, due to the time-dependency of the network conditions. The second component is a network design problem which determines where the capacity should be augmented (that is on which network links) so as to achieve some system-wide objective subject to budget constraints on costs and personnel. The two components are addressed simultaneously using an optimization framework (and the CPLEX package) where traffic flow is modeled using the cell transmission model. The improved sub-network is defined to be the Transportation Security Network (TSN).

3.2 Problem statement

The ENDP seeks the appropriate network design options z_m from the predefined set of network design options $m \in M$, to determine the routing pattern x_i^t (in cells $i \in C$ in time intervals $t \in T$) which minimizes the total travel time that evacuees spend in the evacuation zone. As discussed in Chapter 1, the evacuation zone is a predetermined area surrounding a potential target under threat or attack. Its exact size is directly related to the type and magnitude of the identified threat or disaster.

3.2.1 Parameters

Following the cell transmission model, the network consists of the set of cells $i \in C$, and the set of cell connectors $j \in E$. Each cell belongs to one of the following three independent cell types: the subset of source cells $C_R \subset C$, the subset of destination

cells $C_s \subset C$, and the subset of intermediate cells $C_G \subset C$. The set of the successor cells of cell $i \in C$ is $\Gamma(i)$ and the set of the predecessor cells to cell $i \in C$ is $\Gamma^{-1}(i)$. The set of discrete constant time intervals is $t \in T$. The free flow speed for cell $i \in C$ is v_i , the traffic wave's backward propagation speed for cell $i \in C$ is w_i , and the ratio w_i/v_i for each cell $i \in C$ is δ_i . The constant discretization time interval is τ and the demand (inflow) at a source cell $i \in C_R$ in time interval $t \in T$ is d_i^t . This parameter is responsible for assigning the evacuee population to its starting time and location.

The network design options are denoted by $m \in M$. The binary indicator a_i^m indicates whether the network design option m is associated with the cell $i \in C$. Contra-flow based network design is always associated with at least two opposite (coupled) cells. For each of these cells and for the same design option, the binary indicator a_i^m equals 1. For contra-flow corridors, the associated network design options are associated with more than one set of coupled cells. The initial maximum number of vehicles in cell $i \in C$ is N_i^0 . The maximum number of vehicles in cell $i \in C \setminus (C_R \cup C_s)$, if network design option $m \in M$ is implemented, is N_i^m . Accordingly, the initial maximum number of vehicles that can flow into or out of a cell in a time interval is Q_i^0 and the maximum number of vehicles that can flow into or out of cell $i \in C \setminus (C_R \cup C_s)$, if network design option $m \in M$ is implemented, is Q_i^m .

The maximum flow of cell connector $j \in E$ is Q_j . It is pertinent to note that the notion of an exact flow capacity Q_j to a cell connector $j \in E$ is introduced for the first time in the literature here. It is significant because it provides the ability to model the bottleneck effect of right or left turns in an urban network. Right or left turns typically do not have sufficient length to be modeled as individual cells. The CTM models the various movements (right, straight or left) by limiting the inflows into these movements to be at most the outflow from predecessor cells or the inflow to the successor cells. However, this ignores the notion that turning movements have reduced capacities in reality. To account for this issue, we propose capacity constraints for the cell connectors. This represents an extension to the CTM.

The cost of implementing network design option $m \in M$ is c_m , and the number of trained personnel for the same option is u_m . The cost c_m of implementing a network design option, or more specifically contra-flow operations, is the summation of all budgetary costs like island redesign/removal for making the operations feasible, the cost for training the personnel, and the cost of special equipment/facilities needed (cones, signage, responder vehicles, personnel communication devices, and electronic variable signage). The total budget is B and the total number of available personnel is U .

The set of intersections is $l \in L$ and the binary indicator β_{jl} indicates whether the cell connector $j \in E$ is associated with intersection $l \in L$. An intersection is defined to be exactly two crossing flows (exactly two cell connectors) that cannot be realized in the same time interval. For instance, in a four-way intersection, a crossing conflict is the left

turn of one direction and the opposite direction's through movement. Only one of these can be realized in the same time interval.

Table 3.1 summarizes the parameters of the ENDP formulation.

3.2.2 Variables

The formulation contains two categories of variables: the routing variables and the network design variables. The routing variables are the number of vehicles x_i^t in cell $i \in C$ in time interval $t \in T$ and the number of vehicles y_j^t routed by cell connector j in time interval $t \in T$. The routing variables are non-negative real numbers. The network design variable z_m is a binary variable which indicates whether network design option $m \in M$ is selected. The maximum number of vehicles in cell $i \in C$ for every time interval $t \in T$ is N_i . The maximum number of vehicles that can flow into or out of cell $i \in C$ for every time interval $t \in T$ is Q_i .

The binary variable p_j indicates whether the flow of cell connector $j \in E$ is restricted by an intersection constraint. When $p_j = 1$, the flow represented by the cell connector is assigned a green phase for all time intervals $t \in T$. The variables N_i and Q_i can be time-expanded to N_i^t and Q_i^t . This allows addressing the question of when to add capacity, in addition of where and how much to add. However, due to the combinatorial nature of the network design part of the formulation, the complexity increases exponentially without significant gains in terms of realism. So, even if the “best” capacity addition strategy were time-dependent, the resources to deploy it may not be available.

Table 3.2 summarizes the variables used in the ENDP formulation.

3.3 Formulation of the ENDP

The objective of the formulation is to minimize the total time spent in the network:

$$\min \sum_{t \in T} \sum_{i \in C \setminus C_S} \tau \cdot x_i^t$$

It minimizes the total vehicle-hours spent by all evacuees in the evacuation zone, which consists of all the cells other than the destination cells. Since τ is a constant, it is hereafter excluded from the mathematical formulation of the objective.

Another potential objective function in the evacuation context is the minimization of the network clearance time. The network clearance time is the time elapsed between when the evacuation order is given and when the last evacuee leaves the evacuation zone. While the formulation objective function discussed above addresses the minimization of the average travel time of the evacuees in the evacuation zone, it is mathematically equivalent to the minimization of network clearance time (Jarvis et al., 1982).

The mixed-integer programming formulation for the ENDP is expressed as follows:

minimize

$$\sum_{t \in T} \sum_{i \in C \setminus C_S} x_i^t \tag{3.3.1}$$

subject to:

$$x_i^t = x_i^{t-1} - \sum_{j \in \Gamma(i)} y_j^{t-1} + \sum_{j \in \Gamma^{-1}(i)} y_j^{t-1} \quad \forall i \in C \setminus C_R, \forall t \in T \quad (3.3.2)$$

$$x_i^t = x_i^{t-1} - \sum_{j \in \Gamma(i)} y_j^{t-1} + d_i^{t-1} \quad \forall i \in C_R, \forall t \in T \quad (3.3.3)$$

$$\sum_{j \in \Gamma(i)} y_j^t \leq x_i^t \quad \forall i \in C, \forall t \in T \quad (3.3.4)$$

$$\sum_{j \in \Gamma(i)} y_j^t \leq Q_i \quad \forall i \in C, \forall t \in T \quad (3.3.5)$$

$$\sum_{j \in \Gamma^{-1}(i)} y_j^t \leq Q_i \quad \forall i \in C, \forall t \in T \quad (3.3.6)$$

$$y_j^t \leq p_j \cdot Q_j \quad \forall j \in E, \forall t \in T \quad (3.3.7)$$

$$\sum_{j \in \Gamma^{-1}(i)} y_j^t \leq \delta_i (N_i - x_i^t) \quad \forall i \in C, \forall t \in T \quad (3.3.8)$$

$$\sum_{m \in M} (z_m \cdot a_i^m) \leq 1 \quad \forall i \in C \quad (3.3.9)$$

$$N_i = \left(1 - \sum_{m \in M} (a_i^m \cdot z_m) \right) \cdot N_i^0 + \sum_{m \in M} (a_i^m \cdot z_m \cdot N_i^m) \quad \forall i \in C \setminus (C_R \cup C_S), \forall t \in T \quad (3.3.10)$$

$$Q_i = \left(1 - \sum_{m \in M} (a_i^m \cdot z_m) \right) \cdot Q_i^0 + \sum_{m \in M} (a_i^m \cdot z_m \cdot Q_i^m) \quad \forall i \in C \setminus (C_R \cup C_S), \forall t \in T \quad (3.3.11)$$

$$\sum_{m \in M} (z_m \cdot c_m) \leq B \quad (3.3.12)$$

$$\sum_{m \in M} (z_m \cdot u_m) \leq U \quad (3.3.13)$$

$$\sum_{j \in E} \beta_{jl} \cdot p_j \leq 1 \quad \forall l \in L \quad (3.3.14)$$

$$x_i^t \geq 0 \quad \forall i \in C, \forall t \in T \quad (3.3.15)$$

$$y_j^t \geq 0 \quad \forall j \in E, \forall t \in T \quad (3.3.16)$$

$$z_m \in \{0, 1\} \quad \forall m \in M \quad (3.3.17)$$

$$N_i \geq 0 \quad \forall i \in C \quad (3.3.18)$$

$$Q_i \geq 0 \quad \forall i \in C \quad (3.3.19)$$

$$p_j \in \{0,1\} \quad \forall j \in E \quad (3.3.20)$$

Equations (3.3.2) to (3.3.8) address the traffic flow modeling to route evacuees. Equations (3.3.9) to (3.3.14) model the network design options and equations (3.3.15) to (3.3.20) are the integrality and non-negativity constraints.

Equation (3.3.2) is the mass conservation constraint between cell and cell connectors for all cells other than the source cells. The number of vehicles x_i^t in cell $i \in C$ in time interval $t \in T$ equals the number of vehicles x_i^{t-1} in the same cell in the previous time interval plus the incoming flows from the incoming (predecessor) cell connectors $j \in \Gamma^{-1}(i)$, minus the flows in the outgoing cell connectors $j \in \Gamma(i)$. Equation (3.3.3) addresses the conservation constraint at the source cells, and introduces the demand d_i^t at source cells $i \in C_R$ in time interval $t \in T$. Equations (3.3.4) to (3.3.8) linearly approximate the fundamental traffic flow-density relation (as discussed in Section 2.3 and illustrated in Figure 2.4), taking into account holding of traffic at each cell. Equation (3.3.4) models the free-flow region and states that the outflow on cell connectors cannot exceed the number of vehicles in cell $i \in C$ in time interval $t \in T$. Equation (3.3.5) states that the total outflow from a cell through all the outgoing cell connectors is less than the cell's outflow capacity. Equation (3.3.6) states that the total inflow into a cell through its incoming cell connectors is less than the cell's inflow capacity. By definition, since a cell is a homogeneous section of a road, its inflow and

outflow capacities are equal. Equation (3.3.7) is both the cell connector's individual flow capacity, as introduced and discussed previously, and the intersection flow restriction. Equation (3.3.8) models the over-congested region of the fundamental flow equation, where backward traffic wave effects are met. The flow is limited due to heavily congested traffic conditions downstream. The speed of the backward propagating traffic wave is $w_i = \delta_i \cdot v_i$.

Equation (3.3.9) restricts the selection of network design options to be at most one for each cell, since a single set of characteristic values (maximum flow Q_i and maximum number of vehicles N_i) must be assigned to every cell. If no network design option is selected, a cell retains its initial parameters (Q_i^0 , N_i^0). This can be seen in equations (3.3.10) and (3.3.11), where a cell's maximum occupancy (3.3.10) and its maximum inflow/outflow (3.3.11) take values that correspond either to the selected network design option or their default values. Equations (3.3.12) and (3.3.13) are the budget and the trained personnel constraints, respectively. The total budgetary cost and the total number of required personnel cannot exceed the total available budget and the total available trained personnel, respectively. Equation (3.3.14) allows at most one crossing flow to be realized at an intersection, as defined previously.

3.4 Modeling issues

This section discusses pertinent modeling issues in relation to the formulation discussed in the previous section.

3.4.1 Objective function

Tuydes and Ziliaskopoulos (2005) suggest a potential future extension that a weighted system optimal objective be used instead of the traditional non-weighted system optimal objective to capture behavioral effects. The weighted system optimal objective seeks to capture the notion that the evacuees perceive that they are less threatened the further they are from the target area. However, such an assumption can lead to skewed performance as it focuses only on the distance from the target rather than whether there are proportional benefits in terms of system performance clearance time and congestion mitigation.

Further, in the context of network design, the weighted system optimal objective is not adequate. The notion of routing evacuees even a single foot away without actually evacuating them from the affected area, can lead to the use of the network design resources for just providing more space for minor advancements than offering actual flow capacity for evacuation. Hence, the traditional non-weighted system optimal objective function is used for the model in this study.

A possible extension is to first solve for the network design options using the non-weighted system optimal objective, and then, after introducing the optimal network design options as parameters, solve using the weighted system optimal objective function so as to derive a traffic pattern more consistent with the expected driver behavior.

3.4.2 Time to implement contra-flow operations

The time required to implement the contra-flow option affects the total evacuation. It is the time between the issuance of the evacuation order and when the contra-flow option is implemented in the traffic network. It is a function of the agency preparedness, the location of the contra-flow implementation teams and the prevailing traffic conditions. The accounting of the time of implementation can be performed through two modifications to the problem formulation: (i) time expansion of the variables $N_i \rightarrow N_i^t$ and $Q_i \rightarrow Q_i^t$, and b) identifying the time-dependent capacities for each network design option $m \in M$ for the (same) cell $i \in I$; that is, it is possible that $N_i^{mt} \neq N_i^{m(t+1)}$.

The proposed modeling modifications significantly increase the complexity of the problem. Hence, there is a need to analyze if the additional computational times are justifiable, especially in an operational context. For some natural disasters such as hurricanes, which have sufficient lead times, the evacuation order can be given after the necessary contra-flow options have been implemented. In such instances, the time expansion of the capacity variables is unnecessary. Since the research addresses a planning context, the computational time for obtaining the contra-flow options is not critical. However, the time required for implementing the contra-flow option in the field may need to be factored, especially if the time required is not trivial.

3.4.3 Existence of shelters and capacity allocation

When planning for evacuation, there are three potential choices (or “destinations”) to ensure the safety of the general population: (i) move the evacuee outside the evacuation zone (as is done on this study), (ii) move the evacuee to a designated shelter, and (iii) move the evacuee to a designated area at the origin itself (designated “shelter room” in the building). A shelter can be easily modeled in the current formulation as a destination cell with finite capacity N_s . The formulation can also model planning for construction of shelters, simply by reassigning a capacity N_s^m to the shelter $s \in S$ according to network design option $m \in M$ at a network design cost c_m . An interesting research question from a resource allocation standpoint is whether it is better to build shelters or enhance the network through improvements (as is done in this study) when constrained by a constant security budget.

3.4.4 Modeling contra-flow corridors

The contra-flow option can require performing the operation over several links or a corridor, rather than at one link at a time (as is done in this study). It is a more realistic option in some situations. The problem formulation can easily incorporate this network design option. That is, a contra-flow corridor operation is a network design option z_m that assigns capacities N_i^m and Q_i^m for two or more cells (that form a corridor) simultaneously. The re-designed cells are indicated by setting the corresponding indicator $a_i^m = 1$.

3.4.5 Traffic signal settings

There are three options related to traffic signals under an evacuation scenario: (i) retain the existing signal plan, (ii) implement a modified “static” network-wide signal plan for the duration of the evacuation, and (iii) implement a modified “dynamic” network-wide signal plan. The first option simply retains the existing traffic signal control pattern, which is not necessarily optimal from an evacuation standpoint. This is because evacuation from a region is typically characterized by traffic directionality; that is, there are heavy traffic flows in some directions. This motivates the need for modified traffic signal plans for the evacuation duration. A modified “static” plan which is assumed in our study, provides optimal priorities among intersecting directions, and retains the same phase for each intersection for the evacuation period. Such a plan can also be enforced using police officers at intersections, as is done currently at special events such as football games. A “static” plan has key advantages: (i) it reduces the likelihood of gridlock, and (ii) it is computationally efficient for implementation. A modified “dynamic” signal plan seeks to relate signal phases to demand at the intersection for each time interval in the evacuation period. While this might suggest the best plan from a theoretical standpoint, it may not be particularly effective in practice. This is because the density of traffic in roads can lead to non-compliance or partial compliance of the signal settings by the evacuees. This behavior has been repeatedly exhibited by drivers during special events, and can lead to inefficient blockage of key intersections, resulting in gridlock conditions. Finally, the “dynamic” traffic control

approach is computationally intensive. Hence, the modified “static” plan is preferred, and employed in our study.

3.4.6 FIFO property and bus routing

In a dynamic traffic assignment formulation it is important that the first in, first out (FIFO) property be satisfied. To generate consistency with a single destination DTA, under evacuation planning, all evacuees can be routed to a single destination, the safety zone (Daganzo, 1994). This problem has been addressed in the literature as a single-commodity network flow problem, where the FIFO property is inherently satisfied (Ziliaskopoulos, 2000). However, it has the limitations discussed in Section 2.5.

The satisfaction of the FIFO property becomes a particularly challenging issue when buses are routed to transfer low-mobility people out of the evacuation zone. A bus carrying a significant number of evacuees can be assigned a greater weight, as it is a high occupancy vehicle. However, this can lead the optimization software to deliberately violate FIFO in order to route the bus out of the evacuation zone as quickly as possible.

3.4.7 Entry and exit flow capacities in evacuation zone

The flow capacities related to the entry and exit from the evacuation zone significantly affect the network performance. Hence, the assumptions on these capacities are a key modeling issue. An entry flow capacity is the outflow capacity of a source cell. For example, it can be the flow capacity of a parking lot exit. An exit flow capacity of the

evacuation zone is the inflow capacity of the associated destination cell. For example, it can be physically represented by the outflow from a boundary link in the evacuation zone (Figure 3.2). If these flow capacities are assumed to be constants, then spatio-temporal interactions arising from congestion on the adjacent cells and cell connectors are ignored. Hence flow capacities of source and destination cells are assumed to be high enough so that they are bounded only by the variable maximum flow capacity of the adjacent cells and cell connectors.

Highway ramps are modeled as cell connectors which start or end at a highway cell. The capacities of these cell connectors are those of the associated ramps. The significance of this modeling approach is that it allows contra-flow operations to be consistent with the actual ramp capacities. However, a drawback is that the travel time spent in ramps is not captured. Ideally, highway ramps should be modeled as individual cells in the CTM as they can require more than one time interval to negotiate the ramp length at free-flow speeds. The trade-off is in terms of the additional computational and modeling burden.

3.4.8 Comparison of contra-flow operations to lane addition

As discussed earlier, the network design options considered in this study are the contra-flow options and lane addition. Contra-flow operations are cost-effective, flexible, well-suited for dense urban environments, increasingly commonplace for mass evacuations, and can be tailored to the evolving traffic/infrastructure conditions under the unfolding disaster. By contrast, the lane addition option is expensive by several orders of

magnitude compared to the contra-flow option. Further it represents the addition of new capacity to the network, and is hence purely a long-term planning strategy as the addition of lanes requires a significant amount of time. Therefore, while the contra-flow option can be addressed both in planning and operational contexts, the lane addition strategy is meaningful only in the planning domain.

From an optimization standpoint, the asymmetric cost requirements of the two options imply that the lane addition option is always dominated by the contra-flow option under the same budget constraint for evacuation operations. Therefore, in Chapter 5, we restrict our experiments to the contra-flow strategies.

3.5 Complexity

The ENDP is solved with the branch-and-cut algorithm in CPLEX. It is an exact solution methodology for integer and mixed-integer programs. The computational cost is derived from two factors: (1) the number of tree nodes of the branch-and-cut algorithm, and (2) the computational time at each tree node. To improve the computational effort, specific network design options should be considered rather than searching the whole set of network design options. As discussed in the next chapter, the use of the improved formulation significantly reduces the computational time at each tree node.

The current formulation is a generalized mixed-integer formulation. The constraints responsible for vehicle routing ((3.3.2) to (3.3.8)) are linear. The constraints responsible for the network design options ((3.3.9) to (3.3.14)) involve binary variables, leading a mixed integer formulation.

The computational experience with the ENDP formulation of Section 3.3 suggests that it is highly intensive, even if the problem is fully linearized (that is, when the network design options are not considered binary 0-1 variables). Even if only 10 network design options are considered, the methodology requires a few days to obtain the solution to within the pre-specified percentage optimality gap.

Chapter 4 discusses an improved ENDP formulation to enable greater computational efficiency. It exploits key properties of the cell transmission model to generate stricter bounds on the routing variables.

3.6 *Summary*

This chapter introduces the first formulation for the ENDP with combinatorial network design options. It is a mixed-integer formulation which is composed of a set of linear routing constraints ((3.3.2) to (3.3.8)), and a set of constraints responsible for the network design options ((3.3.9) to (3.3.14)) that include binary variables. The advantage of the combinatorial modeling approach for the network design options is that exact cell parameters (in terms of flow and occupancy) are assigned depending on the specific strategies: contra-flow operations, lane-addition or their combination. Planning for the location and number of shelters can also be addressed. Moreover, capacity reduction (as observed in the context of turning movements) was addressed by introducing of an individual flow constraint for cell connectors representing turning movements.

Initial simulation experiments highlight the computationally intensive nature of the formulation, and indicate the need for a more efficient formulation. The next chapter

discusses an improved formulation obtained by exploiting specific modeling characteristics related to the CTM.

Table 3.1 Summary of the parameters of the ENDP formulation.

Parameter	Description
$i \in C$	The set of all cells.
$C_R \subset C$	The subset of source cells (origin cells).
$C_S \subset C$	The subset of destination cells.
$C_G \subset C$	The subset of intermediate cells.
$j \in E$	The set of cell connectors.
$\Gamma(i)$	The set of the successor cells of cell $i \in C$.
$\Gamma^{-1}(i)$	The set of the predecessor cells to cell $i \in C$.
$t \in T$	The set of discrete and constant time intervals.
$m \in M$	The set of network design options.
a_i^m	The binary indicator showing if the network design option m is associated with the cell $i \in C$.
N_i^0	The initial maximum number of vehicles in cell $i \in C$.
N_i^m	The maximum number of vehicles in cell $i \in C \setminus (C_R \cup C_S)$, if network design option $m \in M$ is implemented.
Q_i^0	The initial maximum number of vehicles that can flow into or out of cell.
Q_i^m	The maximum number of vehicles that can flow into or out of cell $i \in C \setminus (C_R \cup C_S)$, if network design option $m \in M$ is implemented.
v_i	The free flow speed for cell $i \in C$.
w_i	The traffic wave's backward propagation speed for cell $i \in C$.
δ_i	The ratio w_i/v_i for each cell $i \in C$.
τ	The constant discrete time interval's length.
c_m	The cost of implementing design option $m \in M$.
B	The total available budget.
u_m	The number of trained personnel needed for implementing capacity option $m \in M$.
U	The total number of available trained personnel.
d_i^t	The demand (inflow) at source cell $i \in C_R$ in time interval $t \in T$.
β_{jl}	The binary indicator showing if the flow in cell connector $j \in E$ can be restricted by intersection $l \in L$.

Table 3.2 Summary of the variables of the ENDP formulation.

<u>Variables</u>	<u>Description</u>
x_i^t	The number of vehicles in cell $i \in C$ in time interval $t \in T$
y_j^t	The number of vehicles moved by cell connector $j \in E$ in time interval $t \in T$.
z_m	The binary decision variable indicating if the network design option $m \in M$ is selected.
N_i	The maximum number of vehicles in cell $i \in C$.
Q_i	The maximum number of vehicles that can flow into or out of cell $i \in C$.
p_j	The binary variable indicating whether the flow in cell connector $j \in E$ is restricted by an intersection constraint.

Figure 3.1 Methodological components.

Figure 3.2 A bottleneck formed by the flow capacity of a highway ramp

CHAPTER 4. THE IMPROVED ENDP FORMULATION

This chapter discusses an improved formulation for the ENDP obtained by exploiting specific characteristics related to the CTM. Section 4.1 illustrates some issues with CTM. Section 4.2 identifies a mechanism to generate stricter bounds. Section 4.3 states propositions used to generate a computationally efficient formulation. Section 4.4 discusses the improved ENDP formulation. Section 4.5 describes its complexity. Section 4.6 provides some concluding comments for this chapter.

4.1 Properties of the cell transmission model

The linear approximation of the fundamental traffic flow equation used in the CTM (Figure 2.4) has the following key characteristic: the light traffic flow region extends up to the point P_2 at which point the maximum flow is met, as shown in Figure 4.1. This implies that when the CTM is used as part a mathematical model, there is no incentive for the optimizer to consider the region to the right of N_{FF} . This modeling approach is not necessarily the most realistic representation of the fundamental traffic flow relationships. For example, the Highway Capacity Manual (2005) proposes that the light traffic region end at a traffic density strictly less than the traffic density at the

maximum flow. This problem with the modeling approach of CTM, which raises issues of realism, has not yet been discussed in the relevant literature.

4.2 Identification of stricter bounds

The issue discussed heretofore about the possible lack of realism in CTM's fundamental traffic flow relationship, is exploited to provide stricter bounds for the formulation of the ENDP while assuring non-inferior solutions. Unlike in a pure routing problem, the network design problem seeks to increase the maximum flow capacities. Since these capacities are obtained at the bounds of the free-flow conditions, the maximum occupancy N_i of a cell $i \in C$ is reduced and set equal to the maximum number of vehicles Q_i that can propagate to the next cell(s). This is a key contribution of this study, and leads to significant computational efficiencies.

4.3 Propositions

The introduction of the stricter bounds on the maximum occupancy N_i of cell $i \in C$, hereafter equal (and equivalent) to Q_i , justifies a set of propositions that simplify the formulation, while generating non-inferior solutions (validated through the computational experiment in Chapter 5). The propositions are:

- (1) Backward propagating traffic waves are not meaningful at traffic densities of light traffic conditions, and therefore constraint (3.3.8) is redundant.

- (2) The maximum occupancy N_i becomes equivalent to the maximum flow Q_i ;
the N_i variable and the associated equation (3.3.10) can be eliminated.
- (3) The inequality (3.3.4) can be replaced by a strict equality for intermediate cells; evacuees will be allowed to exit the source cells only if free-flow conditions are guaranteed along the entire route from the origin to the destination cell.

Although proposition (3) does not produce a realistic routing pattern for evacuation, it still produces non-inferior solution sets for the ENDP. This is because there is no incentive for the optimizer to push flow out of the source cells unless it can be led without intermediate delays to the destination cells. This proposition can be regarded as a relaxed analog of stage-based evacuation models.

The three propositions hold because it is assumed that at most one out of every pair of crossing flows is allowed for the whole study period. If a traffic signal were to allow different crossing flows for different time intervals, there may be an incentive to increase the occupancy of at least one cell before the signal turns green so as to propagate the maximum flow in the next few time intervals. However, in our study, we assume a “static” traffic signal plan as discussed in Section 3.4.5. This limits the intersecting flow at any intersection to be at most one such flow, for the evacuation period.

4.4 The improved formulation

The improved formulation, labeled iENDP, is as follows:

minimize

$$\sum_{t \in T} \sum_{i \in C \setminus C_S} x_i^t \quad (4.4.1)$$

subject to:

$$x_i^t = \sum_{j \in \Gamma^{-1}(i)} y_j^{t-1} \quad \forall i \in C \setminus (C_R \cup C_S), \forall t \in T \quad (4.4.2)$$

$$\sum_{j \in \Gamma(i)} y_j^t = x_i^t \quad \forall i \in C \setminus (C_R \cup C_S), \forall t \in T \quad (4.4.3)$$

$$x_i^t \leq Q_i \quad \forall i \in C \setminus (C_R \cup C_S), \forall t \in T \quad (4.4.4)$$

$$x_i^t = x_i^{t-1} - \sum_{j \in \Gamma(i)} y_j^{t-1} + \sum_{j \in \Gamma^{-1}(i)} y_j^{t-1} + d_i^{t-1} \quad \forall i \in (C_R \cup C_S), \forall t \in T \quad (4.4.5)$$

$$\sum_{j \in \Gamma(i)} y_j^t \leq x_i^t \quad \forall i \in (C_R \cup C_S), \forall t \in T \quad (4.4.6)$$

$$y_j^t \leq Q_j \quad \forall j \in E, \forall t \in T \quad (4.4.7)$$

$$, \forall j \in \Gamma(i) \cup \Gamma^{-1}(i)$$

$$y_j^t \leq p_j \cdot Q_j \quad \forall j \in E, \forall t \in T \quad (4.4.8)$$

$$\sum_{m \in M} (z_m \cdot a_i^m) \leq 1 \quad \forall i \in C \quad (4.4.9)$$

$$Q_i = \left(1 - \sum_{m \in M} (a_i^m \cdot z_m) \right) \cdot Q_i^0 + \sum_{m \in M} (a_i^m \cdot z_m \cdot Q_i^m) \quad \forall i \in C \setminus (C_R \cup C_S), \forall t \in T \quad (4.4.10)$$

$$\sum_{m \in M} (z_m \cdot c_m) \leq B \quad (4.4.11)$$

$$\sum_{m \in M} (z_m \cdot u_m) \leq U \quad (4.4.12)$$

$$\sum_{j \in E} \beta_{jl} \cdot p_j \leq 1 \quad \forall l \in L \quad (4.4.13)$$

$$x_i^t \geq 0 \quad \forall i \in C, \forall t \in T \quad (4.4.14)$$

$$y_j^t \geq 0 \quad \forall j \in E, \forall t \in T \quad (4.4.15)$$

$$z_m \in \{0,1\} \quad \forall m \in M \quad (4.4.16)$$

$$Q_i \geq 0 \quad \forall i \in C \quad (4.4.17)$$

$$p_j \in \{0,1\} \quad \forall j \in E \quad (4.4.18)$$

This formulation is a modification of the initial formulation discussed in Section 3.3. The constraints that differ from those in the original formulation are discussed hereafter.

Equation (4.4.2) and (4.4.3) enforce free-flow traffic conditions in the intermediate cells. The physical meaning is that since free-flow traffic conditions exist (as discussed in Section 4.3), the number of vehicles propagated to the next cell(s) is equal to the number of vehicles existing in the current cell in that time interval.

Equation (4.4.4) establishes stricter bounds on intermediate cell occupancies; it is the upper bound of traffic density that allows free-flow speed conditions. There is no need for equations (such as (3.3.8)) to track congested and the over-congested traffic flow regions, since the problem is studied only in the free-flow region.

4.5 Complexity of the iENDP

Lemma : The iENDP is NP-hard.

Proof : It is proved by reduction. Consider the instance iENDPR of the iENDP without the trained personnel constraint (4.4.12) and the intersection constraint

(4.4.13). Let the strictly non-negative slack variable r_i^t be added to the left hand side of inequality (4.4.6). Finally add the following constraint:

$$\sum_{i \in C} x_i^{|T|} = \sum_{t \in T} \sum_{i \in C} d_i^t \quad (4.4.19)$$

Then, the routing part of the iENDPR formulation is the acyclic minimum-cost flow problem. Equation (4.4.19) is the conservation of flow at destination nodes; it still holds for any time interval and even for ill-posed instances of the iENDP where not all evacuees are able to reach destination cells in the last time interval $|T|$ of the evacuation period. The network structure is acyclic; simply, there can be no flow looping between different time intervals. When the network design variables are included, the iENDP reduces to the network design problem under a budget constraint, which is known to be NP-hard (Johnson et al., 1978).

4.6 Discussion

This chapter introduces the two key contributions of the research. The first is the observation that the linear approximation of the fundamental traffic flow-density relation, as proposed by Daganzo (1994), states that the maximum flow of a cell can be reached at free-flow conditions; equivalently, a cell cannot “push” more flow to the next cell(s) even if traffic densities greater than the maximum traffic density of the free-flow region are considered. This observation leads to the application of stricter bounds on the routing variables of the ENDP, leading to the iENDP formulation. Traffic assignment in the free-flow region allows the following propositions to simplify the formulation: (1) backward

propagating traffic waves can be ignored, (2) the maximum occupancy variable N_i and the equivalent definitional constraint (3.3.10) are redundant, and (3) evacuees are allowed to exit the source cells only if free-flow conditions are guaranteed. The experiments in the next chapter confirm that these propositions produce non-inferior solutions to the ENDP.

The iENDP formulation is proven to be NP-Hard. This highlights the significance of the second key contribution of the research. We identify that the cell transmission model has an acyclic minimum cost flow structure for the routing constraints. This is important because it enables the reduction of the computational complexity. Further, it leads to the proposition of a generalized graph theoretic sub-structure for the CTM. The generalized graph theoretic CTM has the potential for more efficient formulation of several common problems in the transportation arena.

Figure 4.1 CTM traffic flow relationship.

CHAPTER 5. COMPUTATIONAL EXPERIMENTS

This chapter discusses computational experiments using a test network to derive insights on the performance of the proposed evacuation model as well as on the implications for practical deployment. Section 5.1 discusses some implementation issues. Section 5.2 describes the test network and the experimental setup. Section 5.3 discusses experiments and insights on evacuation strategies using several test scenarios. It also discusses sensitivity analyses for key model parameters. The chapter concludes with a summary of the experimental insights.

5.1 *Implementation issues*

This section discusses key issues that arise in the implementation of the evacuation model for deriving insights through experiments.

5.1.1 Data on budget costs and trained personnel requirements

As discussed in Chapter 3, each network design option is associated with budgetary costs and number of trained personnel requirements. For example, lane addition is associated with an increased budgetary cost only, while contra-flow operations are associated with a number of required trained personnel and a small budgetary cost

mostly related to island removal/reconstruction. However, two issues can potentially arise in the model implementation context. First, data on budget and personnel needs for contra-flow options require a dedicated study on the part of the responsible transportation agency. Hence, these data are difficult to obtain currently, though this may not be an issue in the future as security/disaster preparedness plans become more commonplace. To circumvent this issue, the budget and trained personnel constraints in (3.3.12), (3.3.13), (4.4.11), (4.4.12) are substituted by a more transparent constraint on the number of contra-flow options allowed or equivalently the number of reversed links (RL). That is, the number of reversed links (RL) allowed is used as a proxy for the budget and number of trained personnel required for the corresponding contra-flow option.

5.1.2 Initial traffic conditions

The number of vehicles that need to be evacuated from the evacuation zone is approximately equal to the sum of number of vehicles in parking lots in the evacuation zone and the number of vehicles traveling on the links of the evacuation zone at the time of the evacuation order. To account for the latter group of vehicles (vehicles in the network links at the time of the evacuation order), all intermediate cells of the simulator (ordinary, merging, diverging) are assigned an initial estimate of vehicles d_i^0 , $d_i^0 \leq N_i^0$ at time $t=0$. The initial estimate is either based on historical data, or is obtained from the sensor data on the day of the evacuation order.

However, there is a trade-off between realism and computational times. The improved ENDP formulation assumes traffic assignment at free-flow conditions for

intermediate cells. If dense traffic conditions appear at the time of the evacuation, then the improved formulation will not be valid because the problem would become infeasible. Therefore, current traffic conditions can be aggregated locally at the vicinity of each parking lot (source cell) and assigned there without loss of generality.

5.2 Experimental setup

5.2.1 The test network

The test network for the study is illustrated in Figure 5.1. It consists of a 3x4 grid network that replicates a dense urban environment with highways (light blue long cells), arterials (red medium cells) and side streets (dark blue short cells), as described in Table 5.1. From an evacuation standpoint, the bottom of the network represents the boundary of the evacuation zone (from which vehicles move to the safety zone) to which evacuees are routed. 20 potential sources cells are attached to each arterial and side street cell. The number of evacuees assigned to each source cell depends on the assumed scenario.

The cell parameters are given in Tables 5.2, 5.3, 5.4 using terminology from the cell transmission model. The network design options considered in the experiments are summarized in Tables 5.3 and 5.4. For highway and arterial cell types two network design options are examined for each direction: totally reversing the opposite link and reversing all but one of the opposite link's lanes. For side streets the same concept is followed. One option per side street cell is modeled by reversing the lane of the opposing direction. For example, if a contra-flow design option with 5 lanes in the improved

direction and 1 lane in the reduced direction is selected, then the improved direction is assigned a maximum flow of 5760 vehicles/hour and the reduced 900 vehicles/hour. It is easily noticed that these volumes are lower than the typically assumed levels of 1800-2100 vehicles/hour/lane. This is because capacity reduction occurs under contra-flow operations (Wolshon, 2005), as discussed in Section 2.3.

5.2.2 Computational resources

The computing environment consists of a Sun Ultra Enterprise server E6500 with 26 400-MHz UltraSparc II processors under the multi-user Solaris 7 operating environment with 23 GB of RAM, 131 GB of swap space, and 8 MB of cache. The GAMS modeling language and CPLEX's mixed integer solver were used. The experiments are performed with the improved formulation, as discussed in Chapter 4.

5.3 *Experiments*

In the current study, the test network described in Section 5.2.1 is assumed. There are 3 major scenario sets according to the three major parameters studied. They are: (i) the number of reversed links, (ii) population size, and (iii) the spatial distribution of evacuation O-D demand. The characteristic parameters of the associated scenarios are summarized in Table 5.5.

5.3.1 Design of experiments

The first scenario set examines the effect of different levels of resource allocation for the network design options. Only contra-flow operations are assumed, and as discussed in Section 3.4.8, the resource allocation is quantified by using the number of reversed links as a proxy. Hence, reversed links ranging from 0 to 20 are examined for a uniform distribution of 5000 evacuees to 20 sources. It is expected that these experiments will provide insights on the “ideal” levels of resource allocation for the decision-makers (or planners). The experiments also analyze the computational time efficiencies.

The second scenario set examines the effect of the population size on the evacuation performance for a constant number of reversed links, acquired after the analysis of the first scenario set. It is the number of reversed links at which most of the improvement in network performance is achieved. For this number of reversed links (8), population sizes of 500 to 5000 evacuees are assigned to 20 sources.

The third scenario set examines the effect of the spatial distribution of the transportation demand for evacuation. 5000 evacuees are assigned to 1 source, 2 sources uniformly, and 20 sources uniformly and randomly, and routed to 1 destination, 2 destinations, and 4 destinations. It seeks insights on the topological properties of the selected reversed links. Table 5.6 illustrates the distribution of demand under the random demand distribution scenario.

The three scenarios are evaluated using cumulative curves of evacuees exiting the evacuation zone (as in Figures 5.2, 5.17 and 5.21), the network clearance time (as in

Figures 5.3, 5.18 and 5.22), the evacuation rate (as in Figures 5.4, 5.19 and 5.23), and the graphical view of the test network with the selected reversed links (as in Figures 5.5-5.14, 5.20, and 5.24-5.29). Also, the computational time as a function of the number of reversed links and clearance time is analyzed in Figures 5.15 and 5.16.

5.3.2 Effect of resource allocation on evacuation performance for uniformly distributed population

The cumulative curves of evacuees exiting the evacuation zone for various numbers of reversed links are illustrated in Figure 5.2. The network clearance time, defined in Section 2.1, is used to analyze the network performance under various resource (number of reversed links) constraints. The initial network of 0 reversed links entails a clearance time of 22 minutes. The corresponding value for 20 reversed links is 14 minutes, representing a 36% reduction in network clearance time. This implies that using the contra-flow option in dense urban environments can lead to significant performance enhancements under security-related mass evacuation scenarios. An important practical insight is that most of the potential benefits through contra-flow operations are realized when 8 reversed links are allocated, which results in a network clearance time of 15.9 minutes (Figure 5.3). This illustrates that there is an optimal level of resource allocation beyond which additional benefits are insignificant. This implies that decision-makers (traffic operators) can determine effective contra-flow strategies by identifying the best level of resource allocation from a cost-benefit perspective.

Figure 5.2 further illustrates the sigmoid nature of the cumulative network clearance time curve. The evacuation rate (rate of arrivals to the destination cells), represented by the tangent of the cumulative curve, initially increases. It reaches a maximum rate, and then keeps decreasing. The evacuation rate is illustrated in Figure 5.4. The various characteristics of the results can be explained by tracking the time-dependent nature of traffic congestion. Initially, the clearance rate increases as demand is being serviced below capacity, that is, the network is not congested to capacity. As further demand is serviced, the network links reach their capacities and that is represented by the region of the maximum evacuation rate. As time progresses, demand decreases leading to reduced evacuation rates until all traffic is cleared from the evacuation zone.

The various network design options are illustrated graphically in Figures 5.5-5.14. The selected reversed links for contra-flow operations are indicated with thick lines according to the color coding discussed in Table 5.1. There is a clear topological trend in terms of the formation of contra-flow corridors with increased resources. The reversed links start forming close to the destination cells of the test network and extend inwards to form corridors as the number of reversed links increase. This is because of the directionality of the evacuation flows which makes the capacity closer to the destinations critical in terms of enabling efficient evacuation rates. After the 8 reversed links case, a general tree structure is exhibited. It is important to note that most of the improvement of the network clearance time is achieved at the level of 8 reversed links.

Figure 5.15 plots the relationship between the number of reversed links and the computational time. It indicates that the computational time increases exponentially with

the number of allocated reversed links. Figure 5.16 indicates a marginal improvement in clearance time as computational times increase beyond the 10-15 minutes range. Hence, the insights from the computational times also suggest that beyond some resource allocation levels, the benefits are marginal.

5.3.3 Effect of uniformly distributed population size on evacuation performance

The cumulative curves of evacuees exiting the evacuation zone for various population sizes (under uniform spatial distribution) are illustrated in Figure 5.17. The initial population of 500 evacuees entails a clearance time of 2.5 minutes. The corresponding value for 5000 evacuees is 15 minutes, representing a 600% increase in network clearance time. Figure 5.18 suggests a linear relationship between the evacuee population size and the network clearance time (under the uniform distribution). The linearity is explained by the constant evacuation rate for a long time period. This represents a useful insight for the decision-maker. Figure 5.19 illustrates the time-dependent evacuation rates.

It is useful to note that for small evacuee population sizes, the evacuation rate does not reach the network capacity. However, for large population sizes, the maximum capacity of the network is reached and retained for a long time period, substantially constraining the evacuation performance. It suggests long-term lane addition as a solution to address evacuation needs of large populations. An interesting question is whether the strategies “scale” for large populations, as population in a region increases over time.

The network design options under the various evacuee population sizes are illustrated in Figure 5.20. The selected reversed links for contra-flow operations are indicated with thick lines according to the color coding discussed in Table 5.1. Although some trivial variations exist among the different population sizes, the trend is the one represented in Figure 5.20, and is identical to the solution for the 8 reversed links with 5000 evacuees uniformly distributed to 20 sources (Figure 5.8).

5.3.4 Effect of spatial distribution of evacuation demand on network performance

The cumulative curves of evacuees exiting the evacuation zone for various scenarios of spatial distribution under the 6 reversed links case are illustrated in Figure 5.21. The examined scenarios are combinations of single or multiple sources and/or destinations, as illustrated in Table 5.5. These scenarios are discrete and cannot be physically examined in a continuous manner. The results suggest that the patterns with multiple sources, multiple destinations, and uniform spatial distributions lead to better clearance times (Figure 5.22). This trend is reasonable as multiple sources and destinations avoid local congestion hotspots that can occur due to concentration of demand at few locations. Further, as expected, the uniform distribution scenario performs better than the random distribution scenario. Figure 5.23 illustrates that the larger the amount of time when the bottleneck (severe congestion) exists, the more linear the evacuation curve is.

The various network design options are illustrated in Figures 5.24-5.29. The selected reversed links for contra-flow operations are indicated with thick lines according

to the color coding discussed in Table 5.1. They indicate that capacity is added where bottlenecks exist. This is easily observed especially in the scenarios with 1 or 2 sources or sinks. It is important to note that for the scenarios with 1 and 2 sources to many destinations, there exist links that do not reduce bottlenecks, like 52 and 54 for both scenarios (Figures 5.26 and 5.27). That is, the bottleneck has been optimally improved, and the reversal of links 52 and 54 does not provide additional benefits (it simply satisfies the 6 reversed links requirement).

5.4 *Summary*

The numerical and topological properties, as observed through the different scenarios are of special interest to planners. In the first set of scenarios, it was identified that solving for a specific size of resources is adequate for a “good” solution. In the second set of scenarios, a linear relation between clearance time and population size was illustrated, which provides insights on the capabilities for efficiently solving evacuation problems with large populations through reduced computational times. The third set of scenarios indicated that multiple origins and destinations, and greater uniformity in the spatial distribution of demand lead to better network performance under evacuation.

Table 5.1 Legend of the test network.

Highway Cell
Improved Highway Cell
Arterial Cell
Improved Arterial Cell
Side Street Cell
Improved Side Street Cell
Source Cell
Safety Cell
Cell Connectors

Table 5.2 Cell characteristics of the test network.

Cell Type	Highway	Arterial	Side Street	Source	Destination
Cell IDs	1-22	23-78	79-126	127-146	147-150
Free flow speed (miles/h)	70	35	20	-	-
Time interval (sec)	10	10	10	10	10
Cell length (feet)	1000	500	250	-	-
Number of lanes	3	2	1	3	3
Maximum flow per lane (veh/hour/lane)	2160	1800	1800	2160	2160
Maximum cell flow	18	10	5	infinite	infinite
Reduced maximum cell flow (veh/time step) (due to the evacuation operations)	12	7	3	12	12
Number of vehicles per cell (veh/cell)	108	36	9	infinite	infinite

Table 5.3 Cell characteristics for lane addition design options.

Cell type	Flow capacity increase for the addition of one lane (veh/hour)	Flow capacity increase for the addition of one lane (veh/time step of 10 sec)	Lane addition cost per mile per lane (in million \$)	Lane addition cost per cell (in million \$)
Highway	1440	4	2	0.4
Arterial	1260	3.5	2	0.2
Side Street	1080	3	2	0.1

Table 5.4 Cell characteristics according to contra-flow options.

Direction	Final number of lanes per direction		Maximum cell flow Q_i (veh/h)		Maximum cell flow Q_i (veh / time step of 10 sec)	
	Improved	Reduced	Improved	Reduced	Improved	Reduced
Highway cell (3 lanes per direction)	5	1	5760	900	16	2.5
	6	0	7200	0	20	0
Arterial cell (2 lanes per direction)	3	1	3240	720	9	2
	4	0	4320	0	12	0
Side street cell (1 lane per direction)	2	0	1800	0	5	0

Table 5.5 Characteristic parameters of the experiment scenarios.

Scenario ID (SID)	Description	Population size	Spatial distribution of the population	Number of sources	Number of destinations	Number of reversed links
1.1	Number of reversed links	5000	Uniform	20	4	0
1.2		5000	Uniform	20	4	2
1.3		5000	Uniform	20	4	4
1.4		5000	Uniform	20	4	6
1.5		5000	Uniform	20	4	8
1.6		5000	Uniform	20	4	10
1.7		5000	Uniform	20	4	12
1.8		5000	Uniform	20	4	14
1.9		5000	Uniform	20	4	18
1.10		5000	Uniform	20	4	20
2.1	Population size	500	Uniform	20	4	8
2.2		1000	Uniform	20	4	8
2.3		1500	Uniform	20	4	8
2.4		2000	Uniform	20	4	8
2.5		2500	Uniform	20	4	8
2.6		3000	Uniform	20	4	8
2.7		3500	Uniform	20	4	8
2.8		4000	Uniform	20	4	8
2.9		4500	Uniform	20	4	8
2.10		5000	Uniform	20	4	8
3.1	Spatial distribution of evacuation demand	5000	Uniform	20	4	6
3.2		5000	Random	20	4	6
3.3		5000	Uniform	1	4	6
3.4		5000	Uniform	2	4	6
3.5		5000	Uniform	20	1	6
3.6		5000	Uniform	20	2	6

Table 5.6. 5000 evacuees randomly distributed to source cells in the random distribution scenario.

Source ID	Population
127	235
128	48
129	27
130	73
131	167
132	390
133	214
134	268
135	1042
136	203
137	429
138	81
139	234
140	398
141	111
142	67
143	343
144	97
145	436
146	137

Figure 5.1 Test network.

Figure 5.2 Cumulative curves of evacuees in the safety zone for different number of reversed links.

Figure 5.3 Clearance time as a function of the number of reversed links.

Figure 5.4 Evacuation rate per minute for different numbers of reversed links.

Figure 5.5 Improved network with 2 reversed links for 5000 evacuees uniformly distributed to 20 sources and routed to 4 destinations (SID 1.2).

Figure 5.6 Improved network with 4 reversed links for 5000 evacuees uniformly distributed to 20 sources and routed to 4 destinations (SID 1.3).

Figure 5.7 Improved network with 6 reversed links for 5000 evacuees uniformly distributed to 20 sources and routed to 4 destinations (SID 1.3).

Figure 5.8 Improved network with 8 reversed links for 5000 evacuees uniformly distributed to 20 sources and routed to 4 destinations (SID 1.4).

Figure 5.9 Improved network with 10 reversed links for 5000 evacuees uniformly distributed to 20 sources and routed to 4 destinations (SID 1.5).

Figure 5.10 Improved network with 12 reversed links for 5000 evacuees uniformly distributed to 20 sources and routed to 4 destinations (SID 1.6).

Figure 5.11 Improved network with 14 reversed links for 5000 evacuees uniformly distributed to 20 sources and routed to 4 destinations (SID 1.7).

Figure 5.12 Improved network with 16 reversed links for 5000 evacuees uniformly distributed to 20 sources and routed to 4 destinations (SID 1.8).

Figure 5.13 Improved network with 18 reversed links for 5000 evacuees uniformly distributed to 20 sources and routed to 4 destinations (SID 1.9).

Figure 5.14 Improved network with 20 reversed links for 5000 evacuees uniformly distributed to 20 sources and routed to 4 destinations (SID 1.10).

Figure 5.15 Computational time for 1% optimality gap.

Figure 5.16 Network clearance time as a function of computational time for different number of reversed links.

Figure 5.17 Cumulative curves of evacuees in the safety zone for different population sizes with 8 reversed links.

Figure 5.18 Clearance time as a function of evacuee population with 8 reversed links.

Figure 5.19 Evacuation rate per minute for different evacuee population sizes with 8 reversed links.

Figure 5.20 Improved network with 8 reversed links for all population size scenarios uniformly distributed to 20 sources and routed to 4 destinations (SID 2.1-2.10).

Figure 5.21 Cumulative curves of evacuees in the safety zone for different spatial distributions of evacuation demand with 6 reversed links.

Figure 5.22 Clearance time as a function of the spatial distribution of evacuation demand for 6 reversed links.

Figure 5.23 Evacuation rate per minute for different scenarios of spatial evacuation distribution with 6 reversed links.

Figure 5.24 Improved network with 6 reversed links for 5000 evacuees uniformly distributed to 20 sources and routed to 4 destinations (SID 3.1).

Figure 5.25 Improved network with 6 reversed links for 5000 evacuees randomly distributed to 20 sources and routed to 4 destinations (SID 3.2). The highlighted cells indicated greater population centers.

Figure 5.26 Improved network with 6 reversed links for 5000 evacuees in a 1 source (cell 142, highlighted) and routed to 4 destinations (SID 3.3).

Figure 5.27 Improved network with 6 reversed links for 5000 evacuees uniformly distributed to 2 sources (cells 142 and 134, highlighted) and routed to 4 destinations (SID 3.4).

Figure 5.28 Improved network with 6 reversed links for 5000 evacuees uniformly distributed to 20 sources and routed to 1 destination (cell 148, highlighted), (SID 3.5).

Figure 5.29 Improved network with 6 reversed links for 5000 evacuees uniformly distributed to 20 sources and routed to 2 destinations (cells 147 and 150, highlighted), (SID 3.5).

CHAPTER 6. CONCLUSIONS

This chapter summarizes the research, highlights its contributions, and proposes directions for future research.

6.1 *Summary*

In this study, capacity addition for an evacuation network design problem (ENDP) was formulated as a mixed-integer program. The ENDP seeks to minimize the average time that evacuees spend in the evacuation zone, by selecting the appropriate capacity addition strategy among three potential options: (i) contra-flow operation, (ii) lane addition, and (iii) combination of (i) and (ii). However, option (i) is a dominant option and is hence analyzed through several computational experiments.

The formulation of the ENDP was improved to the iENDP by identifying a special property of the cell transmission model; the maximum flow of a cell is reached at the maximum density at which free-flow speed is achieved. This observation resulted in the transformation of the linear routing constraints to an exact acyclic minimum cost flow structure. The problem was found to be NP-hard, due to the integral network design constraints.

Potential applications of the models developed in this study include contra-flow operations for evacuation under a terrorist or hurricane threat, network re-design planning for regular traffic situations including fixed one-way link design options, and peak hour reversible lane operations. Transportation planning for installing variable contra-flow signage and for contra-flow corridor operations can also be handled accurately through the proposed approach.

6.2 Contributions of the research

This study defines the Evacuation Network Design Problem (ENDP) and formulates it. From a practical standpoint, the overall contribution of this study is its ability to address planning problems faced by emergency response agencies vis-à-vis disaster management. The specific problem addressed here relates to effective evacuation demand management. Under a resource constraint, there is a need to determine an effective selection of links to be reversed so as to optimize network performance under evacuation.

Most studies in the literature have adopted modeling approaches without considering resources limitations, bottlenecks developed from ramp capacity, crossing flows constraints, exact capacity addition options, corridor contra-flow operations, and computationally efficient solution methodologies. This study addresses these critical gaps by developing a single computationally efficient formulation. It does this by extending the cell transmission model and exploiting several of its properties, further enhancing its modeling capabilities and computational efficiency.

From the problem and methodological viewpoints, the contributions of the research are:

1. *Introduction of cell connector capacity constraint (Section 3.2.1)*. Its significance is that it enables the modeling of the left/right turn capacity more realistically.
2. *Exact combinatorial modeling of network design options (Section 3.2.2)*. The capacity addition options (lane addition and contra-flow operations) are formulated using the more generic concept of a “network design option”. This approach also allows the modeling of shelter design options (Section 3.4.3), where a shelter is a destination in the safety zone with a variable occupancy. It also enables the modeling of contra-flow corridors (Section 3.4.4). Furthermore, the lane addition option can equivalently model the effect of “releasing” a lane with parking restriction policies on critical links.
3. *Traffic signal control strategies (Section 3.4.5)*. To account for the constraining effect of intersecting flows, three traffic signal control strategies were identified. They are: (i) retaining the existing signal control scheme, (ii) using a “static” strategy of allocating right-of-way to only one of the crossing flows for the duration of evacuation , and (iii) using a dynamic strategy that optimally allocates phases in a time-dependent manner. The “static” strategy was used as it is computationally efficient and behaviorally consistent.
4. *Formulation of the ENDP (Chapter 3)*. The ENDP integrated previous advancements addressed in narrow contexts simultaneously into a single

mathematical formulation. To our knowledge, this represents the first formulation unifying several practical requirements.

5. *Identification of a key property of the cell transmission model (Section 4.1).* The computational burden of the ENDP formulation led to the identification of a key property of the CTM (for the first time in the literature) that enabled the development of the efficient iENDP formulation. The property recognizes that the maximum flow of a cell is achieved at maximum density under free-flow conditions under the CTM assumptions. This observation was further exploited through the following propositions which generated the improved formulation:

- a. Better variable bounds (Section 4.3.a). Traffic conditions beyond the maximum density of the free-flow speed region do not contain superior solution sets for the optimization problem.
- b. Can ignore the study of the congested region (Section 4.3.b). Congestion phenomena, including their variables and constraints, can be ignored.
- c. Free-flow speed traffic assignment (Section 4.3.c). Holding of traffic is allowed only at sources. An evacuee exits the source cell only if free-flow speed conditions are satisfied.

These propositions were verified through experiments as producing non-inferior solution sets for the ENDP while solving the iENDP.

6. *Acyclic minimum cost flow structure (Section 4.5).* The complexity analysis of the iENDP proved that an exact acyclic minimum cost flow structure exists for the

routing constraints of the iENDP. From a practical standpoint, this implies computationally efficient solution procedures.

7. *Identification of efficient size of resource allocation (Section 5.3.3).* The sensitivity analysis indicated that there is a critical level of resource allocation (in terms of the number of reversed links), beyond which benefits are trivial (in terms of network clearance time).
8. *Topological properties of the allocated network design options (Section 5.3.3).* It was observed that capacity is allocated to the exact location of the bottlenecks. Under uniformly distributed population, capacity was allocated near the evacuation zone exits leading to the formation of corridors and, eventually, trees. In the case of 1 or 2 sources or destinations, capacity was allocated to the links in their vicinity.
9. *Population size (Section 5.3.2).* Network clearance time was observed to be linearly related to the population size.
10. *Spatial distribution of the population (Section 5.3.3).* Uniformity in the spatial distribution, and multiple origins/destinations lead to lesser clearance times.

6.3 Future research directions

The insights from this study led to the development of a graph-theoretic version of the cell transmission model as a generalized model with the potential to address applications in several transportation domains. In future research, we will study its properties; they have the advantage of utilizing exact graph theoretic solution algorithms

leading to computationally efficient implementations for intensive problems such as dynamic traffic assignment.

REFERENCES

- CA DOT, 2002. Modeling small area evacuation: Can existing transportation infrastructure impede public safety? . Final Report, Task Order 3021.
- Campos B.G. V., Da Silva P. A. L., Netto P. O. B., 1999. Evacuation transportation planning: A method of identifying independent routes. Urban Transport V, International Conference on Urban Transport and the Environment.
- Courage, K., Wallace, C., 1991. TRANSYT/7F User's Guide. Federal Highway Administration, DC.
- Cova T. J., Johnson J. P., 2002. A network flow model for lane-based evacuation routing. Transportation Research A 37, 2003, 579-604.
- Daganzo C. F., 1994. The cell transmission model: A simple dynamic representation of highway traffic consistent with the hydrodynamic theory. Transportation Research, 28B(3.3.4) (1994) 269-287.
- Daganzo C. F., 1995. The cell transmission model, Part II: Network traffic. Transportation Research, 29B(3.3.2), 79-93.
- Disaster Management Center, 1982. Self study courses: Aim and scope of disaster management. University of Wisconsin.

Fulkerson D. R., 1958. Increasing the capacity of a network: The parametric budget problem. *Management Science* 5, 1959, pp. 472-483.

Jarvis J. J., Ratliff H. D., 1982. Some equivalent objectives for dynamic network flow problems. *Management Science*, Vol. 28, No 1.

Jayakrishnan R., Mahmassani H. S., Hu T. Y., 1995. An evaluation tool for advanced traffic information and management systems in urban networks. *Transportation Research C* 2 (2), 129-147.

Jeon K., Waller S.T., Ukkusuri S., 2005. Heuristic approaches for discrete network design problem accounting for dynamic traffic assignment conditions: Formulations, solution methodologies, implementations and computational experiences. *Proceedings of the 84th TRB Annual Meeting*.

Johnson D. S., Lenstra J. K., A. H. Rinnoy Kan., 1978. The complexity of the network design problem. *Networks*, Vol. 8, pp. 279-285.

Haghani A. and Oh S. C., 1996. Formulation and solution of a multi-commodity, multi-modal network flow model for disaster relief operations, *Transportation Research - A*, Vol. 30, No. 3, pp. 231-250.

Highway Capacity Manual, Dec 2000.

Kongsomsaksakul S., Yang C., Chen A., 2005. Shelter location-allocation model for flood evacuation planning. *Journal of the Eastern Asia Society for Transportation Studies*, Vol. 6, pp. 4237 – 4252.

Kwon E., Pitt S., 2004. Evaluation of emergency evacuation strategies for downtown event traffic using a dynamic network model. *Transportation Research Board* January, 2005.

Li Y., Waller T. S., Ziliaskopoulos T.. A decomposition scheme for system optimal dynamic traffic assignment models. *Networks and Spatial Economics*, Dec 2003, pg. 441.

Lighthill M. J., Whitham J. B., 1955. On kinematic waves. I: Flow movement in long river; II: A theory of traffic flow in long crowded roads. *Proc. Royal Society A*. 229, 281-345.

Lo H. K., 1999. A novel traffic signal control formulation. *Transportation Research A*, 33 page: 433-448.

Peeta S., Ziliaskopoulos A. (2001). Foundations of Dynamic Traffic Assignment: The Past, the Present and the Future. *Networks and Spatial Economics*, Vol. 1, No. 3/4, pp. 233-266.

Richards P. I., 1956. Shock waves on the highway. *Operations Research* 4, 42-51

Sheffi Y., Mahmassani H., Powell W. B., 1981. A transportation network evacuation model, *Transportation Research A*, Vol. 16 A, No 3, pp. 209-218, 1982.

Southworth, F., 1991. Regional evacuation modeling: a state-of-the-art review. Oak Ridge National Labs, ORNL/TM-11740.

Tuydes H., Ziliaskopoulos A., 2004. Network re-design to optimize evacuation contra-flow, *Proceedings of the 84th TRB Annual Meeting*.

Ukkusuri S., 2004. Linear programs for the user equilibrium dynamic network design problem. M.S. Research, UIUC, December 2002.

Viswanath K. and Peeta S., 2003. The multicommodity maximal covering network design problem for planning critical routes for earthquake response. *Transportation Research Record*, 1857, pp. 1-10.

Wolshon B., 2005. "One-way-out": Contra flow freeway operation for hurricane evacuation. *Natural Hazard Reviews*, August 2005, 105-112.

Ziliaskopoulos A., 2000. A linear programming model for the single destination system optimum dynamic traffic assignment problem. *Transportation Science*, Vol. 34, No. 1, 2000, pp. 37-49.

APPENDICES

APPENDIX A: The GAMS/CPLEX Resources and Code

Official site : <http://www.gams.com/>

GAMS User Guides: <http://www.gams.com/docs/gams/GAMSUsersGuide.pdf>

<http://www.gams.com/docs/gams/Tutorial.pdf>

CPLEX User Guide : <http://www.gams.com/solvers/cplex.pdf>

GAMS code : Evacuation.gms

```

1 file TimeIntervalFile /DataTimeIntervalSet.inc/, RCums /RCums.csv/,
  RCells /R»
  Cells.csv/, RCellConnectors /RCellConnectors.csv/, ROptions
  /ROptions.csv/, R»
  TimeOptions /RTimeOptions.csv/, RAssemblyID / RAssemblyID.csv / ,
  RunIDfile /»
  RunIDfile.itm / ;
2
3 Set i "Cells"/
4 $include DataCSet.inc
5 /;
6 Set j "Cell Connectors" /
7 $include DataCCSet.inc
8 /;
9 Set k "Cell Design Option" /
10 $include DataNDOSet.inc
11 /;
12 Set l "Intersections"/
13 $include DataIntersectSet.inc
14 /;
15
16 Set t "Time Intervals"/ 1*400 / ;
17 set t2(t) "Subset for Time Continuity" / 2*400 / ;
18
19 Scalars
20 ClearanceEst "Estimation of Clearance Time as a Ratio to
  Studyntervals" »
  / 0.90 /,

```

```

21 CutOffEst "Initial Estimation" / 45 /,
22 UtilizationFactor "Percentage of Usage Time" / 0.6 /,
23 RFFSToTWBPS "Ratio of Free-Flow Speed to Traffic Wave's Backward
Propagat»
ion Speed" / 0.25 /,
24 StudyIntervals "Total Study intervals" ,
25 TotalEvacuees "Total Number of Evacuees" ,
26 RunID "Running ID for Databasing results" ,
27 Budget "Total Available Budget" /0/,
28 Personnel "Number of Available Personnel" /0/,
29 BudgetLevel "Variable Study Ratio" /0/,
30 BudgetUpperLevel "Upper Study bound on our constraints"/0/,
31 BudgetLowerLevel "Lower Study bound on our constraints"/0/,
32 Rcases "Number of Resource cases " /2/,
33 CongestionRate "Congestion Rate for Traffic Cells" /0.0/,
34 EvacueesPerSource "Evacuees Per Source"/250/,
35 TimeIntervalLength "Time interval in secs" /10/,
36 NewTime "Got the Time" ,
37 ClearancePeriods "Number of periods need to clear the network"
38 DesignOptions "Total Design Options" /0/ ;
39
40 parameters
41 CNin(i) "Cell's i initial Maximum Occupancy" ,
42 CQin(i) "Cell's i initial Maximum Flow",
43 CCQin(j) "Cell Connectors' j initial Maximum Flow" ,
44 Cdin(i) "Cell's initial Number of Vehicles" ,
45 NDOCost(k) "Cost for implementing NDO k" ,
46 NDOMen(k) "Number of personnel needed for implementing NDO k" ,
47 CCCIM(i,j) "Cell-Cell Connector Incidence Matrix" ,
48 CNoP(i,k) "Cell's i Maximum Occupancy for NDO k" ,
49 CQop(i,k) "Cell's i Maximum Flow for NDO k" ,
50 CType(i) "Cell's type" ,
51 Ca(i,k) "Cell's i Association with NDO k",
52 CCa(j,k) "Cell Connectors' j Association with NDO k" ,
53 CCSC(j) "Cell Connector's Start Cell" ,
54 CCEC(j) "Cell Connector's Start Cell" ,
55 CCCCInt(j,l) "Cell Connector to Cell Connector Intersections",
56 Crowded(t) "Find Clearance Time after Solving" ;
57
58
59 $offlisting
60 $include CNin.inc
61 $include CQin.inc
62 $include CCQin.inc
63 $include NDOCost.inc
64 $include NDOMen.inc
65 $include CCCIM.inc
66 $include CNoP.inc
67 $include CQop.inc
68 $include Ca.inc
69 $include CCCCInt.inc
70 $include CType.inc
71 $include RunIDfile.itm
72 $onlisting

```

```

73
74 set Source(i), Inter(i), Sink(i), Dummy(i), InterConnect(j);
75 Source(i)=YES$(Ctype(i)=4);
76 Sink(i)=YES$(Ctype(i)=5);
77 Dummy(i)=YES$(Ctype(i)=6);
78 Inter(i)=YES$(Ctype(i)=1 or Ctype(i)=2 or Ctype(i)=3);
79 InterConnect(j)=YES$(sum(1,CCCCInt(j,1))>0);
80
81
82
83 *Define Initial Evacuees + Initial Congestion
84 loop (i ,
85 *Highway Cells
86 Cdin(i)$(Ctype(i)=1) = CongestionRate * CNin(i);
87 *Arterial Cells
88 Cdin(i)$(Ctype(i)=2) = CongestionRate * CNin(i);
89 *Side Street Cells
90 Cdin(i)$(Ctype(i)=3) = CongestionRate * CNin(i);
91 *Source Cells
92 Cdin(i)$(Ctype(i)=4) = EvacueesPerSource;
93 *Safety Cells
94 Cdin(i)$(Ctype(i)=5) = 0;
95 *Dummy Cells
96 Cdin(i)$(Ctype(i)=6) = 0;
97 ) ;
98
99 TotalEvacuees = sum( i , Cdin(i) );
100 *StudyIntervals = TotalEvacuees/30 + 30 ) ;
101 StudyIntervals = card(t);
102 loop (i , CNin(i)$(Ctype(i)=5) = TotalEvacuees ;
CNin(i)$(Ctype(i)=4) = 500 ;»
) ;
103
104
105 positive variables
106 x(i,t) "Number of Vehicles in Cell i at Time Interval t",
107 y(j,t) "Number of Vehicles Moved by Cell Connector j at time
interval t",
108 zc(i,t) "Number of Vehicles remaining in cell i at time interval
t",
109
110 Qc(i) "Cell's i Maximum Flow at time interval t";
111
112 binary variables
113 z(k) "Selection of Option k",
114 q(j) "Intersection Allowance for Connector j";
115
116 free variable
117 SOTotalEvacuationTime "Objective Variable: Total Travel Times";
118
119 Qc.up(i) = max(smax( k , CQop(i,k) ), CQin(i) ) ;
120 Qc.l(i) = CQin(i) ;
121 Qc.fx(i)$(Source(i) or Sink(i))= CQin(i);
122 x.up(i,t)$Inter(i) = Qc.up(i) ;

```



```

123 x.up(i,t)$Source(i) = Cdin(i) ;
124 x.up(i,t)$Sink(i)=CNin(i);
125 x.l(i,t) = 0 ;
126 x.fx(i,"1") = Cdin(i) ;
127 z.up(k)=1 ;
128 y.up(j,t) = CCQin(j) ;
129 y.l(j,t)=0 ;
130 q.l(j)$(not InterConnect(j))=1 ;
131 q.l(j)$ (InterConnect(j))=0;
132 q.fx(j)$(not InterConnect(j))=1 ;
133 CCQin(j)=min( CCQin(j) , smin( i$(CCCIM(i,j)<>0) , Qc.up(i) ) ) ;
134
135 equations
136 SystemTravelTimes "System Travel Times Objective Function",
137 FreeFlowCondition(i,t)"Retain Free Flow Conditions",
138 MaxFlowPerCell(i) "The Maximum Flow per Cell",
139 CellVehicles(i,t) "The number of vehicles at each cell at each time
inte»
rval",
140 DivergingFlowOnCells(i,t) "Flow on Diverging Cell Connectors
limited by»
outgoing cell capacity",
141 CapacityOfCellConnectors(j,t) "Flow on Cell Connectors limited by
Cell Conn»
ectors capacity",
142 Intersections(1) "Intersection Constraints for Cell Connectors",
143 OneOptionPerCell(i) "Exactly One Option per Cell i is Selected",
144 TotalDesignOptions "Maximum number of Contra-Flow Operations";
145
146 SystemTravelTimes..
147 SOTotalEvacuationTime =e= sum( (i,t)$ ( CType(i)<>5 ), x(i,t) ) /
TotalEvacuee»
s;
148
149 TotalDesignOptions..
150 sum( k , z(k) ) =e= DesignOptions;
151
152 OneOptionPerCell(i)$Inter(i)..
153 sum(k$( Ca(i,k)=1 ), z(k) ) =1= 1;
154
155 MaxFlowPerCell(i)$Inter(i)..
156 Qc(i) =e= ( 1 - sum( k$(Ca(i,k)=1) , z(k) ) ) * CQin(i) + sum(k$(
Ca(i,k)=1 ),»
( z(k)*CQop(i,k) ) );
157
158 CellVehicles(i,t)$ ( ord(t) > 1 )..
159 x(i,t) =e= sum( j$( CCCIM(i,j)=1 ), ( CCCIM(i,j)*y(j,t-1) ) ) +
zc(i,t-1)$(no»
t(Inter(i))) ;
160
161 FreeFlowCondition(i,t)..
162 x(i,t) =e= sum(j$( CCCIM(i,j)=-1 ) , y(j,t) ) +
zc(i,t)$(not(Inter(i))) ;
163

```

```

164 DivergingFlowOnCells(i,t)$Inter(i)..
165 x(i,t) =l= Qc(i) ;
166
167 CapacityOfCellConnectors(j,t)$InterConnect(j)..
168 y(j,t) =l= q(j)*CCQin(j) ;
169
170 Intersections(1)..
171 sum( j$( CCCCInt(j,1)=1 ) , q(j) ) =l= 1;
172
173 option limrow = 0 ;
174 option limcol = 0 ;
175 option sysll = 0;
176
177 model EvacuationSystem" ... Practically ALL ... " /
FreeFlowCondition ,Sys»
temTravelTimes , TotalDesignOptions , OneOptionPerCell , MaxFlowPerCell
, Cel»
lVehicles , DivergingFlowOnCells , CapacityOfCellConnectors ,
Intersections /»
;
178
179 EvacuationSystem.reslim = 3600000 ;
180 EvacuationSystem.iterlim = 10000000 ;
181 EvacuationSystem.sysout = 1 ;
182 EvacuationSystem.optfile = 1 ;
183 EvacuationSystem.optca = 0.0 ;
184 EvacuationSystem.optcr = 0.07 ;
185
186
187 DesignOptions = 6;
188
189 RunID = RunID + 1 ;
190 NewTime = TimeExec;
191 solve EvacuationSystem using MIP minimizing SOTotalEvacuationTime;
192 * if(BudgetLevel<>0, EvacuationSystem.Cutoff =
SOTotalEvacuationTime.l );
193 NewTime = TimeExec - NewTime;
194 display NewTime;
195
196 *Find Clearance Time after solving
197 loop(t, Crowded(t)=0; if( sum(i$(not CType(i)=5),x.l(i,t))>0 ,
Crowded(t)=1 »
) ; ) ;
198 ClearancePeriods = sum(t,Crowded(t)) ;
199
200 RAssemblyID.ap = 1;
201 put RAssemblyID ;
202 Put
"RunID,Date,Time,SolveTime,ObjectiveType,ObjectiveValue,ClearanceTime,S
t»
udyIntervals>TotalEvacuees,Budget,Personnel,SolverStatus,ModelStatus" /
;
203 put RunID:0:0 " , " system.date " , " system.time " , " NewTime:0:0
" ,DualDestinat»

```

```

ion," SOTotalEvacuationTime.l:0:1 "," ClearancePeriods:0:0 ","
StudyIntervals»
:0:0 "," TotalEvacuees:0:0 "," Budget:0:0 "," Personnel:0:0 ","
EvacuationSys»
tem.solvestat:0:0 "," EvacuationSystem.modelstat:0:0 / ;
204 putclose ;
205
206 RCells.ap = 1;
207 put RCells ;
208 put "RunID,TimeInterval,Cell,Occupancy" / ;
209 loop((t,i)$( x.l(i,t)<>0 ), put RunID:0:0 "," i.tl:0:0 "," t.tl:0:0
"," x.»
l(i,t):0:1 / );
210 putclose ;
211
212 RCellConnectors.ap = 1;
213 put RCellConnectors ;
214 put "RunID,TimeInterval,CellConnector" / ;
215 loop((t,j)$( y.l(j,t)<>0 ), put RunID:0:0 "," j.tl:0:0 "," t.tl:0:0
"," y.l»
(j,t):0:1 / );
216 putclose ;
217
218 RCums.ap = 1;
219 put RCums ;
220 put "RunID,TimeInterval,Evacuees" / ;
221 loop( t , put RunID:0:0 "," t.tl:0:0 "," sum( i$(Sink(i)) ,
x.l(i,t)):0:0 /»
);
222 putclose ;
223
224 ROptions.ap = 1;
225 put ROptions ;
226 put "RunID,Option,Value" / ;
227 loop( k$(z.l(k)>0) , put RunID:0:0 "," k.tl:0:0 "," z.l(k)/ ; ) ;
228 putclose ;
229
230 RunIDfile.ap = 0;
231 put RunIDfile ;
232 put "RunID = " RunID:0:0 " ;" ;
233 putclose ;
234
235 *) ;

```