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Strategies to Improve the Efficiency of a Multimodal Interdependent Transportation System in Disasters

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Abstract

A multimodal transportation system is the prevalent commuting mode in urban areas and may be comprised of various transportation modes with flexible transfer options, such as automobiles, buses, subway, and other types of rail transit. Examining the efficiency and reliability of such an interdependent system in disasters is quite challenging due to the complexities associated with the dynamic nature of the commuting pattern, formation of choke points, and chaos resulted from the disaster that may affect people's route choice behavior in the face of urgent evacuation. For road traffic many transportation engineers utilize route guidance system as a tool for managing traffic away from the disaster area. With uncertainty in the highway network during a disaster, system efficiency is crucial in disaster management planning. Within a multimodal framework, this paper offers different strategies to improve the transportation system efficiency in disasters for two prevalent scenarios of urban commute: (1) users who primarily use the highway system; and (2) users who primarily use a transit system.

Keywords: Evacuation strategies, network efficiency, multimodal transportation, choke points

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1. Introduction

Efficient operation of a highway system during disaster is of fundamental importance in strategic evacuation planning. Recent terrorist events in the United States and around the globe underscore the importance evacuation planning. Government entities such as the United States Department of Homeland Security (DHS) are concerned with having a robust evacuation plan in place during major disasters with the main objective being to remove the maximum number of units (humans, animals) from the disaster area in the least possible time as emergency management resources are deployed to the area. This means that reliable highway networks that support evacuation routes become critical in determining if any efforts to save lives and properties are successful. Delays along the route are not desirable.

In reality, maintaining an acceptable level of service (LOS) throughout the highway network for routine daily traffic is among the biggest challenges for transportation engineers. This challenge is further exacerbated with sudden traffic load introduced by a disaster, evacuation and disaster management efforts as well as other highway network constraints, aging and sometimes out-dated transportation assets. Consequent diversions and road closures affect user route choices for exit and contribute to the already chaotic situation and the effectiveness of the evacuation plans during a disaster.

Most evacuation plans focus on the removal of vehicular components of the transportation network. Often, most especially in urban areas, other modes (such as pedestrian, bicycle and transit aspects of transportation) are usually not adequately accounted for, even though multimodal transportation system is the prevalent commuting mode in urban areas. These modes of transportation may also comprise of other modes with flexible transfer options, such as automobiles, buses, subway, and other types of rail transit. Examining the efficiency and reliability (Jha and Okonkwo 2008) of such an interdependent system in disasters is quite challenging due to the complexities associated with the dynamic nature of the commuting pattern, formation of choke points, and chaos resulted from the disaster that may affect people's route choice behavior in the face of urgent evacuation. For road traffic many transportation engineers utilize route guidance system as a tool for managing traffic away from the disaster area. With uncertainty in the highway network during a disaster, system efficiency is crucial in disaster management planning. Within a multimodal framework, this paper offers different strategies to improve the transportation system efficiency in disasters for two prevalent scenarios of urban commute: (1) users who primarily use the highway system; and (2) users who primarily use a transit system.

1. Literature Review

Literature on evacuation models is well documented. Various researches in this transportation field have focused on evacuation planning from various perspectives. Due to the complexity and dynamic nature of transportation network attributes during a disaster, one of the challenges of evacuation modeling is accurately estimating evacuation time. Lindell et al (2002) presented Empirically Based Large-scale Evacuation Time Estimate Model (EMBLEM) which is an Evacuation Time Estimate (ETE) model. Their research chronicled various contributions in the methodology for ETE. However, they acknowledge its limitation of not accounting for transit dependent users. Wilmot and Mei (2004) compared the relative accuracy of ETE models. They view logistic regression and neural network models as more superior in predicting evacuation more accurately than the participation rate model.

Traffic and incident management strategies require continuous adaptation to dynamic traffic demands. Dynamic Traffic Assignment (DTA) models provide an understanding of highway network characteristics such as link flows and link travel times. Traffic assignments are viewed through static and dynamic categories. Static equilibrium models have been widely used for long-range planning. However, they are deficient in capturing the essential features of traffic congestion. Even though researchers have made tremendous contributions in developing Dynamic Traffic Assignment (DTA) models over the past three decades, proper formulation is still lacking largely due to their complexity when compared to static models. For further details on the advances in past research in DTA, refer to Peeta and Ziliaskopoulos (2001), Viti and Tampere (2010) and Szeto and Wong (2012).

Ozdamar et al (2004) modeled this dynamic time-dependent transportation problem during emergencies from logistics perspective. While their model shows the capacity to provide updated more effective supply lines for distribution of resources as more information becomes available, it does not consider the impact of user choices in a multimodal environment in the overall performance of the highway network. Liu et al (2007) modeled an adaptive control framework for traffic management. Liu's model shares our view of real-time modeling but assumes dynamic OD demands are given and gives relatively minimal consideration to the effect of multimodal choices in their analysis. Lammel et al (2009) simulated time-dependent large-scale evacuation in hurricane prone regions. Even though they acknowledge the need to account for pedestrians in the evacuation scheme, their perspective did not consider the potential effect of access to multimodal transportation in achieving efficient pedestrian evacuation.

Research studies on route choices and transportation network user behavior during a disaster have seen considerable research advances. In origin-destination (OD) trip estimations (Mei 2002; Murray-Tuite and Mahmassani 2003; Fu and Wilmot 2004 and Jha and Okonkwo 2010), and behavior analysis (Baker 1991; Helbing et al. 2000; Fraser-Mitchell 2001) and path planning (Kang et al 2004). They are rarely concerned with transportation cost which affects the overall efficiency of routes to effectively accommodate the sudden loads introduced to the network during evacuation. Knowledge of the dynamic changes within the network in real time is valuable to decision-makers in allocating the resources or advising better travel routes. However, due to the distinct features of different types of disasters, specific planning models have been developed for various evacuation scenarios, including nuclear plant crisis, hurricane, flooding, and fire, etc. Southworth (1991), Urbina and Wolshon (2003), and Alsnih and Stopher (2003) presented detailed discussions on evacuation planning modeling. Rice, Coleman et al (2012) modeled time-based evacuation to determine choke points and shortest path to safe centers from wildfire areas. Their research work involved the use of GIS Network Analyst to develop Closest Facility (CF) solver considering travel time and distance to locate facility closet to a given incident. However, the case study used for the analysis appears to have rural attributes with fairly moderate traffic and spatially limited transit connectivity.

Kang and Jha (2004) also used GIS to model path selection for Unmanned Ground Robot (UGR). While the UGR research focused input parameters to establish robot paths by avoiding enemy zones, no-go and no-drop areas, it shares our idea of network dynamics and continuous path update for the user based on new and current information. In an urban environment such a CBD area, we recognize that in disaster situation, reliability of transit systems is essential in evacuating pedestrians and other transit-dependent users. This notion underlines the importance of considering access to transit mode within the network as evacuation process develops. Mishra et al modelled intermodal connectivity. In this work, the focus was to compare connectivity of transit system performance at line, transfer facility, local and regional levels. In this paper, we apply the connectivity principles presented by Mishra el al but focus our analysis on the delay introduced to the transit system during evacuation. Our interest is the effectiveness of transit mode of transportation under system stress due to sudden influx of system load, directional constraints and the resulting choke points that must be traversed during disaster.

We believe the model presented in the research does address the issues associated with urban highway networks such as heavy vehicular and pedestrian traffic, grid configuration of the highways which further promotes travel delay. This paper seeks to fill this research gap.

1.1. Structure

For the highway system, we propose to improve the system efficiency by minimizing the effect of added load to the road network due to the disaster and external influence caused by vehicles entering the system. The operational framework of a highway system consists of three prevailing states, namely influx, disaster area, and choke points. An effective evacuation strategy should account for the transition through the three states of transformation as system conditions dynamically change. A hybrid simulation (Kang et al. 2011) and analytical framework will be employed to develop an evacuation strategy for a typical urban transportation network, such as Washington, D.C. or Baltimore.

In order to analyze the efficiency of the transit system, the notion of node, line, transfer, and regional connectivity is introduced, which is an extension of one of our recent works (Mishra et a. 2012). It may be assumed that transit commuters will seek the nearest stations to exit the city impacted by the disaster, which will affect the performance of the transit system.

We introduce the formulation for measuring the performance of a transit system located in a Central Business District (CBD), such as Washington, D.C. based on the concept of "connectivity." In order to analyze the performance efficiency of the transit system, the notion of node, line, transfer, and regional connectivity adapted from our previous works (Mishra et al. 2012) is combined into a single connectivity index to derive a quantitative measure of the transportation network performance, which extends the set of performance assessment tools decision makers can utilize to assess the quality of a transit system in disasters.

We first analyze the efficiency of pure vehicular evacuation using the modified concepts developed Jha and Okonkwo (2008) time-reliability under user equilibrium. Second, we introduce the effect of transit modal choices within targeted evacuation area with the application of Mishra's transit connectivity matrices. The results become inputs to our proposed modified UGR model to show continuous network update while minimizing the network overall evacuation time using the efficiency of user decisions, dynamic routing and the choke discharge as primary indicators.

1.2. Problem Formulation

Consider a network of highways located in an urban area such as Baltimore City or Washington DC. If a disaster area develops, rings of zones also develop around the disaster area which determines the level constraints that must be implemented to keep evacuation efficient. We propose that these rings describe three basic zones: disaster area; restricted area; and safe area. Within the disaster area, all flows are outward and away from the disaster and no returns (backward flow) are permitted. Within the restricted area, there are possible constraints (diversions and road closures) that affect user decisions and choices. In the safety zone, there are no restrictions. In this paper, our focus is on the congestion within the disaster and restricted zone. Please refer to … for literature on highway congestion theories outside the safety zone.

The challenge becomes to move quickly and efficiently through the restricted zone from disaster zone to safety zone. Inflow and outflow (arrival and departure rates) matrices of nodes determine whether the network evacuation efficiency is achievable (i.e. whether flow conservation occurs consistently throughout the nodes). As flow through the network in the restricted zone continues to build, some nodes become congested (i.e. node arrival exceeds node departure) creates a momentary back-up in the preceding links. This momentary back-up causes 'shockwave' effect throughout the network. It is this form of delay in entering a node that we call choke points.

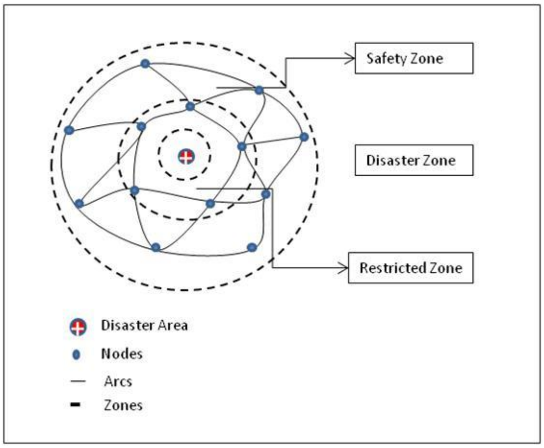

Figure 1. Typical Zones in a Disaster

Choke points are time dependent and are characterized by user perception and decision over time. This means that they are not static. For a given network over a period of time, choke points are dynamic and appear or disappear at defined locations based on the flow characteristics of links and capacity of the nodes to transfer flow.

In order to analyze the concept of network (node) efficiency we offer a mathematical model for identifying choke points. The underlying theory is based on the relationship between link flow and time interval. We will focus on analyzing network conditions beyond the equilibrium state (i.e. when the network begins to disintegrate and becomes less reliable). If flow a link flow q_a, over the time interval t_0 (this can be selected based on industry practice for data collection) is to pass through a node N, the arrival rate b_a over that time interval is given by,

$$\boldsymbol{q_a = \sum_{a=1}^{m} b_a * t_0} \qquad (1)$$

$$\boldsymbol{q_a = q_0 + \Delta q_t} \qquad (2)$$

Where, $\boldsymbol{q_0}$ = Initial link free flow per unit time $\Delta\boldsymbol{q_t}$ = incidental change in link flow due to additional system loading within the interval $\boldsymbol{t_0}$.

If distribution function $\boldsymbol{\beta}$ (given by ratio of link flow to total outflow) is known, we can predict the loading characteristics of the succeeding links by computing the departure rates from the node. Equation (1) can be re-written as,

$$\boldsymbol{q_a = \sum_{i=1}^{m} b_a * t_0} \qquad (3)$$

$$\boldsymbol{a \;\forall\; m;\ \text{and a} \;\neq 0}$$

$$\boldsymbol{\beta_a = \frac{q_a}{\sum_{i=1}^{m} q_a}} \qquad (4)$$

The term $\boldsymbol{\beta_a}$ will change due to the state of the network: free flow versus jammed condition. Under free flow conditions, the outflow split to succeeding arcs is somewhat stable as user choices are unconstrained. However, as disaster and evacuation activities build, some links become undesirable to the user. This coincides with increasing values of $\boldsymbol{\beta_a}$ beyond the stability state and as departure rate, $\boldsymbol{d_N}$ from node approaches zero. We call this the desirability index of the link and as its values approach 1, the more the likelihood of user to choose an alternate path. Desirability index is an indicator of potential choke points. Thus, if flow conservation is maintained through any given node N, Equation (5) below can be written to show that inflow to node ($\sum \boldsymbol{b_a}$) must equal to outflow from node.

Consider a directed network with origin, *O* close to disaster area as shown in figure 1. Let *A* represent the total number of links in the networks with $N = \{N_1, N_2, N_3, \ldots, N_n\}$ number of nodes. In the event of a disaster, the movement tends towards major evacuation exit nodes *N4* and *N7*. The exit paths from *O* to E are $O \rightarrow N_1 \rightarrow E$ or $O \rightarrow N_2 \rightarrow E$. We have chosen two O-D pair network for simplicity. O-D pair in this problem consists of O→E and O→F which represent the path between the O and the exit nodes. Let *a* be any arc (where $a \in A$) with flow, x_a and travel time $t_a = \{t_1, t_2, t_3, \ldots, t_A\}$.

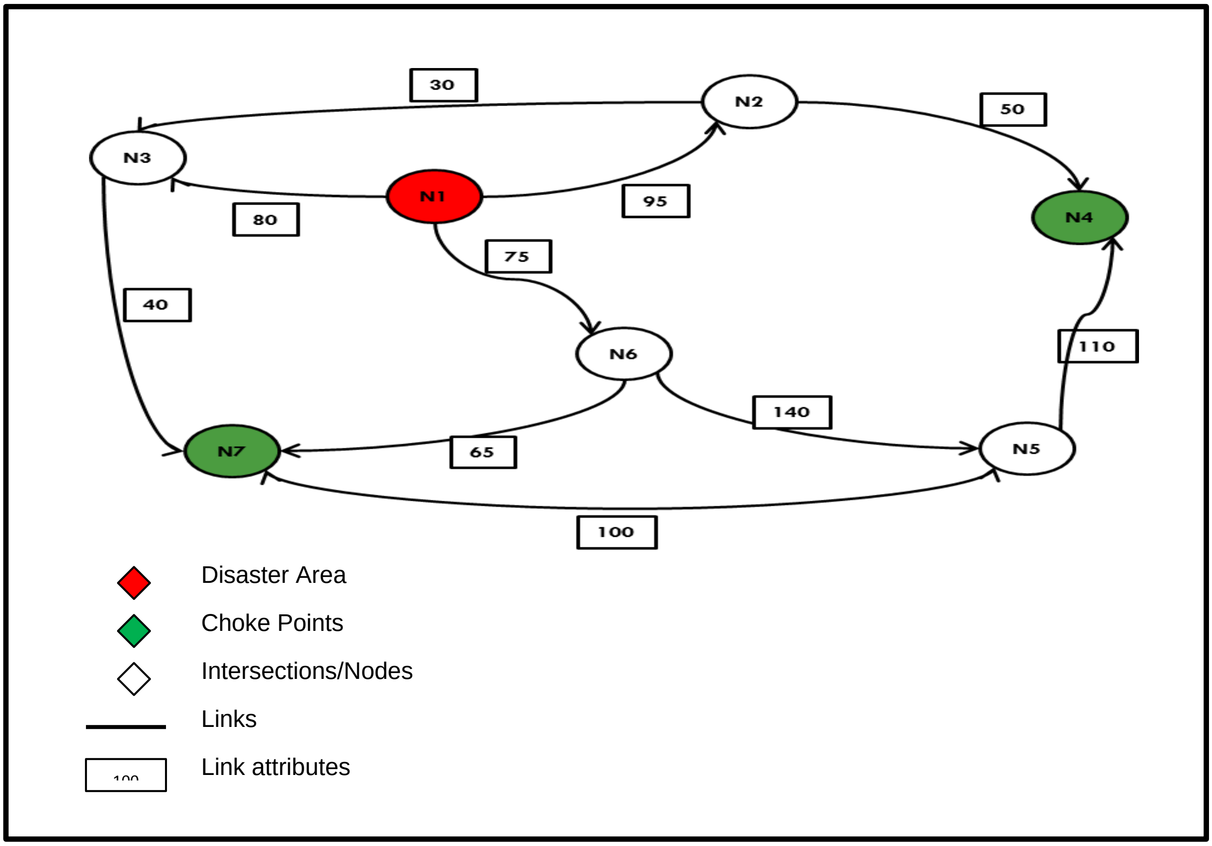

Figure 2 – A directed highway network

For free flow conditions O→E,

$O \rightarrow N_2 \rightarrow N_4 > O \rightarrow N_6 \rightarrow N_5 \rightarrow N_4$ if and only if $t_{1\text{-}2} + t_{2\text{-}4} > t_{1\text{-}6} + t_{6\text{-}5} + t_{5\text{-}4}$

For all arcs, the best solution in minimizing arc flow is at the point where additional delay due to transit activities, Δt_a equates to nothing significant. In other word evacuation is optimal and efficient at $\Delta t_a = 0$ or $t'_a = t_a$ which also satisfies the free flow condition. However, the best solution for an O-D pair may not be optimal for achieving the desired system efficiency for evacuation. Therefore, further iterations to find the optimal values for the travel time that is acceptable to the users (such as acceptable system delay due to evacuation) as well as satisfies system requirements (such as evacuation time goals). **I**n order to estimate travel time considering user choices, we must find a reliable way to predict the likely user choices given a combination of evacuation paths, *k*. According to Jha et al (2008), The travel cost *C* associated with user choices can be estimated using,

$$\boldsymbol{C_k^{OD}} = \sum_{\boldsymbol{a}} \boldsymbol{t'_a \delta_{a,k}^{OD}} \qquad (\mathbf{5})$$

Where,

$\boldsymbol{C_k^{OD}}$ = the total travel time (sum of individual link travel time, t'_a) on path k connecting origin O and the destination D

Therefore along a path, k the objective functions are two-fold: (1) minimize total travel time, T_k required to traverse all the three neighborhoods to safety and in the process enhance evacuation time throughout network; and (2) minimize link flow to reduce the likelihood of potential choke points from developing and facilitate earlier user choices and better load distribution throughout the network. This can be expressed as

$$\min Z = \sum_a x_a * t_a(x_a) \qquad (5)$$

Subject to,

$$\sum_{k=1}^{m} q_k^{OD}, \sum_{k=1}^{m} \beta_{ak}^{OD} = \{O, D\} \quad \textit{Path limit constraint} \qquad (6)$$

$$\sum_{i=1}^{m} \beta_{ak}^{OD} \leq 1 \qquad \textit{Desirability constraint} \qquad (7)$$

$$q_k^{OD}, \beta_{ak}^{OD} \geq 0 \qquad Non = negative\ constraint \qquad (8)$$

$$x_a = \sum_O \sum_D \sum_k q_k^{OD} * \delta_{ak}^{OD} \qquad (9)$$

$$d_N = \sum_{i=1}^{m} b_a \qquad \textit{Node integrity} \qquad (10)$$

Where,

t'_a = travel time of link *a* (t_a) plus differential travel time due to transit activities, Δt_a

q_k^{OD} = the flow on path k connecting the origin O and the destination D pair

q_{kT}^{OD} = the flow on path k connecting transit origin O and the destination D pair

x_a = the flow on link a

r_a = the reliability of link, a which defines t_a (link performance function, $t'_a(x_a)*$ r_a)

$$\delta_{a,k}^{OD} = \begin{Bmatrix} 1 if link\ is\ part\ of\ path\ k\ of\ O-D\ pair \\ 0 \qquad\qquad Otherwise \end{Bmatrix}$$

$$\tau_{a,k}^{OD} = \begin{Bmatrix} 1 if link\ is\ part\ of transit\ route\ within\ an\ O-D\ pair \\ 0 \qquad\qquad Otherwise \end{Bmatrix}$$

In the same way we define a parallel set of parameters to account for non-drivers who must also evacuate. As defined previously, the terms $q_{ak}^{OD}, \alpha_{ak}^{OD}$, and δ_{ak}^{OD} are assigned are flow per unit time along the connectable transit route (i.e. transit line plus transfer station); desirability function that determine user choice along the given path; and binary function that determine if user path leads to transit access point respectively. Transit loads are defined by normal transit loads plus additional loads due to user choices and influx demand caused by desire to leave at the same time. The later element also contributes to the total time required to evacuate all units from disaster area. The base flow for this concept is the ridership for each transit mode. This defines the normal number of users per unit time.

The difference between vehicular and transit modes is that vehicular mode travels through a defined path (the roadway), the transit mode has at least three distinct stages of movement to define a complete path; user path, access points and transfer point. User path is unpredictable and difficult to define. However, it is a fairly reasonable assumption to expect that the user

will be attracted to the nearest 'known' transit access point. Therefore, a true account of all transit users at transit access points could be an onerous proposition. Even though capturing exact flow quantities will enhance the accuracy of the formulation of this problem, we are fairly confident that there are enough trends in the pattern of user path to validate the results of this analysis.
We can express the objective function as,

$$\min Z = \sum_a x_a * (t_a(x_a) + \Delta t_a(x_a) * \tau_{a,k}^{OD}) \tag{10}$$

Subject to,

$$\sum_a q_k^{OD} = \{O, D\} \qquad \forall O, D \tag{11}$$

$$q_k^{OD} \geq 0 \qquad \forall k, O, D \tag{12}$$

$$x_a = \sum_O \sum_D \sum_k q_k^{OD} * \delta_{ak}^{OD} \tag{13}$$

Expanding equation (6) to include transit elements of the network, we have

$$x_a = \sum_O \sum_D \sum_k (q_k^{OD}\, \delta_{ak}^{OD}) + (q_{kT}^{OD}\, \tau_{ak}^{OD}) \tag{14}$$

1.3. Hypothetical Case Study

Let us consider the network shown in Figure 1 for the hypothetical case study. As shown in the figure the disaster zone is close to Node 1 and the exit points are Node 4 and Node 7. Hence, someone evacuating from Node 1 have six alternative routes and they are as follows:

N1→N2→N4 (Route 1)
N1→N2→N3→N7 (Route 2)
N1→N3→N7 (Route 3)
N1→N6→N5→N4 (Route 4)
N1→N6→N7 (Route 5)
N1→N6→N5→N7 (Route 6)

Now, if the existing transit routes that connects the disaster zone and exit points are as follows:

N1→N2→N4
N1→N3→N7

1.4. Numerical Example

In this example, we calculate the desirability index based on randomly generated arrival rate. Our solution showed interesting preliminary results shown in Table 1. Using Poisson distribution, random arrival rate within a 15-minute interval was generated over a 2-hour period for the routes to be analyzed. The flow through each link over the specified time interval was computed. The peak flow for the period of observation can easily be found. The route desirability index which shows the attractiveness to a given route is computed. As shown, after several iterations (3 for this example) which takes into account additional network loading (achieved by incremental assignment), the most attractive route was found to be Route 1

(N1→N2→N4). Even though the number of connecting nodes is higher (i.e. 4 versus 3), Route 2 (N1→N2→N3→N7) was shown to be a better choice in terms of attractiveness than Route 3 (N1→N3→N7). When consideration is given to presence of transit along Routes 1 and 2, very different results were obtained. Even though, Route 1 remained the most desirable, its DI increased from 0.7037 to 0.7198. The most undesirable route also changed from Route 3 to Route 2, thus demonstrating the effect of the presence of transit connectivity on the performance of the network during the evacuation exercise.

Table1 1 – Summary of Flow Computation Results

	λ = 3			λ = 5			λ = 7		
	Flow	Peak Flow	Route Desirability	Flow	Peak Flow	Route Desirability	Flow	Peak Flow	Route Desirability
Without consideration for transit load									
ROUTE 1	945	1320	0.7159	1560	2100	0.7429	2280	3240	0.7037
ROUTE 2	1155	1920	0.6016	2295	2700	0.8500	3210	3720	0.8629
ROUTE 3	1005	1560	0.6442	1785	2220	0.8041	2340	2700	0.8667
With consideration for transit load									
ROUTE 1	1185	1560	0.7596	1800	2340	0.7692	2505	3480	0.7198
ROUTE 2	1650	2460	0.6707	2535	2940	0.8622	3435	3900	0.8808
ROUTE3	1125	1680	0.6696	1905	2340	0.8141	2445	2820	0.8670

1.5. Discussion

The process described above forms the foundation of the solution model to the complex problem presented in the literature. Ideally, travel time (or link reliability) should drive user decisions under equilibrium conditions. However, beyond equilibrium state and considering the panic state and the overall chaotic nature of evacuation, desirability matrix becomes more valuable in user decisions as they go through the network. For large real life networks, several iterations are required keeping in mind the capacity limits of the links and all the network constraints identified in the formulation. As new updates become available and as link capacities are reached, undesirable routes (i.e. with desirability index approaching 1) appear as choke points that must be avoided. The user choices reflect this through increased loading at more desirable links. This continues until the entire disaster area is evacuated. The overall evacuation time is recorded and compared with the pre-established evacuation time goals. The goal of an efficient evacuation system is to keep ratio of actual evacuation time to set evacuation time to less than 1.

In the present formulation we considered the exit nodes with adequate capacity. However, the exit nodes can also become the choke point if adequate capacity for the evacuating vehicles is not available. With additional capacity constraint for the exit node, the problem can be solved easily using the formulation presented in this paper.

1.6. Conclusion

We have described a classic transportation problem, formulated and presented a solution to identify choke points as well as advice users (vehicular and transit) on the available desirable routes to facilitate user choices. The concept of using desirability index for this purposed was presented. While we are confident that the approach utilized showed promising preliminary results, more work need to be done in applying this model to real life urban highway road network such Baltimore City and Washington DC using real data. This will require large scale data collection and computing systems which are yet to be developed. However, we believe the resulting model will be valuable in assisting decision-makers in determining where to allocate resources during a disaster, to facilitate quicker evacuation as well as identify the paths with the least effect on the evacuation activities which can be used to bring in disaster mitigation resources.

1.7. Acknowledgements

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