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AN AGENT BASED MODEL FOR EVACUATION TRAFFIC MANAGEMENT

Manini Madireddy
D. J. Medeiros
Soundar Kumara

The Pennsylvania State University
Department of Industrial and Manufacturing Engineering
310 Leonhard Building, University Park
PA 16801, USA

ABSTRACT

In this paper we build an agent based evacuation model and use it to test a novel traffic control strategy called *throttling*. The evacuee agents travel from a source to a destination taking the dynamic shortest time path (total travel time depends on the distance to destination and the congestion level). Throttling involves closing a road segment temporarily when its congestion level reaches an upper threshold and opening it when congestion level falls below a lower threshold. Experimentation was performed by comparing the total evacuation time obtained with throttling to a base case (non-throttling) using a small test network and the more realistic Sioux Falls network. We found that throttling improves the total evacuation time significantly. To further test the effectiveness of our control strategy we compared it to contraflow on the test network and found the results to be comparable.

1 INTRODUCTION

Evacuation is characterized by immediate and rapid movement of people away from the location of a threat or disaster to a safer destination. This is a primary concern of traffic managers as it leads to congestion and chaos. Hurricanes Katrina and Rita are examples of recent large scale disasters in the U.S. with considerable loss of life and property. (Katrina caused 1833 deaths and $81 billion in damages, while Rita caused 120 deaths and $11.3 billion in damages (McKinney 2007)). Reports indicate that deployment of evacuation plans was delayed in the case of Katrina and as a result both these hurricanes experienced a heavy traffic backup on the interstates leading to vehicles travelling at crawling speeds (Caruso 2005; Kim, Shekhar, and Min 2008). Transportation networks are not built to handle rare events like disasters, as it is not financially practical. Moreover, evacuees typically optimize their individual utility (e.g., travel time) at the possible detriment of overall system performance. Other factors such as the nature of the disaster and the geographical topography further complicate the evacuation process.

Clearly, there is a strong need for effective traffic management strategies during evacuation in order to improve system performance (usually measured as total evacuation time), and several classes of control strategies have been proposed (Liu 2007). Traffic control is implemented when the objective is to use the available traffic network more efficiently by routing the evacuees. The contraflow strategy reverses unused inbound lanes in the direction of destination to increase traffic outflow. Staged evacuation aims at better distribution of evacuee demand by issuing evacuation orders zone wise. The signal control strategy attempts to increase street capacity by implementing an effective signal-timing plan. Of all these control strategies, contraflow has been widely researched and frequently used in practice. Despite its advantages, there have been incidents in the past where this strategy has failed to be rewarding. For example, during hurricane Ivan contraflow created havoc due to lack of coordination between officials. Some of the outbound links were directed onto inbound lanes which were still not reversed (Varney 2008). This created a lot of commotion leading to increased evacuation time.

In this paper we present a new control strategy called *throttling* and test its effectiveness using an agent based evacuation model. Throttling involves closing a road segment temporarily when its congestion level reaches an upper threshold and opening it when congestion level falls below a lower threshold. Throttling is a simple strategy which can be implemented dynamically in real time. Implementation can be simpler and less expensive as compared to existing traffic control strategies. Throttling is counter intuitive as we are reducing the capacity of a road segment, i.e., we are rendering a road segment inactive even before it reaches its full capacity. This approach prevents the road segments from getting over congested, and thus avoids slowdowns on the segment which can increase evacuation times.

To systematically analyze various traffic management techniques, one has to build accurate evacuation models. There are a large number of analytical and simulation based evacuation models in literature. Although analytical models yield richer insights, they often require approximations (for computational tractability) whose validity remains questionable. For this reason, we use an Agent Based Simulation (ABS) evacuation model. The main advantages of ABS are that we can model individual agent behavior and study the emergent system level dynamics in the evacuation environment. More importantly, ABS also helps in answering a number of "what-if" questions regarding various control strategies (Bonabeau 2002, Zhan and Chen 2008).

We model traffic at a single vehicle level. Our model considers vehicles (modeled as cars) to be intelligent agents carrying evacuees from a source to a destination following a certain set of rules. These autonomous agents make dynamic route choices based on the congestion level on roads and the shortest distance to the destination. This is a possibility in today's world as most cars are equipped with radio and GPS. Drivers can perceive road conditions by listening to updates on radio and identify best alternate routes with the help of GPS. Our model also considers the traffic manager as an intelligent agent who implements throttling dynamically as the system behavior evolve.

We investigate the effects of throttling on small test networks and the well-known Sioux Falls network (Bar-Gera 2001). Our results demonstrate that throttling improved the system performance in both these networks. It was also observed that the total evacuation time for throttling and contraflow were comparable in the test network scenario.

2 LITERATURE REVIEW

There are a number of evacuation models available in the literature; Section 2.1 provides an overview of these with a focus on ABS evacuation models. Section 2.2 describes different traffic control strategies with emphasis on the contraflow strategy.

2.1 Existing Evacuation models

Evacuation models can be classified by level of abstraction as macro, meso or micro level. Macro level evacuation models represent traffic flow in terms of traffic density, average speed of vehicles, and average congestion on a traffic network. Meso level models aggregate traffic as platoons. Most of the models at these two levels are formulated as a network flow or traffic assignment problem (Cova and Johnson 2003; Kim, George, and Shekhar 2007; Hamacher and Tjandra 2002). In micro level simulation models, modeling is done at individual vehicular level.

ABS models have become tools for community leaders, disaster managers, and traffic managers as they are helpful in preparing for a disaster by answering a number of "what-if" questions (Bonabeau 2002). The main advantage of ABS is its potential to reveal the system level collective behavior while just modeling individual agent behavior (Rathi and Solanki 1993, Macal and North 2007). Zhang, Kin, and Ukkusuri (2009), built an ABS model to study human behavior under disaster condition. Their model has three different types of agents: normal agents who stick to their initial route, 100% greedy agents who change route every time they come across congestion and 50% greedy agents who change route 50% of the times they face congestion. When agents arrive at an intersection with congested links, greedy agents take the least congested road segment and then use the least distance path to destination. They show that system performance (i.e., total evacuation time) declines as the proportion of greedy agents increases. The agents in our current model start with an initial route choice and dynamically re-route themselves whenever faced with congestion. All the agents in our model are 100% greedy. However, rerouting decisions and path are computed based on global congestion levels as opposed to greedy agents in Zhang, Kin, and Ukkusuri (2009) which consider only local congestion levels. We assume that global congestion level information is available to all users. This assumption is justified because of the radio updates and GPS.

The most common metric used in evacuation papers is total evacuation time, defined as the total time elapsed between the first evacuee leaving the source to the last evacuee reaching the destination (Shendarkar and Vasudevan 2006). The problem of multiple destinations can be converted to a single virtual destination problem using the concept of one destination evacuation described by Wang, Pan and Pan (2009).

2.2 Existing Control Strategies

During a disaster certain road segments need to serve evacuee demands that are higher than the demand they were built for. This causes congestion leading to increasing travel times. Traffic managers apply numerous control strategies in order to mitigate this effect. In this section we will be describing three control strategies – traffic routing, signal control, and contraflow (Liu 2007). Except for contraflow, the other control strategies aim at using the available road network more efficiently. In contraflow the road network is redesigned to meet the evacuee demand. The contraflow strategy has been implemented during several hurricanes and is considered a potential remedy for disaster evacuation (Wolshon 2001; Kim, Shekhar, and Min 2008).

All the evacuation strategies are either staged or simultaneous. Staged evacuation aims at distribution of evacuee demand over time. This helps in preventing congestion on road segments. In this strategy the traffic manager(s) divide the affected area into zones. Each zone is issued evacuation order at different times based on levels of urgency (Chen and Zhan 2006, Chen and Zhan 2004). In simultaneous evacuation as the name suggests all the evacuees in the affected area are issued evacuation order at the same time. The ABS evacuation model we built is a no notice simultaneous evacuation model.

In traffic routing strategy, the traffic manager uses the available road network more efficiently by distributing the evacuee demand across different routes. This is achieved by guiding the evacuees from overcrowded roads to ones with excess capacity. Signal control strategy during evacuation is used to increase the capacity of road segments by implementing an effective signal-timing plan. It can also be used in providing easy access to/from evacuation routes and preventing bottlenecks at access points. The contraflow strategy tries to minimize the total evacuation time by identifying the best network configuration created by reversing the unused inbound lanes in the direction of the destination (Tuydes and Ziliaskopoulos 2006; Kim, Shekhar, and Min 2008). This increases the capacity of outbound road segments and the traffic outflow. It has been successfully employed during several hurricanes including Floyd, Katrina and Rita (Varney 2008, Urbina and Wolshon 2003). Nowadays, contraflow is also being used during non-emergency situations– including before or after popular special events and to meet the morning and evening rush hour demand.

Most of the models in the literature dealing with the contraflow problem are macro or meso level analytical heuristic based models (Kim, Shekhar, and Min 2008; Tuydes and Ziliaskopoulos 2006; Tuydes 2005; Kim and Shekhar 2005). There are a few micro level simulation models; these models have mainly been used to compare different contraflow configurations for the same road network or compare base and contraflow configuration. All these contraflow models are static in nature meaning the traffic manager cannot change the network configuration in real time looking at the evacuee behavior.

The following are some of the most popular micro level contraflow models. Theodoulou and Wolshon (2004) developed a CORSIM microsimulation model with the objective of improving the understanding of traffic behavior under contraflow evacuation conditions; they modeled Interstate I-10 through New Orleans. During hurricane Floyd the North Carolina departments of transportation and public safety with assistance from other departments implemented lane reversal on I-40. This lane reversal was not beneficial. In order to understand the reasons behind this failure researchers built an ABS evacuation model in CORSIM. The model was also used to compare the three alternative contraflow topologies proposed. This work provided the officials with better insights and was able to help them identify the best contraflow configuration (William et al. 2007). Meng, Khoo, and Cheu (2008) developed a bi-level solution algorithm which is a combination of integer programming (IP) and microlevel simulation. The IP model solves the contraflow problem and identifies the reconfigured network. The micro simulation model (built using PARAMICS) takes this reconfigured network as input and evaluates real evacuee behavior on it. The output of the simulation model is the total evacuation time. The algorithm iterates until the stopping criteria is met (number of iterations, or percentage improvement).

3 MOTIVATION

Various control strategies for traffic management now exist to reduce the total evacuation time. However, they are based on two critical assumptions: altruistic evacuee behavior, and accuracy of forecasted data. Most evacuation models assume evacuees sometime take longer routes in order to improve the overall system performance. In real evacuation scenarios, evacuees behave greedily trying to take the shortest path to destination while also responding to system conditions. Also, owing to the uniqueness of disasters, accuracy of forecasted data is highly questionable. These observations serve as a motivation for our real time control strategy *throttling.* Throttling was initially developed to deal with unruly computer programs and is currently being used for the containment of computer viruses. We in this paper for the first time are trying to apply this strategy towards traffic management. The central idea of throttling with respect to computer viruses is to limit the number of new connections a computer can make with other machines in a given time period (Balthrop et al. 2004) by decreasing the outgoing bandwidth. Analogously, we block a road segment once its congestion level reaches an upper threshold and unblock it when the congestion level reaches a lower threshold. Throttling is simple, decentralized, relatively inexpensive to employ, and can be implemented in real time reacting to the evacuee behavior. Moreover, it can be used in harmony with other static control strategies like contraflow to further boost the system performance. Throttling is similar to a closed loop feedback controller like the one in a heating thermostat. The controller in a thermostat tries to maintain the temperature near a desired setpoint by comparing it to actual temperature (feedback). In the case of throttling the traffic manager (controller) tries to keep the congestion level on road segments below an upper threshold by comparing it with current road congestion level. We use two thresholds (upper and lower) to prevent excessive state switching.

4 MODEL DESCRIPTION

Prior to model description, we will introduce notations that will be useful for the rest of the paper. We represented our road network using a directed graph *G (V, E)*, where *V* is a set of nodes that represents road intersections and *E* is a set of all the links that represent road segments. Each node $v \in V$, is given a location (x-coordinate, y-coordinate), and assigned a type (source, transshipment, or destination). Additional information about the fraction of evacuee vehicles generated is provided for each source node. We assume that all evacuee vehicles depart simultaneously towards the destination. Each link $e \in E$, has a *length, capacity* (C_e)*, # of lanes, congestion level* (ρ_e) as attributes. The length of the link is determined by the coordinates of its end points. The capacity of a link is defined as the maximum number of cars that can fit on a link. In other words,

$$C_e = \frac{length\ of\ link\ e\ \times\ \#\ of\ lanes}{Average\ length\ of\ a\ car}$$

The congestion level on a link is defined by the number of cars on the link. More formally,

$$\rho_e = \frac{\#\ of\ cars\ on\ link\ e}{C_e}$$

The ABS evacuation model was built in NetLogo (Wilensky 1999). The model contains the following modules – (i) Evacuee vehicle movement behavior, (ii) Evacuee vehicle route choice, and (iii) Control Strategy.

(i) Evacuee vehicle movement behavior: This module describes the movement of an agent on a road segment. Every vehicle first checks for nearest neighbor in front of it. If there is no neighbor it accelerates up to the speed limit of the link. Otherwise, the vehicle adjusts its speed such that its distance traveled in unit time is less than the distance to its nearest neighbor. These movement rules help in avoiding collisions.

(ii) Evacuee vehicle route choice: Evacuee vehicles move from source of threat to destination making dynamic route choices. Generally, total travel time is a function of distance traveled and the congestion level. Drivers have been modeled to be greedy as they prefer to maximize their utility, i.e., reduce their total travel time by picking the shortest distance path. Also, they are non-strategic as they do not consider the route choices of other agents when choosing their routes. All the agents start from source with an initial route choice, which is the shortest distance path. Vehicles reroute themselves if they encounter a congested link in their initial route. Link is said to be congested if it reaches its maximum capacity. The new routes are calculated assuming the congested links are not available. All the shortest path computations are based on Dijkstra's algorithm.

(iii) Control strategy: In this paper we propose a new control strategy called throttling. This strategy is enforced by the traffic manager on the road network to improve the total evacuation time of the system. In this strategy, the transportation manager blocks a road segment *e* at time *t*, if congestion level on a link reaches upper threshold (*UT*).

Blocking rule: If $\rho_e(t-1) < UT, \rho_e(t) \geq UT,$ then block road segment e

A transportation manager unblocks a blocked link *e* at time *t*, if congestion level on the link falls below the lower threshold (*LT*).

Unblocking rule: If $\rho_e(t-1) > LT, \rho_e(t) \leq LT$, then unblock road segment e

This strategy helps in preventing the road segments from getting over congested which can lead to longer travel time. This approach also aims at efficiently using the underutilized road segments.

5 EXPERIMENTATION AND ANALYSIS

Experimentation was performed to investigate the effectiveness of the throttling control strategy on the evacuation process. We used Total Evacuation Time (*TET*) as an indicator of system performance when subject to a given control strategy. Several settings of control parameters (*UT, LT*) were analyzed and the performance was compared to the base case (without throttling) and the contraflow control strategy. The base case is a particular instance of the control parameters where, *UT=LT=1*. We have used an artificial network and a more realistic network (Sioux Falls) as our test cases.

In all our experiments, the control parameters (*UT, LT*) were varied such that $UT \in \{0.1, 0.2, \ldots, 1\}$, $LT \in \{0, 0.1, \ldots, 1\}$ and $LT \leq UT$. The model parameters such as speed-limit, acceleration, car-size, total population were set as 20m/s, 1m/s^2, 4m, and 1000 (2000 in the case of Sioux Falls) respectively. Experiments were replicated three times to obtain statistical significance. Note that randomness in our model is due to the presence of alternate shortest paths and the behavior of cars at intersections. In the case where more than one car can enters an intersection at the same time, a choice of which car leaves first is made randomly. Further analysis was performed to capture the effect of initial evacuee car locations and presence of alternate paths on the throttling control strategy.

5.1 Application of Throttling in the Test Network

In order to analyze the dependence of *TET* on the choice of (*UT, LT)* we consider an artificial network (Figure 1(a)) as a test bed. The network has three source nodes {1, 2, and 3} from where a given fraction of the total population (0.3, 0.4, and 0.3 respectively) begins their evacuation.

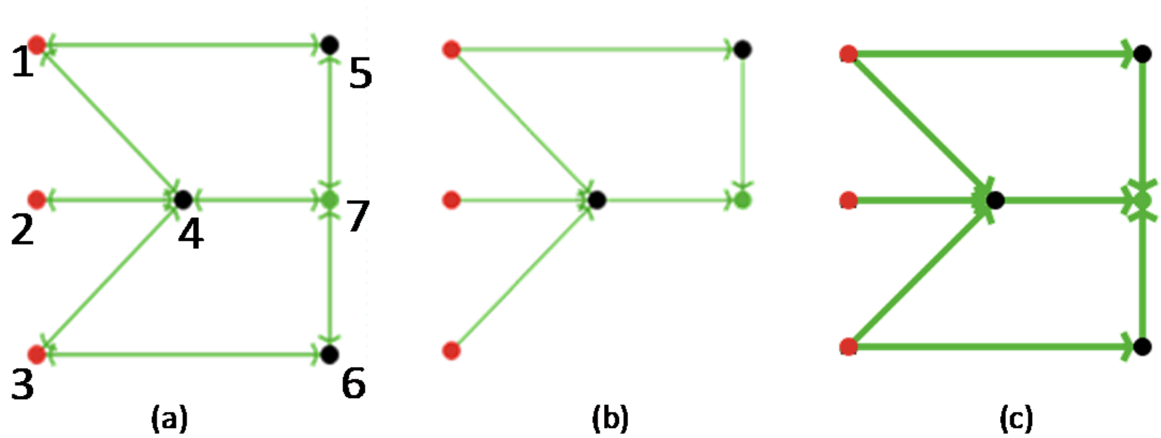

Figure 1: (a) Test Network Topology (NetLogo Screenshot). There are three categories of nodes: Source nodes (Red), Transient nodes (Black), and Destination node (Green). There are two types of links: Blocked (Red) and Unblocked (Green). (b) Modified Test Network (NetLogo Screenshot). (c) Test Network Topology – Contraflow (NetLogo Screenshot). This is a directed graph with link width doubled (compared to Figure 1(a)) as the number of lanes has doubled.

The *TET* for the base case was found to be 2409 and the lowest value was obtained at a combination of (0.1, 0.1). The control parameter setting (0.1, 0.1) indicates that a road segment will be blocked once its congestion level goes beyond 0.1 and will be unblocked when the congestion level reaches or goes below 0.1. From Figure 2 one can observe a general trend of increasing percentage improvement (over the base case) as *UT* decreases. Percentage improvements of 25% or more were obtained at lower values of UT (≤ 0.4). In other words, as the degree of throttling increases, performance of the system improves. This observation is dependent on the topology of the network. Notice that Node 1 has two paths leading to the destination P1:{1-4-7} and P2:{1-5-7}. Although, path P1 is shorter it is heavily congested as traffic from nodes 2 and 3 will use the common link e_{47} (refer Figure 3(a)). The greedy usage of path P1 leads to higher *TET* values. On the other hand, the uncongested path P2 is sparingly used. Our throttling control strategy mitigates the congestion effect by forcibly closing the road segments leading to node 4 (refer to Figure 3(b)). This forces the agents to use alternative path P2 and as a consequence, improve system wide performance. It is worth mentioning that for some agents, the individual travel times will increase as they are forced to take a longer path.

We now test the effect of initial evacuee location on our throttling strategy. We varied the number of cars starting at each source location under different throttling strategies and the resulting *TET* values are summarized in Table 1. For this particular topology, it was observed that the lowest value (represented by the red cells) for all initial evacuee population settings occurred when (*UT, LT*) = (0.1, 0.1). These preliminary results indicate that throttling is not sensitive to initial population locations.

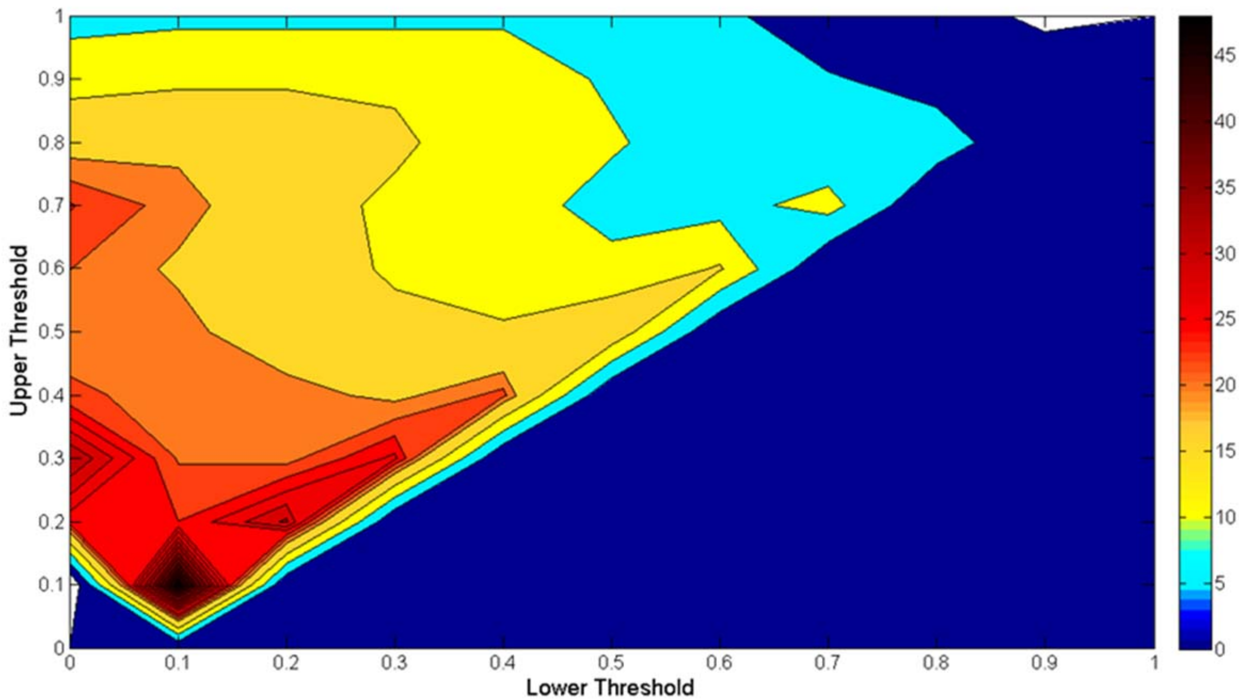

Figure 2: Contour plot of percentage improvement of total evacuation time - test network

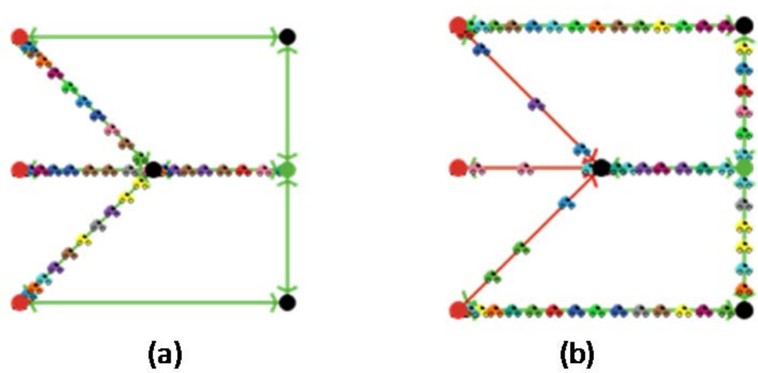

Figure 3: (a) Figure shows evacuee vehicles interacting with each other and the road network. All the cars from node 1, 2 and 3 are trying to take the shortest route path. (b) The road segments that are leading to node 4 are throttled by the traffic manager as they reach maximum capacity. This forces the cars to take alternative routes.

We now investigate the effect of the presence of alternate shortest paths on throttling. To this effect, we modified the topology of the test network by removing a path leading to the destination (refer to Figure 1(b)). The maximum improvement in *TET* when compared to base case is 23% which occurred at (*UT, LT*) = (0.1,0.1) (refer Figure 4). Note that the improvement has come down from 45% due to the absence of alternate paths. We expect this trend to persist in any topology as the presence of alternate paths is critical to throttling. The reason is that without other paths, there is no other outlet for congested vehicles.

Table 1: *TET* values for different source population distribution and control parameter settings. The lowest *TET* value for each configuration is marked with a red color cell and the color gradually changes to green as the *TET* value increase.

Fraction of evacuee vehicles /(UT,LT)	(0.1,0.1)	(0.6,0.2)	(0.7,0.1)	(1,1)
(0.3, 0.4,0.3)	1245	1983	1902	2409
(0.6,0.3,0.1)	1846	2148	2232	2265
(0.5,0.2,0.3)	1520	1767	1806	2184
(0.4,0.4,0.2)	1368	2238	2202	2619
(0.3,0.5,0.2)	1668	2337	2409	2844

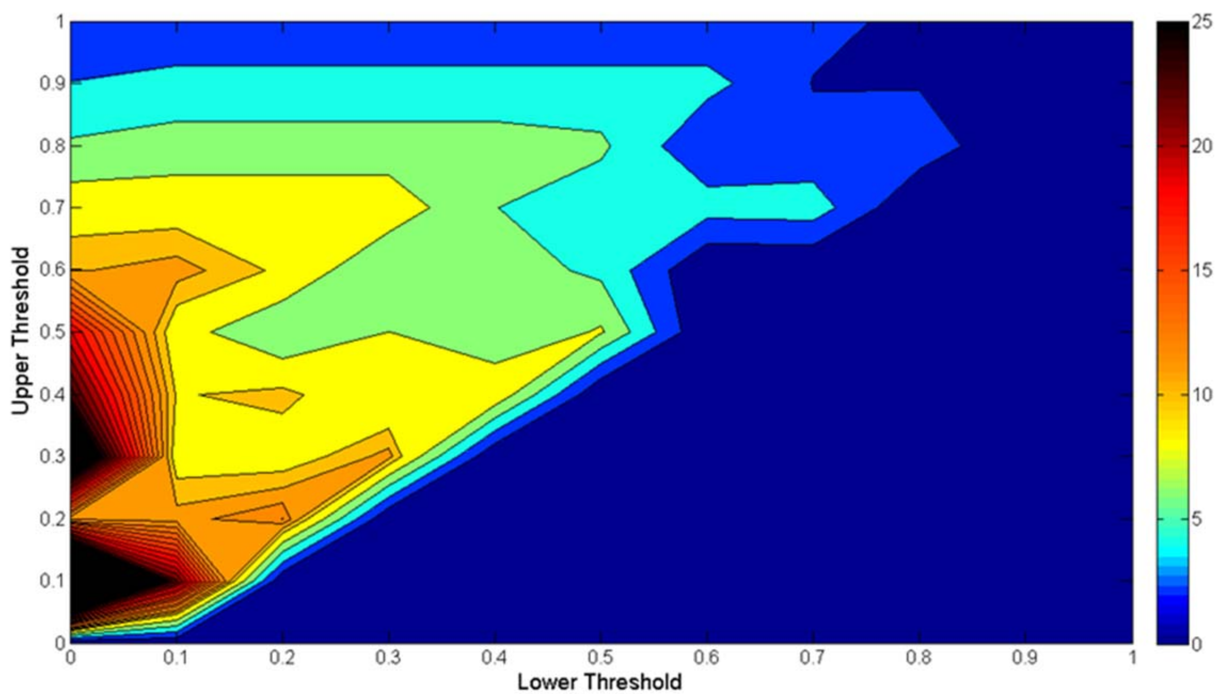

Figure 4: Contour Plot of Percentage Improvement of Total Evacuation Time - Modified Test Network

5.2 Application of Throttling in the Sioux Falls Network

As mentioned earlier the effect of throttling is dependent on network topology. We applied throttling to a more realistic network Sioux Falls (Bar-Gera 2001). We used the same model parameters as in the test network except for the total population which was set to 2000. In our simulation we considered all the peripheral nodes to be source nodes generating the same fraction of the population. The green node at the top is the destination node (Figure 5). The *TET* for each combination of (*UT, LT*) was obtained and the lowest *TET* of 3085 was achieved at (0.2, 0). The contour plot with the percentage improvement over base case can be seen in Figure 6. Unlike in the test network case there is no general trend observed. In any general transportation network we cannot expect any particular trend between *TET* and the control parameters (*UT, LT*).

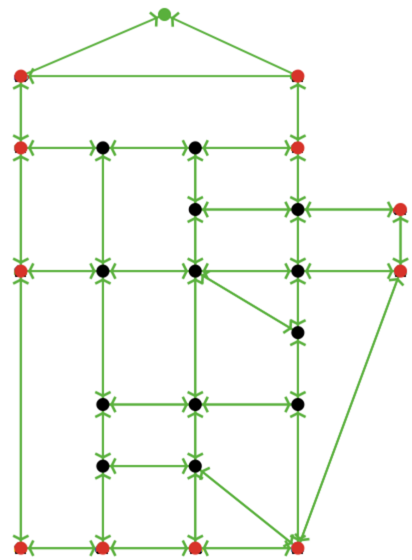

Figure 5: Sioux Falls network (NetLogo Screenshot)

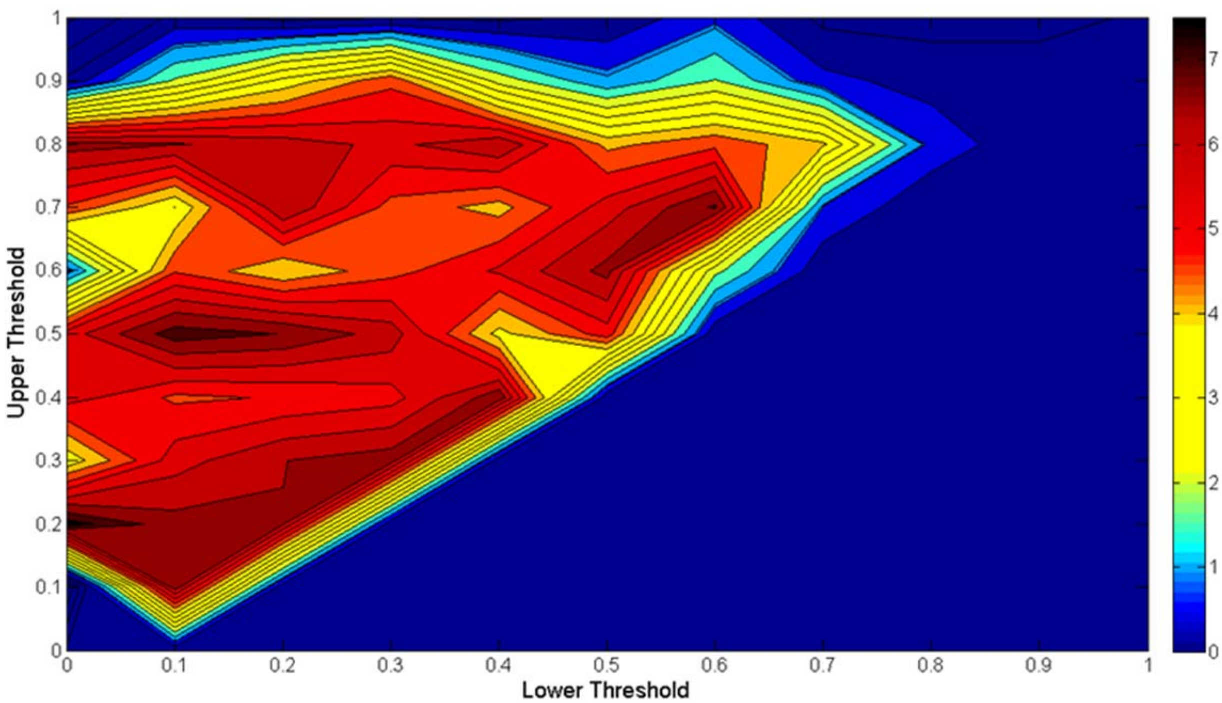

Figure 2: Contour plot of percentage improvement of Total Evacuation Time – Sioux Falls

5.3 Comparing Throttling and Contraflow

The test network was modified to implement static contraflow. This was done by changing the direction of all the inbound links towards the destination. In Figure 1(c), it can be observed that the link widths are doubled as the number of lanes is doubled. The *TET* obtained in the case of contraflow was 2% better than throttling with the values of 1220 ± 1.96 and 1245 ± 1.96 respectively indicating throttling and contraflow are comparable approaches. Though contraflow performs better than throttling, implementing contraflow maybe more cumbersome. As a last part of our analysis we applied throttling to the static contraflow network. The lowest *TET* was obtained at (0.2, 0.2) and is 659 ± 1.96. This shows that the combination of throttling and contraflow yields significant improvement over throttling or contraflow implemented independently.

6 CONCLUSIONS AND FUTURE WORK

In this paper we proposed a new control strategy called throttling. Using an ABS model, we demonstrated that throttling results in reduction of *TET* compared to base case (non-throttling). Moreover, performance of throttling is enhanced as the number of alternate paths to destination increases. Also the choice control parameters are insensitive to minor perturbations to initial distribution of evacuee car population. During our experimentation we observed that most combinations of control parameters improve the system performance and the improvement reaches its maximum at higher degrees of throttling. The natural next step is to use Optimization via Simulation (OvS) to identify good control parameter settings. In our current work all the road segments could be throttled, as a part of future work we want to develop a metric to identify ideal links to be throttled in a road network using metrics from network science and traffic flow. We also found that contraflow is comparable to throttling as a traffic control strategy. Interestingly contraflow and throttling are complementary to each other and can be applied in conjunction. Effective ways of combining them will be an interesting research avenue. There are several practical issues to be resolved before throttling can be implemented in reality. For example, how can one ensure a smooth transition from blocking a road segment to unblocking it? More studies are required to address such practical concerns.

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AUTHOR BIOGRAPHIES

MANINI MADIREDDY is a Ph.D. candidate in the Department of Industrial and Manufacturing Engineering at the Pennsylvania State University. She received her Bachelor's degree in Electrical Engineering from Jawaharlal Nehru Technological University (JNTU), India and Master's in Industrial Engineering from Pennsylvania State University. Her research interests are in Disaster management, Agent Based modeling, Systems Biology, Complex Networks and Data mining. Contact: manini@psu.edu.

D. J. MEDEIROS is an Associate Professor in the Department of Industrial and Manufacturing Engineering at Penn State University. She holds a Ph.D. and M.S. in Industrial Engineering from Purdue University and a B.S.I.E. from the University of Massachusetts. She has held numerous positions for WSC including program chair, proceedings editor, track coordinator, publicity chair, and registration chair. She is a Trustee of the Winter Simulation Conference Foundation. Her research interests include facilities design, logistics, and scheduling in healthcare delivery and manufacturing systems. Contact: djm3@psu.edu.

SOUNDAR KUMARA is the Allen, E., and Allen, M., Pearce Professor of Industrial Engineering at Penn State. He also holds a joint appointment with the Department of Computer Science. He holds an Adjunct Professor position with C.R. Rao Institute of Advanced Mathematics, Statistics and Computer Science, University of Hyderabad, India. His research interests are in engineered large-scale networks, sensor networks, and web services. He is a Fellow of Institute of Industrial Engineers and Fellow of the International Academy of Production Engineering (CIRP). Contact: skumara@psu.edu. .