Study of the Effects of Evacuation Routes and Traffic Management Strategies in Short-notice Emergency Evacuation in Downtown Jackson

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ABSTRACT
The paper presents the study of simulating the emergency evacuation traffic due to an assumed Chlorine gas spill incident in Jackson downtown in Mississippi, identifying best evacuation corridors and comparing possible effective traffic management strategies, in order to increase the cumulative evacuation vehicles out of the protective action zone and decrease the average travel times for the evacuation trips. To relieve heavy traffic congestions around the spill location caused by the sudden increased evacuation demands, traffic management strategies including law enforcement for traffic controls, contra-flow operations and variable message signs were tested for the three major arterial streets in the protective action zone (PAZ) zone to improve the evacuation performance compared to a baseline traffic management strategy. A multi-factor Analysis of Variance (ANOVA) was conducted for the simulation results to numerically assess the effect of each of the possible factors that may contribute to the performance of the short-notice evacuation. Evacuation scenarios used for the comparisons of evacuation effectiveness and the statistical analysis indicated that: 1) the selection of a best contra-flow operation route depends on the interference from the intersecting links and the cost in the traffic management deployment; and 2) using both contra-flow and variable message signs could effectively improve the evacuation performance over using none or only one of the two strategies.
INTRODUCTION

From industrial chemicals to toxic wastes, hazardous materials are part of the environment where we live. They are transported in and around the country through all modes of transportation networks. Toxic gas spill in transport can impose serious risk and threat on the well-being and safety of people and the environment. In Mississippi, several harmful chemical-leaking incidents have happened in the past. In 1986, 4 miles north of Collins, MS, poisonous chlorine gas spewing from derailed tank cars forced the evacuation of about 100 families and closed a 10-mile section of a busy highway in southern Mississippi (1). In 1987, a freight train carrying a toxic flammable chemical derailed at 2 miles west of Corinth, a town of 14,000 residents in northeastern Mississippi, forcing the evacuation of up to 1,000 people (2). In 2009, officials in Pearl, MS had to close down a portion of U.S. 80 near Hinds Community College due to a 3-inch rupture on the natural gas line (3). These past incidents have necessitated the inclusion of the scenario of emergency evacuation due to a chemical leakage in this study for Jackson, MS, which is the largest metropolitan area in Mississippi with a total population of 539,000 in the area.

An emergency evacuation aims to moving a large disaster affected population through a transportation network toward safer areas quickly and efficiently. In emergency and critical infrastructure management, the adoptions of optimal evacuation routes and effective traffic management strategies could well improve the evacuation performance by relieving heavy traffic congestions generated by the sudden surge of the evacuation traffic demand (4). Frequently, traffic simulations are conducted to evaluate the effects of available evacuation routes and candidates of traffic management methods. Hence how to use valid traffic simulations to assess and select good evacuation routes and effective traffic management strategies for an assumed emergency evacuation scenario becomes the objective of this study.

The remainder of the paper is organized as follows: the background reviews the previous studies on evacuation traffic simulation programs and the applications of the dynamic traffic assignment program DynusT in emergency evacuation studies, followed by the determination of evacuation zone, the evacuation trip demand modeling, and the details about traffic management strategies in networks. The simulation results and analysis are presented and discussed in the next section. The last section summarizes the main findings of the study.

BACKGROUND

Evacuation Traffic Simulation Programs

Recently, several dynamic traffic assignment (DTA) simulation programs were frequently used in evacuation studies because of their modeling features of handling real-time traveler information and the effect on driver’s dynamic choice of trip routes, such as Vissim (5), Aimsun (6), TransModeler (7), DynaSmart (8), DynusT (9) and DTALite (10). Since the simulation models are of different degrees of granularity in network representation, they are marked as microscopic (small), mesoscopic (medium), and macroscopic (large). The main disadvantage of a microscopic model is
the extensive data and computer resource requirements to characterize each individual vehicle. On the other hand, a macroscopic model does not have the capability of keeping track of individual driver decisions. In contrast, mesoscopic models can denote greater geographic area than micro models and enables for more precise results than macro models as they track each driver’s route choice when the vehicle traverses through links between the origin and destination. As a mesoscopic DTA simulation program, the Dynamic Urban Systems for Transportation (DynusT) was used to establish the simulation network models for this study due to the sizes of the population and area.

DynusT contains demand forecasting procedures for planning functions and traffic simulation models for operational applications. Traffic operations such as contra-flow can be deployed and assessed using the traffic simulation models in the program. In addition, the simulation models also support evaluation of intelligent transportation system (ITS) deployment options, through the use of simulation-based DTA. DynusT provides the capability of modeling the evolution of traffic flows in a traffic network, which result from the decisions of individual travelers seeking the best en-route paths over a given planning horizon. It overcomes many of the known limitations of the static tools. These limitations pertain to the types of alternative routes that may be represented and evaluated, and the policy questions that a planning agency is frequently required to address.

Traffic Simulations for Evacuation Studies

The modeling and design of a more effective emergency evacuation plan has been rigorously investigated (11, 12, 13) since the early studies dealing with traffic management under emergency conditions. The previous research has identified the most feasible operational strategies to maximize the efficiency and performance of transportation infrastructure under evacuation conditions to be: 1) contra-flow operation (4, 14, 15, 16); 2) mass transit utilization (17, 18, 19); and 3) coordinated evacuation operation (20, 21, 22). In addition, the definitions and modeling for Protective Action Zone (PAZ) and Emergency Planning Zone (EPZ) (23), and for origin, route, and destination for evacuations (24, 25) also help improve traffic simulations for emergency evacuation studies. The following two studies evaluated different evacuation strategies in traffic simulations using the dynamic traffic assignment model DynusT.

Details of developing an optimal zone-based vehicle evacuation strategy based on an optimization-simulation approach were discussed by Zheng et al. (26). The optimal egress strategy was obtained by solving a universal quickest flow problem and the solution was implemented and evaluated in DynusT. Evacuees would follow optimal routes to safe locations outside the hot zone and then select behaviorally realistic routes to their final destinations. Background traffic was included in the model to simulate more realistic traffic conditions and the route choice of background traffic in response to the evacuation strategy and driver information strategies was carefully addressed. The scenario study on the basis of a bomb threat scenario at a football stadium showed that the proposed methods could generate the reasonable and
meaningful results for the intended no-notice scenario.

The Texas DOT sponsored a study to develop a decision support tool to help determine whether the strategies with the widening and completion of evacuation lanes on I-10 and US-290 as well as a partial contraflow plan for the I-45 corridor, after implementing contraflow operations on I-45 to relieve massive evacuee congestion departing Houston to the north during the evacuation for Hurricane Rita in 2005, and also on I-10 during the Hurricane Ike evacuation in 2008, would adequately handle the evacuation demand for various Houston–Galveston region evacuation scenarios. In order to accomplish this, Songchitruksa et al. (27) described the quantitative assessment of the performance of alternative evacuation strategies using a dynamic traffic assignment model DynusT. The evaluation results indicated the evacuation lanes on I-10 and US-290 can sufficiently handle high evacuation demand on both routes without the contraflow operation. In addition, a partial contraflow plan for I-45 was shown to provide sufficient capacity to handle high evacuation demand in lieu of full-scale contraflow operation.

These studies have shown the applicability of the DynusT program to regional evacuation problems in evaluating the effects of evacuation routes and contraflow operations for short-notice as well as planned evacuation scenarios. The DTA nature of the program also makes it capable of testing the effect of the deployment of variable/dynamic message signs (VMS or DMS) that provide real-time traffic information to the evacuees as an ITS technology.

Study Methodology
In this study, a chlorine gas spill incident in Jackson downtown as a freight train derailed at the major railroad yard was considered to justify a no-notice or short-notice emergency evacuation for the affected area. The traffic operations during the emergency evacuation over the whole road network for the affected population to leave the protective action zone (PAZ) and arrive in safe destinations were simulated using the DTA program DynusT. Various traffic management strategies such as contra-flow operations and variable message signs (VMS) were deployed on different alternative evacuation routes in order to improve the evacuation performance. Different evacuation traffic demand levels were assumed along with the selected traffic management strategies and routes to identify the best strategy and route for different evacuation intensities. A multi-factor analysis of variance (ANOVA) was conducted to numerically evaluate the effects of the contributing factors for the study.

EVACUATION ZONE DETERMINATION
Significance of Study
Jackson is the capital city and the most metropolitan area of Mississippi. Jackson is a railroad town with the presence of Canadian National (CN) and Kansas City Southern (KCS) and Amtrak. As early as in 1870's, the Illinois Central (IC), as the predecessor of the present Canadian National had started railroad transportation service in Jackson and Mississippi. The CN North Jackson Yard on N. Mill St is located in the heart of
the Greater Jackson area, only a few miles to each of the densely populated cities Jackson, Ridgeland, and Madison. In the very near vicinity (3.5 miles) of the railroad yard are several social-economically important locations that include Jackson State University’s football stadium or Mississippi Veterans Memorial Stadium (MVMS), University of Mississippi Medical Center campus (UMMC), Millsaps College, Belhaven University, Baptist Hospital, St Dominic's Medical Center, and G.V. "Sonny" Montgomery VA Medical Center (28). Figure 1 shows some of the important locations near the CN railroad yard. The map also shows the existence of Interstate highway 55, and three major arterial streets near the CN railroad yard, which are N West St, N State St, and Woodrow Wilson Ave (WWA).

![Figure 1 CN North Yard and Social-economically important locations.](image)

A spill of the highly toxic chlorine gas as a freight train with 30,000 gallon tanker derailed during the afternoon peak hours at the railroad yard near N. Mill Street, Jackson downtown was assumed to trigger a no-notice or short-notice emergency evacuation. If the emergency evacuation occurred during the football season and an ongoing game, there might be a significant increase in the number of vehicle trips generated near the stadium. A traffic simulation study of the performance of the highway network under such an emergency evacuation situation would be quite meaningful and necessary for the railroad yard and the railroad companies, the affected community, the local and state traffic engineers, and the emergency management agencies to be more prepared.

**Threat Zone Calculation**

The Areal Locations of Hazardous Atmospheres (ALOHA) developed by the U.S.
Environmental Protection Agency (EPA) and National Oceanic and Atmospheric Administration (NOAA) program was adopted for the Protective Action Zone (PAZ) calculation to determine the zone area affected by the spill incident (29). Figure 2 shows the threat zone due to the chlorine spill, calculated by the ALOHA software.

![Threat zone determined by ALOHA](image1)

![Protective Action Zone of evacuation](image2)

**Figure 2 Estimate of affected area for evacuation.**

As shown in Figure 2(a), the PAZ is outlined by a confidence line, which includes uncertainty in a safe manner. The downwind distance of the outlined zone is 6.0 miles and the widest span perpendicular to the wind direction is about 4 miles. The outermost area (yellow) inside the outlined zone is at Acute Exposure Guideline Level 1 (AEGL-1) by the 60th minute after the spill incident. The next area (orange) is at AEGL-2 in 60 min. The innermost (red) area is at AEGL-3 in 60 min. To have maximum safety, the area outlined by the confidence line with a downwind distance of 6.0 miles and a span of 4.0 miles at the wide end was taken as the Protective Action Zone.
Zone or the evacuation zone, totally 17.3 square miles, which is shown in Figure 2(b).

The gas spill incident was assumed to happen in an afternoon when the worst prevalent wind intensity and direction and the afternoon peak hour traffic condition were all to be considered. The Jackson State University MVMS stadium with a capacity of more than 60,000 audience seats located only a few blocks away from the railroad yard was also considered in the study.

EVACUATION TRIP DEMAND MODELING

The simulation program dynamically assigned each vehicle a “shortest path” over the highway network with nodes and links, traffic control devices and traffic management deployments, and real-time traffic information, for each of the OD (origin and destination) pairs due to the trip demands for routine transportation needs and evacuation needs in the Greater Jackson area. Therefore, the simulation program needed two major data inputs which were the highway network model and the OD demand. The highway network model was provided by the Planning Division of the Mississippi Department of Transportation (MDOT). The MDOT network model geographically divided the Greater Jackson Area into 691 traffic analysis zones (TAZ) with 4,607 nodes and 10,288 links. Characteristics data for each node and link, and social-economic attributes for each TAZ zone were also contained in the model. The steps for preparing the trip demand data are discussed in the following paragraphs.

Evacuation Trip Demand Components

The trip demand due to daily and routine transportation needs is called background traffic. The background traffic for each TAZ was first calculated in terms of trip production and trip attraction for the TAZ zone, by plugging the MDOT TAZ attribute data into the travel estimate models developed by Central Mississippi Planning & Development District. The trip productions and attractions for all TAZs were then applied to the gravity models with friction factors by Martin et al (30) using the TransCAD program (7) to generate the 24-hour O-D demand tables which were the background trip distribution among the TAZs.

The evacuation demand included two parts. One part was a reduced background demand, and the other was an impact demand. The order of the evacuation had a reducing effect on the background demand. From the moment when evacuation operation was in effect, all newly generated trips whose destinations were located within the PAZ were cancelled due to the chlorine spill and the evacuation order. The impact demand was the evacuation traffic in response to the incident that moved evacuees away from the PAZ. During the simulated evacuation operation, the impact evacuation traffic demand was added to the reduced background demand.

Evacuation Trip Origins and Destinations

For the impact evacuation trips, the origins and destinations of the evacuation trips needed to be determined. The evacuation trips should originate from the TAZs in the PAZ and be headed to TAZs in the safe area. Based on MDOT’s data, there were 27
TAZs in the PAZ with 6,007 occupied dwelling units, 45,431 employees, and 11,588 school attendants in the PAZ. The 27 TAZs were seen as origins to produce evacuation traffic except for TAZ #163, in which no habitant was found.

On the other hand, evacuation trips were assumed to have destinations in TAZs out of the PAZ. The number of evacuation trips with destinations in a TAZ was in proportion to the number of dwelling units in the TAZ. This was based on the assumption that every evacuee could find home or temporary housing in the Greater Jackson area. There were 604 TAZs out of the evacuation zone that had non-zero dwelling units. People with no access to car use would rely on public transit and ride on buses. The bus users were assumed to travel to shelters near the PAZ. There were 4 TAZs in the city area with public shelters.

Evacuation Trip Production Levels
The total impact evacuation demand was estimated at 55,281 vehicles by private car and 193 bus vehicles by public transportation when there was not an activity in the MVMS stadium. If a game activity was going on in the stadium when the chlorine spill happened, more evacuation trips and vehicles would be expected. The capacity of the stadium is 60,492 seats. With a stadium activity considered, additional trip production would be added from the activity audience in Zone #149 where the stadium is located. The number of evacuation vehicles from the stadium was assumed to be in four different levels as 0 (baseline), 20,000, 40,000, and 60,492 vehicles, respectively.

Evacuation Trip Distribution and O-D Demand Table
The impact evacuation trip distribution and O-D demand tables were also generated by applying the impact evacuation trip production and attraction to the gravity model and friction factors mentioned earlier using the TransCAD software. The reduced background demand matrix and the impact demand matrix for each hour were combined and input to the simulation program DynusT to run simulation results for the evacuation traffic demands and traffic management strategies deployed in the network.

TRAFFIC MANAGEMENT STRATEGY DEVELOPMENT
Baseline Traffic Management
The network setup of traffic control for the baseline management plan is shown in Figure 3(a). After the order of evacuation, traffic controls were (with law enforcement) placed at upstream links of relevant highways or streets to block inbound traffic from entering the PAZ zone. For example, traffic on I-55 SB and I-55 NB were forced to exit the freeway before the Meadowbrook interchange and E Fortification St. interchange, respectively. However, the freeway segment between the Meadowbrook interchange and E Fortification St. interchange remained open for the evacuation traffic to leave the PAZ zone.
Besides the traffic controls at the entry points to the PAZ, traffic controls were deployed on the collector streets at the MVMS stadium when there was a stadium activity. In a baseline, no advanced traffic management strategy was deployed.

**Advanced Traffic Management Strategies**

In the study, the effectiveness of deploying contra-flow operation and portable variable massage signs (VMS) was evaluated for three arterial streets. The reversal use of inbound traffic lanes with light or little traffic volumes for the heavily used outbound direction has been proved effective in many studies and successfully implemented in practices as well. As an Intelligent Transportation System facility, a VMS device can be connected to and remotely controlled by a traffic management center (TMC) through fiber optic cables or wireless technologies to display dynamic real-time traffic information such as congestion, incident, or detour information to
assist the road users to avoid the congested routes or locations and therefore increase mobility for the network.

Three candidate arterial streets: N West Street, N State Street, and Woodrow Wilson Avenue, each with four or more traffic lanes in two directions, were selected to test and compare the effectiveness of deploying advanced traffic management strategies on an arterial corridor in simulations. The three streets were selected because they are the closest traffic corridors to the railroad yard and the MVMS stadium.Traffic management strategies contra-flow operations and portable VMS devices were deployed on each of the three corridors and simulated under evacuation scenarios.

As shown in Figure 3(b), the contra-flow operation on each of the three candidate arterial streets is described in the following: 1) The simulated contra-flow operations on Woodrow Wilson Avenue were for both westbound and eastbound directions which were separated by a segment between Mill St and N West St where the railroad yard is located. The contra-flow operation on the west segment of Woodrow Wilson Ave was from Mill St until Medgar Evers Blvd and the contra-flow operation on the east segment was from N West St to I-55. The west and east segments were made westbound and eastbound respectively moving traffic away from the PAZ. 2) The trial contra-flow operation on N State St was on the north segment by reversing the direction of the southbound traffic lanes to northbound over that segment, beginning at Woodrow Wilson Ave and ended at Meadowbrook Rd. The Old Cannon Rd was diverged from N State St and was also deployed northbound contra-flow up to I-55. 3) N West St runs parallel to N State St and is on the other side of the MVMS stadium. A possible contra-flow operation was deployed on the north segment of the street beginning at Woodrow Wilson Ave and ended at Meadowbrook Rd. Table 1 shows the list of flow-reversible candidate facilities in this study.

<table>
<thead>
<tr>
<th>Street Name</th>
<th>Network Connectivity</th>
<th># of Access Points</th>
<th>Segment Length (mi)</th>
<th>Contra-flow Lane Configuration</th>
<th>Control Strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>N West St.</td>
<td>MVMS</td>
<td>2</td>
<td>1.7</td>
<td>4:0 Northbound</td>
<td>Contra-flow/VMS</td>
</tr>
<tr>
<td>N State St./Old Canton Rd.</td>
<td>MVMS, Universities, I-55</td>
<td>7</td>
<td>3.6</td>
<td>4:0 Northbound</td>
<td>Contra-flow/VMS</td>
</tr>
<tr>
<td>Woodrow Wilson Ave. (WWA)</td>
<td>MVMS, I-55</td>
<td>5</td>
<td>2.0</td>
<td>4:0 Westbound/Eastbound</td>
<td>Contra-flow/VMS</td>
</tr>
</tbody>
</table>

A lot of literature has reported successful experiences of deploying contra-flow operations on freeways, simply because of the significant capacity increase added by the reversed traffic lanes on a freeway. In this study, the segment of interstate highway I-55 inside the PAZ zone would be ideal for contra-flow deployment. However, the no-notice nature of the evacuation did not allow the lengthy preparation process and
complexity usually associated with a contra-flow deployment on a freeway. Similarly, it would be noticeable that a contra-flow operation in the southbound direction was not used in the study for two reasons: 1) The street network in Jackson downtown immediate to the south of the railroad yard has many one-way streets. Therefore a major two-way traffic corridor would be needed for that area to have better connectivity. 2) A majority of the residential TAZ zones are located to the north, east, and west of the PAZ in this study, which may mean more trips would be generated in these three directions than in the southbound direction.

Meanwhile, considering the population characteristics in the study, it would be reasonable to assume that drivers would dynamically choose alternative routes based on their prior experiences and real-time traffic information about the network. This assumption corresponded well with the DTA modeling features of DynusT. The incident control function of the software was used for the streets with a contra-flow operation and the inbound upstream links of the reversed links respectively. Portable VMS devices were used at the inbound upstream links of the reversed segments and major intersections. Real-time information for congestion warning and mandatory detour by traffic engineers at MDOT’s Traffic Management Center was simulated and disseminated through the VMS signs to the drivers. To reflect the familiarity of local drivers with the highway network, the simulation software was appropriately set up to use a functioning percentage for the vehicle drivers who would respond to the congestion warning under an emergency evacuation situation.

**Signalization Control**

The detailed possible traffic signal timing data during emergency evacuation were not available from transportation planning and traffic operations agencies, and therefore traffic signal control data were not included in this study. To enable a relatively realistic simulation process in DynusT, the study assumed that all signalized intersections were equipped with actuated signal controllers, which could automatically adjust green time allocations for different approaches depending on their incoming time-varying traffic volumes. Although this modeling strategy might slightly overestimate the available traffic capacity on the arterial streets, the method served as the best available approximation to normalize the effects of the traffic signal control, and therefore provided a platform for the study to evaluate and compare the effects of interest for the advanced traffic management strategies and other contributing factors under normalized traffic control conditions. It should be noted that although there was no advanced traffic management deployed on any of the three arterial streets in a baseline plan, traffic controls including traffic signalization were still required to direct vehicles from the stadium to one of the three candidate arterial streets, respectively.

**Simulation Calibration**

To evaluate the accuracy of the dynamic traffic assignment model in DynusT and to determine input parameters for hourly volume percentages, the calibration comparison procedure was followed. This was an iterative process of determining the calibrated
input parameters to make computed traffic volumes satisfy predefined criteria under
hours and to estimate the daily traffic distribution pattern. In the study, hourly traffic
volume percentages at the afternoon peak from 2:00 to 6:00 p.m. were determined as
6.2%, 6.8%, 7.9%, and 8.8%, respectively. Four hourly OD demand matrices were
produced by multiplying the initial traffic volume percentages to the total background
demand matrix and then imported to the DynusT program for calibration simulation
runs. Traffic counts were conducted for selected highway locations during the
afternoon peak hours. In addition, traffic volume data collected during a previous
evacuation event was provided by MDOT’s Traffic Division and used for simulation
calibration.

The calibration was an iterative trial and error process. The calibration method
employed the GEH test statistic and target limits for the traffic volume calibration (31)
and the GEH (derived from the model author’s name) formula is shown in Equation
(1):

\[
GEH = \sqrt{\frac{2(M-C)^2}{M+C}}
\]  

(1)

Where GEH is the test statistic, M is the model estimated hourly traffic volume, and C
is the field measured hourly traffic volume.

After more than 50 simulation trials, the calibrated input parameters for hourly
volume percentages for the four peak hours and link capacities of the arterials were
adjusted, satisfying all target limits. The difference between the overall assignment
volume for all links in the network and the traffic volumes provided by MDOT was
within the ±5% limit. The difference between the total assigned freeway volume and
the observed total was within the ±7% limit. The errors on specific links between
assigned hourly volumes and observed ones were all within the ±12% limit.

**SIMULATION RESULTS AND ANALYSIS**

The chlorine spill event was assumed to happen at (or a little earlier than) 3:00 PM
and emergency evacuation was ordered by City/County authority to start at 3:00 PM.
The simulation duration was at 2:00-6:00PM. To be more real, the evacuation traffic
was not added until the second hour of the simulation period. Therefore in the first
hour of simulation there was only background traffic, and in the other three hours
both the reduced background and impact evacuation demand components were loaded
concurrently. To reduce randomness, ten simulations runs were made in the study for
each set of data inputs for network and demand. The average cumulative number of
evacuation vehicles out of the protective action zone at the end of the simulation
duration of four hours (three hours of evacuation operations) was used as the Measure
of Effectiveness (MOE) for the performance of the evacuation operation under
different management and demand scenarios, which were collected and calculated for
the simulated traffic operations under the emergency evacuation.

There were four evacuation scenarios in this simulation study: Scenario#1, evacuation
scenario without a stadium volume included; Scenario#2, evacuation
scenario with a stadium volume of 20,000 vehicles included; Scenario#3, evacuation
scenario with a stadium volume of 40,000 vehicles included; and Scenario#4, evacuation scenario with a stadium volume of 60,492 vehicles included. In summary, the following four factors were evaluated in the simulation study: 1) advanced traffic management strategy contra-flow operation at “full” or “none” operational levels; 2) advanced traffic management strategy ITS/VMS deployment at “yes” or “no” operational levels; 3) three different arterial streets with different connectivity and locale characteristics; and 4) evacuation traffic demand at four levels.

Cumulative Evacuated Vehicle Volumes
The cumulative evacuated vehicle volume referred to the total number of vehicles that were generated within the PAZ zone after the order of the evacuation and were successfully evacuated out of the PAZ zone by the end of the three-hour evacuation operation in the simulation. In a simulation run, each completed trip consists of a sequence of nodes and links that connect the origin and destination of the trip, which is the trip trajectory. If a trip could not be finished before the end of the simulation duration, it still has a trajectory that connects the origin with a sequence of nodes and links up to the last point of route when the simulation is terminated. A macro program was developed to count the total number of vehicles that passed the boundary of the PAZ during the three hours of evacuation operation in each of the simulation runs. Table 2 lists the average total cumulative evacuated vehicle volumes for the different advanced traffic management strategies, traffic demand scenarios, and arterial streets.

Table 2 Cumulative Evacuated Vehicle Volumes in Simulations

<table>
<thead>
<tr>
<th>Demand Scenario</th>
<th>Arterial Street</th>
<th>Without Contra-flow without VMS</th>
<th>VMS without Contra-flow</th>
<th>Contra-flow without VMS</th>
<th>Contra-flow with VMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>West St</td>
<td>50580</td>
<td>51643</td>
<td>51468</td>
<td>54495</td>
</tr>
<tr>
<td></td>
<td>State St</td>
<td></td>
<td>50788</td>
<td>49000</td>
<td>49294</td>
</tr>
<tr>
<td></td>
<td>WWA</td>
<td></td>
<td>50628</td>
<td>50330</td>
<td>50468</td>
</tr>
<tr>
<td>#2</td>
<td>West St</td>
<td>63735</td>
<td>65539</td>
<td>65763</td>
<td>67358</td>
</tr>
<tr>
<td></td>
<td>State St</td>
<td>65880</td>
<td>66023</td>
<td>64222</td>
<td>66162</td>
</tr>
<tr>
<td></td>
<td>WWA</td>
<td>60487</td>
<td>62431</td>
<td>63596</td>
<td>65337</td>
</tr>
<tr>
<td>#3</td>
<td>West St</td>
<td>65134</td>
<td>70311</td>
<td>70913</td>
<td>70758</td>
</tr>
<tr>
<td></td>
<td>State St</td>
<td>74299</td>
<td>74535</td>
<td>75686</td>
<td>76449</td>
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<tr>
<td></td>
<td>WWA</td>
<td>68327</td>
<td>68415</td>
<td>71395</td>
<td>74898</td>
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<tr>
<td>#4</td>
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<td>70995</td>
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<td>76076</td>
<td>77800</td>
<td>78431</td>
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<tr>
<td></td>
<td>WWA</td>
<td>68479</td>
<td>69779</td>
<td>77206</td>
<td>78544</td>
</tr>
</tbody>
</table>

Note: For demand scenarios #2, #3, and #4, traffic controls were used to direct stadium traffic to the respective arterial street.

The total cumulative evacuated vehicle volume values in Table 2 show that the deployments of the two advanced traffic management strategies for using contra-flow operation and ITS/VMS devices could help improve the performance of an evacuation, especially under an evacuation situation with a heavy evacuation traffic demand. The
simulation results also suggest that different traffic corridors exhibit difference levels of evacuation performance due to their connectivity and locality characteristics. The following are summary of the simulation results.

**Summary of Simulation Results**

When there was not an activity in the MVMS stadium, the existing network capacity seemed quite adequate to evacuate a majority of the 55,281 evacuation vehicles out of the PAZ in three hours of evacuation operation. While VMS signs could improve the evacuation performance, the contra-flow operation should be cautiously considered for a relatively low evacuation traffic demand. A contra-flow deployment on N State St and Woodrow Wilson Ave. respectively literally worsened the evacuation performance for evacuation demand scenario #1, probably because the interference from the traffic of the intersecting feeding streets outweighed the gained capacity from the contra-flow operation. As a matter of fact, several university campuses and hospitals are located along N State Street, making a contra-flow deployment on the street even more difficult than the other two arterial streets.

When there was an activity in the MVMS stadium, especially with a higher traffic demand at the stadium, the deployment of the advanced traffic management strategies were justified because the conventional highway capacity was not adequate to handle the heavy evacuation traffic demands in the scenarios 2, 3, and 4. Under these scenarios, the deployment of VMS signs alone was nearly as effective as the deployment of contra-flow operation in improving the evacuation performance over the baseline cases. Furthermore, the combined use of both contra-flow operation and VMS signs was found the most effective among the traffic management deployment options in each of the evacuation scenarios with a traffic demand from the MVMS stadium.

For all the three evacuation scenarios with traffic volumes from the stadium, the performance improvement due to the deployments of the two advanced traffic management strategies on N State St. was the smallest compared with the improvements on the other two street options. This was probably due to the special links features of N State St. The many population concentration locations along the N State St. made the traffic feeding characteristics along the street different from the characteristics of the other two arterial streets. The benefit of capacity gain due to the contra-flow operation was partially cancelled out by the interference of traffic on the many intersecting streets that fed vehicles to the N State St. This canceling-out effect could explain the smallest performance improvements due to the deployments of contra-flow operation on N State St for all the three evacuation demand scenarios 2, 3 and 4 when there was a stadium activity, and similarly the reduced evacuation performance due to the contra-flow operation deployment on the same street when there was not a stadium activity. Therefore, N State St should not be selected for contra-flow deployment for an emergency evacuation although the street deployed with the advanced traffic management was frequently found to have the highest cumulative evacuated vehicle volumes in the simulations.
Cost-effectiveness Analysis
When the costs of the deployments of the advanced traffic management strategies were to be considered, it would be easy to identify the best route for a possible contra-flow deployment from the three arterial options. With the costs included, it would also be easy to understand why traffic management deployments on N State St frequently had the highest cumulative evacuated vehicle volumes in the simulations. The lengths of the link segments in miles and the numbers of access points on the link segments in Table 1 would be a good index for the costs incurred to the transportation agency that would be responsible for the possible traffic management deployments over the link segments. Therefore the quantity of dividing the cumulative evacuated vehicle volume by the deployment length or by the number of access points would be the cost-effectiveness (C-E ratio1 and C-E ratio2 considering deployment length or number of access points, respectively) for the traffic management.

Figure 4 Cost-effectiveness ratios of traffic management on routes.

Figure 4 illustrates the C-E ratios for the “Contra-flow with VMS” deployments for the three arterial street options under the four evacuation demand scenarios. Clearly N West St exhibited the best evacuation performance for the traffic management deployments under all the four evacuation demand scenarios. This could be related to the relatively small traffic volumes in the inbound link direction and the intersecting link directions. Figure 4 also shows that Woodrow Wilson Ave and N State St ranked 2nd and 3rd in cost-effectiveness ratio.

Multi-factor ANOVA Analysis
Contra-flow operation, ITS/VMS signs, arterial streets for traffic management deployment, and evacuation traffic demand were the four major factors that
contributed to the simulation results for the cumulative evacuated vehicle volumes out of the PAZ during the simulation duration of three hours. All the four factors should be included and compared when one wants to study the numerical effects of these factors on the simulation results. A multi-factor ANOVA can test several sample means for several different effects. The linear model for the multi-way ANOVA is shown in Equation (2),

\[ y_{ijkl} = \mu + \tau_i + \beta_j + \gamma_k + \omega_l + \varepsilon_{ijkl} \quad (2) \]

Where \( y_{ijkl} \) is the cumulative evacuated vehicle volumes out of the PAZ during the simulation duration of three hours for the \( i \) th level of factor \( A \), contra-flow operation, the \( j \) th level of factor \( B \), ITS/VMS signs, the \( k \) th level of factor \( C \), route for traffic management deployment, and the \( l \) th level of factor \( D \), evacuation traffic demand. \( \mu \) is the overall mean, \( \tau_i \) is the effect of the \( i \) th level of factor \( A \), \( \beta_j \) is the effect of the \( j \) th level of factor \( B \), \( \gamma_k \) is the effect of the \( k \) th level of factor \( C \), \( \omega_l \) is the effect of the \( l \) th level of factor \( D \), and \( \varepsilon_{ijkl} \) is a random error component. The objective of the multi-way ANOVA was to test the four null hypotheses of equality for all the four aforementioned effects, i.e., \( H_0: \tau_1 = \tau_2 = \cdots = \tau_a = 0 \), \( H_0: \beta_1 = \beta_2 = \cdots = \beta_b = 0 \), \( H_0: \gamma_1 = \gamma_2 = \cdots = \gamma_m = 0 \), and \( H_0: \omega_1 = \omega_2 = \cdots = \omega_n = 0 \).

### Table 3 Multi-factor ANOVA Test Result

<table>
<thead>
<tr>
<th>Test Factor</th>
<th>Degree of Freedom</th>
<th>F Test Value</th>
<th>P Value</th>
<th>R(^2) of Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contra-flow</td>
<td>1</td>
<td>10.79</td>
<td>0.002</td>
<td>92.96%</td>
</tr>
<tr>
<td>ITS/VMS</td>
<td>1</td>
<td>3.09</td>
<td>0.087</td>
<td></td>
</tr>
<tr>
<td>Arterial street</td>
<td>2</td>
<td>6.02</td>
<td>0.005</td>
<td></td>
</tr>
<tr>
<td>Traffic demand</td>
<td>3</td>
<td>167.31</td>
<td>0.000</td>
<td></td>
</tr>
</tbody>
</table>

The variability in data due to the treatment under each test effect is compared to the variability due to random errors and the resulting ratio is an \( F \)-value for that test effect. The \( F \)-value is then compared to a standard critical table value in the \( F \)-distribution to check the significance of that test effect. A \( P \)-value could be given to show how likely the specific \( H_0 \) is true in the case of the computed \( F \)-value. A large \( F \)-value and a small \( P \)-value can normally lead to a rejection of the null hypothesis \( H_0 \). In addition, an \( R^2 \) value is given to index the adequacy of the analysis model. The \( R^2 \) value indicates how much of the data variability is explained by the model in Equation (2). The ANOVA test results are shown in Table 3. The \( P \) values show all the four factors are all significant at a 95% confidence level. The \( F \) test values show the descending order of significance for the contributing factors 1) evacuation traffic demand, 2) contra-flow operation, 3) arterial street, and 4) ITS/VMS installation are
CONCLUSIONS
This paper studied the emergency evacuation problem due to an assumed chlorine spill incident at the NC Railroad Yard in downtown Jackson in Mississippi using the DTA-based simulation model DynusT. The protective action zone was estimated using the analytical program ALOHA developed by NOAA/EPA. Trip production, attraction, distribution, and assignment models were followed to prepare OD demand data. Baseline and advanced traffic management strategies were developed and set up in network data. Simulation software was calibrated using valid field dataset. Experiment design method was used to test the effects of deployments of advanced traffic management strategies contra-flow operation and ITS/VMS signs on different arterial street options and under different evacuation traffic demand levels. The cumulative evacuated vehicle volume during the simulation duration was used as the MOE for the evacuation performance. A cost-effectiveness ratio model was used to select the best arterial route for contra-flow deployment. A multi-factor ANOVA was conducted to numerically evaluate the effects of the contributing factors. The simulation results showed that the selection of a best contra-flow operation route depends on the interference from the intersecting links and the cost in the traffic management deployment; and that using both contra-flow and variable message signs could effectively improve the evacuation performance over using none or only one of the two strategies. The ANOVA test on the simulation results showed that all the four factors were significant and the descending order of significance for the contributing factors were 1) evacuation traffic demand, 2) contra-flow operation, 3) arterial street, and 4) ITS/VMS installation are in the order.

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REFERENCES


