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Agent-Based Modeling for Evacuation Traffic Analysis in Megaregion Road Networks

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Abstract

Numerous recent catastrophic disasters have underscored the need to better plan and manage regional traffic associated with mass evacuations. Over the past three decades, traffic simulation has been applied to evaluate traffic management options and to forecast regional traffic patterns associated with evacuations. As the level of sophistication of simulation systems has increased, so have expectations for ever more detailed assessments of larger and more complex road networks, especially for evacuations. Historically, traffic modeling has required a fundamental trade-off between wide area analyses with low resolution or high resolution analyses over comparatively small areas. Recent advancements in agent-based traffic modeling, however, now permit very large areas to be simulated at high resolution. In this paper, results from a series of projects in which the TRANSIMS agent-based traffic simulation system was applied to assess and evaluate traffic conditions associated with various threat conditions and the regional traffic management approaches are summarized. These findings are valuable to enhance the understanding of the mass emergency movement of traffic and can be applied more-practically for wide-scale, regional, and even multi-state evacuation planning.

Keywords: agent based modeling; traffic simulation; evacuation; big data

1. Background

In the wake of the catastrophic tropical storm season of 2005 in which two of the ten costliest natural disasters in the history of the United States (Hurricanes Katrina at a cost of $149B and Rita at a cost of $19B) occurred within a two week period, there was a recognized need to better understand, analyze, and manage regional traffic associated with mass evacuations. At that time, traffic simulation had already been shown to be effective for the planning and
analysis of contraflow evacuation traffic operations\(^1\) and to forecast regional evacuation movements in which traffic moved from one state to another\(^2\). However, increasing expectations led to requests for ever more detailed assessments of performance measures and larger, more complex representations of road networks. An example of this was illustrated by a request from the then-Secretary of the Louisiana Department of Transportation and Development (LA DOTD) for travel time and delay estimates from New Orleans to shelter destinations throughout the State. Such information was important to public officials because it could be used to support critical policy and planning decisions.

At the time of Katrina, detailed traffic simulation modeling at the agent-based (microscopic) level was effectively limited to the analysis of corridor segments, typically about 20 miles in length, and to short time durations, around 20 hours and less.\(^3\)\(^4\) While this level of modeling was quite useful for the development of traffic control and contraflow freeway plans (in which the direction of flow in the inbound lanes are reversed to carry traffic in an outbound direction), it was limited in its ability to examine wide areas. At that time, regional transportation assessments could only be undertaken at the macroscopic level, using the planning models of the day.

The manner in which traffic flow is represented in micro and macro models is quite different. In macro models, traffic flow is represented by average conditions of a stream of vehicles or a section of roadway.\(^5\)\(^6\)\(^7\) While these types of aggregated representations of vehicles are effective to assess conditions on a large scale, they are not capable of assessing the movement of individual vehicles and their interactions at the agent level. This limited resolution also prohibits the assessment of localized traffic control and geometric design treatments. It also does not allow the wider effects of traffic surges to be examined as they propagate through a network. During an evacuation, where travel demand is at, or in excess of, the available capacity for hours and days at a time, even small disturbances in traffic flow can move rapidly through the system and their effects can be observed or for many hours in duration.\(^8\) More importantly from a practical application perspective, the limitations of small-area micro simulation and wide-area macro simulation does not permit the effects of planning and policy decisions in advance of an emergency to be tested.

Since the initial evacuation modeling of the early- to mid-2000’s, large scale agent-based traffic simulation systems have become more readily available.\(^9\)\(^10\) Among the advancements that they have brought has been the ability to model millions of individual vehicles, moving over hundreds of thousands of miles of roadway network, while encompassing time durations that can span multiple days. These capabilities make them ideally suited for the analysis of hurricane evacuations, in particular, because the events include travel over regional and even megaregional levels.

To highlight some recent advances in the field, this paper summarizes the methods and results from a series of research projects that sought to develop and apply an agent-based megaregion evacuation traffic model of the Gulf Coast region of the United States (US).\(^15\)\(^16\)\(^17\) The model was used to assess and evaluate traffic conditions associated with various threat conditions and the regional traffic management approaches that could be used to facilitate the mass, emergency movement of traffic across a multi-state region of the US. The paper also highlights related efforts to address other important issues of modeling at this level, including the ability to validate model output results and assess the effects of traffic management and policy on a regional level.

2. The TRANSIMS Agent-Based Simulation System

The \textit{Transportation ANalysis and SIMulation System} (TRANSIMS) is an activity-based microscopic simulation model developed to model the trip-making behaviour of individual persons at the household level. This is done by creating a computer-generated “population” that is statistically representative of the socio-demographic characteristics of a study area. It then assigns travel activities to individuals based on known travel characteristics, then routes these individuals within a road network at specified times and places. This information is then fed into a vehicular microsimulator that routes and advances people and vehicles between their origins and destination. A schematic representation of the TRANSIMS conceptual simulation framework is shown in Fig 1. Additional details on the TRANSIMS systems and coding for evacuations can be found in a related paper.\(^11\)

The development of the Gulf Coast \textit{TRANSIMS} megaregion model was completed within a framework of three primary tasks. The first was the creation of a “base model” that included the link, node, and control features of the regional road network. This effort also included model calibration and validation based on the 2005 Hurricane Katrina and 2008 Hurricane Gustav evacuation traffic counts. The second step was to build a series of evacuation scenarios based on theoretical hazards and response conditions. The last step of the process was to extract the relevant performance measures and analyse them within the context of a regional wide framework.
2.1 Model Development

Although there are numerous other models which may be capable of achieving similar results, TRANSIMS was selected based on its ability to model the traffic to utilize existing data that was readily available in the area. To code the road network, a geographic information system (GIS) software was used to convert existing Metropolitan Planning Organization (MPO) road network models from the six major metropolitan areas in the region, including New Orleans, Baton Rouge, Lafayette, Lake Charles, Louisiana as well as Beaumont and the Houston-Galveston of Texas. Each of these separate networks was merged into a single mega-network and the “empty spaces” between them were filled by manually connecting the roads based on various online and printed maps. Each road was coded as a link connecting two nodes, A and B. Each of these links also had attributes such as a direction; one or two way operation; a speed limit; and a functional classification such as interstate highway, arterial, major road, local road, etc. The coverage area and road density of the resulting network is shown in Fig. 2.

2.2 Evacuation Demand

Another critical component of the simulation was the generation of the evacuation travel demand; specifically when evacuees departed, where they departed from, and where their shelter destinations were located. To accomplish this, a time dependent sequential logit model was combined with a series of evacuation destination choice models, then applied to the synthetic population. This population was a statistical representation of the area from 2010 US Census data for all travel analysis zones (TAZs) in the megaregion. The details of the binary logit model were described in a separate study Gudashala and Wilmot.12
2.3 Model Validation

The TRANSIMS model was validated using the methods developed by Dixit, Montz, and Wolshon. During an evacuation, one of the most sought-after performance measures is evacuation clearance time (e.g., the time it takes for all evacuees to exit the threat area). In the simulation, this value was computed using the total number of evacuees passing threshold lines of "safety" at a given time. For this reason, the cumulative number of vehicles passing these locations during periodic intervals was used to validate the model. The simulated cumulative volume was then compared to volume data collected during the 2005 Hurricane Katrina and 2008 Hurricane Gustav evacuations using regression analysis. The \( y = x \) regression line had an acceptable fit, with \( R^2 \) values of greater than 0.90, suggesting that the TRANSIMS simulation model performed reasonably well in estimating the cumulative evacuation volumes. This validation procedure was quite innovative because it could not be accomplished using convention methods available at that time.

2.4 Test Scenarios

Once the base model was validated, a series of threat-response scenarios were created to evaluate the regional traffic conditions that might occur under various hurricane events. These scenarios, described and illustrated in a related paper, were based to varying degrees on several prior hurricane events in the area, some recent and others that took place more than 100 years ago. They were important because, if repeated, they could necessitate the evacuation of all cities in the area, simultaneously. The test scenarios included:

- Scenario 1: The storm growth pattern and movement track of Hurricane Gustav in 2008
- Scenario 2: Hurricane Gustav, but increased to Category 4 strength
- Scenario 3: Hurricane Gustav, but increased to Category 5 strength
- Scenario 4: A Category 4 storm based on an 1867 hurricane with a forecast level of uncertainty that would threaten the entire Gulf Coast study area
- Scenario 5: A Category 4 storm based on a 1914 unnamed hurricane, traveling east to west, with a forecast uncertainty that would threaten the entire Gulf Coast study area
- Scenario 6: A stronger, Category 5 version, of the Scenario 5 event

Using these scenarios, the time dependent sequential logit model was applied to predict the evacuation participation rate and departure times for each metropolitan area as well as the coastline areas in Louisiana and Texas. The evacuation participation percentage for each scenario varied as a function of the perceived threat from each storm. For example, only Scenario 4, which made an initial direct track toward the Houston-Galveston area, precipitated an evacuation response from the Houston region.

3. Network Performance

In response to the six storm scenarios, two traffic management plans were evaluated. These plans sought to improve the performance of the road network using contraflow and phased evacuation orders. The contraflow plans were derived from Louisiana State Police and LA DOTD plans from the 2008 Hurricane Gustav evacuation. The phased evacuation orders was developed from perceived storm threat. The methods of and results from these strategies are presented in the following sections.

3.1 Effects of Contraflow

To quantify the impact of the various contraflow strategies, average travel speed (ATS) was used as a measure of effectiveness. In addition to the control scenario, where no contraflow plan was used (No CF), two contraflow plans were analyzed: Contraflow Plan 1 (CF Plan 1) which followed the 2008 Hurricane Gustav evacuation of south Louisiana and Contraflow Plan 2 (CF Plan 2) was essentially same but over a longer duration. The evaluations were conducted over one-day (24hr Evac.) and two-day (48hr Evac.) periods. Figure 3 shows the resulting ATSs from the various scenarios.

In general, the findings were logical and expected. Fundamentally, as demand increased, ATS decreased. As expected, the use of contraflow had a positive effect on ATS. It is also worth noting that as the duration of contraflow operation was extended, the ATS showed a corresponding benefit. The advantage of contraflow was even more
pronounced when evacuation demand surpassed 0.55 million vehicles for 1 day evacuations and 1.1 million vehicles for 2 day evacuations. The benefit of contraflow was also shown to be more significant for two-day evacuations compared to single-day evacuations, suggesting that only a marginal benefit would be gained from shortening or lengthening the duration of contraflow operations.

3.3 Effect of Phased Evacuation Orders

In the simulation, two separate geographic response areas (Region 1 and Region 2) were developed from household distribution and storm track trajectories. Region 1 included six metropolitan areas, including Houston-Galveston, Texas. Region 2 consisted of seven metro areas that covered Beaumont, Texas, through Lake Charles, Lafayette, Baton Rouge, and New Orleans Louisiana. Evacuees from these areas were assumed to depart at a constant rate in phased evacuation scenario, and the departure times for each based on the principles described in a related paper.17 The phased evacuation results are shown in Table 1. These data suggest that the phased evacuation improved the overall efficiency of the evacuation. The smallest improvement for any of the demand scenarios was 26 percent. The change in average travel speed followed a similar trend. However, it was not as prominent as the “Completed Evacuation” percentage (e.g., the proportion of evacuees who exited the network out of the total of evacuees who entered the network). From these results it was broadly concluded that when heavy congestion existed in the network, phased evacuation plans yielded improvements by increasing the percentage of evacuees who cleared the network and the average travel speed at which they were able to move. Interestingly, the benefit of the phasing also increased as demand increased. However, when the network was uncongested, there was only a minimal positive improvement gained from phased evacuation orders.

<table>
<thead>
<tr>
<th>Evacuation Demand and (% of total population)</th>
<th>Completed Evacuation (%)</th>
<th>Average Travel Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Non-Phased</td>
<td>Phased</td>
</tr>
<tr>
<td>566,979 (20% population)</td>
<td>77.1</td>
<td>97.5</td>
</tr>
<tr>
<td>850,468 (30% population)</td>
<td>64.1</td>
<td>83.7</td>
</tr>
<tr>
<td>1,133,957 (40% population)</td>
<td>52.2</td>
<td>69.3</td>
</tr>
<tr>
<td>1,417,447 (50% population)</td>
<td>38.8</td>
<td>59.1</td>
</tr>
<tr>
<td>2,834,893 (100% population)</td>
<td>24.4</td>
<td>40.1</td>
</tr>
</tbody>
</table>

Fig 3. ATS Network Performance for 1 day and 2 day evacuation scenarios
4. Conclusion

The research described in this paper summarizes the results of a half decade of research to apply agent-based traffic simulation to study evacuation traffic processes at the megaregion-level. It is expected that these results will be useful to researchers as well as practitioners seeking methods to improve the clearance time, travel speed, and overall network productivity of their evacuation plans. This work reveals several key aspects of evacuation processes at regional and megaregional levels. Most notably, the relationship between demand generation and the use of capacity enhancing techniques like contraflow and temporospatial phased evacuation orders. Ongoing research is now using these results to show even more details of network performance. These network productivity functions seek to optimize the movements throughout an entire system by maximizing aggregate travel speed of all individual agents in the network.

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6. References