DEVELOPMENT OF A LARGE-SCALE TRAFFIC SIMULATION MODEL FOR HURRICANE EVACUATION

– A CASE STUDY OF VIRGINIA'S HAMPTON ROADS REGION

Siddharth Sharma
Graduate Research Assistant
Department of Civil and Environmental Engineering
University of Missouri-Columbia
211 Waugh Street, APT – D
Columbia, MO 65201
Email: sstc6@mizzou.edu
Ph. No. (573) 673-8454

Dr. Praveen K. Edara
Assistant Professor
Department of Civil and Environmental Engineering
University of Missouri-Columbia
Email: edarap@missouri.edu
Ph. No. (573) 882-1900

Midwestern District of ITE

ABSTRACT

Hurricanes are one of the most catastrophic events resulting in severe consequences including loss of life and property damage. The magnitude of devastation was evident in the aftermath of hurricanes Katrina and Rita in the Gulf coast. Emergency management teams play a huge role in safeguarding the lives of people in endangered areas by evacuating them to safer locations as efficiently as possible. An evacuation plan is an essential component of an emergency plan.

The evacuation plan for the state of Virginia has been developed after thorough analyses of the consequences of all the strategies but, as with most states, the operational characteristics of the plan at a microscopic level had never been evaluated in a comprehensive manner. The evacuation planning documents previously developed by the Virginia Department of Emergency Management (VDEM) adequately describe the numbers of evacuating vehicles, their origin and route taken at a macroscopic level.

The current study was undertaken to evaluate the traffic control plan (TCP) and the performance of all the evacuation routes - interstate routes (I-64, I-264, and I-664) and arterial routes (Rt. 58, Rt. 460, Rt. 60, Rt. 17, and Rt. 10) using large-scale traffic simulation models. Road network is coded in a state-of-the-art microscopic simulation program, VISSIM. The study area comprised of the following nine evacuation areas – cities of Virginia Beach, Norfolk, Chesapeake, Portsmouth, Suffolk, Hampton, Newport News, Poquoson, and York.

The following objectives were achieved in this research - 1) estimated the traffic performance of evacuation routes and other major arterial streets, 2) located the major bottlenecks, congestion, or other operational difficulties in the areas covered by the network, 3) estimated the total network evacuation time, 4) conducted what-if scenarios (e.g., incident occurrences), and 5) recommended amendments to the TCP to improve the traffic performance.

INTRODUCTION

Hurricanes are one of the most catastrophic events resulting in severe consequences including loss of life and property damage. The magnitude of devastation was evident in the aftermath of hurricanes Katrina and Rita in the Gulf coast. Emergency management teams play a huge role in safeguarding the lives of people in endangered areas by evacuating them to safer locations as efficiently as possible. An evacuation plan is an essential component of an emergency plan.

The federal government, through the Federal Emergency Management Agency (FEMA) requires all the states to have a comprehensive emergency operations plan. FEMA, with the objective of dealing with hurricanes, encouraged the development of a hurricane evacuation study (HES) for each state. An HES consists of different aspects of planning, such as, evacuee behavioral analysis, sheltering analysis, etc, in addition to the transportation analysis. For Virginia, the HES is in the form of an abbreviated transportation model (ATM) *(1)*. The ATM determines the number of people (and vehicles) who will evacuate from each geographic zone, based on 2000 U.S. census data, under a hurricane threat within each jurisdiction in the Hampton Roads region of Virginia. An emergency evacuation plan has been developed for the Hampton Roads region of Virginia intended to facilitate the outbound movement of large numbers of people in vehicles from the region facing a hurricane threat.

A traffic control plan (TCP) *(2)* has been developed as a part of the overall plan to provide detailed information on the procedures to be followed during the evacuation of traffic in the event of an approaching hurricane. The intent of the plan is to provide the most efficient movement of vehicles out of the region. The TCP uses a phased approach to ensure that those most at risk are given the opportunity to leave the region first. Phase 1 evacuation, which is assumed to take place 24 to 14 hours prior to the onset of hurricane, includes evacuating people from Virginia Beach, Norfolk, York, Poquoson and parts of Hampton. Phase 2 evacuation, which takes place beginning 14 hours prior to and ending with the first contact of hurricane with the mainland, evacuates Portsmouth, Chesapeake, Suffolk, Newport News, and the remainder of Hampton. Figure 1 shows the designated evacuation routes for the area under study with evacuation routes highlighted in red color.

FIGURE 1 Evacuation areas and designated evacuation routes

The plan does not assume to directly affect the driver behavior in terms of choosing a particular route or evacuate or stay back during the period of evacuation. Although, ramps providing access to I-64 are designated as open or closed, and many are metered in an attempt to influence the route choice of evacuees so that there could be a balance between the demand across the evacuation routes. Public information and education campaigns are designed to encourage the public to follow official advice with respect to route and time of departure. In addition to I-64, Routes 17, 460, 58, 60, and 10 are all designated evacuation routes and vehicles are assigned to each based on their originating zone.

PURPOSE AND SCOPE

The evacuation plan for the state of Virginia has been developed after thorough analyses of the consequences of all the strategies but, as with most states, the operational characteristics of the plan at a microscopic level had never been evaluated in a comprehensive manner. The evacuation planning documents previously developed by the Virginia Department of Emergency Management (VDEM) adequately describe the numbers of evacuating vehicles, their origin and route taken at a macroscopic level. However, the traffic characteristics of vehicles from the origin till they get on to the evacuation routes was not mentioned in the planning documents.

The objectives of this study were to, 1) obtain the traffic performance of evacuation routes and other major arterial streets, 2) locate the possible bottlenecks, congestion, or other operational difficulties in the areas covered by the network, 3) estimate the total network evacuation time 4) conduct what-if scenarios (e.g., incident occurrences), and 5) recommend amendments to the TCP to improve the traffic performance. The results from the study would also help in the placement of portable traffic monitoring devices at priority locations so that they can be continually monitored and the data can be made available for future evacuation studies.

METHODOLOGY

The methodology followed for the research was very similar to the course of action that was taken in the first phase of the project. However, there were some additional steps involved because of the increase in the scope of study. The methodology followed for this research effort is divided into three main steps: 1) design of the simulation network, 2) estimation and assignment of the origin-destination (O-D) flows, 3) simulation and analysis of various scenarios.

Development of the Model

The first step involved in the development of the model was the selection of the analysis tool. The objective of this study was to evaluate the traffic operations on all the evacuation routes and the intersecting cross-streets during an evacuation. The evaluation involved measuring travel times, locating potential bottlenecks, delays to vehicles, etc., which could be most effectively performed by using a microscopic simulation tool. VISSIM, a product of PTV AG (PTV Vision Suite), is a state-of-the-art microscopic, time step and behavior based simulation model used for modeling traffic operations. The selection of VISSIM as the simulation tool for this research effort was due to its capability to effectively model traffic operations under various conditions. It also has the ability to model origin/destination based traffic demand which makes it a strong tool for use in evacuation modeling. VISSIM uses the psycho-physical driver behavior model developed by Wiedemann *(3)* unlike the constant speeds and deterministic car following models used by other simpler simulation models. This feature increases the accuracy of the results obtained from the simulation. The stochastic distributions of speeds and spacing thresholds enable VISSIM to model a more realistic simulation of the real world scenario and thus produce more reliable outputs to make inferences from.

The next step was to code the road network geometry in the VISSIM tool. The common way of doing this is to manually draw the network by tracing a background image on the screen. This approach is convenient for small road networks with few signalized intersections. The road network being studied in this research has a total length of approximately 1800 miles (includes all evacuation routes and cross-streets) and hence, manual coding of the network geometry was not an option. A more efficient method to code the network was to use geographic maps in conjunction with VISUM software. VISUM is a travel demand modeling software that integrates all individual and public transport types in a single model. It is a part of the PTV Suite that includes VISSIM. It is possible to import geographic maps into VISUM to create road networks automatically. The maps can be in a geographic information system (GIS) shape file format or a NAVTEQ tile. NAVTEQ tiles are the background maps for all major online mapping websites such as Google maps, yahoo maps, and map quest. The state of Virginia is divided into three tiles – north, east, and south. The east and south tiles covered all cities in the Hampton roads region and the city of Richmond. These two tiles were merged in VISUM and significant pruning was done to create the road network with all major evacuation routes and the important cross-streets. The created network was then exported into VISSIM simulation tool. The VISSIM network was further tuned to match the lane configurations and add any missing links. Traffic signal timing plan information was obtained from all the cities in the Hampton roads region and from Virginia DOT for state maintained signals. It was a challenge to transfer the signal timing information into VISSIM due to the varying formats used by different cities. The formats varied from hard copy timing plans to SYNCHRO optimization plans. The interpretation of parameters within the plans was not always straightforward. There were 165 traffic actuated signals (NEMA) and 120 fixed time signals in all in the entire network. Also, the ramp meters were coded using a fixed time or a NEMA control depending upon the information from the TCP. Some of the ramp meters had different metering rates for the two phases of evacuation and hence NEMA was used to code such an arrangement. While coding the timing plans, the intersections geometry was cross-verified with the geometry included in the signal files. On several occasions, left and right turn lanes were missing and were manually added.

Base Case (BC) Model

The base case model was prepared to simulate conditions when a lane reversal is not ordered. The model was constructed based on the information from the TCP and the ATM. The base case was modeled for all storm categories (1-4) and for all scenarios (discussed later). This was done to compare the potential benefits of ordering a lane reversal and for pointing out the storm category and scenario for which it would be warranted.

Lane Reversal (LR) Model

The lane reversal case was modeled with the eastbound lanes of I-64 too going outbound. The starting and the end point of cross over being, the I-64/ 4th View St. interchange and I-64/ I-295 interchange respectively. Similar to the base case, the lane reversal case was also modeled for all storm categories and scenarios.

Estimation and Assignment of Origin-Destination (O-D) Flows

The total evacuating traffic demand and the routing assignment was obtained from the ATM. The ATM is based on tracts and population data from the 2000 U.S. Census. These tracts are also used in the non-digital surge maps prepared by the U.S. Army Corps of Engineers to refer to the ATM tables of evacuating population by destination. The temporal distribution of the total vehicle trips identified in the ATM for each origin was determined using Table 1. The O-D matrix thus obtained was loaded onto the VISSIM network.

TABLE 1 Temporal Distribution of Traffic Demand

Start Hour	End Hour	% of Total Demand	Evacuation Phase
0	5	10	1
5	10	60	1
10	14	20	1
14	24	10	1
14	18	60	2
18	24	40	2

Study Scenarios and Simulation Details

There were six evacuee scenarios obtained from the ATM which reflected on the combinations of storm intensity, Saffir-Simpson scale, *(4)* and hotel occupancy (L for low occupancy, H for high). The Saffir-Simpson scale is a classification for hurricanes that divides the hurricanes into five categories depending on the intensities of their sustained winds.

Data collection points were created for all the evacuation routes at their entrance into the Richmond region to obtain the temporal demand entering Richmond. These were created to obtain information about the throughput (total number of vehicles), evacuation time, and average speeds of vehicles successfully evacuating. Additional data collection points were deployed on an imaginary screen-line that cuts across all evacuation routes. The screen-line was at a location before which most of the travel demand for the evacuation routes has entered the routes.

Specifically, travel time sections were used in VISSIM. These were defined for particular segments of the network for which data regarding travel time, number of vehicles crossing the segment, travel speeds, etc. were to be determined. For some parts of the network, node evaluation was used to determine the throughput by movement.

Key Assumptions of the Simulation Model

The simulation model was developed in accordance with the data from TCP and the ATM. However, for a microscopic traffic simulation model, certain assumptions have to be made for various traffic parameters in the absence of sufficient information. Some of the important assumptions that were made in the course of the model development are described here.

Traffic Composition: The generated traffic was assumed to be consisting of 98% of "Cars" and 2% of "Heavy Ground Vehicles (HGVs)". The vehicle input in VISSIM can be defined by the user according to the objective of the problem. "Cars" and "HGVs" are two of the available categories of vehicles that can be included in the analysis. Since, most of the evacuees were assumed to use their own vehicles for evacuating; the traffic composition mostly consisted of cars.

Speed Distributions: Vehicles generated in simulation were assigned speeds based on a user-defined stochastic speed distribution. Three speed distributions were created for the model. The first one (40-50 mph) was used as the default speed for the originating vehicles. The second was the speed with which vehicles were assumed to travel on the freeways (50 – 60 mph). Another speed distribution (55- 65 mph) was created for the vehicles after crossing the "screen line" on I-64. These upper bounds of these speed intervals were consistent with the existing speed limits of roadways in the evacuation region.

Driving Behavior: The car following model controls the various aspects of driving behavior with parameters of lane changing, average standstill distance, additive part of safety distance, and multiplicative part of safety distance. The Weidemann 74 car following model, which is the default VISSIM model, was used to model the driving behavior for all roadway links in the network.

RESULTS AND ANALYSIS

As mentioned earlier, various storm categories and scenarios were simulated in order to evaluate the traffic performance. The measures of effectiveness included section travel times, vehicle through put, queue lengths, and spot speeds. Results obtained for base case and lane reversal cases were then compared to determine the efficiency of lane reversal. The data collected from travel time sections provided the information on bottleneck locations and the congestion time periods. When traffic was simulated for category 1 and 2 storm conditions, there was no congestion in the network and all vehicles evacuated within the 24 hour lead time. Since the main intent of this research was to identify where the potential bottlenecks were, the results of category 1 and 2 low traffic volume conditions are not shown in this research. Results for categories 3 and 4 for both low and high hotel occupancy scenarios follow. Due to the space limitations of this paper, only the results for category 4 storm scenario with lane reversal are shown. Interested readers are encouraged to refer to the detailed thesis document (Sharma, 2008) (5).

The worst-case scenario, in terms of the storm intensity and volume of evacuating traffic, is the category 4 storm with high (H) hotel occupancy. In this section, results of this scenario will be summarized starting with the lane reversal case. Figure 2 shows the performance of traffic on Rt 58 over time. There are four travel time sections along Rt 58 that are analyzed in this plot. The first section is in the Virginia Beach region between the intersections of Rt 58/ Rt 408 and Rt 58/ Rt 13. This is a 2 mile section, used primarily by vehicles from the Virginia Beach region that evacuate using Rt 58 or Rt 460. The next section is between the Rt 58/ Rt 13 intersection and the entrance of the Midtown Tunnel. This is a 6 mile section that is used by traffic from Norfolk and Virginia Beach. The third section is 16 miles long starting at the Midtown tunnel and ending after the 58/I664 interchange but before Rt 58 and Rt 460 diverge in Suffolk. The final travel time section for Rt 58 runs till Rt 58 reaches I 95 in Richmond. Due to the high travel times during congested periods it was necessary to choose a logarithmic scale for the travel time axis. It should be noted that these travel time sections were used by vehicles evacuating in the first phase of evacuation and hence the travel time plot has data points till the last vehicle exits from the section. As it can be seen from the plot, for the first section congestion sets in after 9 hours of simulation and the travel times continue to rise after that. For the second section, travel times start to rise after 5 hours of simulation. The travel times on the other two sections also increased briefly but the increase was not significant.

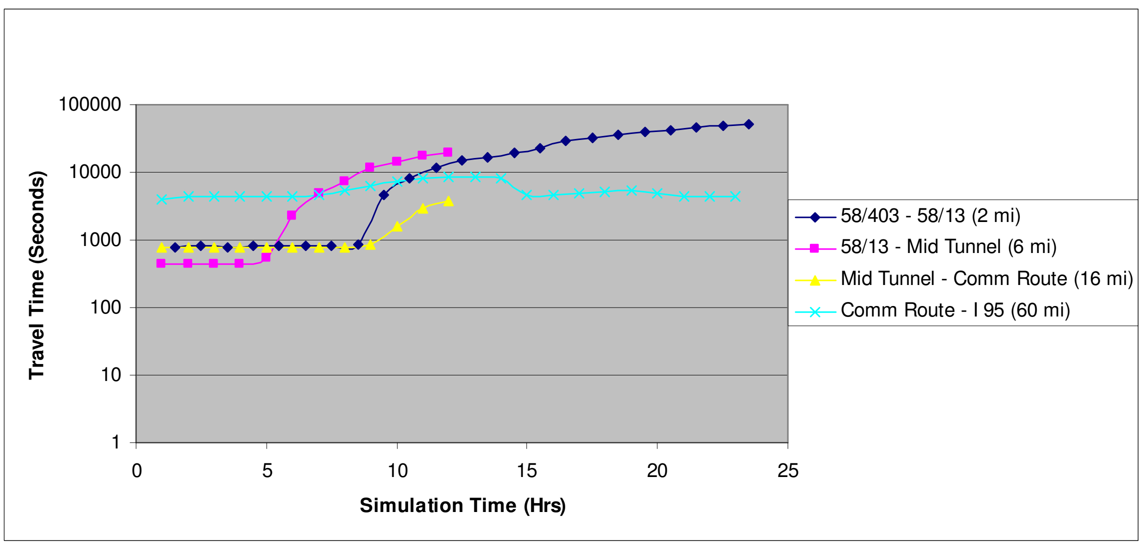

FIGURE 2 Travel time v/s simulation time for 4H LR (ATM) for Rt 58.

An analysis of the critical travel time sections on I-64 is depicted in Figure 3. There are four travel time sections that were created to determine the overall performance of this evacuation route. It can be observed that the section of reversed lane from HRBT to Richmond and the section of regular lanes between HRBT and I-64/ Fort Eustis Blvd interchange had steady travel times.

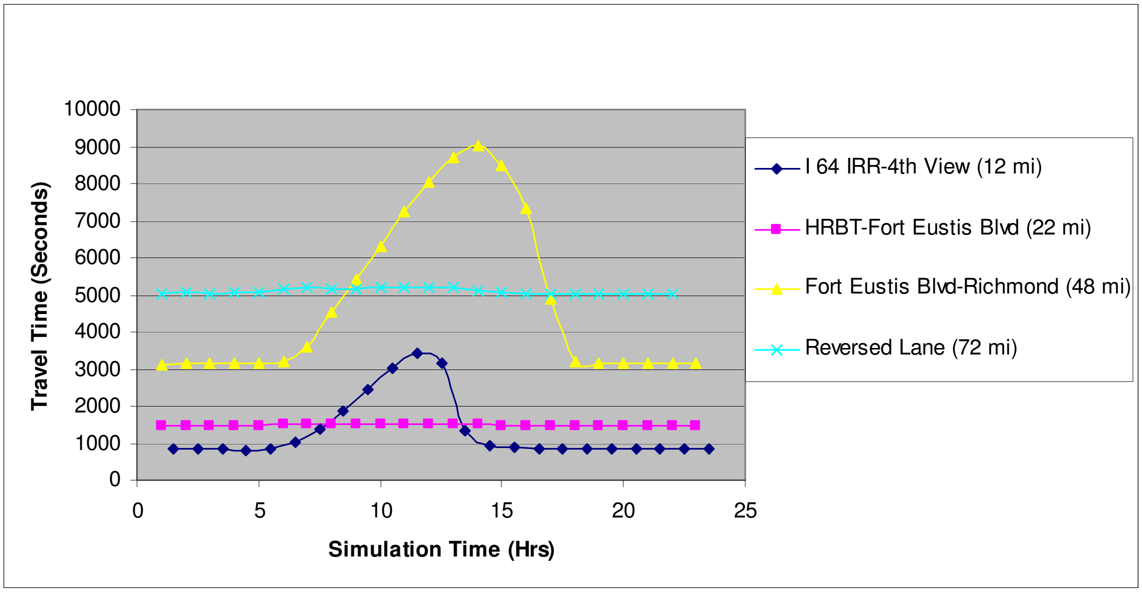

FIGURE 3 Travel time v/s simulation time 4H LR (ATM) for I-64.

Vehicles evacuating on Rt 460 go through the same travel time sections as for those on Rt 58 since Rt 58 and Rt 460 are the same until they split at Suffolk Northern Bypass. Hence, the only different travel time section was the 40 mile long section from the Rt 460/ Rt 258 interchange to the Rt 460/ I-95 interchange. Apart from the similar delays as for those on Rt 58, the vehicles diverging for Rt 460 through the Suffolk Northern Bypass did not have any further congestion in the evacuation route as seen in Figure 4.

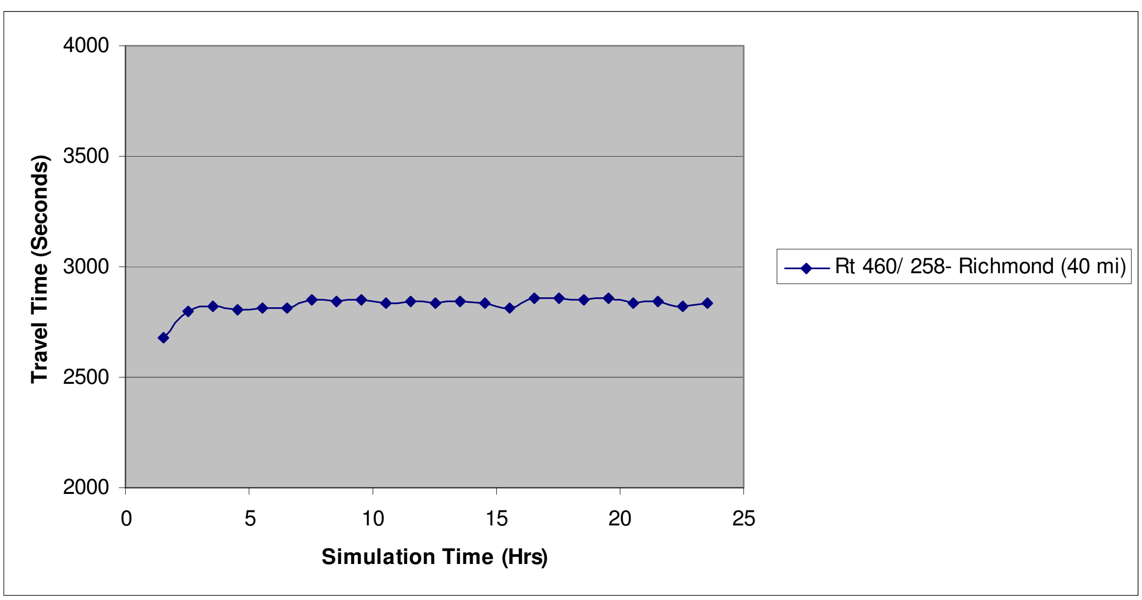

FIGURE 4 Travel time v/s simulation time 4H LR (ATM) for Rt 460.

Rt 60 east of HRBT is mostly used by vehicles from the Virginia Beach and Norfolk to get on to I-64 and Rt 17 in Hampton. These vehicles encounter some signalized intersections on their way to the on-ramp at 4th view/ I-64 interchange. Two travel time sections were defined to understand the travel conditions for this segment of Rt 60. The first section between the Great Neck road and the I-64/ 4th view interchange is about 13 miles in length. The results show that vehicles experience congestion during 7th and 12th hours of evacuation. Similar results are obtained for the second travel time section between Independence Blvd and I-64/ 4th view interchange which is about 9 miles in length. The vehicles experience a maximum delay of around 25 minutes for the two sections as seen in Figure 5.

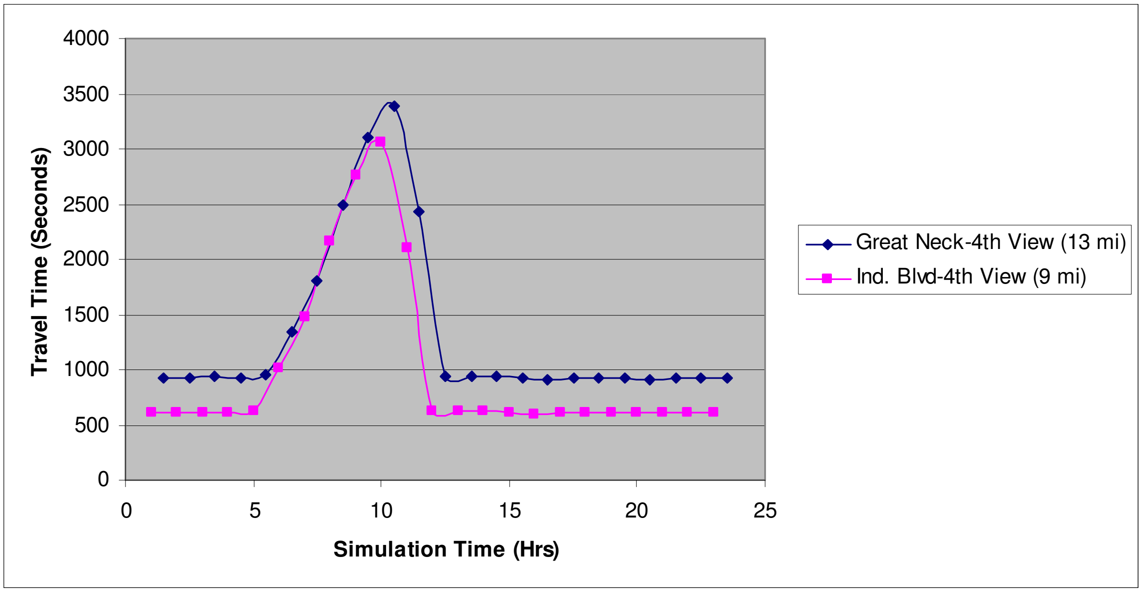

FIGURE 5 Travel time v/s simulation time 4H LR (ATM) for Rt 60.

Vehicles from Virginia Beach and Norfolk using Rt 17 as the evacuation route get on to I-64 to take exit 262 towards Rt 17 via Rt 134 in Hampton. These vehicles also use the on-ramp from I-64/ 4th view interchange to I-64. Hence, these vehicles experience similar travel times and driving conditions until exit 262 where the vehicles move on to Rt 134 and finally onto Rt 17. Since the previous travel time sections on I-64 has already covered the route until exit 262, only one travel time section was defined for Rt 17 to capture the traffic conditions for the remaining part of Rt 17. The travel time section defined was about 80 miles long with its end point upstream of the Rt 17/ Rt 301 intersection in Richmond. Figure 6 shows consistent travel times for the vehicles on this travel time section. This suggests that apart from the delay encountered on I-64, the vehicles using Rt 17 travel without experiencing any additional congestion.

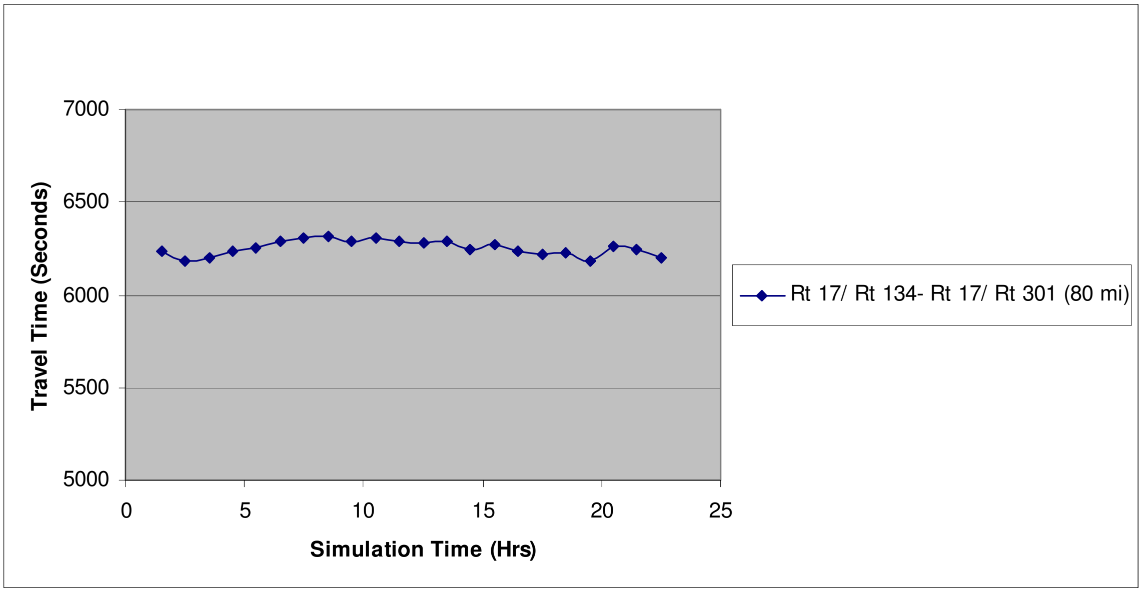

FIGURE 6 Travel time v/s simulation time 4H LR (ATM) for Rt 17.

The number of vehicles using Rt 10 for evacuation is not very significant, mainly because of the limited capacity of Rt 10. Similar to vehicles evacuating on Rt 58 and Rt 460, most of the vehicles taking Rt 10 for evacuation use Rt 58 travel time sections (defined earlier) until they reach Rt 10. Hence, only one travel time section was defined for understanding the traffic flow separately on Rt 10. The section defined was about 40 miles in length and had one single lane. As it can be seen in Figure 7, the travel times did not vary much suggesting congestion less conditions on this evacuation route.

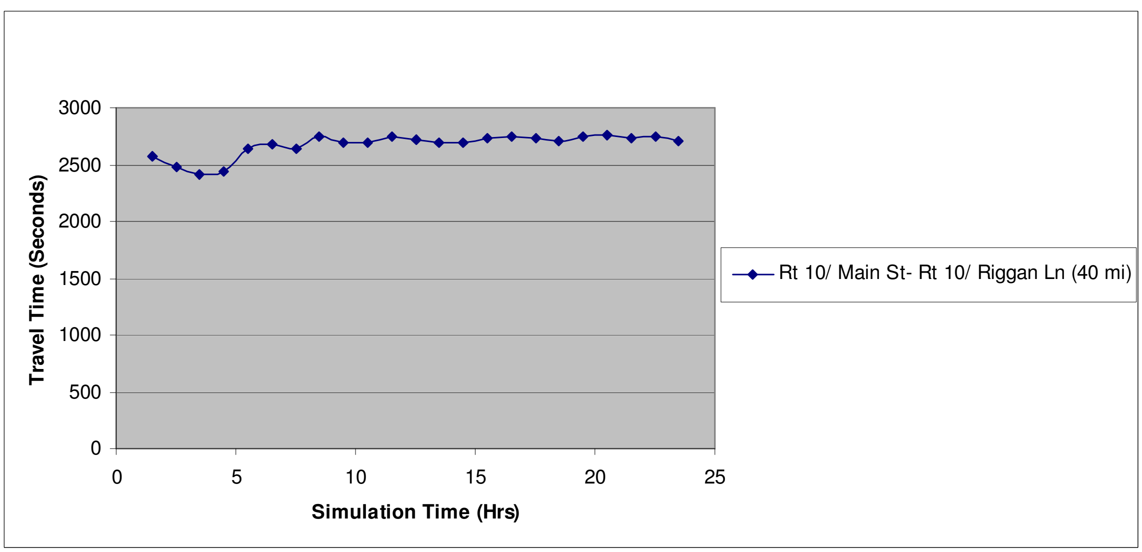

FIGURE 7 Travel time v/s simulation time 4H LR (ATM) for Rt 17.

The results from the plots show that there was heavy congestion in the base case as well as the lane reversal case when the traffic followed the ATM assignment for evacuation. In this research some modifications were done to the current ATM in terms of routing the vehicles to the evacuation routes. The major changes were done in Virginia Beach and Hampton regions. The traffic was routed on alternate paths to evacuate without making any changes to their original O-D characteristics.

The results of through put for each evacuation route were obtained using the data collection points coded at the end of these routes. Through put values for the base case and lane reversal, and modification scenarios are shown in Table 2 along with the travel demand. The values are slightly higher for the lane reversal scenario as compared to the base case for the ATM assigned flows.

TABLE 2 Throughputs for Evacuation Routes

Evac Route	Demand	4 H BC (ATM)	4 H LR (ATM)	4H LR (Modified ATM)
		Th.put	Th.put	Th.put
I 64	66,130	55,665	56,449	60,126
Rt 58	47,000	28,314	29,781	39,218
Rt 460	18,434	11,821	12,517	18,207
Rt 258	2,090	1,986	1,978	2,090
Rt 10	1,931	614	610	867
Rt 17	13,651	11,411	11,490	12,932
Rt 60	3,313	2,484	2,471	2,445
Total	152,549	112,295	115,296	135,732

CONCLUSIONS

Based on simulation results, the following conclusions can be made,

- For a category 4 or higher storm a lane reversal should always be implemented to achieve the optimal traffic performance. For a category 4 storm with high hotel occupancy, almost all vehicles (99%) were able to exit the network by the end of 27 hours. It might be reasonable to add this 3 hour cushion to the typical 24 hour lead time given under evacuation situations.
- The traffic assignment procedure recommended by the ATM does not produce the best results for category 3 or 4 storm scenarios. The modifications to the ATM suggested in this research must be used in order to maximize the efficiency of all evacuation routes.
- Traffic demand on I-64 is much more than its capacity for the section between I-64/Fort Eustis Blvd and I-64/I-295 interchanges. This forces the vehicles to move very slowly but all of these vehicles are able to evacuate to safer region despite the delays.

- The following bottlenecks were identified during the simulations for category 4 storm
    - I-64 regular lanes have a lane reduction from 3 lanes to 2 lanes downstream of the I-64/Jefferson Ave. interchange (exit 255). There is a considerable backup upstream of this location.
    - The traffic has to merge from 2 lanes to 1 lane at the Rt. 58/337 interchange upstream of the Midtown Tunnel since the Rt 58 traffic needs to take a single lane cloverleaf exit at this interchange to get on to Rt 58.
    - At the on-ramp of I-64/Mercury Blvd interchange (exit 263) there is a lane reduction from 3 lanes to 1 lane for traffic approaching from W Mercury Blvd.
    - For the base case scenario, there is congestion on the metered entry points on I-64 at I-64/Northampton Ave, I-64/IRR, and I-64/4th View interchanges.

- Simulation of a 1-hour long incident on one of the three lanes of two evacuation routes, Rt 58 and I-64, at the selected locations brings down the overall throughput (for I-64, Rt 58, Rt 460, and Rt 17) by 1% of the total throughput from an incident-free model. On I-64, the total travel time increased from 6975 vehicle-hours to 7405 vehicle-hours and on Rt 58, the total travel time increased by 500 vehicle-hours. This means that the faster clearance of incidents through incident management techniques such as cameras installed in the vicinity of the potential bottleneck locations will be necessary for efficient traffic operations.
- The ramp metering rates used in the TCP, particularly for I-64/IRR, I-64/Northampton Blvd, I-64/4th View, and I-64/Victory Blvd are not capable of handling the demand getting onto the main line I-64. After a number of iterations, some optimized metering rates were reached at for these entry points to avoid the backup of this traffic onto the arterials. For I-64/Northampton Blvd, I-64/ Mercury Blvd, and I-64/Victory Blvd entry points, 720 vph was found to be performing well. Whereas, for I-64/4th View entry point, a metering rate of 900 vph gave better results.
- Simulation results show that the reversed lanes are being underutilized as compared to their capacity. Some of the traffic from Virginia Beach and Norfolk region, taking I-64 regular lanes, could be diverted to the reversed lanes to increase the utilization of the reversed lanes. However, this would need few geometric changes at the crossover location.
- The future research should focus on improving the computational efficiency of the evacuation simulation models using parallel processing approaches. The network should be broken down into smaller sub-networks and each sub-network should be run on a separate processor. By doing this, the simulation run times would be significantly shorter than the current run times.

REFERENCES

1. *Virginia Hurricane Evacuation Study; Technical Data Report.* US Army Corps of Engineers. Norfolk, 1992.
2. *Hampton Roads Hurricane Traffic Control Plan.* Virginia Department of Transportation, Virginia Beach, 2001.
3. Wiedemann, R., and Reiter, U. "Microscopic Traffic Simulation The Simulation System Mission." Dissertation. 1991.
4. National Weather Service. National Hurricane Center. The Saffir-Simpson Hurricane Scale. http://www.nhc.noaa.gov/aboutsshs.shtml. Accessed February 26, 2008.
5. Sharma, S. "Development of a Large-Scale Traffic Simulation Model for Hurricane Evacuation-A Case Study of Virginia's Hampton Roads Region." Thesis. University of Missouri, Columbia. 2008.