Traffic modelling and simulation for regional multimodal evacuation analysis

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Abstract: History has shown that evacuation planning has been based largely on lessons learned from prior events. While it yields incremental improvements, this approach also results in plans that tend to address failures 'of past evacuations', while leaving vulnerabilities to unforeseen conditions. Traffic simulation is a tool that can be used to evaluate evacuation plans and test contingencies not yet experienced or imagined. This paper discusses an effort to develop and test an agent-based travel demand and simulation model of the New Orleans regional multimodal evacuation plan. It is among the first to integrate a multimodal evacuation process into a regional traffic model with over a million vehicles, covering thousands of square miles, over two days and the first to use field recorded evacuation data for calibration and validation. The result of the model were used to quantitative and qualitative assess speed, volume, density, and congestion formation and recovery throughout the evacuation network.

Keywords: evacuation; traffic simulation; TRANSIMS; speed profiles; USA.

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1 Introduction

Transportation networks are among the largest, most critical, and highly visible components of a national civil infrastructure system. They also have an enormous impact on the efficiency and economic welfare of the country. During disasters they also play a critical role in the movement of people away from dangerous conditions as evidenced by several recent hurricanes along the Gulf Coast of the USA; wildfires in California and Australia; and in flood disasters throughout the world.

The highly-publicised failings to effectively evacuate threatened populations from Houston and New Orleans during Hurricanes Rita and Katrina highlighted the need to more effectively utilise transportation networks during evacuations. In these events two significant failures were evident. The first was a failure to recognise and plan for the evacuation needs of low-mobility populations. The second was the need to manage evacuations at a regional scale. Hurricanes, for example, can put regions the size of several states at risk. This can lead to an enormous number of people evacuating over long distances within a very short time period. Perhaps most alarming is that this demand must be served by road networks which were never planned or constructed for such conditions. Media reports and later analyses (Wolshon et al., 2005a, 2005b) demonstrated the extent to which mass evacuations impact regional traffic. The post event analysis of the evacuation of New Orleans for Hurricane Katrina showed that traffic impacted cities as far as Baton Rouge, Houston, Memphis, and Atlanta. The system-wide impacts also show the need for tools and techniques to analyse and evaluate the implications of evacuation planning and management decisions at regional scales.

The current state-of-practise for the planning and management of transportation system during evacuations has been largely based on lessons learned and a process of trials and errors. Another persistent problem that is hampered efforts to analyse evacuation processes has been a near-absence of traffic flow data collected during evacuations. Even when such data was available it did nothing to contribute to an understanding of the movement of low mobility populations during evacuations.

To scientifically respond to the challenges of developing efficient evacuation plans for both mobile and mobility-limited populations, a recent study funded by the US Department of Transportation (US DOT) sought to develop a simulation model to reproduce the spatio-temporal processes of a mass evacuation. The effort was based on the application of the *TRANSIMS* agent-based travel demand modelling and microsimulation system. In the project, the emergency transportation plan for the New Orleans metropolitan region used during Hurricane Katrina was developed and coupled with the new multimodal citizen-assisted evacuation plan (which did not exist prior to Katrina). The ability of *TRANSIMS* to model traffic networks at scales and level of detail not possible only a few years ago made it both an intriguing and useful tool. This paper briefly describes the *TRANSIMS* system and how it was applied to this problem and summarises the results that were gained from its use.

2 Limitations of prior work and the need for improvement

Regional scale evacuation simulation has several key requirements that need to be addressed. These include the ability to model vast geographical areas, with an enormous number of vehicles; time durations which cover multiple days; and individual vehicular dynamics coupled with the ability to calibrate and validate the results so that the spatial and temporal patterns of traffic observed in the simulation reflect realistic conditions. Until recently, the ability to achieve any one – let alone all – of these of the requirements has been difficult if not impossible.

Early studies to apply to traffic simulation for evacuation were limited in their geographical scales and time durations. Evaluation studies conducted with high fidelity microscopic simulation could only be achieved on small networks over time durations of 12 to 20 hours. Several of the earliest focused on the design and traffic operations at contraflow crossovers (Theodoulou, 2003; Lim and Wolshon, 2005), the evaluation of evacuation routing (Theodoulou, 2003; Williams et al., 2007; Dixit et al., 2008) and impact of evacuation-level demand on small urban signal networks (Jha et al., 2004; Sbayti and Mahmassani, 2006). The simulation of larger regional networks was limited to aggregate-level analyses using macroscopic traffic modelling (Hobeika and Jamei, 1985; KLD, 1984; Kirschenbaum, 1992). From this, only approximate evacuation clearance time and delays could be made, but no understanding of bottlenecks and traffic impacts could be achieved because of the low resolution of the models. Another significant limitation was that few of these models could be calibrated or validated because of the lack of actual traffic data sets. More commonly they were calibrated for normal day traffic with various broad and approximating assumptions of emergency traffic conditions. This was due to the difficulty in acquiring data during actual evacuations to calibrate the networks.

Earlier analyses were also often limited to scales and scopes that were far less than that of realistic evacuations. For example, time durations were limited to less than 12 hours, much below the more typically observed evacuation durations of 24 to 48 hours. Similarly, evacuation traffic volume was often limited to demands of less than 200,000 vehicles. Again, far below the half million vehicles recorded during the Katrina evacuation in Louisiana and only a tenth of the estimated two million vehicles estimated during the Rita evacuation of Houston. In fact, no existing micro-scale transportation simulation model can model the scope of a mass evacuation, neither in terms of the number of people/vehicles nor in the duration of the event.

The initial effort to regionally manage evacuation traffic in Louisiana was undertaken as a direct result of the failings of the 2004 Hurricane Ivan evacuation. Although limited by the capabilities of the models that existed at that time, the simulation results that were developed had an enormous impact on the coordinated regional evacuation plan for the 2005 hurricane season. In fact, the overwhelming successes of the highway-based evacuation for Hurricane Katrina can be traced directly to the 2004 modelling effort. Two recent studies by Wolshon et al. (2005a, 2005b) showed that the Katrina evacuation plan not only diminished the most significant traffic related issues from the Ivan evacuation, it cut the estimated time required to evacuate the city nearly in half, from 72 to 38 hours. Rarely have the benefits of traffic simulation modelling been so clearly and obviously been illustrated. It is not surprising that many transportation and emergency management agencies are now using simulation. However, it remains difficult to accomplish in an accurate and meaningful way.

Recently, Chiu et al. (2008) conducted a regional scale simulation study using *DynusT* to evaluate regional impacts of various evacuation strategies for the Houston-Galveston Texas metropolitan region during Hurricane Rita. This model represented a significant advance over prior work in that it was among the first to evaluate the traffic impacts of an evacuation at a regional scale. However, it was limited in two key aspects. First, the model relied on stated-preference survey data to determine the departure time and origins of evacuees. Second, the simulation output data could not be calibrated to the Rita evacuation event because of a lack of available data. Rather, it was calibrated using routine non-emergency daily traffic.

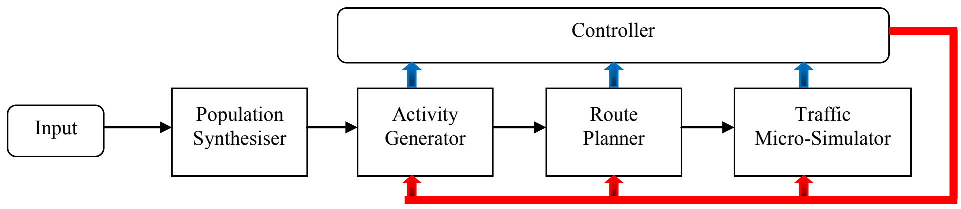
Due a near absence of traffic data during evacuations, prior simulation efforts have utilised survey data or normal day traffic to calibrate and validate the simulation models. Unfortunately, it is very likely that these are not realistic representations of what actually occurs during a mass evacuation. In the most recent Louisiana efforts traffic data collected by the Louisiana Department of Transportation and Development (LA DOTD) during Hurricane Katrina gave a unique opportunity to develop a calibrated and validated regional simulation model for the evacuation of New Orleans. This paper highlights the development and outcomes of this study. This effort also represents among the first attempts to utilise real world evacuation traffic data to calibrate and validate a regional level evacuation model.

3 Transportation analysis and simulation system

The *TRansportation ANalysis* and *SIM*ulation *System* (TRANSIMS) is a microscopic simulation model developed to model the trip-making behaviour of individual persons within individual households. It operates by creating a computer-generated ‘population’ that is statistically representative of the socio-demographic characteristics of a study area then assigning travel activities to individuals based on known travel characteristics. These activities are then assigned to a roadway network at specified times and places. This information is then used to feed a vehicular micro-simulator that moves people and vehicles between their origins and destination.

Figure 1 shows a schematic diagram of the simulation framework. In the New Orleans study described in this paper, the highway and transit networks were coded using existing geographic information systems (GIS) and TransCAD™ road networks developed by the LADOTD. Each rectangular box in Figure 1 corresponds to a module, which are further discussed in the following sub-sections.

Figure 1 TRANSIMS framework (see online version for colours)



3.1 *Population synthesiser*

The *Population Synthesiser* module within *TRANSIMS* was designed to create disaggregate synthetic populations based on aggregate population statistics. Effectively, the system uses US Census data to build synthetic households for a study area, then uses Public Use Microdata Samples (PUMS) and land-use data to locate the households relative to the transportation network. The final output of the *Population Synthesiser* module is a group of synthetic households (and their occupants) with characteristics and travel behaviour that mirror those of the real population including information on the number of vehicles that belong to each household.

In the New Orleans study, the *Population Synthesiser* estimated a total of 392,535 households, and 996,952 persons within the study area. This was used to estimate the total evacuating population and the availability of vehicles in each household. From this, the location and number of low-mobility population was also determined. The ability of *TRANSIMS* to generate households and their corresponding locations gave a unique opportunity an opportunity to test the transit plans which have been recently developed for low-mobility populations in New Orleans.

3.2 *Activity generator module*

In *TRANSIMS* the synthetic population and household activity survey files that are routinely collected by planning agencies serve as input to the *Activity Generator*. A household activity survey file consists of the departure time and destination. The *Activity Generator* then assigns activity pattern to household members and then distributes them to specific locations and modes, which may also include transit busses and trains. Because *TRANSIMS* was not developed with evacuation modelling in mind, these processes have been conceived for the purpose of modelling routine daily travel patterns. In this case, however, the departure times and locations were assigned to reproduce the Katrina evacuation travel patterns. As such, a Monte Carlo-based sampling process was developed based on weighted probabilities the temporal patterns that were observed LA DOTD traffic count data (described later). Similar methods were used to determine the destinations by the evacuees.

3.3 *Router and micro-simulator*

The synthetic activity and coded traffic network next serve as inputs to the *TRANSIMS Router* to generate travel plans. The data generated by the Router is then used to simulate vehicular movements and their interactions within the network. As is necessary for routine daily travel analyses, the New Orleans evacuation study also used an iterative procedure to calibrate and validate the model. Each iteration seeks to balance the assignment of trips evenly across the network. A network is considered to reach an equilibrium once there are no, or minimal differences, between success runs. The New Orleans model required 24 iterations to reach a convergence in the route assignment after which the output volumes were compared to the corresponding observed values. Based on the relative match of the volumes and any unacceptable statistical errors, adjustments were made to the *TRANSIMS* run-control settings to induce a movement of traffic to, or away, from routes that was under, or over, utilised and the process was repeated. The ultimate results of this effort showed that *TRANSIMS* was able to predict the volumes quite reasonably based on the general direction of evacuation. The simulation output modelled the total westbound traffic within an error of 1.58%, eastbound traffic within an error of 9%, northbound within an error of 3%, and southbound within an error of 5%.

4 Katrina evacuation traffic data set

In the study, traffic count data from six LA DTOD permanent count stations was used to compare the actual traffic patterns observed during the Katrina evacuation to that produced by the TRANSIMS simulation on the major outbound evacuation routes from the New Orleans metropolitan area. The approximate locations of these stations are shown in Figure 2. These six stations were selected because they were not necessarily ideal, but they were the only stations located on outbound routes from the New Orleans area and could be used to generally form a cordon around the region. They were also assumed to reduce the potential inclusion of local ambient (i.e., non-evacuation specific) traffic.

Figure 2 Location of LADOTD count stations used for volume comparison (see online version for colours)

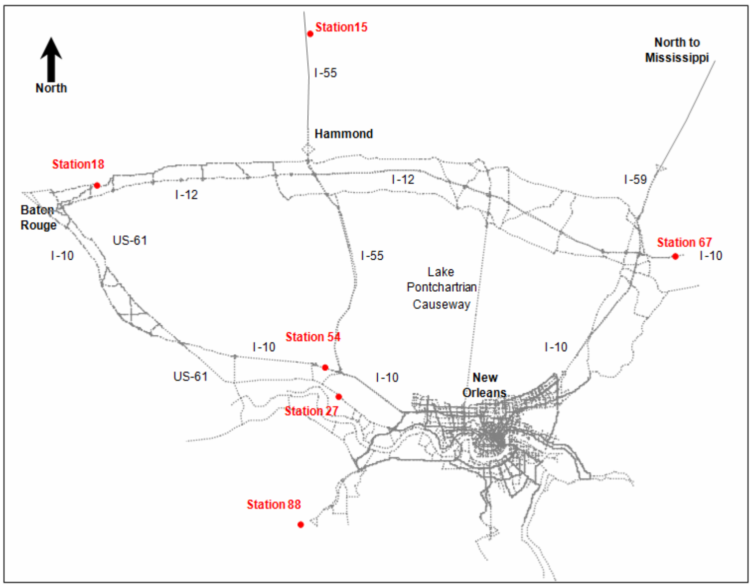
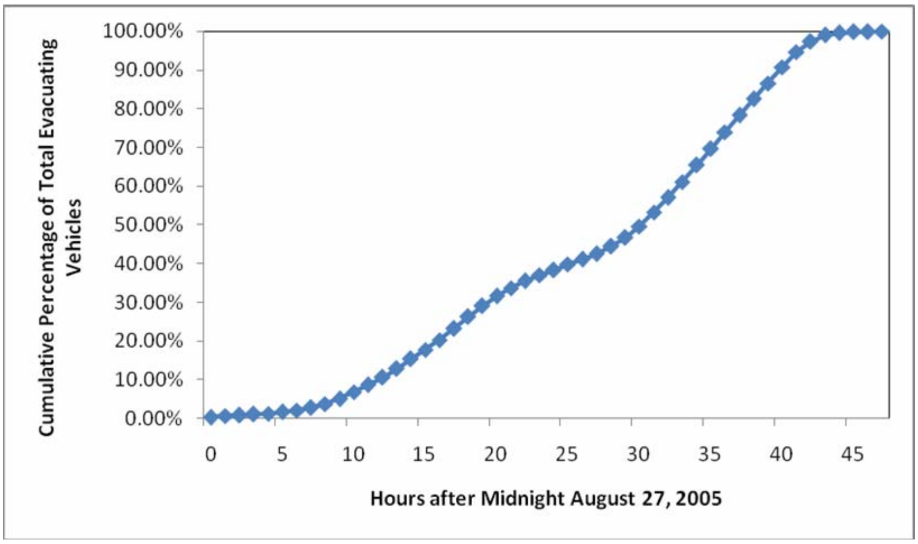


Figure 3 Temporal cumulative evacuation outbound traffic distribution (see online version for colours)



Of the six stations, three were on freeways. Station 15 was on I-55 about 20 miles south of the Mississippi border, Station 54 was on I-10 in LaPlace immediately after the I-10 contraflow termination, and Station 67 was on eastbound I-10 a few miles south of the Mississippi border. The other three stations were located on four-lane divided US-highways. Station 27 was on US-61 in LaPlace parallel to I-10 and near Station 54, Station 88 was located on US-90 the southwest-bound route out of the metro area, and Station 18 was on westbound US-190 parallel to I-12 heading into Baton Rouge.

The hourly traffic count data from these stations was tabulated and used to calibrate and validate the *TRANSIMS* simulation model to fit the Katrina evacuation conditions. The data suggested that the evacuation encompassed the 48 hour period between 12:00 AM Saturday, August 27th and 12:00 AM Monday August 29th. During this period, the hourly traffic volumes varied, however, the cumulative volume trend, aggregated for all six stations, resulted in the characteristic two-day double-S cumulative distribution curve shown in Figure 3. This was used to estimate the departure time distribution.

5 Results

Once calibrated and validated The New Orleans *TRANSIMS* model provided a realistic representation of the New Orleans evacuation during hurricane Katrina. With this it could then be used to quantitatively and qualitatively examine the spatio-temporal characteristics (speed, volume, density, queuing, and congestion formation/recovery) of the evacuating traffic, and evaluate the newly developed, though as-yet unused, citizen assisted transit evacuation plans.

5.1 Spatio-temporal speed analysis

To visualise the output results of the simulation, colour coded maps of speed were used to graphically represent traffic patterns over space and time. This method was found to be useful to display data in an easy-to-understand manner for analysis. The colour maps were particularly valuable for the identification of bottlenecks and understanding the spatio-temporal distribution of speed and volume along various routes. They were also useful for demonstrating the benefits and shortfalls of the contraflow operations at various locations.

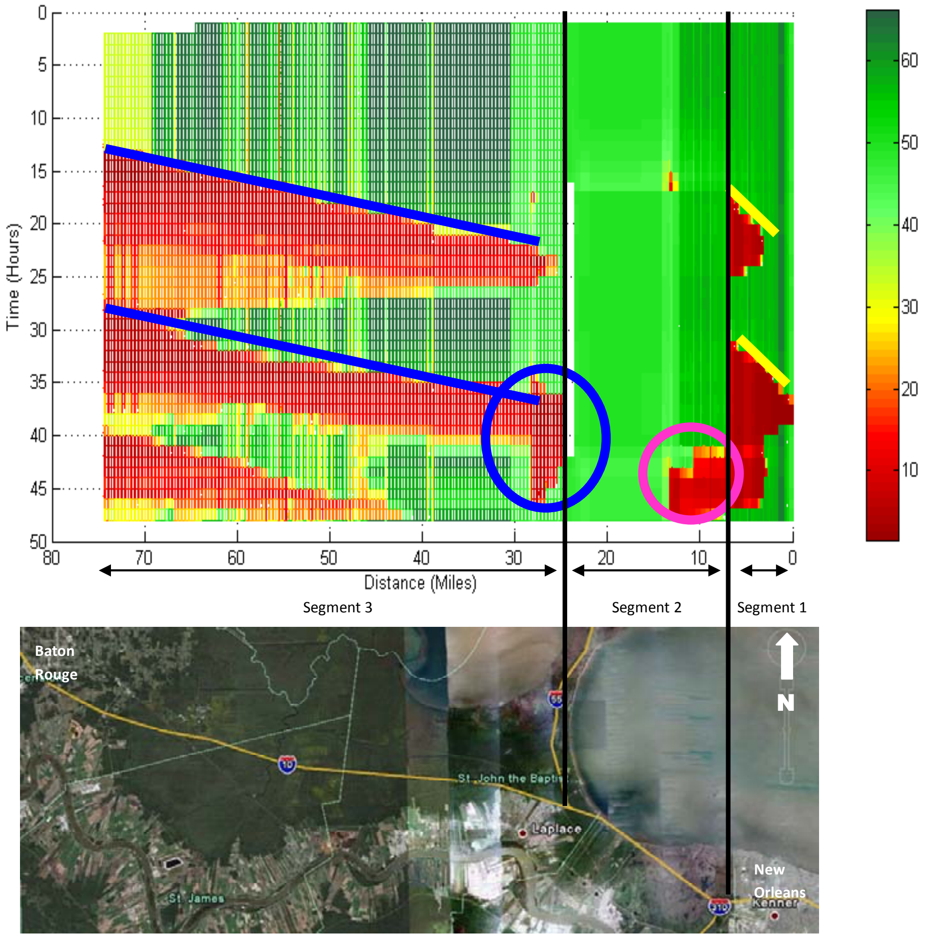
The spatio-temporal speed profile along westbound I-10 from New Orleans to Baton Rouge shown in Figure 4. In the figure, the three segments of the westbound I-10 route from New Orleans to Baton Rouge are shown, including Segment 1 from the New Orleans Superdome to Clearview Avenue, Segment 2 from Clearview Avenue the I-10/ I-55 interchange in Laplace, and Segment 3 from Laplace to Baton Rouge. During the Katrina evacuation, contraflow operations were in effect on Segment 2 of this route from Hour 16 to Hour 40.

These graphs were also helpful to show conditions at particular points and times along the route. A vertical cross-section through any of these graphs represents speed or volume at a specific point during the entire 48-hour duration of the event. Correspondingly, any horizontal cross-section through the graphs represents speed or volume at a specific point along a specified route during the 48 hours of the evacuation. Perhaps even more valuable from a traffic analysis standpoint were the interfaces between the various flow conditions. The angles of colour differences within the various graphs can also be used to estimate the speed and direction of changes in flow state through time and space. These lines represent flow *shockwaves* that occur at the interface of freely flowing and congested states of traffic and move as traffic congestion builds and releases. The angle of these lines suggested the speed of the movement of the changing conditions; the steeper the line, the faster the conditions move through the system.

Figure 4 brings attention to several interesting findings. The red zones indicate locations and periods of low speeds, which also signify a state of queue formation. The blue and yellow lines indicate the progression of queue formations in space and time. It was observed that the shockwave speeds in Segment 1, depicted by yellow lines, are steeper as compared to the shockwaves observed in Segment 3, which are depicted by blue lines in the figure. This is thought to reflect more concentrated demand conditions closer to New Orleans. Here, the flow rate into Segment 1 was highest close in to New Orleans resulting in a faster rate of queue formation on Segment 1 compared to Segment 3.

The slope of the evacuation response curve of Figure 3 was found to be steeper during the late morning and afternoon periods of the two days. The high demand that was generated during these periods is manifested in the red zones of low speed observed in Segment 1 and Segment 2. These peaks in demands also increase the density of traffic and decreases its speeds. The shockwaves in Segment 3 were attributed to the limited capacity of the downstream exits and the additional local traffic in Baton Rouge. This suggests that the exits from the evacuation routes at Baton Rouge could be improved to facilitate and evacuation of New Orleans. In Segment 1 queues formed at the contraflow crossovers. Contraflow crossovers have been known to create bottlenecks due to the lower speeds and manoeuvring through the crossover transition lanes. No queues were observed in Segment 2 during contraflow operations but after the termination of contraflow in Hour 42, queues were observed in this segment. These also spilled back into Segment 1, as shown within the pink circle. This suggests that the contraflow operations on this route may have been terminated prematurely.

Figure 4 Spatio-temporal distribution of speed on westbound segments (see online version for colours)



The contraflow operations on Segment 2 also played an important role in dissipating the queues on Segment 3. The contraflow termination design was efficient in that it did not allow queues to spillback from Segment 3 into Segment 2. This is highlighted by the blue circle in Figure 4, where congestion did not extend spatially into Segment 2, but did extend temporally. This resulted in improved mobility for evacuees destined to northbound locations. This was crucial since Segment 2 provided access to vehicles going north on I-55. A queue extension into Segment 2 would have resulted in adverse effects on access onto northbound I-55.

5.2 Transit-assisted evacuation

After the failure to effectively coordinate the movement of low- and non-mobile populations prior to Hurricane Katrina, public officials in Louisiana sought ways to better assist its mobility-limited citizens. The plan that was developed is called the *New Orleans City-Assisted Evacuation Plan* (City of New Orleans, 2007). The plan basically calls for a two-tiered system of busses to first circulate locally within the city to pick up evacuees, then transport them to regional coaches for movement to more remote shelter destinations. The transit evacuation plan that was modelled in *TRANSIMS* was based on the published plan for New Orleans and its surrounding parishes. The number and percentage of residents and tourists that are expected to utilise this assisted evacuation was estimated using the number of people in carless households from the *Population Synthesiser* module.

Evacuees requiring transit assistance were assumed to be moved over a period of 20 to 21 hours. Another, more temporally condensed, S-shaped response curve was assumed for the departure time distribution of the assisted evacuees. A slightly modified response curve and separate bus routes were assumed for tourists seeking transport to the airport. The simulation was used to determine the trips that would be required by bus transit to evacuate all the low-mobility populations, to their intended destinations.

Although several alternative strategies continue to be tested, the most obvious test strategies were carried out first. Using the obviously effective strategies, it was found that the most effective scenarios for transit-based evacuation were those that were carried out during time periods during which the auto-base evacuation was in its off-peak periods, particularly in the early morning and late evening periods. Using offset travel peaks resulted in an approximate 51% reduction in overall travel time.

TRANSIMS was also found to be useful in identifying bottlenecks when including transit busses within the regional network. It is expected that it will next be used to help estimate the number of transit trips will likely be required and to develop strategies that more effectively evacuate low-mobility people from the local neighbourhoods. It will also be utilised to test and plan relative to other contingencies and scenarios.

6 Conclusions

The history of mass evacuation practise has shown that evacuation traffic management plans have been based largely on lessons learned from failures identified in prior events. This approach has resulted in evacuation plans which have been developed to cater to ‘failures of the last evacuation’. Unfortunately, this does little to address the future and may leave the public vulnerable to unforeseen conditions. The use of simulation modelling to evaluate evacuation plans provides somewhat of ‘crystal ball’ and holistic view of the entire evacuation operation that can also be used to test any contingency that can be imagined and not experienced in the past. For this reason, simulation can help develop more robust and effective evacuation plans.

Since traffic data collected during evacuations are scarce and is limited to specific locations on highways, present information set are not able to provide a complete pictures of the evacuation processes. Also, since most of the data regarding evacuation is limited to highway data, it is virtually impossible to understand the evacuation of low-mobility individuals who must rely and provided services. Through the use of up-to-date census data and real evacuation traffic data, this research effort showed that it was possible to calibrate and validate a *TRANSIMS* simulation model capable of creating a realistic representation of the Hurricane Katrina evacuation. In particular, the system's *Population Synthesiser* was a useful tool to determine the probable numbers and locations of low-mobility persons. The geographical scale and the simulation time duration budgets permitted by *TRANSIMS* were also enormously helpful to provide quantitative and qualitative insights into the regional impacts and progression of the New Orleans auto-based and transit-assisted plans. This study is also among the first to utilise actual field recorded evacuation traffic data to calibrate and validate a regional scale model.

From an operational-level standpoint the work described in this paper illustrates the value of regional micro-level modelling and how strategic management decision-making can be supported. An example of this was illustrated by the development and interpretation of the colour coded maps of the spatio-temporal distributions of speeds. In this simulation it was found that contraflow crossovers, if not properly controlled to facilitate an unimpeded flow of traffic, can become a source of bottlenecks. Similarly, bottleneck can develop at far away downstream locations due to exiting restrictions at near the sheltering destinations. The illustration of the spatial and temporal propagation of traffic congestion from these critical points suggests the need to closely monitor and manage traffic at these locations. Another way that the simulation can be helpful was to show how extending the contraflow operations can contribute toward reducing system-wide congestion and decreasing the clearance time of the overall evacuation. Because a system like *TRANSIMS* can seamlessly marry a population synthesiser with a micro-simulator it can help to determine the number and location of assisted evacuees then compute their travel times and delays throughout the network as they ride. Although the evaluation of alternative strategies has only been accomplished a simplistic level at present, it nevertheless showed how the manipulation of bus scheduling was able to materially enhance the travel times.

When combined, models and concepts such as those demonstrated here provide a significant resource for policy-decisions both large and small. TRANSIMS could be used to test other policy scenarios, such as providing incentives for people to shelter in certain locations, such as secure hospitals and schools, or to test the feasibility of encouraging regular folks to leave their cars at home and evacuate via transit for the option of designating certain routes as bus-only evacuation corridors. Currently, spatio-temporal speed graphs such as the ones presented are being considered for use in determining the locations to place en-route fuel services for vehicles running low on fuel as well as comfort and medical services to those in need. In the future, plans are also being developed to incorporate other modes of traffic such as air and rail to provide an even more robust illustration of evacuation operations.

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