Assessing the Effectiveness of Flexible Response in Evacuations

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Abstract: The past 20 years have seen significant improvements in the way regional mass evacuations are carried out in the United States. Today's use of phased evacuation orders, contraflow, and citizen-assisted transit evacuations have come about as lessons learned from previous evacuations and have led to improvements in later ones. This paper summarizes a study to examine what may be a future step in this improvement process: the concept of flexible evacuation responses to major catastrophic hazards. Within this idea, evacuation plans would be developed in which the timing, direction of movement, and regional traffic-management plans would be changed based on the characteristics (e.g., strength, speed, movement, etc.) of a particular threat. This study was carried out using an integrated model that combines a calibrated evacuation demand model with a calibrated microscopic simulation model to evaluate a set of flexible evacuation plans for four theoretical hurricane conditions. The experimental results showed that even simple alterations to a single, static, one-size-fits-all-scenarios plan had significant benefits to the movement of traffic. In addition, such improvements could provide over $400,000 in fuel savings over the existing static plan. Whereas this research was based on evacuation from a hurricane, it is expected that similar results could be attained for evacuations from other threats. **DOI:** 10.1061/(ASCE)NH.1527-6996.0000101.

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Introduction

Over the past 20 years, the threat of hurricanes in coastal areas of the United States has led to numerous mass-scale evacuations of highly populated regions. Over this time, the lessons learned for previous evacuations have led to significant improvements in later ones. Difficulties experienced in the evacuations for Hurricane Floyd in Florida, Georgia, and South Carolina in 1999; Hurricane Ivan in Louisiana and Mississippi in 2004; Hurricane Katrina in Louisiana, Mississippi, and Alabama in 2005; and Hurricane Rita in Texas in 2005 have all led to incremental improvements in the way we prepare for and carry out mass evacuations.

Continuing in this pattern of needs identification and improvement, the concept of using a flexible or adaptive response to carrying out evacuations has been suggested as a way to further increase the ability to better respond to catastrophic threats (Wolshon 2001; Urbina and Wolshon 2003). Under such a strategy, the use of transportation resources and networks would be spatially and temporally adapted to the extent, movement, and forewarning afforded by a particular hazard. Many examples of flexible response concepts already exist in areas that use graduated traffic-management measures such as phased evacuation orders, implementation of contraflow and road/bridge closures, and citizen-assisted transit evacuation plans that are needed based on changing threat conditions. Phased evacuation strategy assigns evacuees in different zones different departure times. Usually, the most vulnerable areas are allowed to evacuate before less vulnerable areas. Contraflow and road/bridge closures are used together most often to increase the capacity on vital routes leading away from evacuation zones. Citizen-assisted transit evacuation plans refer to specialized plans for the transit-dependent residents of an evacuation zone. Whereas all these concepts may be employed to create more strategic evacuation plans, it is important to recognize that not all these strategies will be useful in every scenario. In particular, this research seeks to advance the use of a set of evacuation plan based on variable threat scenarios rather than a single, static, one-size-fits-all plan.

An illustration of spatially adaptive evacuation planning can be seen today in California, where no specific evacuation plan exists for wildfires; rather, emergency response and planning officials use a general template of action. In areas threatened by fires, formal evacuation plans are not able to be developed in the way they are for hurricanes. This is so because hurricanes approach land from generally the same direction, whereas wildfires can move in any direction at speeds of 145 km/h (90 mi/h) or more based on wind conditions. As a result, a fixed or predesignated evacuation plan could be rendered useless if fires overtook an evacuation route and made it impassable before the evacuation started or while it was underway. To avoid this, California officials use evacuation frameworks that include an identification of all routes leading away from threatened areas. Then, as the speed and forecast movement of the fires become clear, a formal evacuation plan with specified risk areas and routes out is developed, and specific orders are issued (Wolshon 2009).

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Whereas the idea of flexible evacuations has many benefits, it may be difficult to implement in practice, particularly for large-scale threats such as hurricanes or hazards that give little or no advanced warning. First, communication is difficult during emergencies. Even during hurricane threats, when several days are available to convey clear, simple, and effective guidance to evacuees, communication is a challenge. Evacuees must actually receive the order to evacuate and follow it. Many potential evacuees choose to ignore orders until they feel sufficiently threatened, whereas others do not understand the order or are confused about how and when to respond. Because of these realities, hurricane evacuation orders are issued many hours, if not days, before the effects are predicted to occur. Further, the overall plan, including evacuation routes, is publicized throughout the year, particularly before and during the active hurricane season (Baker 1991; Dash and Gladwin 2007). If a single plan is already difficult enough to implement, a plan that changes with each new storm cannot be expected to be implemented easily by officials.

To examine the theoretical implications of flexible and adaptable response ideas, the authors have engaged in an effort to evaluate the traffic effects of this type of evacuation planning. To accomplish this, they have taken advantage of a large-scale microscopic model recently developed for the southeastern Louisiana region around New Orleans that was earlier calibrated to match the actual spatial and temporal movements of traffic during several prior storms (Wolshon et al. 2009). To go beyond traditional traffic simulation modeling, the New Orleans model has been integrated with a recently developed evacuation travel-demand model that forecasts the origins, destinations, and departure times of evacuees under any particular set of storm threat conditions (Montz et al. 2011). Combined, this integrated model provides the ability to generate and assign evacuation traffic to the network and then compile and assess the resulting traffic-flow conditions over the entire region for two full days at the individual-vehicle level.

This paper summarizes the results of the research effort. A set of alternate evacuation plans was developed for the New Orleans region by making small changes to the existing regional contraflow evacuation plan that has been in use for the area since 2005. Changes were made based on the idea of prioritizing major evacuation routes considering the spatiotemporal evacuation demand that was forecast with models based on what people said they would do in response to a series of hypothetical storms. For comparative purposes, the effects of the alternate plans were examined against those that would be expected to occur under the existing fixed plan. The assumptions and methods used, as well as the results gained from them, are discussed in the sections that follow.

Background

A review of the literature shows a large amount of progress in the area of optimizing roadway networks, especially in the special case of emergency evacuation. The idea of using existing intelligent transportation system infrastructure to establish real-time traffic management was explored by Liu et al. (2007). Staged evacuation exercises have been explored by both Liu et al. (2006) and Sbayti and Mahmassani (2006). Both Ng and Waller (2009) and Abdelgawad and Abdulhai (2009) conducted studies that altered network capacity based on different storm scenarios. Whereas these studies all used mathematical optimization to alter network conditions, this study used a more basic approach that relied on prior hurricane experience and heuristic judgment to arrive at alternative evacuation plans.

The development of models to forecast evacuee destination choice and departure time to simulate spatiotemporal travel-demand profiles during an evacuation has been ongoing for several years. The sequential logit model developed by Fu et al. (2006) provides a method to estimate overall evacuation response and departure-time choice. In their paper, the authors discuss the estimation of the model using data from Hurricane Floyd in South Carolina and how the model was transferred to fit southeastern Louisiana data by adjusting the model's alternative-specific constant (ASC). The transferred model's RMS error was found to be 4.53 evacuations per 6-h period, which was considered reasonable. The reader is referred to Fu et al. (2006) for more details on the development of their model. In this study, the transferred sequential logit model (with ASC = −8.18) was used to estimate evacuation response and time profiles for experimental storms using the following factors:

- Hurricane wind speed (in miles per hour),
- Time of day,
- Evacuation order (voluntary or mandatory), and
- Distance of storm (miles) to the emergency planning zone (EPZ) center (transformed with the gamma distribution).

In a related study, Cheng et al. (2008) developed two multinomial logit models that are able to estimate an evacuating household's destination choice. In this study, the friends/relatives model from Cheng et al. (2008) was used to estimate the percentage of evacuees choosing a destination based on the following information:

- Destination's distance from origin city,
- Relative risk of destination to experience tropical-storm-force winds,
- Destination population, and
- Destination's racial makeup.

Cheng et al. (2008) reported Estrella's index of the model to be 0.6903 and McFadden's likelihood-ratio index (LRI) to be 0.1613, both of which indicate a reasonable fit.

Computer modeling of evacuation has provided a tool to evaluate and test several scenarios. This has led to improvements in crossover designs that have been made through simulation of corridors and small-scale networks (Theodoulou and Wolshon 2006). Today, the simulation of larger, regional networks is becoming the new standard for general evacuation planning. Because evacuation events generate traffic volumes that extend over periods of up to several days, cover areas of thousands of square miles, and involve millions of vehicles, there is a need to conduct simulation studies at a regional level (Wolshon et al. 2009; Chiu et al. 2008). Abdelgawad and Abdulhai (2009) developed a multimodal evacuation plan for the city of Toronto for a no-notice evacuation event. The increasing processing power of computers has made it easier to evaluate simulations of a dynamic large-scale evacuation event.

A recent series of projects sponsored by the U.S. Department of Transportation (USDOT) and the U.S. Department of Homeland Security (USDHS) sought to evaluate the use of *TRANSIMS* for the analysis of regional evacuations (Wolshon et al. 2009). A traffic-simulation model using *TRANSIMS* was developed for the New Orleans region. The regional network used for this study is shown in Fig. 1. The figure also shows the origin points of evacuees (the EPZ) and the four points representing the proximate destinations of evacuees. Evacuation trips in the model where estimated using Census 2000 household data for the EPZ. A combined model was developed for this study that integrated both the departure-time and destination-choice models discussed earlier with the *TRANSIMS* traffic-simulation model. This combined model could estimate an empirically based evacuation demand for different storm scenarios and then simulate the demand on a regional network. The combined model was calibrated in a previous study using traffic data recorded during the evacuation for Hurricane Katrina in 2005. For simplicity, the model's demand contained only permanent-resident evacuation traffic at a rate of one evacuating vehicle per household. Detailed

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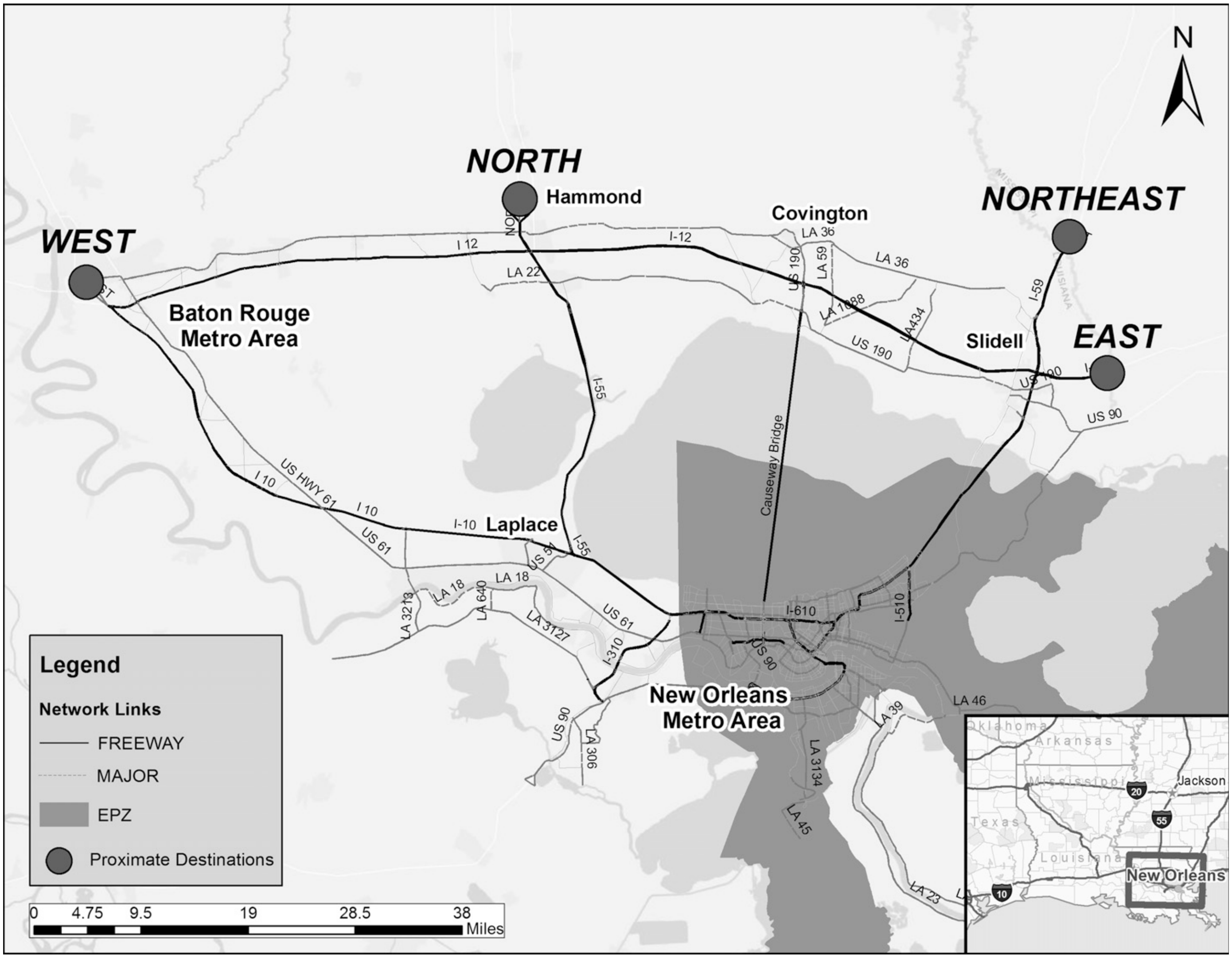


Fig. 1. *TRANSIMS* network and destinations (data from Montz, et al. 2011; Screenshot used by permission. Copyright © ESRI and its data providers. All rights reserved)

demand data such as background, shadow, transient, and transit-dependent data were not considered for this initial study. For more details concerning the traffic model and its calibration, the reader is referred to Montz et al. (2011).

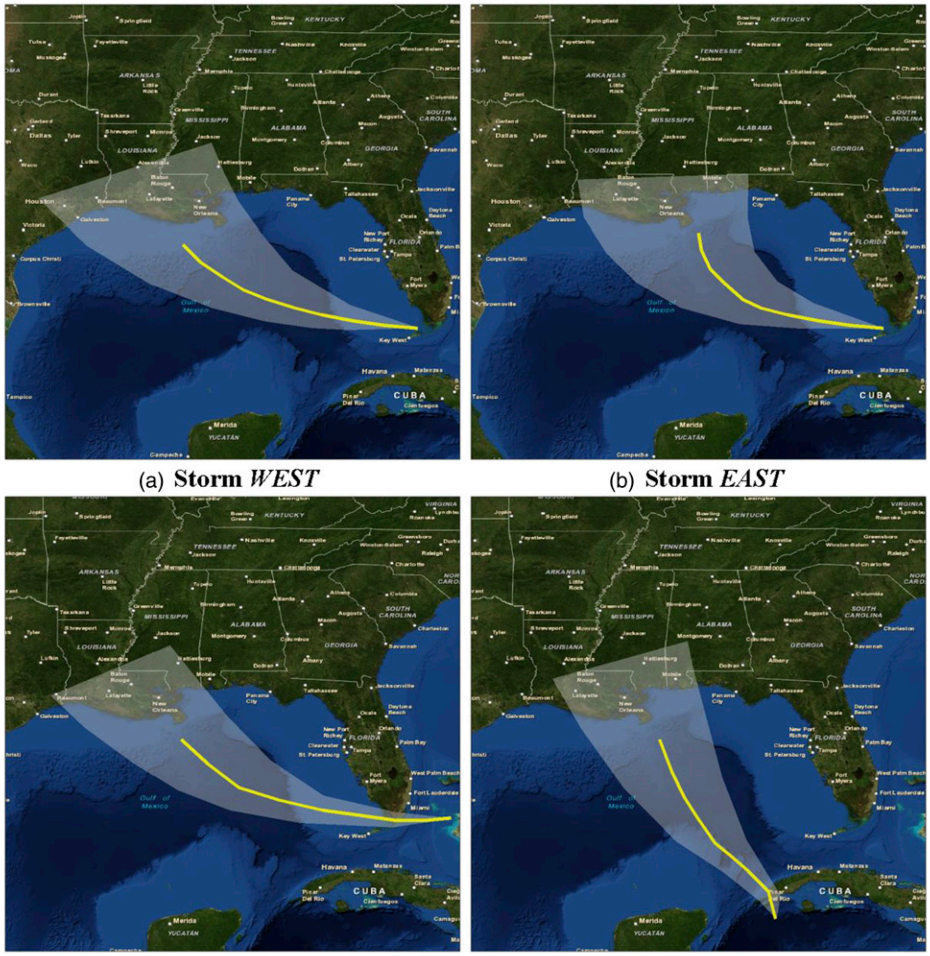
Storm Scenario Methodology

To test the spatiotemporal effects of hurricanes on evacuation, four storm scenarios were created for experimentation purposes. The four tracks were then mapped to estimate the distance to landfall during the two-day evacuation period for each storm scenario. The first two storm tracks were designed to have paths that made landfall in different areas, but the time-dependent characteristics (e.g., landfall distance, wind speed, evacuation order, and time of day) were kept constant. This resulted in different destination-choice responses among the evacuees. The second two hurricane tracks varied in the time-dependent characteristics but made landfall in approximately the same area, and this resulted in temporal variations in evacuee demand.

The tracks of each storm scenario were based on historical storm records maintained by the National Oceanic and Atmospheric Administration (NOAA). The storm scenarios eliciting a varied spatial response are referred to as Storm Scenarios West and East, indicating the cardinal direction of landfall with respect to New Orleans. Both these storms were actually the 1992 Hurricane Andrew path that was altered to generate varied spatial responses. Storm Scenario West had a westward approach path, whereas Storm Scenario East had an eastward approach path. The storm scenarios eliciting a varied temporal response were named Camille and Betsy because the paths of these scenarios were unaltered from actual hurricanes by the same names.

Storm Scenario Description

Maps showing the paths and cones of uncertainty for the four storm scenarios are provided in Fig. 2. The cones of uncertainty were used to determine the destinations that would be affected by each storm at a point approximately 48 h before landfall (the assumed evacuation period). A 48-h evacuation period was assumed based on previous traffic data in Louisiana for Hurricane Katrina, which indicated that a majority of traffic evacuated 2 days before landfall (Wolshon and McArdle 2009). Using the evacuation-demand models, the distribution of evacuees was predicted from a list of



(a) Storm *WEST* (b) Storm *EAST*

(c) Storm *BETSY* (d) Storm *CAMILLE*

Fig. 2. Storm-scenario paths and cones of uncertainty (Screenshot used by permission. Copyright © ESRI and its data providers. All rights reserved): (a) Storm Scenario West; (b) Storm Scenario East; (c) Storm Scenario Betsy; (d) Storm Scenario Camille

14 possible destination cities for each scenario. The destination-choice model included an indicator variable for any potential destination appearing within the cone (Fig. 2). The presence of the indicator variable would lower the potential destination's utility and therefore its desirability as a destination. The destination cities were reduced to four proximate destinations located on the model's network after considering the shortest route between New Orleans and the destination city. The final destination distribution is shown in Table 1. As expected for Storm Scenarios West and East, only the North proximate destination demonstrated no change, whereas the three other destinations exhibited large differences. In contrast, the table shows that the destination distribution probabilities were not significantly different ($\leq 5\%$) between Storm Scenarios Betsy and Camille.

Fig. 3 shows the probability distributions from the evacuation departure-time model. The evacuation departure-time model predicted the peak evacuation hour to be at 7 a.m. of the second day. As expected, no discernible difference in temporal patterns was found between the two storm paths. The peak wind speeds of both storms were modeled to reach 274 km/h (170 mi/h) at 1 p.m. on the second day of the simulation. The evacuation ended at midnight for both storms, which was 6 h before each storm made landfall.

Fig. 3(b) shows the departure-time curve for Storm Scenarios Camille and Betsy. The differences in time profiles were attributed to both the timing and the maximum wind speed of the two storms.

Table 1. Destination Choices for Storm Scenarios

Destination	Storm Scenario West	Storm Scenario East	Storm Scenario Betsy	Storm Scenario Camille
West	37%	49%	40%	43%
North	20%	20%	19%	21%
Northeast	13%	9%	12%	12%
East	31%	23%	29%	24%

Storm Scenario Betsy had a peak wind speed of 250 km/h (155 mi/h) at midnight on the second day, which was 6 h before the storm made landfall. Storm Scenario Camille reached a maximum wind speed of 306 km/h (190 mi/h) around 6 p.m. on the second day, again 6 h before landfall. It should be noted that even though the two storms had different landfall times, the evacuation period was still assumed to last 48 h, ending 6 h prior to the respective storm landfalls. Therefore, when making comparisons between these two storms, the evacuation-period hour should be used instead of the time of day. The peak evacuation departure rate occurred at Hour 32 for Storm Scenario Betsy and Hour 36 for Storm Scenario Camille, as indicated by the slope of each storm's cumulative time profile at these respective hours. In summary, Table 2 shows the time variables used

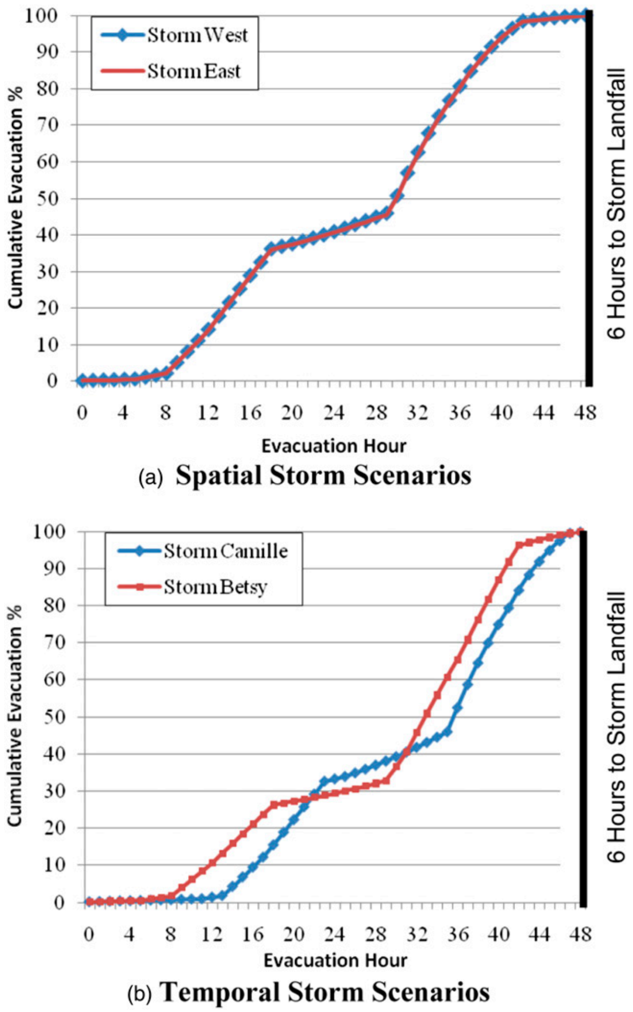


Fig. 3. Cumulative evacuation departure-time curves: (a) spatial storm scenarios; (b) temporal storm scenarios

to create the storm scenarios. The evacuation departure-time model also predicts the total percentage of evacuees who will choose to evacuate for the given variables. This percentage is provided in the last column of the table. Note that in Fig. 3 the departure curves show a cumulative total of those who elect to evacuate.

Alternate Evacuation Plans

Next, the research sought to examine plans tailored specifically for these experimental scenarios. The current evacuation plan used for the entire southeast Louisiana region, including New Orleans, is shown in Fig. 4. This plan was implemented for both Hurricane Katrina in 2005 and Hurricane Gustav in 2008 and was therefore used as the base plan in this study.

The set of alternate plans consisted of four separate plans that corresponded to each storm scenario described earlier. The basic modeling assumption when implementing any alternate plan was that emergency management officials would select the proper plan out of the set of flexible plans only after evaluating the storm conditions. The selection of a particular plan would be made when official evacuation orders were given.

Alternate plans were developed by changing the base plan—either opening or closing major routes—to make more efficient use of the network capacity. This also included eliminating some contraflow segments that were not needed. The development of the alternate plans relied on heuristic judgment rather than mathematical models. For example, based on previous empirical evacuation data in Louisiana, contraflow lane capacity is approximately 950 vehicles per hour per lane, whereas adjacent normal-flow lane capacity is 1,300 vehicles per hour per lane (Wolshon 2008). Therefore, contraflow sections would only be justified when the demand was expected to exceed this capacity. In addition, interstate lane restrictions can be used to control an evacuee's possible routes. However, when a key destination is blocked by these restrictions, evacuees will be forced to use local roads, which might lead to an extended evacuation time. Therefore, any interstate lane restriction should show an understanding of evacuees' desired routes and destinations. In this study, a macrosimulation for each storm was performed to obtain a high-level picture of the network. Expected lane capacities and bottlenecks due to lane restrictions were identified from the macro model, and the alternate plans were developed to address major network deficiencies. Whereas more complicated algorithms should be developed in future research, one of the key ideas of this study was to show that even small changes could result in improved evacuation conditions.

For all storms, traffic on I-10 eastbound at Slidell was allowed to continue on eastbound I-10 into Mississippi or northbound on I-59. This was done to allow an expected 20–30% of evacuees (Table 1) to proceed unhindered to the East destinations. The contraflow section on I-59 was eliminated in all alternate plans because of a demand generated in the macro models that was less than the capacity. Given the potential bottleneck from the merging of I-12 and I-10 eastbound, I-12 was closed to eastbound traffic starting at the U.S. 11 exit at Slidell, and priority was given to eastbound traffic leaving New Orleans on I-10. Any potential traffic heading westbound into Louisiana from Mississippi would be allowed to choose between northbound I-59 or westbound I-12 but could not proceed on westbound I-10 to New Orleans. These modifications to the Slidell area interchanges are shown in Fig. 5.

As seen in Table 1, Storm Scenarios West and Betsy had less traffic demand for destination to the West. To respond to this spatial variation in demand, the configuration at the I-12/I-55 junction in Hammond was altered to allow traffic to choose westbound I-12 before the contraflow crossover point. Also, a directional fork was created on westbound I-12 with one lane that would divert to northbound I-55 and one lane that would continue on westbound I-12. This configuration was not used for Storm Scenarios East and Camille because the larger demand traveling west was expected to lead to congestion, especially in Baton Rouge.

All alternate plans preserved the existing configurations in the suburbs west of New Orleans because it was recognized that Baton Rouge would remain the most attractive destination, regardless of the approach direction of the storm. The configuration at the northern terminus of the Lake Pontchartrain Causeway was also preserved to encourage New Orleans traffic to select this additional route out of the city. For both plans, I-12 westbound in Baton Rouge was closed at Airline Highway. This closure sought to prevent a major bottleneck at the I-10/I-12 merge in Baton Rouge. Traffic was forced to use U.S. 61 and then U.S. 190 if evacuees sought to continue to Baton Rouge. Again, these changes are noted in Fig. 5.

The alternate plans implemented for Storm Scenarios Betsy and Camille involved a temporal shift in the implementation timeline of the current existing evacuation plan. The timeline used for the current existing evacuation plan was the same as for Hurricane Katrina, which began at Hour 16 in the simulation (corresponding to 4 p.m. on the first day) and ended at Hour 40 (corresponding to 4 p.m. on the second day). For the alternate plans, it was hypothesized that starting contraflow plans during the expected second-day spike in

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Table 2. Time Variables and Evacuation Rates for All Storm Scenarios

Variable	Simulation time (h) 0	6	12	18	24	30	36	42	48	Evacuation participation rate (%)
Storm Scenarios West and East										
Time of day	1 a.m.	7 a.m.	1 p.m.	7 p.m.	1 a.m.	7 a.m.	1 p.m.	7 p.m.	1 a.m.	
Distance (km)	922	816	703	610	510	432	351	267	195	81.3
(mi)	573	507	437	379	317	268	218	166	121	
Wind speed (m/s)	49	51	51	51	65	74	76	72	67	
(mi/h)	110	115	115	115	145	165	170	160	150	
Warning	—	—	V	V	V	M	M	M	M	
Storm Scenario Betsy										
Time of day	1 a.m.	7 a.m.	1 p.m.	7 p.m.	1 a.m.	7 a.m.	1 p.m.	7 p.m.	1 a.m.	
Distance (km)	1274	1191	1087	948	822	665	606	364	213	69.2
(mi)	792	740	675	589	511	413	376	226	132	
Wind speed (m/s)	56	56	56	54	56	60	63	65	69	
(mi/h)	125	125	125	120	125	135	140	145	155	
Warning	—	—	V	V	V	V	M	M	M	
Storm Scenario Camille										
Time of day	7 p.m.	1 a.m.	7 a.m.	1 p.m.	7 p.m.	1 a.m.	7 p.m.	1 a.m.	7 a.m.	
Distance (km)	1152	1032	913	819	741	610	508	387	240	82.4
(mi)	716	642	568	509	460	379	315	240	149	
Wind speed (m/s)	51	47	54	63	67	72	80	83	85	
Wind speed (mi/h)	115	105	120	140	150	160	180	185	190	
Warning	—	—	—	V	V	M	M	M	M	

Note: V = voluntary; M = mandatory.

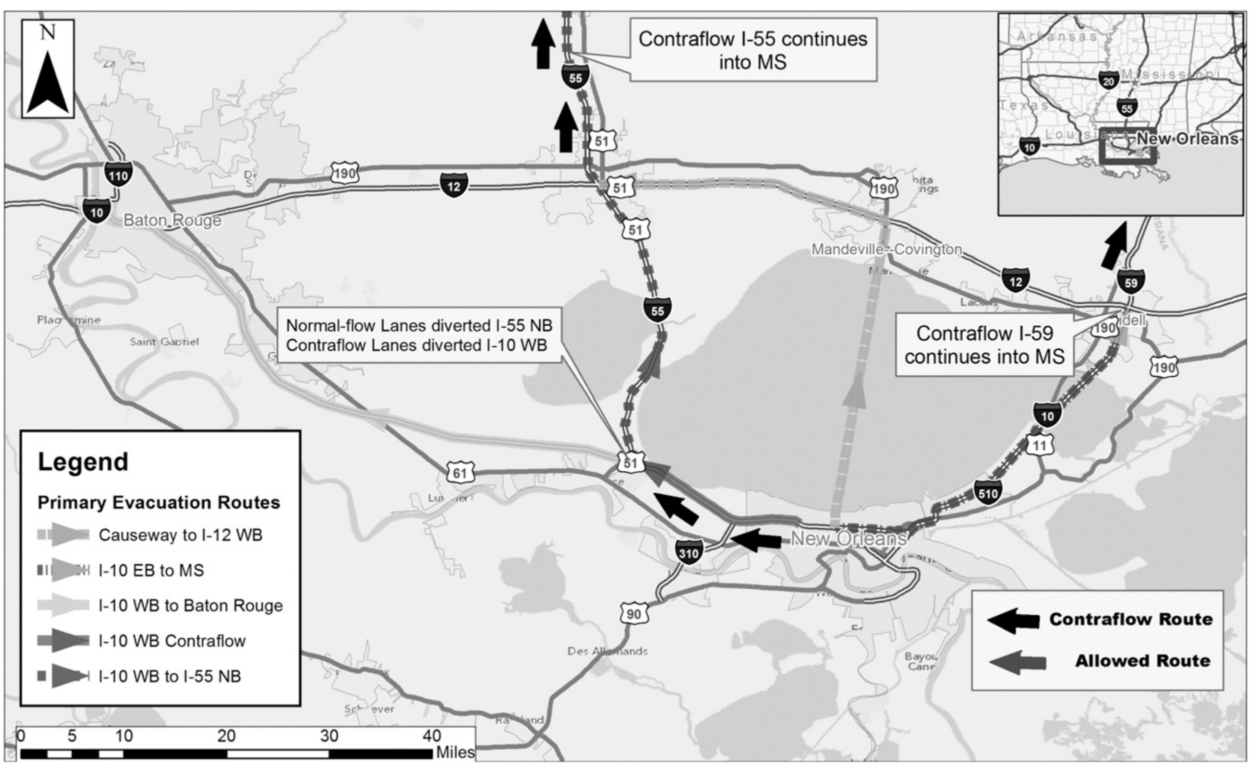

Fig. 4. Metropolitan New Orleans contraflow plan (data from Louisiana DOTD; Screenshot used by permission. Copyright © ESRI and its data providers. All rights reserved)

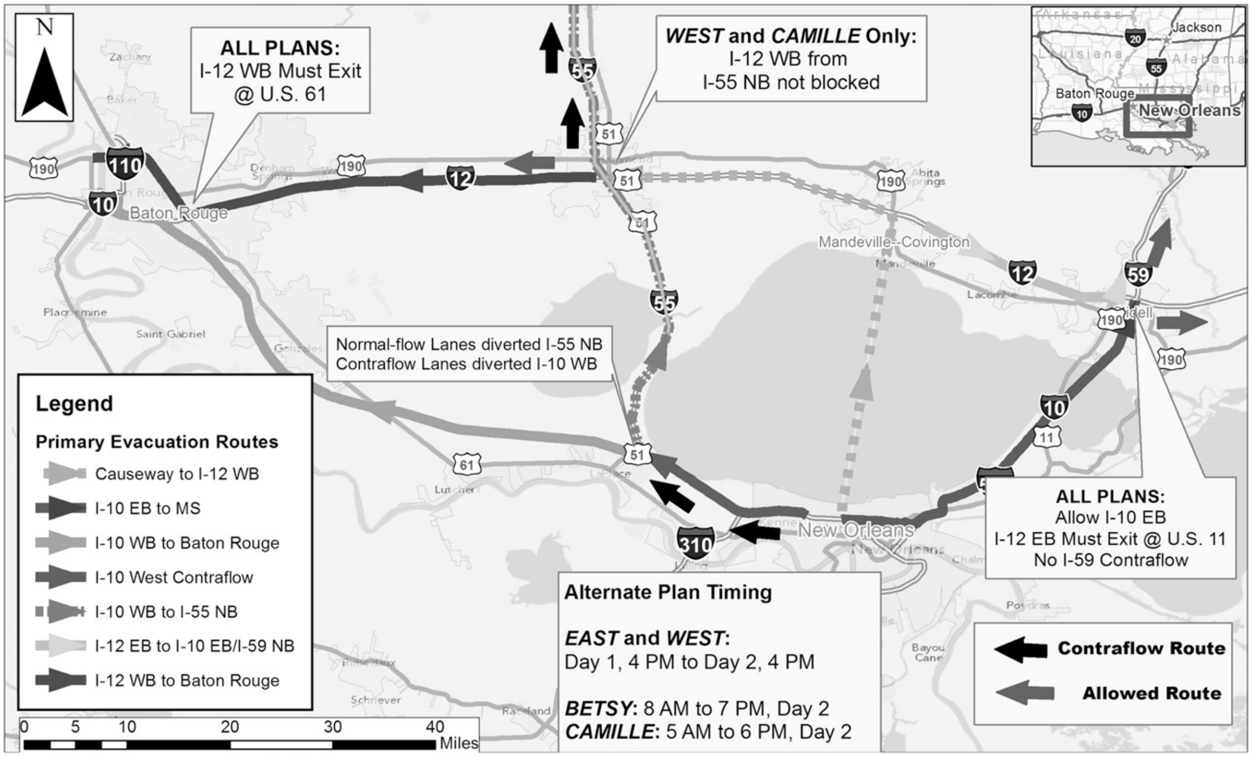

Fig. 5. Alternate evacuation plan configurations and timings (Screenshot used by permission. Copyright © ESRI and its data providers. All rights reserved)

traffic would be the most efficient use of the road network. Otherwise, the traffic levels would not be high enough to justify using contraflow.

In the case of Storm Scenario Betsy, the storm slowly progressed toward New Orleans during the first 24-h period with an average forward movement of 21 km/h (13 mi/h). The storm then more rapidly approached the city for the second 24-h period, with a forward movement of 27 km/h (17 mi/h) reported at 1 a.m. on the second day. The storm had reached Category 4 status at Hour 31. Therefore, contraflow plans were started at Hour 32 (8 a.m. on second day, simulation time), corresponding to the spike seen in the evacuation departure-time curve shown in Fig. 3(b). The contraflow plan was terminated at Hour 43 when traffic levels subsided, leading to an 11-h contraflow period. Storm Scenario Camille gained Category 5 status overnight between the first and second simulation days. Contraflow plans for this storm were started at Hour 35, which corresponded to 5 a.m. on the second day in the simulation. The start of contraflow occurred slightly before the spike in traffic seen in Hurricane Camille's evacuation departure-time curve in Fig. 3(b). The contraflow plans for this storm were allowed to continue until the end of the simulation, corresponding to landfall of the storm. The resulting evacuation period totaled 13 h. A summary of all alternate-plan junction configurations and timings is presented in Fig. 5.

Integration of Travel-Demand Forecast into the *TRANSIMS* Model

The final step was the simulation of the four storm scenarios and their corresponding evacuation plans. The four storm scenarios were simulated in the *TRANSIMS* model under both the base plan and an alternate plan. The macrosimulations mentioned earlier to develop each alternate plan were also run in *TRANSIMS* using only the vehicle-routing module. The macro-level routing assignment in *TRANSIMS* is a static user-equilibrium (UE) solution that relies on Bureau of Public Roads (now Federal Highway Administration) formulas to estimate travel time for each link. When microsimulation is introduced, the routing assignment becomes a dynamic UE solution because the *TRANSIMS* router will use fine-grained traffic-flow and travel-time information produced in the simulator to assign traffic. To develop the complete results, full microsimulations of each scenario were run five times with altered random seed numbers. This led to a total of 40 microsimulation runs being processed by *TRANSIMS*. To consolidate the data, the results from the five runs were averaged for each storm.

Two critical files were created by the model. The first was a volume file that aggregated the total number of vehicles on each link for each hour of the simulation. The second was an average-speed file that produced the average speed on each link for each hour of the simulation. This data were analyzed to assess the traffic impact of using the flexible-plan set when compared with the current static plan.

Visualization of Traffic Simulation

The congestion levels for each simulation were analyzed by creating time-space diagrams. The diagrams used a color map to represent the average speeds observed on each link in miles per hour. Red areas indicated the existence of traffic shock waves, which produced a drop in speeds. The plots informed not only where but also how long these disturbances lasted.

Three separate sections of I-10 were examined. Route 1 was the contraflow section of I-10 that began in the New Orleans central business district (CBD) and extended to the I-55 interchange in Laplace. Route 2 stretched from the New Orleans CBD to the

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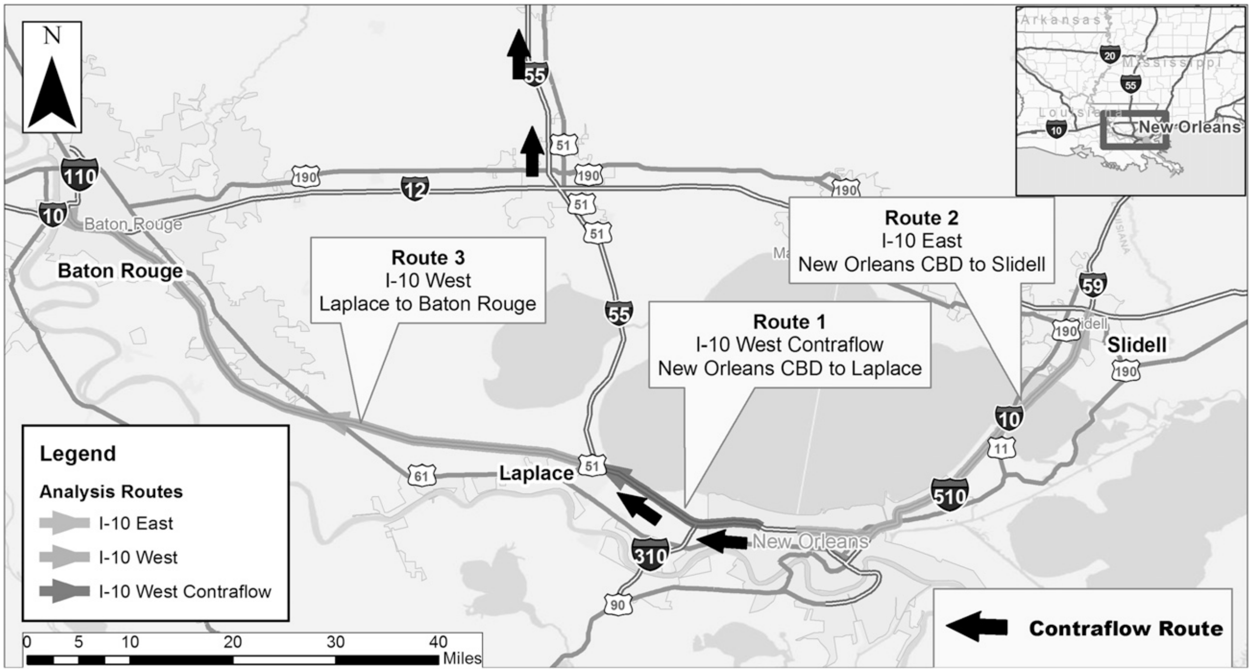

Fig. 6. Routes analyzed with time-space plots (Screenshot used by permission. Copyright © ESRI and its data providers. All rights reserved)

termination of the network in Slidell. Route 3 extended from the I-55 interchange in Laplace to the termination point of the network in Baton Rouge. Routes 1 and 3 followed the westbound direction of I-10. It should be noted that even though Route 1 included contraflow lanes, these lanes were not included in the analysis. The third section followed the eastbound direction of I-10 and also did not include contraflow lanes. A map of the routes is presented in Fig. 6.

To demonstrate the benefits of simulation in identifying bottlenecks and compare evacuation operations, the congestion levels under existing and alternate plans for Storm Scenario East along (a) Route 1, (b) Route 2, and (c) Route 3 are presented in Fig. 7. For the Storm Scenario East, a majority of traffic was expected to choose destinations to the West. The main congestion area on Route 1 [Fig. 7(a)] occurred at the contraflow crossover location located around Mile 7. An additional area of congestion appears just past the change in speed limit around Mile 12. This area was the result of the interchange with I-310 and the subsequent lane drop after that interchange. These congestion periods were only present during the contraflow period beginning at Hour 16 and ending at Hour 40. The shift in hue shown in Fig. 7(a) was due to a speed-limit reduction incorporated into the network links beginning at Mile 12. This point corresponds to the beginning of a bridge section of highway that operates at a reduced speed.

Fig. 7(b) compares congestion levels for Storm Scenario East for Route 2. A reduction in traffic demand was expected because of the desired eastern destinations for this scenario. Therefore, the reduced amount of congestion along this route was expected. Again, under the current existing plan, travelers must divert off the interstate to continue east into Mississippi. This diversion resulted in the congestion observed in Fig. 7(b) (current plan). The alternate plan diagram shows the relief in congestion experienced when travelers were allowed to continue on I-10 eastbound.

Fig. 7(c) compares congestion levels for Storm Scenario East for Route 3. Again, an increased level of traffic was expected to desire western destinations under this storm scenario. Therefore, the increased congestion found was reasonable. Two main areas of congestion occurred. The first was due to the traffic stream entering the Baton Rouge area and encountering an artificial reduction in speed to mimic the ambient traffic levels present in this area. The second occurred in the Gonzales area as more opportunities for traffic to enter and exit the interstate were introduced along the route. Similar conclusions can be reached based on a comparison of the spatiotemporal speed profiles between the existing and alternate plans for the other three storm scenarios. Some notable highlights include a lack of congestion seen along Route 3 for Storm Scenario West. This was an expected finding given that more evacuees favored destinations to the east of New Orleans for this scenario. Also notable, along Route 1 for Storm Scenario Camille, reducing the contraflow period led to slightly increased congestion at the contraflow origination point for the alternate plan compared with the base plan.

Results

The alternate evacuation plans were compared with the base plan by tabulating key measures of effectiveness generated by the microsimulator for each storm scenario. When comparing the mircosimulation results between the static and flexible plans, reductions were found for certain key measures of effectiveness. The overall results are highlighted in Table 3. A reduction in both the average trip time and total vehicle hours was experienced for each storm scenario tested when run under the alternative plan compared with the existing plan. It should be noted that the results were calculated for trips made within the network modeled and not to each person's ultimate destination. Both types of storm scenarios, both the spatial and temporal variations, showed reductions, although no clear pattern between the two types can be seen.

If an average is taken for the trip time reduction across all scenarios, the result is nearly 14 min. This time savings is substantial when viewed from a fuel- and cost-saving perspective. Assuming an average traveling speed of 72 km/h (45 mi/h) and an average fuel economy of 8.5 L/100 km (27.5 mi/gal), approximately 1.5 L (0.4 gal) of fuel is saved by each vehicle experiencing a 14-min reduction in travel time. This savings totals to 445,603 L (117,716 gal) of fuel

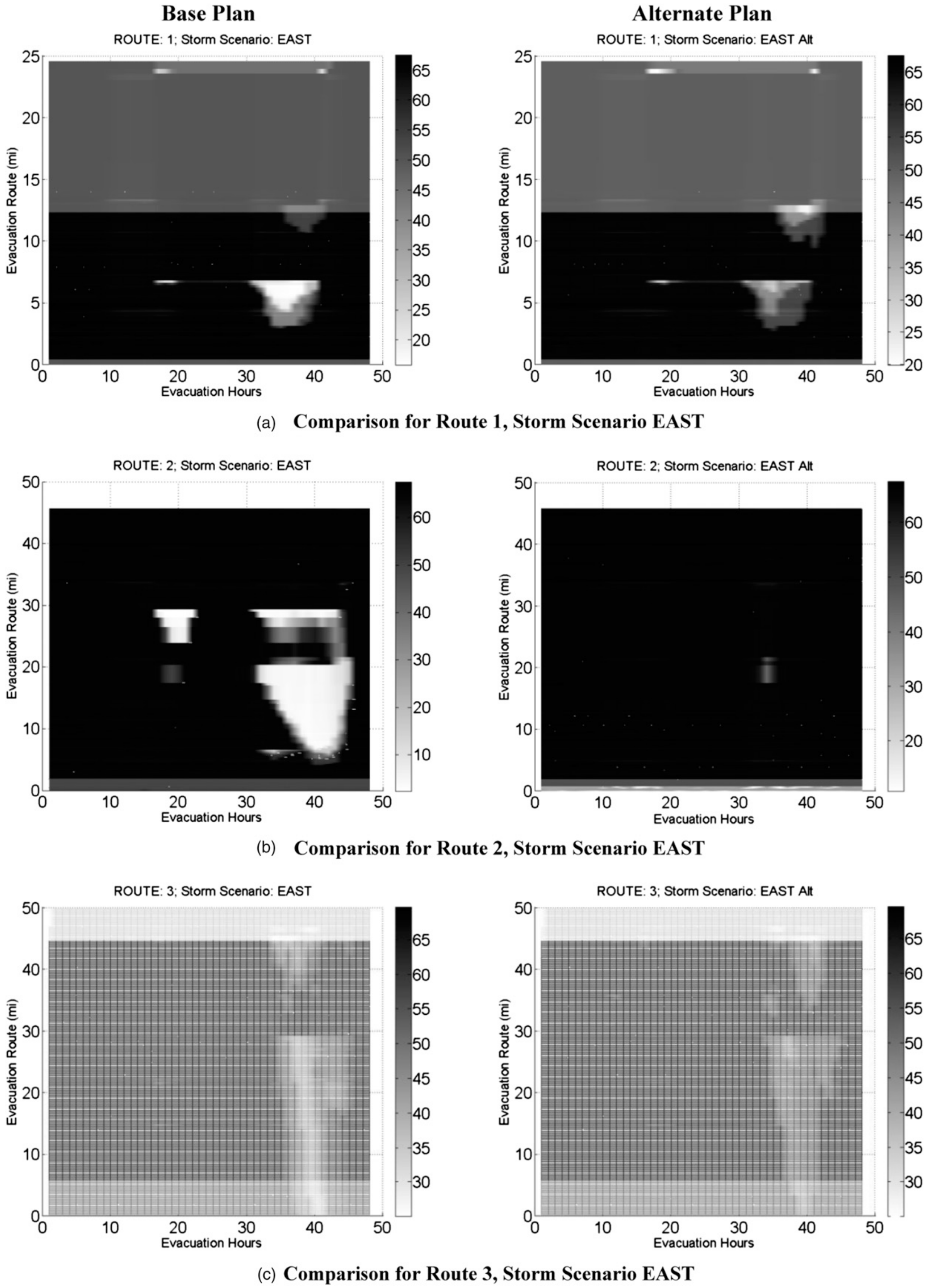

Fig. 7. Time-space diagrams for Storm Scenario East (Screenshot used by permission. Copyright © ESRI and its data providers. All rights reserved): (a) comparison for Route 1, Storm Scenario East; (b) comparison for Route 2, Storm Scenario East; (c) comparison for Route 3, Storm Scenario East

Table 3. Overall Results Comparing Existing Plans to Alternate Plans

Measure	Storm Scenario East	Storm Scenario West	Storm Scenario Betsy	Storm Scenario Camille
Average trip time reduction (min)	15.74	9.38	16.94	13.49
Average trip time reduction (%)	15.97	10.36	19.10	13.68
Total vehicle hours reduction	65,074.72	21,652.54	46,075.80	60,955.78
Total vehicle hours reduction (%)	13.83	5.05	12.62	12.43

Note: Results calculated based on travel from origin to within-network destination.

saved for the average 294,290 evacuees simulated in each scenario. Furthermore, the savings would amount to $412,006 for an average fuel price of $0.93/L ($3.50/gal).

The overall results shown indicate that flexible evacuation plans can provide savings in travel time and other costs over the use of a single evacuation plan. Different storms generate different evacuation patterns, and the results indicate that these altered patterns are better served by flexible evacuation plans.

Conclusions

The concept of using modifiable evacuation plans is an avenue of research that has the potential to improve future evacuation processes. The idea for flexible plans comes from the observation that different disaster-threat scenarios require different evacuation responses. Whereas the use of these plans can be generalized to any form of threat that would require an evacuation, this study has focused on their use in the context of a hurricane evacuation.

To test the traffic impact of using a flexible hurricane response, different storm scenarios were simulated in a combined demand and traffic-simulation model under both alternate plans and a base plan. Four scenarios were created. Two scenarios exploited the model's capability of dispersing traffic spatially, and two scenarios exploited the temporal traffic-prediction capabilities. In addition, alternate contraflow operation plans were created that would aid in effective traffic movement based on the expected traffic conditions predicted by the household decision models. The plans included eliminating contraflow sections that were unwarranted, removing restrictions, and imposing new restrictions to prevent bottlenecks. The plans were developed using a heuristic judgment approach after reviewing a macrosimulation of each storm scenario.

The results showed that simple alterations to the existing plan had significant impacts on the simulated network. Removing the restriction on the eastbound ramp along I-10 in Slidell during contraflow hours resulted in relieved congestion along the entire eastbound I-10 route. This alteration encouraged evacuees to use the interstate system rather than local roads. In addition, adjusting the timing of the base plan to match the expected peak evacuation periods for Storm Scenarios Betsy and Camille resulted in a net decrease in both travel time and vehicle hours traveled. The results showed a decrease in both the average trip completion time and the total vehicle hours reported in each storm scenario when flexible evacuation plans were used. On average, a 14% reduction in average travel time and an 11% reduction in vehicle hours traveled within the network were achieved by implementing alternate plans for varied hurricane characteristics. This reduction is substantial when put in terms of fuel and other costs saved. Over $400,000 in fuel costs alone could be saved by adapting a static evacuation plan to fit a set of likely evacuation responses.

The significance of these results lies in their ability to move people more efficiently out of danger when faced with a threat when compared with a single, one-size-fits-all evacuation plan. The primary motivation of this research is that to begin to effectively transport these evacuees, something must be known about how they are likely to react to any given threat. A single, static evacuation plan is not likely able to consider the broad range of responses that could come from evacuees because they are themselves adapting to the specific conditions (e.g., expected intensity and point of landfall) associated with a given hurricane. Evacuation plans that have been adapted to suit a range of likely evacuation responses have been shown in this study to better serve evacuees. The vision of this research is for local and state emergency officials to be able to use a set of evacuation plans based on variable scenarios rather than a fixed plan. The key limitation that would need to be overcome before any of these actions could be realistically achieved in practice would be to ensure that evacuees would be able to hear, comprehend, and follow changeable and potentially complex evacuation orders. Whereas this may be difficult to achieve today, future technologies such as in-route guidance could make it easier to implement.

Although this research was based on a hurricane case study, it is likely that the results discussed here could be generalized to evacuation planning for any threat. Future research could apply the idea of flexible plans to evacuations from other threats, such as nuclear power plant problems, wildfires, and terrorist attacks. This study could be further expanded by exploring flexible-plan sensitivity to changing and uncertain storm variables. Also, flexible plans could be improved by the development of a robust optimization method for the network as an alternative to heuristic judgment. Thus, both the procedure used and the general results gained from it should be valuable to researchers in the evacuation field, and it is expected that this new approach can be used by emergency planners to make better evacuation decisions.

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