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Emily M. Jannace

Abstract

Mass evacuations have changed greatly in the past two decades. Evacuations such as Louisiana during Hurricane Katrina, Florida during Hurricane Irma, and New York during the 9/11 Terrorist Attacks, Hurricane Sandy, and Hurricane Irene have had significant impacts on future mass evacuations in terms of transportation. This paper takes these methods and analyzes the best approach in given situations based on volume capacity, impact, and cost to make recommendations that can be used by the three previously mention municipalities. With so many different techniques available, it is important to choose the one that moves the most people out of harm's way as quickly and effectively as possible while still being economical. Data from various transportation engineering professionals is used to examine different techniques. Many of these papers have been published by Transportation Research Board. Additionally, a subject matter expert interview was conducted with Dr. Scott Parr, Ph.D. from Embry-Riddle Aeronautical University.

Based on the research conducted, Emergency Shoulder Usage (ESU) is a superior option to contraflow. Fee suspension also has a significant impact on areas with a low-income area. In areas where there was a switch from pretimed signal timing to semi-actuated or fully actuated signal timing a better LOS during mass evacuations was seen. For the implementation of these techniques to be beneficial, resiliency is important and why the last recommendation calls for professionals to petition for better infrastructure and resiliency.

Introduction

Background

In 2005, 1.7 million people were evacuated from Louisiana prior to Hurricane Katrina making landfall while another 150,000 to 200,000 remained due to a lack of available resources needed to evacuate (Institute of Medicine, 2007). Mass evacuation efforts rely heavily on transportation.

Public transportation, personal vehicles, and evacuation-specific transportation all affect the flow of traffic and efficiency of the network. Evacuation efforts are considered either "Notice" or "No-Notice" events. A "Notice" event means there is at least 24 hours before impact on the area, such as in an event of a hurricane or Nor'easter. A "No Notice" event means that there is less than 24 hours before the impact, or the amount of time to evacuate the area would be longer than the time left before impact, such as in the case of chemical plant failure.

According to Parr and Kaiser, mass evacuations require "improving traffic operations at critical intersections [and] models that accurately emulate traffic congestions" (Parr & Kaiser, 201, p. 62). All traffic modeling requires trip generation, trip distribution, mode choice, and route choice to be taken into account. When determining mass evacuation procedures specific evacuation factors must be taken into account such as cancellation of transit, restriction of routes, and road closures (Parr and Kaiser, 2011).

The effect these evacuations have on more affluent areas is vastly different than lower income areas within the same county. Lower income areas are more likely to put a higher stress on public transportation, whereas higher income areas are more likely to put stress on the roadway networks using private or personal cars.

The main problem with evacuation efforts is the uncertainty in both the event at hand and people's choices. The number of people that will evacuate for a recommended evacuation is very different than the number that will evacuate during a mandatory evacuation. Some people already outside the evacuation area will return to secure their belongings or retrieve their friends and family unable to evacuate on their own. Transportation systems need to be able to move people out of harm's way and yet be resilient enough to move the people back into the area after the evacuation ends.

Statement of the Problem

Moving as many people as possible out of the path of imminent danger is imperative. Evacuation efforts need to be planned and prepared for well in advance. These efforts need to consider population, geography, topology, and economics. Techniques such as contraflow, no tolling, and signal optimization are implemented throughout evacuation efforts. Multiple escape pathways need to not be impeded by barriers, such as construction at the same time.

Traffic signals need to be optimized to allow for the best Level of Service (LOS), lowest volume/capacity ratio (v/c ratio), and delay time. Contraflow allows for bi-directional roadways to be partially reversed to allow for twice as many lanes leaving the area in turn for no lanes entering the area on that stretch of roadway. The removal of fees allows for faster exiting of traffic on major roadways with tolls and within public transportation and also enables people who cannot afford to move themselves or their family due to high toll prices or public transportation fees to evacuate as well.

Purpose

The objective of this research is to compare the different evacuation techniques for Notice and No-Notice Evacuation events. This report will make recommendations that can be used by municipalities such as New York City Department of Transportation, Louisiana Department of Transportation, and Florida Department of Transportation who require extensive mass evacuation planning but does not address concerns specific to each area. It will recommend evacuation techniques with the highest output volumes and lowest implementation and operational costs that should be used and how resiliency should play a role in infrastructure planning. Mass evacuations have major implications on transportation patterns and require studies to be conducted long before they are needed. This comparative analysis paper focuses on this problem and the best methods used to alleviate these problems in the future. Transportation professionals strive to make sure that systems will work in a resilient manner and provide safe and cost-effective routes for the area's inhabitants.

Scope

This comparative analysis report will focus on specific points that should be considered when examining mass evacuations:

1. Types of evacuations (Notice vs No-Notice)
2. Contraflow
3. Emergency Shoulder Use (ESU)
4. Signal Timing Optimization
5. Fee Suspension
6. Resiliency of Infrastructure

A major limitation of this report was the lack of raw numerical data. The data that was examined has already been processed. Additionally, the metropolitan New York area has only been affected with three major evacuations (two Notice and one No-Notice). During the previous two decades New York experienced major evacuations during Hurricane Irene, Superstorm Sandy, and the 9/11 Terrorist Attacks. Consequently, evacuation results in this area are not as prevalent as other areas; therefore, past evacuations such as Louisiana during Hurricane Katrina and Florida during Hurricane Irma will be analyzed. Each of these evacuations used different methods to remove people in urban areas from the path of danger using means available.

Terms

LOS-Level of Service is the weighted average of the control delay (delay that in incurred from a traffic light, stop sign, yield sign, etc.) LOS is measured in seconds and given a letter grade based on that. For signalized intersections, a delay of 0-10 seconds has a LOS A and is considered to be in free flow. A delay of 10-20 seconds has a LOS B and stable flow with slight delays. LOS C has a 20-35 second delay and is considered to have stable flow with acceptable delays. A delay of 35-55 seconds with a tolerable delay is LOS D. Unstable flow with a delay of 55-80 second has a LOS E and a delay of greater than 80 seconds with congestion and uncleared queues has a LOS F. Typically a LOS C or better is considered acceptable (HCM: Highway Capacity Manual, 2010).

v/c ratio-Volume/capacity ratio shows the intersections overall ability to move the given volume through the intersection based on its available capacity. A v/c ratio below 0.85 is consider acceptable.

DOT-Department of Transportation

TRB- Transportation Research Board is a part of the National Research Council and conducts research and provides research opportunities to professionals. Research submitted and peer-reviewed are published in the yearly journal.

MTA-Mass Transportation Authority is the governing body of the Metropolitan Commuter Transportation District is lower New York, New Jersey, and Connecticut. It operates the light rail and commuter rails, buses, bridges, and tunnels in the region.

Research Methodology

This report focuses primarily on mass evacuations in urban coastal areas of the United States, such as New York City and Long Island. The research from professionals at states' department of transportation and various contributions from Transportation Research Board (TRB) was used for this report. Additionally, research conducted by professionals at universities such as University of Louisiana at Baton Rouge was examined. These papers are all scholarly peer-reviewed articles published in academic journals. They investigate signal timing, contraflow, taxi rides, and subway trips and the effects these evacuations had on these methods.

An interview was conducted with a subject matter expert Dr. Scott Parr, Ph.D. of the Civil Engineering Department at Embry-Riddle Aeronautical University who has degrees in Civil Engineering and Transportation Engineering with specializations in Evacuation Planning from universities such as University of Louisiana at Baton Rouge and Florida Atlantic University. Dr. Parr answered questions like the following:

1. What limitations have you faced from DOTs? (3-second limitations on green time, etc…)
2. How do you approach evacuation methods differently for Notice vs No-Notice?
3. What aspects of previous evacuations are important in future planning and analysis?
4. Is contraflow typically used in both Notice and No-Notice Evacuations?
5. In your opinion what is the best method of evacuation?

This subject matter expert interview helps allow for analysis of the data form an industry standard standpoint. This research overall will allow for municipalities to understand different mass evacuation techniques than just the ones they currently use.

Search terms used during this research are listed below. These terms allowed for comparative analysis of different studies that were submitted to peer-reviewed transportation journals including the Transportation Review Board (TRB) for national implementation into standard manuals such as the Highway Capacity Manual (HCM.)

- No notice evacuation
- Notice evacuation
- Signal timing
- Contraflow
- Lane reversal
- Hard shoulders
- Emergency shoulder usage
- Fee suspension
- Resiliency
- Hurricane evacuation (Hurricane Katrina, Hurricane Irene, Superstorm Sandy)

Data Analysis

Types of Evacuations

Mass evacuations fall into two general categories, Notice and No-Notice Evacuations. A Notice Evacuation means there is a 24-hour time frame before impact. This can mean until a hurricane makes landfall or until a nuclear reactor or chemical plant reaches failure. A No-Notice Evacuation means there is less than 24 hours until impact will be felt, or it will take longer than that to evacuate civilians. This can include a terrorist attack, wildfire, or chemical spill.

There are various levels of evacuations as well such as voluntary, mandatory, and forced. A voluntary or recommended evacuation means that there is a threat or the possibility of a threat to life, but it is not yet imminent. A mandatory evacuation occurs when a threat is imminent. People cannot be forcibly removed; however, according to the City of Kenner in Louisiana "all public services will be suspended during a mandatory evacuation and those failing to comply with a mandatory evacuation order shall not be rescued or provided with other lifesaving assistance" (City of Kenner, n.d., p. 1). A forced evacuation is more often seen during a chemical leak where staying in place would definitely lead to death. During a forced evacuation, emergency personnel go door-to-door to advise people to leave immediately and all public services are again suspended as in a mandatory evacuation.

Since evacuations vary greatly on location and storm intensity, states implement their own required public notification times based on storm category. As seen in Table 1, these times vary greatly from 9 hours for areas less prone to flooding and with less coastline to 72 hours for areas that are surrounded by areas prone to flooding during storm surge.

Table 1: State's Evacuation Time Requirements Based on Strom Category

Evacuation advanced notification time (in hours)					
State	Category of the storm				
	1	2	3	4	5
Massachusetts	9	9	12	12	12
Rhode Island	12-24	12-24	12-24	12-24	12-24
Maryland	20	20	20	20	20
Virgina	12	18	24	27	27
South Carolina	24	24	32	32	32
Georgia	24-36	24-36	34-36	24-36	24-36
Mississippi	12	24	24	48	48
Louisiana	24	48	72	72	72

(Urbina & Wolshon, 2002, p. 262)

In past mandatory evacuations, such as the evacuation of Louisiana during Hurricane Katrina in 2005 and Texas during Hurricane Harvey in 2017, local news reports such as NBC reported that residents refusing to follow the mandatory evacuation order were "given permanent markers and asked to write their Social Security number, next of kin and a phone number on their arm or across their abdomen" (Blome, 2005). This was partially used as scare tactic to help persuade more people to leave by showing them that they may end up as a dead body that needed to be identified. This has been seen in many mandatory and forced evacuation scenarios since Hurricane Katrina and Hurricane Harvey.

Methods of Evacuation

Contraflow

Contraflow takes "four-lane routes allowing the reversal of two travel lanes" which leaves the entire arterial traveling in a single direction rather than having opposing flow (Florida Department of Transportation, 2005, p. 1). Contraflow allows for a theoretical doubling of outbound volume capacity. As per Florida Department of Transportation (FDOT), "contraflow operations only occur during daylight hours to ensure safety" (Florida Department of Transportation, 2005, p. 1). This leaves a limited amount of time to remove as many civilians as possible from the impending threat. Contraflow takes a considerable amount of planning to implement. A microsimulation model needs to be analyzed to help determine the best location to start and end the contraflow corridor.

In a study conducted for the Florida Department of Transportation, two main parts of evacuations were determined to be the pre-positioning of vehicles and the use of alternative routes. Pre-positioning of vehicles means that "emergency vehicles may be compelled to position themselves along the route at certain interchanges to ensure reasonable response time during contraflow operations" (Florida Department of Transportation, 2005, p. 16). However, the pre-positioning requires a larger number of emergency responders to be available and on scene during an event and will likely raise evacuation costs due to increase in the number of hours needed to pay for emergency responders. During Hurricane Irma in September 2017, emergency responders and government officials cost the tax payers a total of $5.2 million in overtime in the Treasure Coast area of Florida (Gardner, Greenlee, & Wixon, 2017). On the other side of the peninsula in Key West, $1,972,553 in overtime was paid out during Hurricane Irma (Filosa, 2017). This high cost

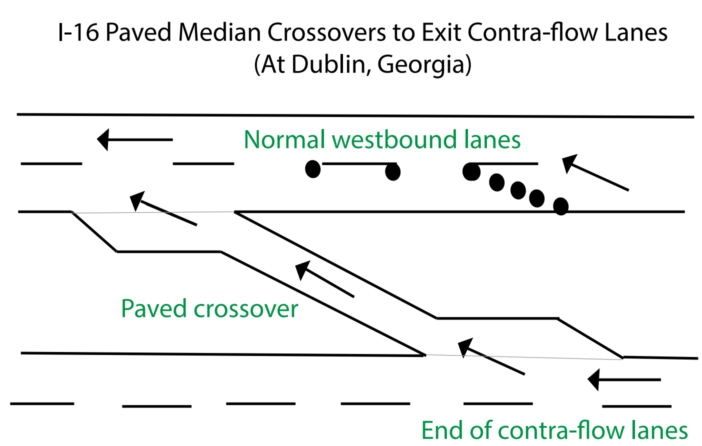

Figure 1: Prepositioned Crossover from Contraflow on I-16 in Georgia (511 GA, n.d.)

to taxpayers did not include the costs of implementing contraflow, emergency supplies, or the shutdown of businesses that stopped bringing money into the economy during that time.

Coastal areas frequently hit by hurricanes and that often require evacuations have crossovers designed into their highways. As seen in Figure 1, the I-16 in Georgia has this implemented. Although these crossovers are primarily used for mass emergency evacuations, they can be used in other emergency situations such as during a collision, fire, or area lockdown. These crossovers are beneficial in more than just emergency evacuations; they also help with the movement of emergency officials during non-mass evacuations and the movement of construction crews. Contraflow lanes come at a high cost though. In 1981, it cost Houston $2.151 million to implement a contraflow lane along I-45 (McCasland, 1981). Today that would cost approximately $6.145 million.

Contraflow may require emergency responders to deviate to routes that "are close and approximately parallel to the contraflow corridor" (Florida Department of Transportation, 2005, p. 16). When examining an evacuation route to impose contraflow on alternate routes surrounding the area must also be examined. Although it might be assumed that if contraflow was being imposed that no one would need to travel in the opposing direction, this is not the case. In the event of an accident or medical emergency along the evacuation route, emergency responders would need to move in the opposite direction. Supplies crucial to prepare for the event need to be moved into the area; additional responders such as EMS, police, National Guard, Army Core of Engineers, and utility companies may need to be moved into the evacuation area as well. Without the ability to move these people and goods into the area in a fast and effective manner, the likelihood for an even more devastating loss to property and life increases greatly.

Contraflow implementation may not be necessary in all scenarios. According to subject matter expert Dr. Scott Parr, contraflow is typically used only during Notice Evacuations (personal communication, April 3, 2018). For hurricanes, "the hurricane's strength, its direction of travel, and the point of anticipated landfall" are all considered pertinent to the decision to implement contraflow or not (Florida Department of Transportation, 2005, p. 1). Contraflow costs a considerable amount of money to implement regardless of where it happens. However, along different types of arterials it would differ. Along a highway or parkway, police presence would be more necessary at the start and end of the corridor and at the entrance and exit ramps along the reversed area. Along a turnpike where intersections occur more often, a heavier police presence is necessary to make sure conflicting movements do not occur.

As seen in Table 2, the start and end of contraflow operations are governed by different authorities in different states. In most states the power to do so falls

Table 2: Authority to Impose and End Contraflow Based on State

Authority to start and end contraflow operations

State	Start	End
New Jersey	Governor	Governor
Delaware	Governor	Governor
Maryland	Local Emergency Management with the State Police & Maryland DOT	Local Emergency Management with the State Police & Maryland DOT
Virgina	Governor	Governor
North Carolina	Governor	Governor
South Carolina	Governor	Department of Public Safety
Georgia	Governor in conjunction with Georgia DOT and GEMA	Georgia DOT
Florida	Governor	Highway Patrol
Alabama	Alabama DOT	Alabama DOT
Louisiana	Governor	Governor
Texas	High Patrol Captain in Corpus Christi	High Patrol Captain in San Antonio

(Urbina & Wolshon, 2002, p. 269)

on the governor; however, in some states the DOT, highway patrol, or local emergency management team can decide. These agencies must decide when to enact contraflow conditions to help move the greatest number of people out of harm's way while still making sure it is economically feasible to do. Even if the governor is solely in charge of making that call s/he will still coordinate and seek advisement from the state's DOT and from emergency management officials.

A difficulty in microsimulation modeling is often the data, and when examining the data from Hurricane Katrina this was evident. Future evacuation analysis that need to be done to determine contraflow conditions for future evacuations require this data to be ran, but the data was already reduced and had considerably variabilities that should be examined. Raw data must be reduced and then quality assured and corrected by removing any outliers. When examining the contraflow volumes during this evacuation an increase in volume was seen; however, on Friday, August 26 there was a New Orleans Saints games and the increase was minimal enough that despite the emergency declaration made "the slightly elevated volumes at this location have been suggest to be associated with a New Orleans Saints football game that was played that evening" (Wolshon, 2008, p. 41). To determine if this should be considered an outlier or not traffic data patterns from a similar date when there was a game in years past should be examined, as well as, traffic patterns at that location in years following the hurricane.

Another major part of contraflow modeling is trying to determine the number of vehicles that will be evacuating. The average household has 1.10-2.15 cars and will take multiple cars with them when evacuating. These people travel from 67 to 132 miles to evacuate, some even out of state (Wu, Lindell, & Prater, 2012). This can be difficult to model when more evacuees than expected leave in their personal vehicles (Kim, Shekhar, & Min, 2008). These vehicles may include personal cars with or without trailers, RVs, and motorcycles. The use of trailers and RVs would increase the heavy vehicle percent and thus decrease the overall LOS of an arterial. This causes problems in microsimulation modeling due to the uncertainty in both number of vehicles and vehicle type which both play major roles in analysis.

According to subject-matter expert Dr. Scott Parr, the biggest problem with contraflow is that it does not remove the bottleneck but rather pushes it further upstream. The way to eliminate this is to provide one side of the highway for one direction and the other side of the highway for an alternative route (personal communication, April 3, 2018). This means that signs and the relaying information to drivers is even more important than with normal contraflow conditions because once these drivers enter the highway there is no changing their mind. One side of the highway would continue in a northbound or southbound direction and the other side of the highway would continue in an eastbound or westbound direction.

Emergency Shoulder Usage (ESU)

As alternative to contraflow is the use of the shoulder that runs along the arterial as an additional lane. This is commonly known as a hard shoulder when being implemented for Emergency Shoulder Usage (ESU). Hard shoulders are pre-paved into the roadway geometry for this purpose and striped with blue lane markings. According to the U.S. Department of Transportation Federal Highway Administration (FHA), "shoulders provide refuge for vehicles in emergency situations, access for first responders, and additional recovery for drivers trying to avoid conflicts in the adjoining travel lane" (n.d.-b). The benefits these shoulders provide are crucial and are why the FHA requires a minimum shoulder width in highway design (Federal Highway Administration, n.d.-b). Typically, lane width is no smaller than 10 feet wide.

The argument for ESU rather than contraflow is the reduced cost and more mobility in start and end points. Hard shoulder implementation does not require "traffic cones, barriers, signs, and arrow boards to alert motorists of the closure and operations" (Florida Department of Transportation, 2018, p. 12). Hard shoulders cost money to implement on existing roadways. Many shoulders and the bridges over them need to be reconstructed or widened. Intelligent Transportation System (ITS) analysis is also important. Maintenance costs to implement their use include police presence, roadway maintenance, driver training, and ITS (Florida Department of Transportation, 2018). However, these costs are much lower than those needed to implement contraflow.

Hard shoulders require less microsimulation modeling. Microsimulation with an additional lane takes considerably less time and money to do than to remodel a corridor for contraflow conditions. The use of hard shoulders is becoming more prevalent than the use of contraflow due to the ease in analysis that it has in

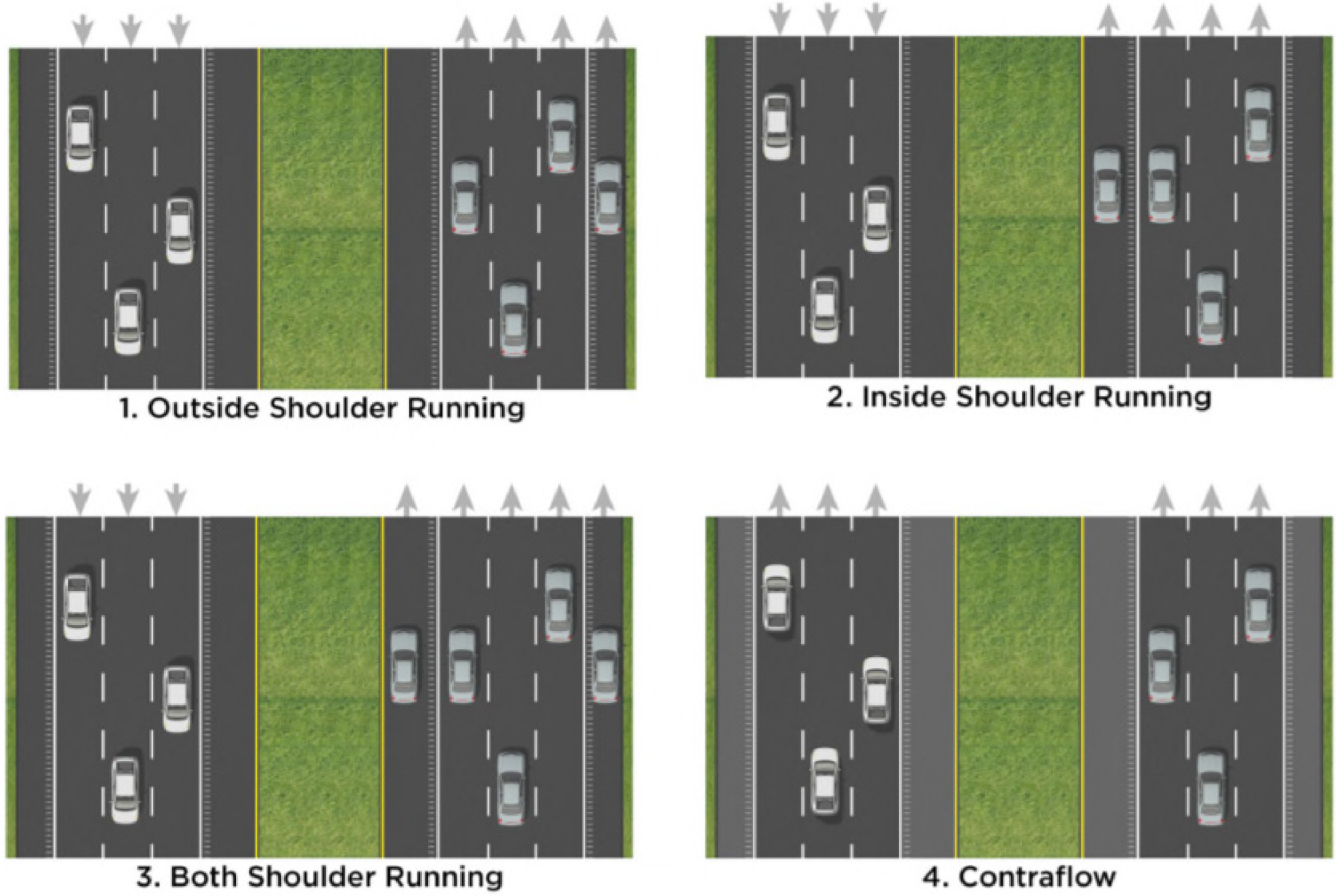

Figure 2: Emergency Shoulder Usage (ESU) verse Contraflow (Jin, 2017, p. 4)

preparation efforts and cost.

Hard shoulders allow for the easier movement of supplies such as food, water, and fuel into the evacuation area by not cutting off critical routes into the area. A major benefit of using a hard shoulder according to FDOT is the "reduced number of law enforcement personnel required to support ESU" (2018, p. 17). This allows for their expertise to be used in other areas such as storm preparedness and vehicle collisions that occur during evacuation procedures.

During Hurricane Irma, many evacuees were upset that contraflow was not being implemented but they did not realize that use of hard shoulders was having the same effect. According to subject matter expert Dr. Scott Parr, "60 percent of roadways in Florida were considered uncongested." This meant they had a LOS A, B, or C. "Most evacuees did experience at least 30 minutes of LOS F at which they did not move or only moved slightly followed by LOS A for the remainder of the hour averaging LOS C" (personal communication, April 3, 2018). The use of ESU also helped to reduce the amount of time required until it could be implemented because conflicting travel did not need to be flush from the arterial (Ballard & Borchardt, 2006). This meant that more evacuees could move throughout the system before the storm hit.

Figure 2 shows how hard shoulder use is different than contraflow. Contraflow has only one way to be implemented where both sides of the arterial are traveling in the same direction. Alternatively, ESU has three different methods of how it can be implemented. This includes outside shoulder running, inside shoulder running, and both shoulder running. According to Parr, inside shoulder running is much easier on an arterial's movement; however, they are harder to find. Outside shoulder running although more popularly seen does cause issues when it comes to traffic exiting and entering the arterial (personal communication, April 3, 2018). When implementing ESU into arterials in the future municipalities should analyze the use of interior shoulder and the cost benefit to implement it.

Fee Suspension

Another way to help with the movement of evacuees out of the area of danger is with fee suspension. This includes highway and bridge tolling and fees related

Table 3: Fees for Main Methods of Evacuation Out of New York City

Location	Fees
Bronx-Whitestone, Throgs Neck, RFK, Hugh L. Carey, QMT	E-Z Pass $5.76 Toll by Mail $8.50
Verrazano-Narrows Bridge (only entering Staten Island)	E-Z Pass $11.52 Toll by Mail $17.00
Henry Hudson	E-Z Pass $2.64 Toll by Mail $6.00
Cross Bay and Marine Parkway Bridges	E-Z Pass $2.16 Toll by Mail $4.25
Light Rail and Buses	$2.75
Express Bus	$6.50
Commuter Rail	$6.25-$29.25

(Metropolitan Transportation Authority (MTA), n.d.-a)

to the use of public transportation. Fee suspension has become a standard since Hurricane Katrina (S. Parr, personal communication, April 3, 2018). The issue with fees not being suspended is in areas where the tolls to use these arterials or fares for the public transportation can be very expensive. People in evacuation areas who cannot afford these fees can see this as a reason not to evacuate.

As seen in Table 3, tolls in New York City can be as high as $17 one-way. Although light rail, buses, and express buses have reasonable fares they are per person compared to per vehicle and these modes can only take a person within the city limits or to other boroughs that most likely will also be evacuating. To move completely out of the city a commuter rail is necessary which has considerably higher one-way fares per person.

The high cost of public transportation affected Louisiana's evacuation for Hurricane Katrina. Although a plan was made it was not implemented to help the low-income areas that are reliant on public transportation. This was in part due to the timing of the storm and to notice that was given to the residents to evacuate. Although the storm hit as expected the real destruction came when the levee broke without notice. Low-income areas are found in flood prone locations. It becomes difficult to use public transportation such as buses when the roads have already begun to flood.

Evacuation costs can be extremely high per household especially in low-income areas. Although more than half of evacuees tend to go to the households of family and friends not in the evacuation area, others go to hotels or shelters. To evacuate to a hotel costs a household on average approximately $470. A shelter costs a household approximately $144 and even when evacuating to friends and family the cost is approximately $174 per household. The costs include lodging, food, entertainment, travel costs, and time (Whitehead, 2003). According to FEMA, these costs are not refundable unless the home is deemed to be too damaged to return to (FEMA, n.d.). For many who do not take the warning to evacuate seriously, these costs are not worth it.

In Florida, "most toll operators have a policy of suspending tolls during hurricane evacuation for general purpose traffic," and for "relief workers during the recovery phase" (Ballard & Borchardt, 2006, p. 37). The removal of tolls helps to keep traffic moving efficiently particularly for those without a toll pass so that queues do not form at the toll plaza and slow down the evacuation process. The suspension of tolls was also put into place to allow for evacuees to "more easily be able to prepare for any potential storm impacts, access important hurricane supplies, and quickly and safely evacuate when necessary" (Governor Scott's Office, 2017).

Another example of fee suspension was during the aftermath of Hurricane Sandy in October-November 2012. Following the storm's landfall, the subway system run by the Metropolitan Transportation Authority (MTA) did not collect fares for the first two days (Zhu, Ozbay, Xie, & Yang, 2016). This helped to move people back into the city and return people to work in the Central Business District to help restart the economy.

Signal Timing

Signal optimization is important in every day conditions and even more so during mass evacuations. Most cities still use pre-timed signal timing. This means that depending on the time of day the major arterial has a set amount of time and the minor arterial has a set amount of time. During these times any protected turns (a turn with no opposing traffic) or permitted turns (a turn allowed while opposing traffic has the ability to be present but is not) occur. During mass evacuations semi-actuated or fully actuated signal timing plans are much more important. Semi-actuated and actuated intersections use detectors to determine cycle lengths. In semi-actuated signal timing plan detectors are only used on the minor arterial. At fully actuated intersections detectors are used at all approaches to determine when to change the direction of flow. Large cities such as New

York use pre-timed signal timing due to the fact that they have the lowest operational costs. According to Parr and Kaisar, “these cities represent targets of terror attacks.” Their pre-timed plans can “slow evacuation times resulting in further loss of life and property” (Parr & Kaisar, 2011).

Although optimizing signal timing is an important feature for mass evacuations, sometimes it still does not do enough during No-Notice Evacuations. Instead flash mode is used to help keep traffic moving on the major arterial (Niloy & Fries, 2018). A flashing yellow light acts as a yield and a flashing red light acts as a stop. There are three types of flash mode commonly used. They include flashing yellow on the major arterial and flashing yellow on the minor arterial, and dynamic flashing yellow. Dynamic flashing yellow helps to flush the minor arterial. It involves a flashing yellow on the major arterial while the minor arterial has a flashing red signal. The major arterial then gets a solid red light while the minor arterial gets a green light for a short period of time. It then returns to the flashing yellow and flashing red (S. Parr, personal communication, April 3, 2018). By implementing these features an increased number of vehicles can be moved through these intersections that have high saturation rates and even higher v/c ratios.

Resiliency

Resiliency has become an extremely important and heated topic in politics and is often times the topic of debate following a mass evacuation. According to Hesaslip et al., “resilience is defined as “the ability for the system to maintain its demonstrated level of service or to restore itself to that level of service in a specified timeframe” (as cited in Zhu et al., 2016). Resiliency can be broken down into four phases: normality, breakdown, self-annealing, and recovery. The goal of resiliency is to maintain normality or a full functioning system and to get through recovery or the restoration of system infrastructure and service as fast as possible. Most systems see a breakdown or disruption and reduction of system performance on the regular. It is when self-annealing or when users of the system attempt to find alternative route or travel modes that there is a problem. This causes the entity to lose money and puts a stress on other modes of transportation.

In 2012, Hurricane Sandy took a toll on the New York City subway system resulting in “minor delays for the evacuation, significant work deterioration after the hurricane impact, and disruption that took more than five days to recover from” (Zhu et al., 2016). In the two days following the storm only 14 of the 23 subway lines were active putting stress on those subway lines, buses, and ferries.

In 2011, Hurricane Irene only disrupted the subway system for two days which included the storm time and the time it took for ridership to return to normal levels. Hurricane Sandy took the entire network off-line for three days and took ten days for ridership to return to normal levels (Zhu et al., 2016). To date there are still subway lines, stations, and tunnels closed due to the effects of these two storms.

After Hurricane Sandy, the MTA stated they would need $300 million dollars in repairs for the Long Island Railroad (LIRR) system alone. This included restoration to substations, switches, signals, and the third rail (MTA, n.d.-b). These infrastructure repairs are still influencing service six years later. The LIRR is constantly seeing signal problems and delays due to the failing infrastructure that was only made worse by Hurricane Sandy.

The terrorist attacks on 9/11 in New York City cost $10 million in infrastructure damage (Sanchez, 2001). Nowadays, that infrastructure lost would cost the city $14.168 million. After the attacks subway lines, roads, bridges, and buildings in the area had to be inspected for their ability to operate while still being structurally sound before being permitted to reopen. The attacks caused repairs to be needed for 1,800 feet of the N/R and 1/9 subway lines’ tunnels costing $1.7 billion dollars in repairs. During that time $245 million was lost in revenue (McCall, 2001).

Without resilient infrastructure, storms and terrorist attacks can not only damage the infrastructure but also debilitate the local economy due to the high cost of repairs and the loss in revenue entering the area. Although, the 9/11 Terrorist Attacks decreased the volume of people entering the area to conduct business and take part in leisurely activities. In the months following this tragedy, the inability of those who were still entering the areas to get there using the N/R and 1/9 subway lines was important. The 9 subway line ran directly under the World Trade Center and was extensively damaged after the attacks. Service was suspended following the attacks for a year for the system to be rebuilt in that area.

Conclusion

Although each mass evacuation is different in what it requires and its timeline, all evacuation planning calls for the same goal. The goal of any evacuation is to remove as many people as possible in the shortest amount of time, while doing so at the lowest price and in the safest way before the threat arrives. Since so many different techniques are used for the different types of evacuations scenarios it is important to thoroughly examine them.

All the techniques examined had both benefits and drawbacks. The recommendations that have been made are believed to be the best techniques to aid in most major mass evacuations. They help to remove an increased volume of evacuees by shortening the queue, decreasing delay, and making the overall LOS better.

The implementation of ESU will help to increase outbound capacity while still allowing emergency responders into the threat area and minimizes cost when compared to contraflow. Signal optimization using semi-actuated or fully actuated signals help to time the signals based on demand. Flash mode helps to reduce delay time by having a near continual flow of vehicles on the main arterial and then flushing the minor arterial. Fee suspension helps to move even low-income members of the community out of harm's way and then back into the area later. Overall, a call for resilient infrastructure is the most important part of mass evacuations. Resilient infrastructure aids in the ability to move people out of the threat area before impact and then back into the area to begin restoration after the threat has passed.

Recommendations

Transportation engineering for mass evacuations has many parts to it. Based on the research done for this report the following points are being recommended to the municipalities for future planning and analysis of mass evacuations.

Implementation ESU as an Alternative to Contraflow

Based on the research examined, ESU is just as good of an option as contraflow during Notice Evacuations. Both help to increase the network capacity and achieve a better overall LOS. The fact that ESU has a much lower cost to implement than contraflow makes it a better alternative in many cases. ESU could also be used during No-Notice Evacuations because it does not require a great deal of planning since a portion of roadway does not need to be closed and flushed of opposing traffic, and an exponential increase in police presence is also not needed. It is recommended that in future analysis of evacuation corridors it should be examined if shoulder use is possible and where it is to be implemented. When municipalities are looking to redo roadways or create new ones they should be advised to add an ESU if they are in evacuation prone regions.

Suspend Fees on Public Transportation

The implementation of fee suspension on public transportation like that following Hurricane Sandy was the boost to get people back into the Central Business District that New York City needed to help start its road to recovery. Although fee suspension on highways and bridges became common following Hurricane Katrina fee suspension on public transportation is not as widely used as seen following Hurricane Irene. Fee suspension can help to save numerous lives by moving people out of the threatened area particularly those in low-income areas. This helps to increase the timeline for evacuation and for recovery. Fee suspension does cost money because services are being ran and no fees are being collected, but it does cost a very minimal amount of money to implement the halting of toll collection.

Change to Semi-Actuated or Fully Actuated Signal Timing

Areas prone to evacuations should investigate switching over to semi-actuated or fully actuated signal timing plans as opposed to pretimed signal timing plans. Even though the overall cost is higher to implement it helps considerably with emergency evacuations, as well as, with daily traffic operations and capacity. The increased cost could be justified, and the implementation could happen over an extended period of time to help defer the costs. Intersections deemed most important to evacuation operations could have actuators installed first and those deemed less important later down the line. This technique helps to remove an increased volume of evacuees by shortening the queue, decreasing delay, and making the overall LOS better.

Call for an Investment in Resilient Infrastructure

Resiliency is by far one of the most important aspects of evacuation planning. Transportation professionals and local municipalities should be continually calling for more resilient infrastructure following so many of these major storms and terrorist attacks. Without resilient infrastructure moving people back into the area following the threat becomes even more difficult. It also adds millions of dollars of work that will need to be done to repair infrastructure damaged by storms that could have been prevented with more sound systems and roadways.

Although these techniques come with a high upfront price tag, they help to reduce the overall cost of evacuation and to move an increased number of people out of the threat area leading up to the threat and back into the area during recovery.

References

Ballard, A. J., & Borchardt, D. W. (2006). *Recommended practice for hurricane evacuation traffic operations* [PDF]. Retrieved from https://static.tti.tamu.edu/tti.tamu.edu/documents/0-4962-P2.pdf.

Blome, R. (2005). Staying? Better write your SS# on your body. *ABC News*. Retrieved from: http://www.nbcnews.com/id/9439537/ns/us_news-katrina_the_long_road_back/t/staying-better-write-your-ss-your-body/#.WrkIHIjwZPY

City of Kenner. (n.d.). *Evacuation* [PDF]. Retrieved from http://www.kenner.la.us/6/Evacuation_General_Info.pdf

Federal Emergency Management Agency. (n.d.). *Mandatory evacuation expenses*. Retrieved from https://www.fema.gov/faq-details/Mandatory-evacuation-expenses-1370032116280

Filosa, G. (n.d.). Key West paid $1.9 million in Irma overtime to employees, including salaried department heads. *Flykeysnews.com*. Retrieved from http://www.flkeysnews.com/news/local/article187706848.html

511 Georgia. (n.d.). *Contra-flow lanes: I-16 one-way driving guides*. Retrieved from http://www.511ga.org/static/hurricane-oneway.html

Florida Department of Transportation. (2005). *Contraflow plan for the Florida interstate highway system* [PDF]. Retrieved from http://www.fdot.gov/traffic/traf_incident/pdf/050808_FI-HS-Contraflow-MASTER.pdf

Florida Department of Transportation. (2018). *Hurricane Irma emergency evacuation report and recommendations* [Newsrelease]. Retrieved from http://www.fdot.gov/info/CO/news/newsreleases/020118_FDOT-Evacuation-Report-Appendix.pdf

Gardner, K., Greenlee, W., & Wixon, C. (2017). Hurricane Irma overtime costs running into millions for Treasure Coast governments. *TCPalm.com*. Retrieved from: https://www.tcpalm.com/story/weather/hurricanes/2017/10/19/hurricane-irma-overtime-running-into-millions-caused-millions-overtime-pay-treasure-coast-government/667896001/

Gov. Scott's Office (n.d.) Gov. Scott directing the suspension of all tolls across Florida. Retrieved from https://www.flgov.com/2017/09/05/gov-scott-directing-the-suspension-of-all-tolls-across-florida/

HCM 2010: Highway Capacity Manual. (2010). Washington, D.C.: Transportation Research Board.

Institute of Medicine. (2007). *Environmental public health impacts of disasters: Hurricane Katrine: workshop summary*. Washington, DC.: The National Academies Press. Retrieved from: https://doi.org/10.17226/11840

Jin, L. (2017, October 19). *Illustrations of different evacuation operations* [PowerPoint slide]. Retrieved from: http://www.fsutmsonline.net/images/uploads/mtf-files/Li_Jin_Hard_Shoulder_VS._Contraflow_Evacuation_FSUTMS_MTF_.pdf

Kim, S., Shekhar, S., & Min, M. (2008). Contraflow transportation network reconfiguration for evacuation route planning. I*EEE Transactions of Knowledge and Data Engineering*, *20*(8), 1115-1129. doi: 10.1109/TKDE.2007.190722

McCall, C. (2001, December). *The impact of the World Trade Center tragedy on the Metropolitan Transportation Authority* [PDF]. Retrieved from http://www.osc.state.ny.us/osdc/rpt902.pdfMcCasland, W. R. (1981). *Evaluation of first year of operation, I-45 contraflow lane, Houston* [Research Report No. 205-9]. Retrieved from https://static.tti.tamu.edu/tti.tamu.edu/documents/205-9.pdf.

Mass Transit Authority. (n.d.-a). *Fares & Tolls*. Retrieved April 20, 2018, from http://web.mta.info/fares/

Mass Transit Authority. (n.d.-b). *Superstorm Sandy: fix & fortify efforts continue*. Retrieved from http://web.mta.info/sandy/lirr.htm

Niloy, M. A., & Fries, R. N. (n.d.). *Actuated signal timing optimization for a no-notice evacuation: A simulation study of residents near an oil refinery*.Unpublished manuscript, Southern Illinois University Edwardsville, Edwardsville, IL.

Parr, S., & Kaisar, E. (2011). Critical intersection signal optimization during urban evacuation utilizing dynamic programming. *Journal of Transportation Safety & Security*,*3*(1), 59-76. doi:10.1080/19439962.2011.532297

Sanchez, R. (2001, September 11). 9/11/01: When the subways went still. *Newsday*. Retrieved from https://www.newsday.com/911-anniversary/9-11-01-when-the-subways-went-still-1.790103

Urbina, E., & Wolshon, B. (2002). National review of hurricane evacuation plans and policies: A comparison and contrast of state practices. *Transportation Research Part A: Policy and Practice*. doi:10.1016/s0965-8564(02)00015-0

U.S. Department of Transportation Federal Highway Administration. (n.d.-a). *Catastrophic hurricane evacuation plan evaluation*. Retrieved from https://www.fhwa.dot.gov/reports/hurricanevacuation/execsumm.htm

U.S. Department of Transportation Federal Highway Administration. (n.d.-b). *Use of freeway shoulders for travel - guide for planning, evaluating, and designing part-time shoulder use as a traffic management strategy*. Retrieved from https://ops.fhwa.dot.gov/publications/fhwahop15023/ch1.htm

Whitehead, J. C. (2003). One million dollars per mile? The opportunity costs of hurricane evacuation. *Ocean & Coastal Management*,*46*(11-12), 1069-1083. doi:10.1016/j.ocecoaman.2003.11.001

Wolshon, B. (2008). Empirical characterization of mass evacuation traffic flow. T*ransportation Research Record: Journal of the Transportation Research Board*, *2041*, 38-48. doi:10.3141/2041-05

Wu, H., Lindell, M. K., & Prater, C. S. (2012). Logistics of hurricane evacuation in Hurricanes Katrina and Rita. *Transportation Research Part F: Traffic Psychology and Behaviour*,*15*(4), 445-461. doi:10.1016/j.trf.2012.03.005

Zhu, Y., Ozbay, K., Xie, K., & Yang, H. (2016). Using big data to study resilience of taxi and subway trips for Hurricanes Sandy and Irene. *Transportation Research Record: Journal of the Transportation Research Board*, *2599*, 70-80. doi:10.3141/2599-09

Appendix I

Subject-Matter Expert Interview with Dr. Scott Parr, Ph.D.

An interview with subject matter expert Dr. Scott Parr, PhD was done in person on April 3, 2018. Dr. Parr is a Visiting Assistant Professor at Embry-Riddle Aeronautical University. Dr. Parr has a Bachelor's and Master's Degree in Civil Engineering from Florida Atlantic University and received his Ph.D. in Civil Engineering from University of Louisiana at Baton Rouge. His dissertation focused on mass evacuations. Currently at Embry-Riddle he teaches Introduction to Transportation Engineering, High-Speed Rail Design, and Traffic Data Collection and Analysis.

1. In your opinion what is the best method of evacuation?

It depends primarily on geographic size and population. For Florida, a large-scale evacuation uses hard shoulders nowadays. In Louisiana, all their plans are set for contraflow so that is all they will use. Contraflow gives more capacity. Traffic engineering relies solely on supply and demand. Hard shoulders are placed on roadways for evacuation purposes. They are stripped with blue lane markings. Right shoulder use causes a problem with on- and off-ramps and can lead to accidents. Left shoulders are better but are much harder to come by. Hard shoulders only give 1 additional lane compared to contraflow which gives 2-3 extra lanes and thus more capacity. Contraflow only moves the bottleneck and doesn't get rid of it if the opposing sides remerge at the same point. This can be eliminated by making the northbound lanes continue going north for example continuing on I95 to Savannah and the southbound lanes merge west for example to I10. No tolling is now a standard to prevent state liability post Katrina.

2.. What limitations have you faced from DOTs? (3-second limitations on green time, etc.)

In the early years there was much more push back but since Katrina there is virtually none. FDOT is very good and LaDOTD is amazing.

3. How do you approach evacuation methods differently for notice vs no notice?

The main thing is the departure curve. No-Notice Evacuations are typically smaller scale. Congestion is typically not a problem. It is a timing issue. The best method is public transportation such as trains and subways. However, in the event of something like a terrorist attack these can be compromised as well.

4. What aspects of previous evacuations are important in future planning and analysis?

Katrina was an amazing evacuation from a traffic stand point. The problem was people in the city who did not have the means to evacuate. There was a plan created but never enacted for moving the low-income people who relied on public transportation. State governments and federal governments now allocate a considerable amount of money for this after that. For Irma most of Florida evacuated 72-48 hours before landfall. There really were no problems with it. 60% of roadways were considered. People would sit in traffic not moving at LOS F for 30 minutes and then move at LOS A for the next 30 minutes. The hard shoulder helps to increase overall speed and LOS.

5. Explain dynamic flashing yellow.

The main road has flashing yellow and the size road flashing red. The main road turns to solid red and the side road to green. Then goes back to flashing yellow and flashing red. The point is to help flush out the side road.

6. Is contraflow typically used in both Notice and No-Notice Evacuations?

Typically, just Notice because there is not enough time to plan during No-Notice Evacuations.