TECHNISCHE UNIVERSITÄT MÜNCHEN

Faculty of Civil, Geo and Environmental Engineering

Chair of Urban Structure and Transport Planning

Master’s Thesis in Transportation Systems

Resilience in urban areas: An approach to study interaction between evacuation and land use & transportation structures

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DER TECHNISCHEN UNIVERSITÄT MÜNCHEN

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Resilience in urban areas:
An approach to study interaction between evacuation and land use & transportation structures

Background

The notion of resilience is rapidly gaining ground in the urban sustainability literature (Sharifi, Yamagata 2014). This is mainly because most of the world population is living in cities and is accompanied by increasing rate of urbanization. The foreseen population rise is expected to put huge pressure on the cities to survive, adapt and grow despite the stresses and shocks (100 Resilient Cities 2016) is becoming a challenge.

The concept of resilience has traditionally been used in physics and psychology to respectively indicate the ability of an object to return to its original position after receiving a hit and the ability to successfully survive a shock or trauma (Sharifi, Yamagata 2014). But human communities are very different, they have social and economic components among other variable components, which makes a definition of resilience even more difficult.

Preparedness to shocks and learnings from the previous experiences have been studied worldwide to better prepare for the future. Dow et al. (2015) have observed that during Hurricane Floyd, traffic concerns have been one of the top three reasons for not to evacuate even if the people belong to mandatory clearing zone. The available research has two dimensions to it, behavioral and operational. Behavior patterns have revealed some unexpected outcomes (Dow et al. 2015). Although operational research in the field of land use and integrated transport is quite limited, it was studied that evacuation using public transport can lead to reduced congestions and travel times (Victoria Transport Policy Institute 2010); the other advantages associated with it are better communication amongst the operators, better route selection and destination choice.

A lot of research is going on in the field of optimizing the traffic signals and calculation of shortest paths during active evacuation. Since evacuation is a dynamic process and using real time information from sensors takes a lot more than which obviates its practical application (CHEN, XIAO 2008). It gives planner a great opportunity to address this matter from another angle (Wolshon et al.), i.e. using the existing tools of land use and transportation planning, which is also the aim of this research.

Research questions

This research will focus to study the role of land use and transport planning in dealing with emergency response. The response of people during evacuation has been seen irrational and raised more concerns (Neill Coleman 2013; ERIC KLINENBERG 2015, Dow et al. 2015, 2015; Todd Litman 2006) and qualms for foreseen population increase in cities. But the important questions here are what steps can transport planners take to prepare for shocks? How does existing land use and transport policy address potential shock scenarios? And how can this be supported by adequate models simulating such response? Which conceptual and methodological conclusions can be deduced from the analysis?

Objectives

The research aims to establish a solid literature on understanding urban resilience, shocks and related response. It also aims to investigate the role of land use and transport planning during a warning based shock - for example hurricane, flooding and tsunami - and simulate the same under different scenarios. The research will look into responses for evacuation by private cars, buses and trains. The criteria for validation will be used from the available research; and comparison will be based on outputs like evacuation time, congestion problems and related parameters. These findings are expected to produce interesting results which can lead to new learnings and applications. The overall objective of this research can be summarized to prove the following hypothesis.

Hypothesis: Transit oriented developments if faced with a shock perform better than car dependent city structure.

Methodology

With the intention to address these questions, this project will first create a clear literature background to understand and explain resilience. It will be followed by study of different kinds of shocks and respective responses. Warning based shocks, e.g. hurricane will be considered for further analysis. At this point the knowledge gained so far will be put to work to understand what transport planners can learn from existing research and what steps can be taken to address such issues. The research will then be supported with simulating a response using a modelling tool, to a defined shock in two different cities, one with private car oriented land use and other which has the characteristics of good public transport and transit oriented land use. The aim is to generate results close to realistic scenarios. Validation will use the traffic flow properties which will be collected from available scientific studies on emergency response. Finally, having analyzed these interesting results, the study aims to conclude with commenting on the stated hypothesis and subsequent learnings and recommendations.

Supervision

One week after the day of issue the student submits a concept and a detailed structure of his work to his supervisor (Dipl. Geogr. Benjamin Büttner). Further appointments for any advisory service during the processing time can be made according to necessity. No later than two weeks after the last day of processing time the candidate has to give a presentation of about 20 minutes with a scientific discussion followed. The presentation is a part of the evaluation.

The master thesis is supervised by the Chair of Urban Structure and Transport Planning. The candidate is completely responsible for all results.

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Declaration of Authorship

I hereby certify that the content of the present Thesis is the result of my own independent work, using only references and sources as listed. I also state that this Thesis has not been submitted for a higher degree to any other University or Institution.

München, August 15, 2016 Bharat Dikshit Sharma

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Abstract

The usage of the word resilience in the last decade has tremendously increased in several fields, including the field of urban planning. Generally understood as "capacity to absorb and bounce back"; resilience aims to prepare a person or a city for uncertainties, shocks, and stresses.

The development of urban structure varies across the world. Recently increased awareness regarding environmental and air quality has attested the advantages of Transit Oriented Development over Transit Adjacent or Automobile-Oriented development.

In this thesis, an attempt to analyze the response of cities with different land use structure when stuck with warning based disaster has been made. Therefore, same transport infrastructure and supply has been modeled so as to generate results close to the reality. Different parameters - for instance, evacuation time, queue lengths, vehicle travel time, average delay time, and average speed - were analyzed for both cities.

The quantitative analysis using VISSIM 7 software confirmed the hypothesis that "transit oriented developments if faced with a shock, perform better than car dependent city structure."

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1. Introduction

The notion of resilience is rapidly gaining ground in the urban sustainability literature (Sharifi and Yamagata 2014). This is mainly because most of the world population is living in cities and is accompanied by increasing rate of urbanization. The foreseen population rise is expected to put a tremendous pressure on the cities to survive, adapt and grow despite the stresses and shocks (100RC 2016) becoming a challenge.

The concept of resilience has traditionally been used in ecology and physics to indicate the ability of an object to return to its original position after receiving a hit and in psychology to indicate the ability to successfully survive a shock or trauma (Sharifi and Yamagata 2014). But human communities are very different; they have social and economic components among other variable components, which makes a definition of resilience even more challenging.

The evolution from resilience to urban resilience has instigated policy makers and transport planners to take appropriate measures to control the disruption in the city functions. Many national and international projects have already been started, for instance, Rockefeller Foundation's '100 Resilient Cities' and Indian Government's 'Smart Cities Project'.

The word resilience is also associated with an intrinsic question of *resilience to what?* (Meerow, Newell, and Stults 2016) Shocks and stresses disrupt the equilibrium of an individual, community or of an entire city. Stresses have long term impacts and shocks have short term and sudden impacts. The shocks can be man made or natural and can have a different scale of impact. Only a few shocks have warning times which allow governments and residents to take appropriate actions.

Preparedness to shocks and learnings from the previous experiences have been studied worldwide to better for the future. Dow et al. (2015) observed that during Hurricane Floyd, traffic concerns was one of the top three reasons for not to evacuate even if the people belong to mandatory clearing zone. The available research has two dimensions to it, behavioral and operational. Behavior patterns have revealed some unexpected outcomes (Dow and Cutter 2002). Although operational research in the field of land use and integrated transport is quite limited, it was studied that evacuation using public transport can lead to reduced congestions and travel times (VTPI 1992); the other advantages associated with it are better communication amongst the operators, better route selection, and destination choice.

A lot of research is going on in the field of optimizing the traffic signals and calculation of shortest paths during the active evacuation. Since evacuation is a dynamic process and using real time information from sensors takes a lot more than which obviates its practical application (Yueming and Deyun 2008). It gives a planner great opportunity to address this matter from another angle (Wolshon et al. 2005a), i.e. using the existing tools of land use and transportation planning, which is also the aim of this research.

1.1. Problem Definition

This research has focused on studying the role of land use and transport planning in dealing with emergency response. The response of people during evacuation has been seen irrational and has raised more concerns (Coleman 2013; Klinenberg 2015; Dow and Cutter 2002; VTPI 1992) and qualms. But the important questions here are: what steps can transport planners take to prepare for shocks? How does existing land use and transport policy address potential shock scenarios? And how can this be supported by adequate models simulating such response? Which conceptual and methodological conclusions can be deduced from the analysis?

1.2. Objectives

To clearly approach the above-mentioned concerns, initial emphasis was given to understanding the meaning of urban resilience. Secondly, different kinds of shocks were studied - with warning times- and their learnings guided the scenario definitions and traffic inputs. Then the scope of work (including study areas) and a shock was selected which tested the evacuation response of a transit oriented and car oriented development quantitatively using VISSIM 7 Software. Hence, a link between land use structure and defined shock was established. The lessons from previous mistakes during the evacuation responses and the results of the thesis forms the recommendation for transport planner. At last, the outcomes of this thesis has shown the benefits of transit oriented development in emergency evacuations.

The overall objective of this research can be summarized to prove the following hypothesis.

1.2.1. Hypothesis

“Transit oriented developments if faced with a shock, perform better than car dependent city structure.”

Thesis outline

With the intention to address these questions, this project first created a clear literature background to understand and explain resilience. It was followed by a study of different kinds of shocks, responses, and lessons. Warning based shocks, e.g. hurricane was considered for further analysis. The study area was so chosen to include one transit oriented region and one car oriented region. The aim was to generate the model as close to reality hence it had same transport infrastructure and supply as in real world. Different scenarios were defined based on literature review. The simulations were run in VISSIM 7 software and the generated results were discussed in detail. An attempt to establish qualitative proof was also included. At last the hypothesis was proved and it was followed by recommendation and scope for future works.

2. Literature Review

Based on the motivation behind this thesis, it is critical to have all the requirements defined and clarified in the initial stages of work. Since urban resilience is relatively new term, it is explained in this chapter. The associated shocks and stresses, a detailed literature review of hurricanes were also included. Briefly, land use structure, within the scope of this study, was discussed.

2.1. Resilience Definition

The popularity of “resilience” has exploded recently in academic and policy discourse. There are numerous explanations and definitions, henceforth it becomes a challenge to accept one (Hosseini, Barker, and Ramirez-Marquez 2016; Meerow, Newell, and Stults 2016). The primary questions when one refers to the risk assessment are (Hosseini, Barker, and Ramirez-Marquez 2016):

1. What can possibly go wrong?
2. What is the probability of such a disruptive scenario?
3. What are the results of such a scenario?

Risk management usually aims to reduce the possibility of happening of such an event and reducing its consequences. *It emphasizes on the mitigation options i.e. designing systems to avoid and absorb undesired events* (Hosseini, Barker, and Ramirez-Marquez 2016). No matter how hard we try to avoid undesired events, we cannot prevent them from happening. For example, Hurricane Sandy in 2012 had hugely impacted the multiple networked systems (even after months power was not restored) (Manuel 2013) and approximately one million cubic yards of debris blocked the transportation networks (Lipton 2013). The other important shocks like the August 2003 US blackout caused transportation network disruptions (Minkel 2008). Further, the overwhelming emergency response in 2003 during Hurricane Isabel devastated the transportation system (Smith and Graffeo 2005). Besides, the 2011 9.0 magnitude earthquake and tsunami that struck Japan causing 15,000 confirmed deaths (MacKenzie, Santos, and Barker 2012), and in 2004 again 9.0 magnitude tsunami originated in Indian ocean stranded thousands of people and disrupted the global supply chain (Hori et al. 2007). It is because of all these large-scale events that Department of Homeland Security had placed emphasis on resilience through preparedness, response, and recovery (Lentzos and Rose 2009).

The word resilience originated from the Latin word "resiliere or resilio" (Hosseini, Barker, and Ramirez-Marquez 2016; Meerow, Newell, and Stults 2016), which means to "bounce back." Early definitions of resilience apply to diverse fields of ecology, materials science, psychology, economics, and engineering. The word "resilience" usually implies (Hosseini, Barker, and Ramirez-Marquez 2016):

"*the ability of an entity or a system to return to the normal condition after the occurrence of an event that disrupts its state.*"

2.2. Evolution of Urban Resilience

The definition of the resilience as explained in section 2.1 has vagueness that can make resilience difficult to operationalize, or to develop generalized indicators. The tensions that are present in the broader definition are (Meerow, Newell, and Stults 2016):

1. equilibrium vs. non-equilibrium
2. positive vs. neutral conceptualizations of resilience
3. mechanism of system change (i.e., persistence, transitional, or transformative)
4. adaptation vs. general adaptability and
5. timescale of action

Using the resilience concept in urban research; the definition which includes the sixth conceptual tension is as follows (as defined by Meerow et al. (Meerow, Newell, and Stults 2016)):

"***Urban resilience refers to the ability of an urban system-and all its constituent socio-economical and socio-technical networks across temporal and spatial scales- to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity.***"

In an attempt to define this concept, Meerow et al. reviewed the following definitions of the urban resilience (Meerow, Newell, and Stults 2016):

1. "... the degree to which cities tolerate alteration before reorganizing around a new set of structures and processes (Alberti et al. 2003, p. 1170)"

2. "... a sustainable network of physical systems and human communities (Godschalk 2003, p. 137)"

3. "... the ability of a system to adjust in the face of changing conditions (Pickett, Cadenasso, and Grove 2004, p. 373)"

4. "To sustain a certain dynamic regime, urban governance also needs to build transformative capacity to face uncertanity and change (Ernstson et al. 2010, p. 533)"

5. "... the capacity of a city to rebound from destruction (Campanella 2006, p. 141)"

6. "... a system that can tolerate disturbances (events and trends) through characteristics or measures that limit their impacts, by reducing or counteracting the damage and disruption, and allow the system to respond, recover, and adapt quickly to such disturbances (Wardekker et al. 2010, p. 988)"

7. ".. the capacity of systems to reorganize and recover from change and disturbance without changing to other states...systems that are 'safe to fail' (Ahern 2011, p. 341)"

8. "... the capacity of the city to tolerate flooding and to reorganize should physical damage and socioeconomic disruption occur, so as to prevent deaths and injuries and maintain current socioeconomic identity (Liao 2012, p. 5)"

To discuss each and every tension in detail and delving into each parameter is beyond the scope of this research. The focus of this research is on the practical application of urban resilience confined within the framework of the defined hypothesis (see section 1.2.1). The definition and parameters that have led to this research are explained in section 3.1.

2.3. Different Shocks and Stresses

Based on the adopted definition of Urban Resilience, as defined in section 3.1, it is important to understand the shocks and stresses that a city can experience. The chronic stresses are stresses that weaken the underlying structure of a city on a daily or cyclical basis, for example (100RC 2016):

- high unemployment
- overtaxed or inefficient public transportation system
- endemic violence

- chronic food and water shortages.

The acute shocks are sudden, sharp events that threaten a city, for example (100RC 2016):

- earthquakes
- floods
- disease outbreaks
- terrorist attacks

The stability of the city is affected by several types of acute shocks or disasters such as fires, crashes, hurricanes, earthquakes, flooding, explosion, etc. which cause severe damages. These events present various transportation issues (VTPI 1992):

- Evacuation before, during or after an event
- Delivery of emergency supplies and services, including water, food, medical care
- Search and rescue operations
- infrastructural repairs

The transportation management response can differ according to the type and scale of the shock. Table 2.1 gives an overview of the types of transportation issues presented by different kinds of disasters (VTPI 1992).

The transportation issues are characterized by the kind of the disaster. Therefore, it is evident to focus on resilience from the engineer's and planner's perspective. It is important to understand the value of resilience, which refers to the ability of a system to accommodate variable and unexpected conditions without complete failure, or the capacity to absorb shocks (VTPI 1992). Resilience increases if the system has diversity, redundancy, efficiency, autonomy, and strength. Their presence allows the system to continue functioning even after a link breaks, or a particular resource becomes scarce, or if a specific decision maker is not available, etc (VTPI 1992).

For this research, the hurricane evacuation was selected to measure the response of the defined study area, described in section 3.3. The main reason for selecting hurricane evacuation is the prior warning associated with the landfall's forecast. Usually, one or two-day warning is given to the region depending on the severity of the hurricane. Following sections provides few case studies of hurricanes.

Table 2.1.: Transportation issues pertaining to different disasters; Source: (VTPI 1992)

Type of Disaster	Geographical Scale	Warning	Evacuation	Emergency Services	Search & Rescue	Infrastructural repair
Hurricane	Very large	Days	√	√	√	√
Earthquake	Large	None	√	√	√	√
Tsunami	Very large	Short	√	√	√	√
Flooding	Large	Days	√	√	√	√
Forest fire	Small to large	Usually	√	√	√	√
Volcano	Small to large	Usually	√	√	√	√
Blizzard/ice storm	Very large	Usually		√	√	√
Explosion	Small to large	Seldom	√	√	√	√
Bus/train/aircraft crash	Small to large	Seldom		√		√
Radiation/toxic release	Small to large	Sometimes	√	√	√	
Riot	Small to large	Sometimes	√	√		
War	Small to large	Usually	√	√		√
Terrorist attack	Small to medium	None	√	√		√

2.4. Lessons from Hurricane Floyd

Floyd was a Category 4 major hurricane in the 1999 Atlantic hurricane season. It was formed on 7th September 1999 and dissipated on 19th September 1999. The damage was approximated to $6.9 billion (NWS 1999). The figure 2.1 shows the track and amount of rainfall during Hurricane Floyd.

2.4.1. Coastal Development and Associated Vulnerabilities

The recent research has compelling documentation stating that tremendous increase in population and investment along the coast has led to increased vulnerabilities of coastal residents in South Carolina. Also, the tourism-based economic growth has been more than the required traffic infrastructure growth that could sufficiently accommodate the usual summer (and hurricane season) crowds. Between 1988 and 1993, the number of insured property grew 48% to reach a total amount of $21.4 trillion (Dow and Cutter 2002). At the same time, it has been observed that the clearance/evacuation time for coastal communities exceeded reasonable expectations of present estimate and future prognosis (Dow and Cutter 2002). It has been observed that the coastal population growth is outstripping the transportation network's capacity to efficiently handle all the traffic(Tibbetts 2002). The evacuation during Hurricane Floyd (Southeastern Atlantic coast of the USA) in mid-September 1999 highlighted the potential pressure on the transportation system both at the state and regional levels. It was the biggest evacuation of the South Carolina till that time with more than one-half South Carolinians leaving their homes. They were also joined by other two million residents from Florida, Georgia, North Carolina, and Virginia who also left their homes because of the Hurricane Floyd(Dow and Cutter 2002).

2.4.2. Traffic Congestion Related Issues

The maximum wind speeds when the hurricane reached Florida were just below the category five on the Saffir-Simpson scale. The path of the Floyd was from eastern Florida then to Georgia and South Carolina and then continuing North. As the result of this course, the evacuees from Florida and Georgia going north (parallel to the coast on Interstate- 95), were met by the evacuees from South Carolina going west and north. This led to the lengthy traffic jams (on Interstate-26) westbound out of Charleston and to the implementation of unplanned lane reversal to Columbia. Despite all the efforts and changes in plans, some evacuees experienced a ten-fold increase in normal travel times (Dow and Cutter 2002).

The traffic jam so caused compelled people to think that the probability of getting stuck in the traffic is more than staying at home. Some returned home because of inconveniences of being on the road. *Brenda Gonnella and her two sons were stuck in the interstate I-26 for nine hours. They were just able to cover 35 miles, and she was worried that the car could run out of gasoline. Finally, she left the interstate and turned back home (Tibbetts 2002).* Trips that used to take two hours on a typical day, took 16 to 18 hours. Many cars ran out of gas and broke down (Tibbetts 2002).

2.4.3. Governance Related Issues

Each state carried out its independent evacuation in isolation as if it were an independent republic with defined boundaries. “The evacuation was not a concerted, coordinated effort.” Approximately two million Floridians left home during Floyd described as an exodus that over stressed the transportation network. As they entered South Carolina, they were encountered with the evacuating traffic traveling west from Savannah and Charleston. The consequence was a gigantic traffic gridlock (Tibbetts 2002).

The communication system also failed severely. The radio systems used by the agencies were incompatible and the cell phones were unreliable during peak usage times. So the authorities were unable to communicate with people stuck in the massive congestion. It was also reported that many people had to work on the day when the voluntary evacuation was announced. After the official announcement of the mandatory evacuation, the influx of vehicles contributed to the traffic jams. It is clear that people need to evacuate earlier to avoid congestion, however, if they come to the road at the same time, the congestion is unavoidable (Tibbetts 2002).

2.4.4. Transportation Considerations in South Carolina

The development in evacuation planning has focused attention on infrastructure capacity issues, such as departure times, destinations, and shelters, rather than evacuees'decision about routes, or details of the mode of transportation. Regardless of the counter traffic flow proposals, much has to be researched regarding the safety and efficiency. But, this measure can multiply and accelerate the demand for transportation systems during critical times. The engineering-based studies on transportation-demand investigations focus mainly on evacuation times to help in making evacuation decisions. So far, the reported clearance times have increased substantially in many coastal areas (Dow and Cutter 2002).

The research also includes that human behavior during evacuations is novel and limited. One of the transportation models from Army Corps of Engineers (ACOE), known as Evacuation Travel Demand Forecasting System, incorporated some assumptions about behavior. For example, it states that there is 20 to 30 percent chance that households may take the second car during evacuations, but the rationale behind it has not been inspected on differentiation based on household size. The transport models assumed the route planning within the state, mainly because of the relatively local nature of previous evacuations. But long distance interstate evacuations were seen during Hurricane Floyd. The experiences with Hurricane Floyd illustrated the need for greater attention to several aspects of evacuation route planning (Dow and Cutter 2002).

One of the reasons that increase the congestion problems during an evacuation is the ‘**shadow evacuations**’. *Shadow evacuations are the evacuation carried out by areas or residents who do not fall under those areas of mandatory evacuations.* During Hurricane Floyd, it contributed to significant congestion on the highways along the coast (Tibbetts 2002). In South Carolina, the evacuation rate from non-coastal counties ranged from 21 percent in the northern part to 49 percent in the central part and averaged around 28 percent in the state. Another factor that contributed to congestion is the tourist populations. South Carolina has witnessed a great increase in the number of tourists. Unfortunately, the peak tourist seasons coincides with the hurricane season. One of the studies involving by Drabek (Drabek 1996) involving tourists and other transit populations, reported that approximately 48 percent of the hurricane evacuees took private cars and about 24 percent of took rental cars to evacuate. It can be an underestimate of the evacuation carried out during Hurricane Floyd, considering the nature of infrastructural development for tourists. 98 percent of the tourists coming to South Carolina are US based and cars or recreational vehicles are the primary transportation choices, rather than airlines and the evacuations is carried out by the same, approximately 84 percent (Dow and Cutter 2002).

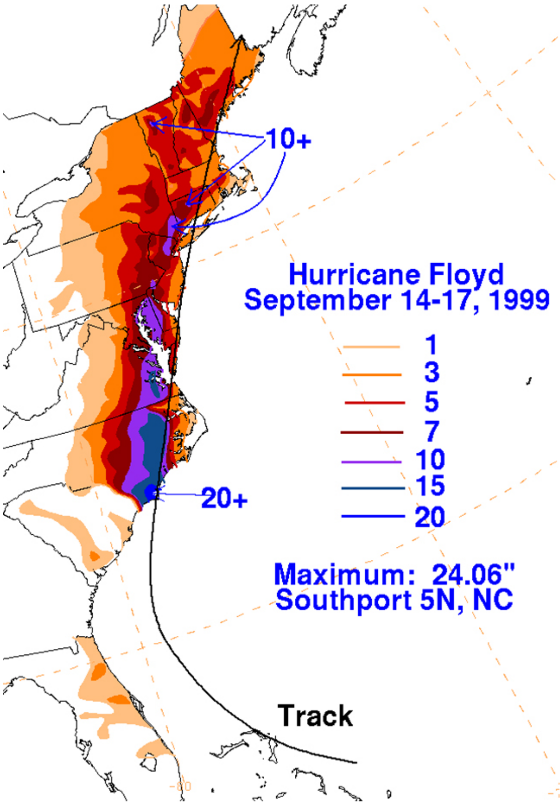


Figure 2.1.: Amount of rainfall recorded during Hurricane Floyd (in inches); Source: (NWS 1999)

2.4.5. Behavioral Influences Stressing Transportation Systems

A total of 65% of the residents of the mandatory evacuation zones reported leaving during Hurricane Floyd. The main reasons that influenced people to leave were storm severity, landfall locations, and the governor's mandatory evacuation orders. Among the people who stayed, traffic concerns were the second most commonly mentioned factor, after the safety of the home. It was ascertained for the first time that traffic concerns were among the top three reasons for staying at home despite the evacuation warning (Dow and Cutter 2002).

The previous research highlighted the importance of togetherness of the households during emergency situations and assumed that families would evacuate together (Sorensen 2000). Floyd witnessed that 25% of the South Carolina residents used more than one vehicle to evacuate. In three and four person household 31% were reported taking two or more cars. Surprisingly, 21% of the two people household took two cars. It was unclear that what motivated people to take more vehicles, despite the fact that 92% of the household even after splitting went to the same destination. The traffic flow was significantly hindered by heavy loading of the vehicles and pulling trailers (Sorensen 2000). Evacuation among the hurricane event shows that departure times are consistent and two days prior to the landfall evacuation is carried out (Baker 2000). This is also the basis of the scenario one as explained in section 5.2.1.

The distance of the evacuation destinations was larger than previous evacuations experienced in South Carolina. 56% of the people left the state, 32% stayed in the state and 9% stayed in the county of origin. Hurricane Floyd attested longer trips that led to the congestion and flow problems to extend beyond the coastal areas of the state. The reasons namely, (1) house of friends and family, (2) severity of the intense hurricane and (3) to find available lodging, were presented by the out of state evacuees (Dow and Cutter 2002).

2.5. Household Decision Making and Evacuation in Response to Hurricane Lili

Hurricane Lili originated off the west coast of Africa on 16th September 2002. It traveled over the Gulf of Mexico towards Texas from 28th September until mid-afternoon on 2nd October, with the intensity of Category 4 hurricane. National Hurricane Center (NHC) issued a *hurricane watch* for west coast between St. Louis Pass and mouth of Mississippi River. On 1st October a *hurricane warning* was issued (Lindell, Lu, and Prater 2005). Results of the mail survey of the households in Louisiana parishes of Vermilion and Cameron and the Texas counties of Orange, Jefferson, and Chambers are discussed in following subsections (Lindell, Lu, and Prater 2005).

2.5.1. Hurricane Information System

Most people reported relying on the local news media followed by national news media. No significant correlation of the demographic variable with the utilization of information, but of geographical variables, was noticed. Houses located closer to the coast, rivers, or lakes were more likely to rely on local news media. Listening to the county sheriff at the doorstep has more profound effect on evacuation decision than listening to the news on television. In conclusion(Lindell, Lu, and Prater 2005): local authorities>local news media>national news media>peers>internet.

2.5.2. Information Type

The greatest consideration was given to environmental cues. Personal experience was next in the list based on previous hurricane experience and unnecessary evacuation. Social cues and observations from peers were next in consideration list. In conclusion (Lindell, Lu, and Prater 2005): environmental cues>personal experience>social cues>observation of peers.

2.5.3. Evacuation Decision

The Hurricane evacuation decision was governed by the proximity to the lakes, rivers, and coast. Second was Building structure type characterized by mobile homes, single family, and multi-family. People living in mobile homes and weak structures were likely to evacuate earlier. The single families were also likely to take the decision and prepare for the evacuation, earlier and faster than the multi families with children. The next two were information sources and (absence of) impediments(Lindell, Lu, and Prater 2005). In conclusion: proximity to lakes,rivers,and coast>mobile homes>single family>multi family>information source>absence of obstructions.

2.5.4. Timing of Evacuation

Most people were likely to evacuate in the morning time and gradually decrease during the course of the day. Also, the residents farther from coast took more time to make an evacuation decision than residents in proximity to the coast(Lindell, Lu, and Prater 2005).

2.5.5. Hurricane Preparation Time

Hurricane evacuation time is total time taken to (1) leave from work, (2) travel from work to home, (3) gather all persons who would evacuate, (4) pack items that would be taken along, (5) protect property from storm damage and shut off utilities, (6) secure the home, and (7) reach the main evacuation route. The respective time duration for the activities in this survey were 15 minutes,7.9 minutes, 30.2 minutes, 46.1 minutes, 38.8 minutes, 33.6 minutes, and 24.6 minutes. The average total time was 196.2 minutes,just more than 3 hours (Lindell, Lu, and Prater 2005).

One interesting finding in regards to the preparation time was that the preparation times were negatively related to the distance from the coast. So, the residents of farther inland areas took less time to prepare than people living at more risk areas. The net result is the canceling out the hazard proximity on decision times and preparation times, leaving departure times approximately random on hazard proximity. This also means that evacuation with less forewarning in inland areas would impede the evacuation of those closer to the coast. The time needed for activities

(5) protection of property and (6) secure the home were longer in areas with closer proximity to the coast than inland areas (Lindell, Lu, and Prater 2005).

2.6. Learning from Hurricane Katrina and Rita

Hurricane Katrina was the fifth hurricane of 2005 Atlantic hurricane season. The total property damage was estimated at $108 billion and at least 1,245 lost their lives. It was originated over the Bahamas on 23rd August and strengthened to Category 5 over the waters of Gulf of Mexico. It finally dissipated on 30th of August 2005 (Knabb, Rhome, and Brown 2005). Figure 2.2 was captured on 28th August 2005.

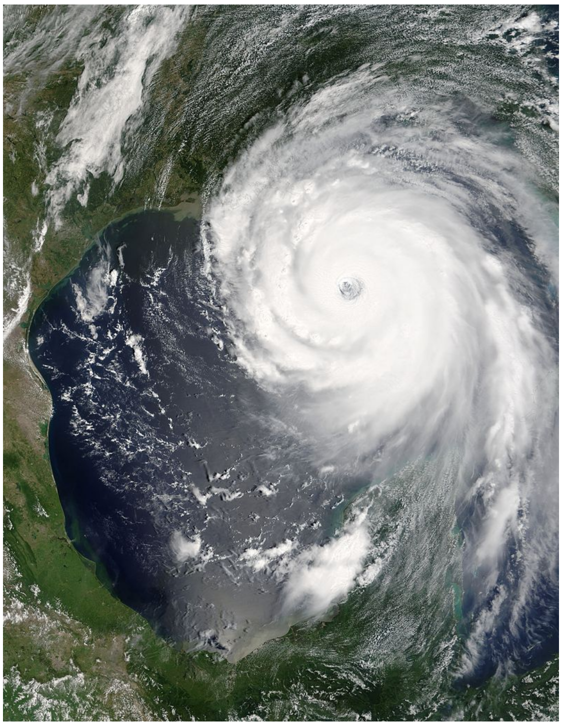


Figure 2.2.: Hurricane Katrina picture on 28th of August; Source: (NHC 2005)

2.6.1. Poor Governance during Katrina

Similar to other hurricanes, Hurricane Katrina also experienced a very slow moving traffic and congestion. The congestion enhanced when automobiles ran out of fuel or suffered mechanical problems. There was no effective plan to evacuate transit dependent residents. Only 60% of the residents in high-threat areas were willing or able to leave. Of many reasons, lack of transportation and lack of outbound roadway capacity were important ones. As per the estimate, 200,000 to 300,000 people did not have the access to a reliable personal transport (Litman 2006).

This suggests that public officials were aware of and willing to accept the risk of the residents who were not able to evacuate due to non-availability of transport. Although the city established ten pickup locations, the service was unreliable. Many low-income residents faced with a barrier of a high commercial fee that existed by public transportation. The evacuation plan of Louisiana directs to use personal transportation as the primary mode of transportation, school buses and municipal buses to be used in emergencies. But there was nondeployment of the buses on ground. The city had only 500 transit and school buses, but a minimum of 2,000 buses were needed to evacuate those who wanted. Not only the limited amount of buses but the unavailability of drivers worsened the situation even more (Litman 2006).

The shelter Superdome, where transit evacuees were directed, had insufficient water, food, medical care, and security. This led to a medical and humanitarian crisis (Litman 2006).

2.6.2. Obstacles to Transportation during Rita

The evacuation of 3 million people from Texas coast, created a 100-mile-long traffic jam. The traffic was crawling at just a few miles per hours, that left many stranded and out of fuel. Many gas stations ran out of fuel because the refueling truck drivers did not report to work. To save fuel, drivers did not turn on the air conditioning despite the high humidity and temperature. Several vehicles failed along the way because of overheating, empty fuel tanks; thus exacerbating the congestion problem (Litman 2006).

Like Hurricane Floyd (see section 2.4.2), after creeping only 10 to 20 miles in nine hours, some drivers returned home to take their chances at home rather than being caught up in open when the hurricane struck (Blumenthal 2005). County officials also admitted that their plan had not anticipated the volume of traffic. They made the situation worse by announcing at one point that inbound lanes to be used for easing the outbound pressure, which they later aborted due the need of supplies still in the city. This resulted in confusion and more delays(Litman 2006).

2.7. Land Use Structure

Several urban practitioners have claimed that there is a strong relation between the standard of living and demand for cars and more private spaces; increasing household incomes inspire people to purchase a car and relocate in low-density suburbs, resulting in the change of land-use and transportation. The aforementioned phenomenon has been witnessed in Australian and North American cities, but the universal applicability of the statement is questioned by several European cities which had compact development with rising living standard. Many urban planners have tried to push cities to opt for sustainable development and reduce the car dependency. However, urban planners are also scared to take decisions to make driving unattractive (Aljoufie 2016). Some promising steps have been taken by the government of Singapore, which has witnessed the downfall in the number of total cars despite the growing populations and increasing per capita incomes (LTA 2015).

Shifting from car to public transportation is quite a challenging task for the decision makers. Private transport, especially cars, are treated as the most convenient mode of transportation. The acceptability of public transportation has to be supplemented by bigger goals of reliability, efficiency, security and safety. The global discussions on environmental quality have ignited the feeling to grow sustainable and to increase in the steps to reduce the transport emissions, but several cities in the Gulf countries are car obsessed; characterized with cheap cars and fuel (Aljoufie 2016).

The increase in the car ownership of India and other developing nations has tremendously increased with the growth in per capita income. Low-cost cars and societal stature attached to the car ownership has lead to more cars on the road than an increase in the transportation supply. Recently, India has witnessed massive congestions; cities have experienced the worst face of it (Ghate and Sundar 2014). It is important for the developing countries to take proper actions to control or check this non-sustainable growth before it becomes the part of behavior.

2.7.1. Transit Oriented

"Transit Oriented Development (TOD) refers to residential and commercial centers designed to maximize access to Transit and Non-motorized transportation, and with other features to encourage transit ridership. (VTPI 2015)"

A typical TOD has a rail or bus station at a center which is surrounded by the high density development and progressively lower densities outwards. The main features of transit oriented development are (VTPI 2015):

- The neighborhood is designed for non-motorized transportation modes (cycling and walking), with adequate facilities and attractive street conditions.
- Streets have good connectivity and traffic calming features to check traffic speed.
- Within each neighborhood, there is a mixed-use development that includes shops, schools and other public services.
- Parking management is aimed to reduce the amount of land devoted to the parking, and take advantage of the parking cost savings associated with reduced automobile use.

- Transit stops and stations that are convenient, comfortable and secure, with features such as comfortable waiting areas, refreshments, and magazine shops, washrooms, etc.

Other associated advantages of TOD are namely, reduced car trips, less transport related emissions, enhance non-motorized mode of transportation and a reduced number of car ownership which can result in vehicle reduction. There are numerous examples of the places where TOD was implemented and the transit mode share was tremendously increased. It is also important to mention that TOD also offers equity, it benefits the lower income groups, non-drivers and increases racial diversity and household affordability (VTPI 2015).

One of the aims of TOD, called Neighborhood Mobility (studied at Technische Universität München) is a tool which seek to increase the non-motorized development and enhance the quality of life; focuses on pedestrians, cyclists, networks connecting public transport nodes and mobility restricted people. The approaches that can be taken to attain the aim can be following (Wulfhorst 2014):

- concept of city as a place of short trips
- the city as a living space
- entitlement to identify and develop urban attractiveness
- options for local activities, quality of life and movement
- consistent connections of functional transport aspects of service sized to the use structure of the area and urban development

A lot of research is going on now to find what kinds of social benefits are associated with the non-motorized transportation. It is believed that TOD enhanced the social capital, however, empirical evidence of this relationship is lacking. Kamruzzaman et al. (2014) conducted a survey in Brisbane, Australia to check whether TOD increases the social capital (Kamruzzaman et al. 2014). *Social cohesion is the network of social connections that exist between people, their shared values and norms of behavior, which enable and encourage mutually beneficial social co-operation.* The components of social capital are local social interaction, sense of community, informal social control, and social cohesion. The result of the survey was as follows (Kamruzzaman et al. 2014):

“ The results showed that individuals living in TODs had a significant higher level of trust, reciprocity and connections with neighbors compared with the residents of Transit Adjacent Development (TAD)s. It appears that TODs may foster the development of the social sustainability.”

Singapore has a great share of public transport (63%), high population density, and very low vehicle per head (9 vehicles per 100 people, which qualifies it to be a

TOD city (LTA 2015)). More details in the scope of the thesis are further explained in section 3.3.

2.7.2. Automobile Oriented

Automobile oriented transportation conflicts with the urban density because it is space intensive (for roads and parking). Large scale park & ride facilities tend to conflict with TOD because a rail station surrounded by large parking lots and arterials with heavy traffic are not suitable for residential development and pedestrian access (VTPI 2015).

Table 2.2.: Transit Oriented vs Transit Adjacent; Source: (Renne 2009)

Transit Oriented Development	**Transit Adjacent Development**
Grid street pattern	Suburban street pattern
Higher densities	Lower densities
Limited surface parking and efficient parking management	Dominance of surface parking
Pedestrian- and bicycle oriented design	Limited pedestrian and cycling access
Mixed housing types, including multi-family	Mainly single-family homes
Horizontal (side-by-side) and vertical (within the same building) mixed use	Segregated land uses
Office and retail, particularly on main streets.	Gas stations, car dealerships, drive-through stores and other automobile-focused land uses.

Many cities in the USA have Transit Adjacent Development, which is conventional automobile-oriented development located near transit stations. The comparison between TOD and TAD by John Renne is shown in table 2.2 (Renne 2009).

The policies to reduce oil consumption in the United States have been significantly successful in stationary use (e.g., industry and home heating) and improving the vehicle fuel efficiency rather than on reducing the need for automobile use. The high per capita consumption of fuel in the United States is primarily because of land use and transportation planning factors, rather than price or income variations. The average gasoline consumption in U.S. cities was nearly twice as high as in Australian cities, four times higher than European cities and ten times higher than in Asian cities (Newman and Kenworthy 1989).

3. Scope of Study

3.1. Defining Study based Resilience

The most relevant definition of the Urban resilience within the scope of thesis research is given by Rockefeller Foundation's project called 100 Resilient Cities. It is stated as follows(100RC 2016):

"Urban Resilience is the capacity of individuals, communities, institutions, businesses, and systems within a city to survive, adapt, and grow no matter what kinds of chronic stresses and acute shocks they experience."

Different shocks and stresses that city experiences are explained in section 2.3 and the shock within the scope of the study is explained in section 3.2.

Improving the individual sections that make up a city will increase the resilience of the city overall. "Resilient systems withstand, respond to, and adapt more readily to shocks and stresses to emerge stronger after tough times, and live better in good times (100RC 2016)."

According to Rockefeller Foundation, the characteristics a city should possess are (100RC 2016):

1. **Reflective**: using past experience to inform future decisions

2. **Resourceful**: recognizing alternative ways to use resources

3. **Inclusive**: prioritize broad consultation to create a sense of shared ownership in decision making

4. **Integrated**: bring together a range of distinct systems and institutions

5. **Robust**: well-conceived, constructed and managed systems

6. **Redundant**: spare capacity purposively created to accommodate disruption

7. **Flexible**: willingness and ability to adopt alternative strategies in response to changing circumstances

3.2. Defined Shock

Evacuation is not a suitable response to all disasters. Some of the man-made and natural disaster do not provide any warning at all; subsequent evacuation is carried to escape the aftermath of the disaster, for example, earthquakes or chemical spillage. Other hazards such as tornadoes are preceded by warning but it is insufficient to evacuate. Hurricanes perhaps provide the greatest warning time of all (Wolshon et al. 2005b). Table 3.1 shows different types of disasters and associated warning time (increasing from top to bottom). Concerns associated with hurricanes

Table 3.1.: Hazards requiring evacuation; Source: (Wilmot 2001)

Hazards requiring evacuation	
Man-made events	Natural events
Terrorist attack	Earthquake
Chemical release	Volcanic eruption
Nuclear power plant accident	Tornado
Dam failure	Tsunami
	Wildfire
	Flood
	Hurricane

are storm surge, extreme rainfall , extreme winds and tornadoes, and wind driven waves. One of the biggest catastrophe due to storm surge flooding occurred in Bangladesh in 1970 where 300,000 people lost their lives. With developments in better weather forecasts, the live loss has reduced drastically, but the property loss is still a major concern as most of the coastlines have developed in last decade (Dow and Cutter 2002). The cost of the hurricane evacuation can exceed more than one million dollars per mile because of the direct costs and losses in tourism. Therefore hurricane evacuation warnings are issued in the areas which possess a significant risk to human life (Wolshon et al. 2005b).

Despite how accurate the hurricane forecast may become, uncertainties will exist in storm track; as natural and built environment interact with the path of the hurricane. As discussed in sections 2.4, 2.5, and 2.6, over-stressing the transport systems causes congestion and possibly reduces the access to those who are most at risk. An emergency management maxim describes hurricane evacuation as (Wolshon et al. 2005b):

"Run from water, hide from wind."

In cases where populations are unable to evacuate from storm surge zones, vertical evacuations might be employed. *Vertical evacuation is the use of the top floors of high-rise buildings within the flooded area (Wolshon et al. 2005b).*

The total time required to carry out evacuation is the sum of clearance time and

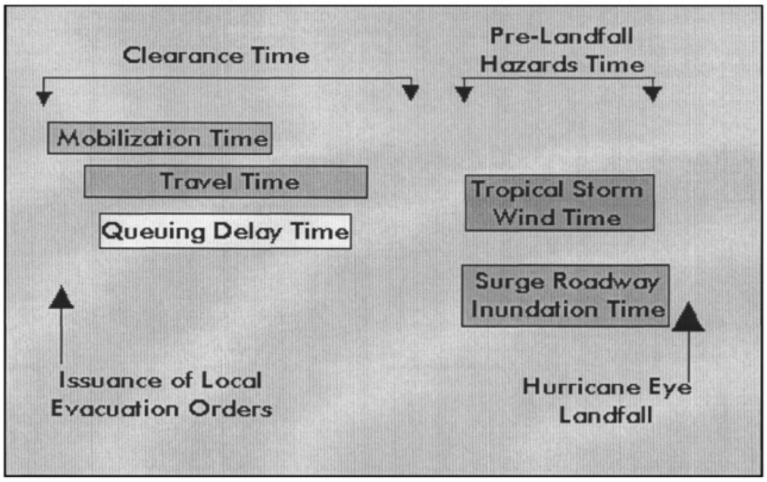


Figure 3.1.: Components of Evacuation Time; Source: (Wolshon et al. 2005b)

pre-landfall hazard time (see figure3.1). The usual time taken to initiate an evacuation is 12 hours. *"Clearance time is the time required to configure all traffic control elements on the evacuation routes, initiate the evacuation, and clear the routes of vehicles once deteriorating conditions warrant its end. Pre-landfall hazards time is the time during which hazardous conditions exist prior to actual hurricane landfall"* (Wolshon et al. 2005b).

There are different types of evacuation orders (Wolshon et al. 2005b):

1. **Voluntary evacuation**: The evacuations which are targeted towards the people most vulnerable to storm surge and extreme winds. No special transportation measures are taken during this type of evacuation, and people can stay if they choose to.

2. **Recommended evacuation**: The evacuations orders are issued when a significant threat to people in high-risk areas exist, due to strong storm surge. Few transportation arrangements are made by the authorities.

3. **Mandatory evacuation**: Mandatory evacuations are the most serious type of evacuation. It is when authorities put maximum emphasis on encouraging people to evacuate. These evacuation are carried out by the evacuation transport plans.

Of all the different shocks, the scope of this study was confined to Hurricane event and among the type of evacuation, a mandatory evacuation was assumed were all the residents had to evacuate.

3.3. Study Area

The study area in this research comprises of two regions:

1. **Kenner and Metairie, Louisiana, USA**: Louisiana is a state located in the southern region of the United States of America (USA). It is 25th most populous state in the USA. It has a total area of 135,382 sq.km. and a population of 4.6 million (2014) (DataUSA 2014b).

   Kenner is the sixth-largest city in the State of Louisiana, the USA. It is a census designated place in the Jefferson Parish and second most populous suburb of New Orleans. It has borders with Metairie, River Ridge and St. Rose. Few basic facts on Kenner are as follows (DataUSA 2014a):

   - Population (2014) : 66,926
   - Land area : 39 sq. km
   - Population density : 1,798.8 per sq. km
   - Median Household income (2014): $49,771
   - Median age (2014) : 38.1

   More information on Kenner is discussed in chapter 5.

   Metairie is the fourth-largest city in the State of Louisiana, the USA. It is a census designated place in the Jefferson Parish and most populous suburb of New Orleans. It has borders with Elmwood, Harahan, Kenner and New Orleans. Few basic facts on Metairie are as follows (DataUSA 2014c):

   - Population (2014) : 140,074
   - Land area : 57 sq. km
   - Population density : 2,408.5 per sq. km
   - Median Household income (2014): $51,808
   - Median age (2014) : 40.7

   More information on Metairie is available in chapter 5. The study area is shown in figure 3.2.

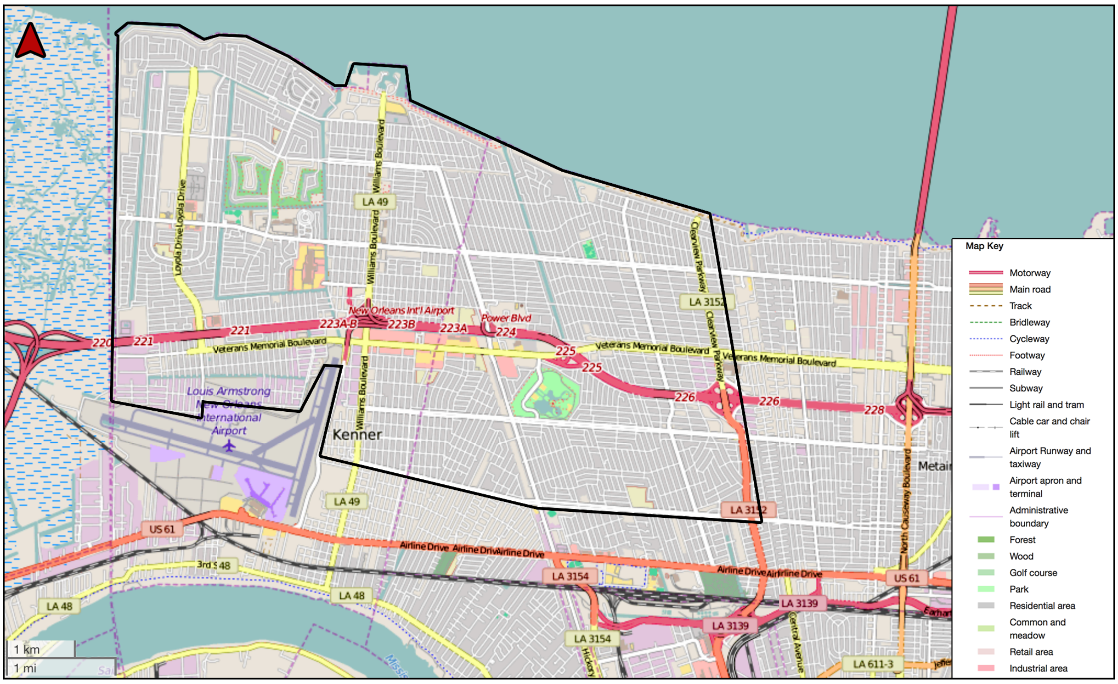


Figure 3.2.: Study area of Louisiana, USA; Source: (Openstreetmap 2016a)

2. **Tuas, Pioneer, Boon Lay and Jurong West, Districts of Singapore**: These all are the population districts of Singapore area as defined by the Singapore Land Authority and is the second region or study area of this thesis. Singapore is the world's only island city state and often referred to as Lion City and the Garden City. Few basic facts of Singapore are as follows (LTA 2015) :

    - Population (2014) : 5,470,000
    - Land area : 719.1 sq. km
    - Population density : 7,697 per sq. km
    - Median Household income (2014): $7,870 (SBR 2014)
    - Median age (2014) : 33.8 (Indexmundi 2014)

    More information on the study area of Singapore is available in chapter 5. The study area is shown in figure 3.3.

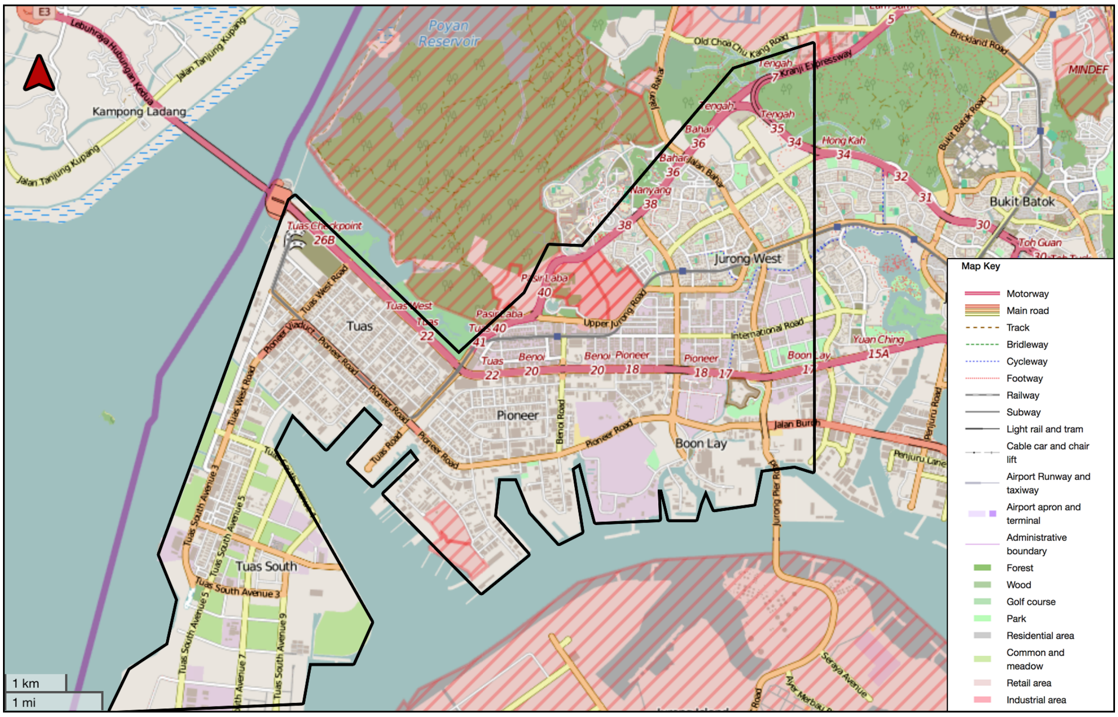


Figure 3.3.: Study area of Singapore; Source: (Openstreetmap 2016b)

3.3.1. Demographics

The population per age group for both regions is shown in subsequent subsections.

Kenner

Figure 3.4 shows the population distribution per age group of the city of Kenner. The Median age of Kenner is 38.1 (DataUSA 2014a).

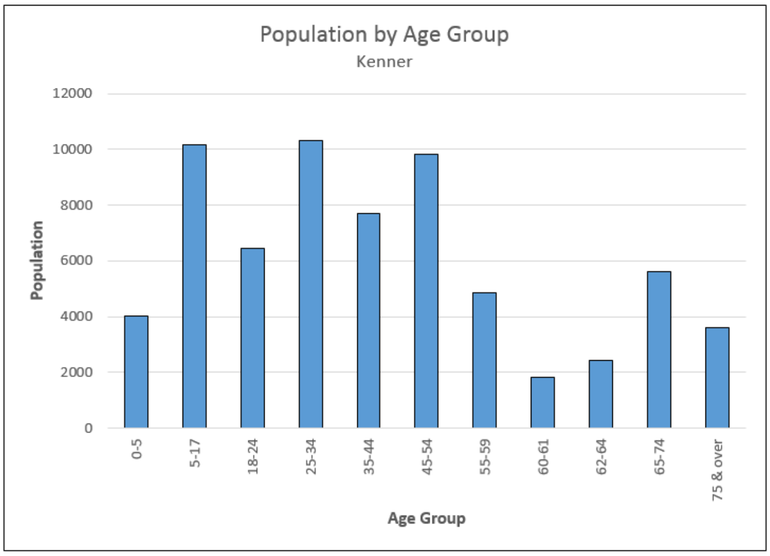


Figure 3.4.: Population by Age group - Kenner; Source: (DataUSA 2014a)

Metairie

Figure 3.5 shows the population distribution per age group of the city of Metairie. The Median age of Metairie is 40.7 (DataUSA 2014c).

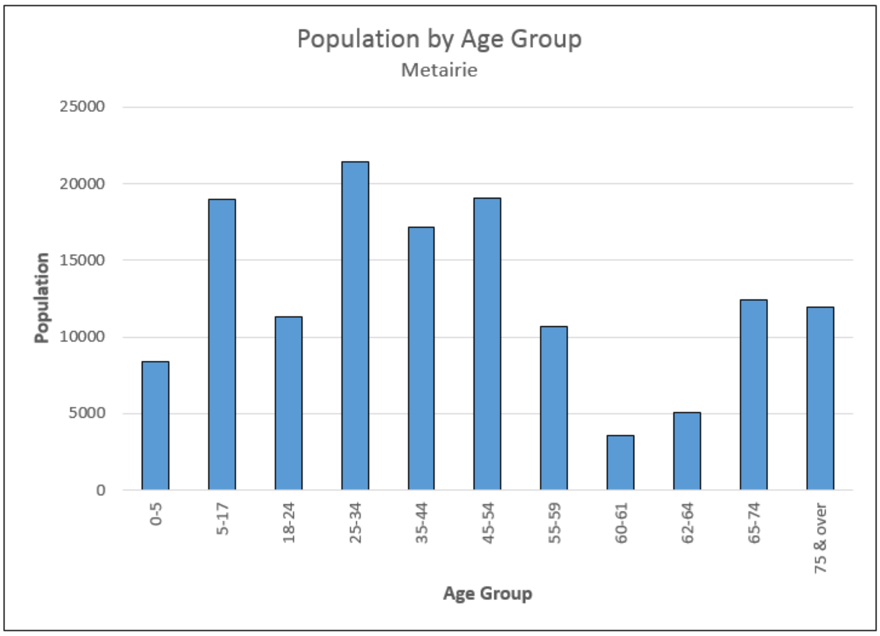


Figure 3.5.: Population by Age group - Metairie; Source: (DataUSA 2014c)

Tuas, Pioneer, Boon Lay and Jurong West, Districts of Singapore

Figure 3.6 shows the population distribution per age group of the study districts of Singapore. The Median age of Singapore is 33.8 (DataUSA 2014c).

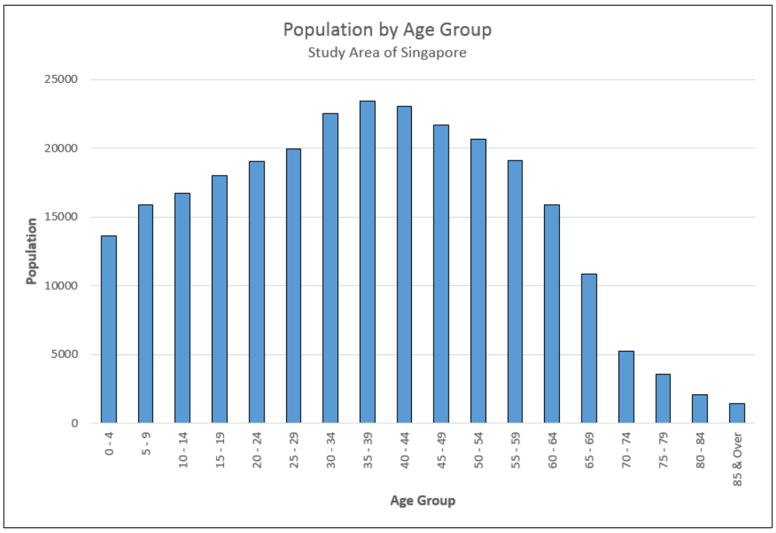


Figure 3.6.: Population by Age group - Singapore (Study Area); Source: (DOS 2015)

3.3.2. Modal Split

The modal split of Kenner City, Metairie City and Singapore shown is following sections.

Kenner

The largest share of commuters in Kenner 'Drove alone' to work. Additionally, the preferred secondary means of transportation to work for Kenner is 'Carpooled'.The modal split of Kenner is shown in figure 3.7.

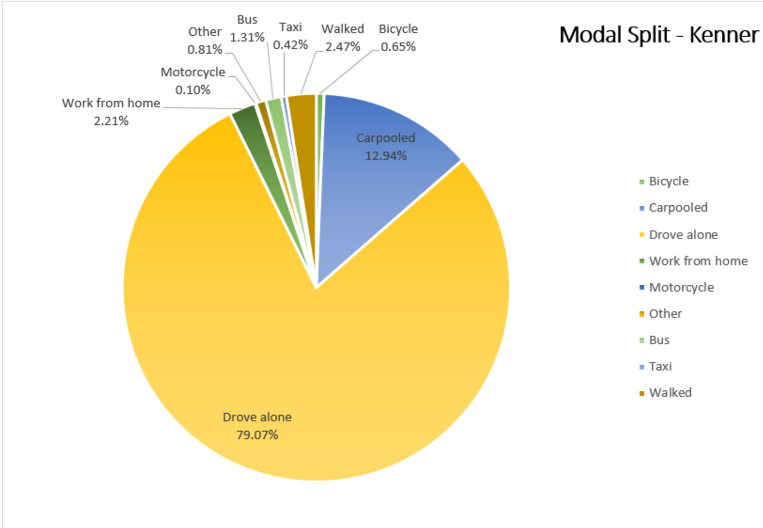


Figure 3.7.: Modal split of Kenner; Source: (DataUSA 2014a)

Metairie

The largest share of commuters in Metairie 'Drove alone' to work. Additionally, the preferred secondary means of transportation to work for Metairie is 'Carpooled'.The modal split of Metairie is shown in figure 3.8.

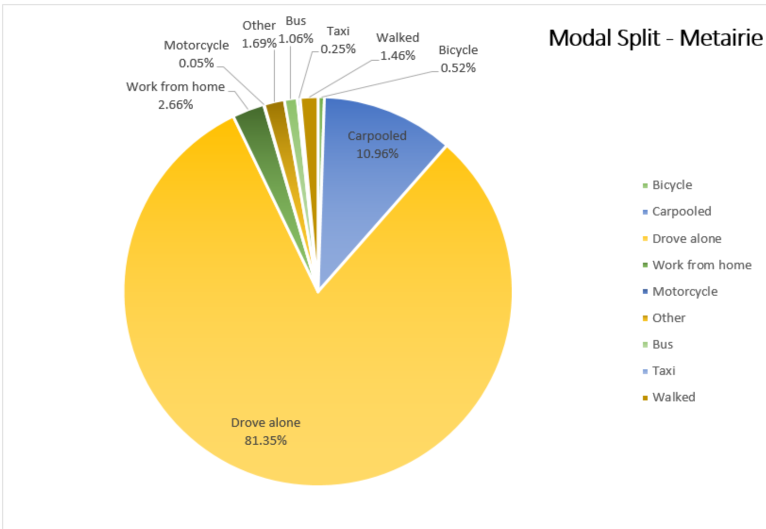


Figure 3.8.: Modal split of Metairie; Source: (DataUSA 2014c)

Singapore

Lifestyle Survey shows that 63% of the respondents take some form of public transport (bus, train or taxi) on their way to work. A lower proportion (31%) takes private vehicles or motorcycle to work. The modal split of Singapore is shown in figure 3.9.

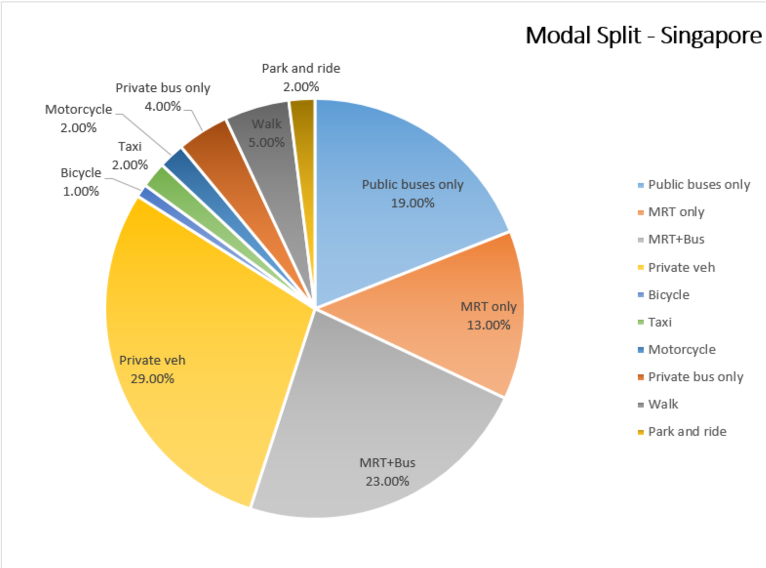


Figure 3.9.: Modal split of Singapore; Source: (URA 2010b)

3.3.3. Car Ownership

The largest share of household in Metairie and Kenner have two cars. The figure 3.10 shows the number of cars owned by the proportion of the household.

The total number of household in Kenner in 2014 were 31,772 (DataUSA 2014a) and according to figure 3.10, the number of cars available are 68,455. The total population of Kenner in 2014 was 66,926 (DataUSA 2014a), which leads to more than one car per person.

On the contrary, Singapore has a total population of 5,470,000 and the total number of private cars 536,882 (LTA 2015). This means 9.8 cars per 100 persons.

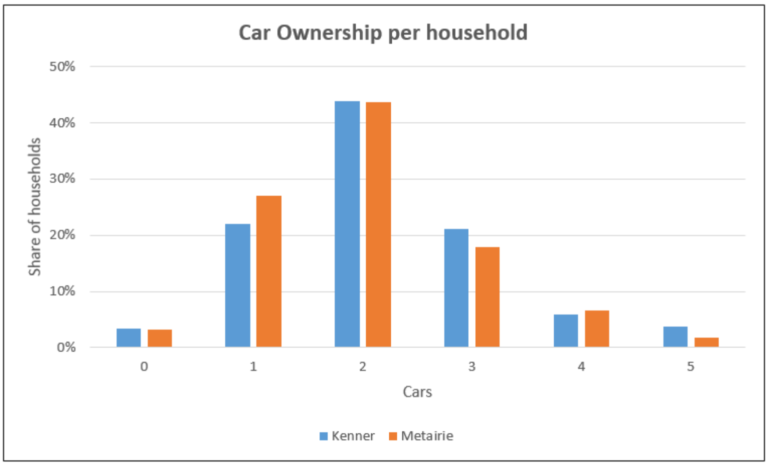


Figure 3.10.: Modal split of Singapore; Source: (DataUSA 2014a)

4. Methodology

4.1. Microscopic Traffic Simulation Modeling

Microscopic traffic simulation is a technique in which individual vehicle positions are determined based on their interaction with other vehicles and surroundings (Barceló 2010). Improvements in computational power of computers have helped in developing complex traffic simulations tools, and various tools are available for microscopic traffic simulation. This section briefly explains the fundamentals of one of the tools i.e. VISSIM 7.0 (PTV 2015a), developed by Planung Transport Verkehr (PTV) AG in Karlsruhe, Germany.

4.1.1. Introduction to VISSIM

VISSIM is a time-step oriented, behavior based tool for modeling different traffic scenarios microscopically (PTV 2015b). VISSIM provides high level of visualization based on realistic traffic models mainly for longitudinal and lateral movement of vehicles.

Car Following Model

Longitudinal movement of vehicles is based on the famous psychophysical car following model developed by Wiedemann in 1974. The basic idea of the model is that when a car approaches a slower leading vehicle, it activates a response in the driver of the following car after a certain threshold. Since the driver is unable to estimate an exact speed of leading car, it follows the leading car with an oscillating speed (Fellendorf and Vortisch 2010). Figure 4.1 shows how a car goes through various stages as it approaches the leading car and causing it to slow down as it reaches desired safety distance.

Many parameters in the model determine the aggressiveness and reaction time of the following car driver. For detail of each parameter, the reader may refer to Wiedemann and Reiter (1992) (Wiedemann and Reiter 1992). Values of these parameters can be adjusted to calibrate the model and obtain a certain saturation flow rate. VISSIM also incorporates Wiedemann 1999 model, which is modified version of Wiedemann 1974 with additional parameters. According to PTV Group (PTV 2015b) Wiedemann 1974 suits more for urban areas whereas Wiedemann 1999 model is suitable for freeway traffic.

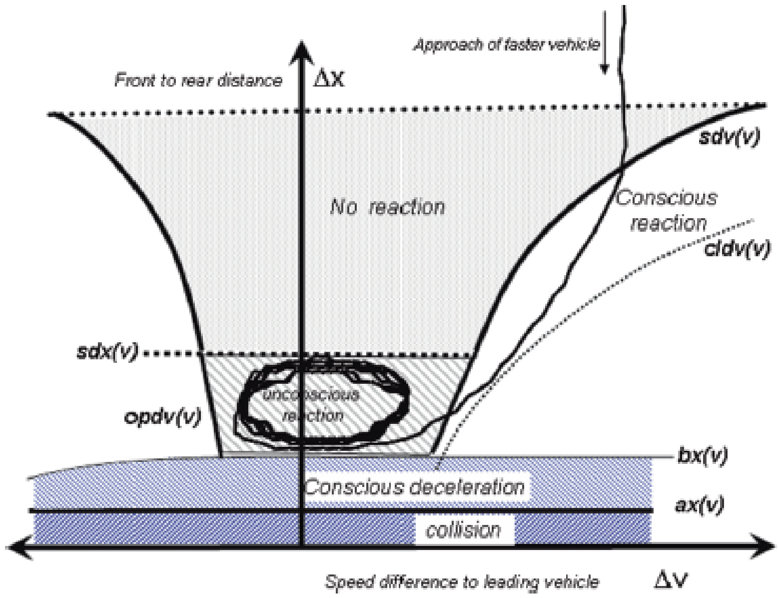


Figure 4.1.: Car following model by Wiedemann (1974), Source: (Fellendorf and Vortisch 2010)

Lateral Movement

Behavior model for lateral movement defines which lane to choose and which lateral position to take within a lane. VISSIM divides lateral movement in two categories i.e. necessary lane change and free lane change (PTV 2015b). Necessary lane change occurs due to the desired turn of a vehicle at a downstream intersection to reach its destination. Lane is selected using the discreet choice model by giving a certain utility to each lane. On the other hand, when a vehicle is far enough from any decision point it tries to search for a lane that has a best interaction situation (Fellendorf and Vortisch 2010). A vehicle does so by first considering its current situation and in case it does not fulfill free flow condition it then looks for a better lane that has higher time to collision. In both lane cases, a lane change is possible only if there is a certain gap in the adjacent lane that allows the vehicle to maneuverer in safely. Acceleration, deceleration or gap acceptance can be set different for each case. There are few more parameters that help in modeling lane change more tactically like advanced merging, cooperative lane change etc.

Viswalk

PTV Viswalk is an add-on module for VISSIM that can be used to simulate pedestrians. It can be used as a standalone module to study the behavior of pedestrians for a specific scenario or it can be combined with vehicular traffic. In the later case, it is helpful in areas where numbers of pedestrians are large enough to affect the network performance. Such cases may include intersections with a large number of pedestrians crossing a road, calculating dwell time of public transport using pedestrians at the waiting area, modeling shared spaces and so on. Viswalk uses social force model developed by Helbing and Molnar in 1995 (PTV 2015b). The basic principle of this model is that social, psychological and physical forces (repulsive and attractive) sum up to a force that decides movement of a pedestrian. These forces are made up from a desire to reach a certain point by avoiding certain obstacles and keeping some distance from other passengers. Different parameters are present to control the sensitivity of each type of force. For further details of the forces and parameters involved, the reader is referred to the paper by Helbing and Molnar (Helbing and Molnar 1995).

4.1.2. Developing a Model

Figure 4.2 shows the work-flow of a typical simulation study. It starts with defining objectives and scope of the simulation study regarding complexity, temporal boundaries, and geographic boundaries. Measures of effectiveness (MOE) are identified in the beginning to assess the quality of the model. Development and calibration of the model are briefly explained in the following section. For further details regarding modeling techniques, the reader can refer to VISSIM PTV VISSIM 7 User Manual (PTV 2015b) Development of base model can be classified into three categories (Fellendorf and Vortisch 2010) explained as following:

Modeling of Infrastructure

VISSIM uses “links” and “connectors” to build road and public transport network. Links are placed on roads and it has certain properties such as a number of lanes, gradient, vehicle class allowed etc. On the other hand, connectors are used to build a connection between two links, so it is mainly used to model crossings, merging and diverging. Important properties of connectors include lane change and emergency stop distance both of which have an impact on routing decisions of vehicles.

Modeling Public and Private vehicles

Public transport (PuT) is modeled by defining the stops and the PuT line. Stops are placed on the links and the stop can either be on curbside or a bus bay (PTV 2015b). PuT line can be a bus, tram or a light rail vehicle with a fixed route, timetable and sequence of PuT stops. Each stop can have a specific dwell time for each bus route. Dwell times can either be calculated based on pedestrian load or by providing a time distribution (normal or empirical). Essentially bus routes are fixed in VISSIM however; static partial PuT route can be assigned where multiple links are present.

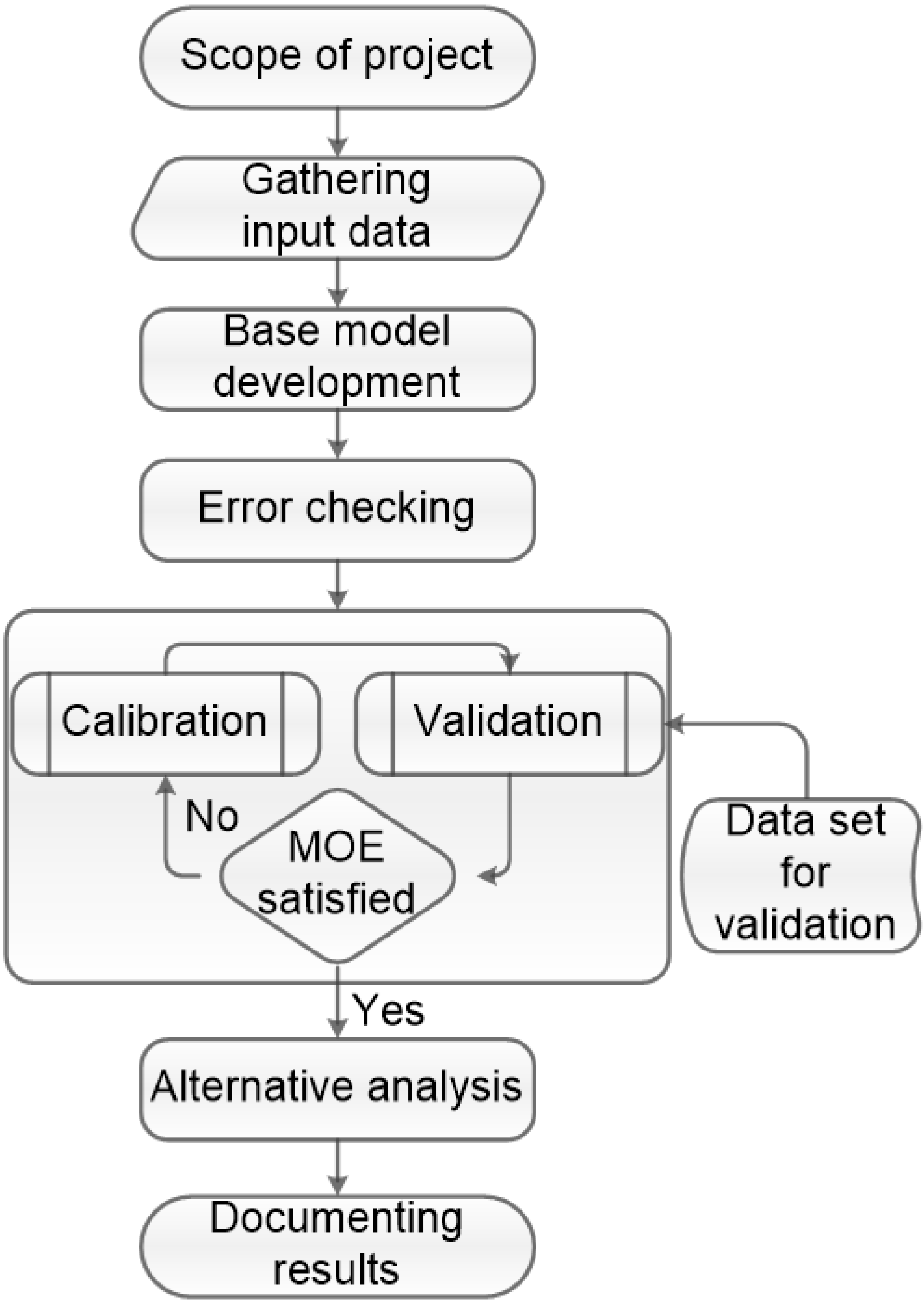


Figure 4.2.: Workflow of simulation study (based on Leonhardt, 2014))

Private traffic (PrT) in VISSIM is a mix of different vehicle classes of cars, trucks, motorbikes and bicycles. Every vehicle class has its own technical features e.g. dimensions, maximum acceleration, desired speed, maximum deceleration etc. All these parameters can be set in base data of VISSIM network and they have big impact on simulation results (Fellendorf and Vortisch 2010). Vehicles are generated randomly at defined links and they search for route individually. Route assignment can be static or dynamic for PrT, later is used in a case when it is required to model “route choice” behavior of vehicles. On the other hand, commonly used static routes, distribute traffic flow to multiple destinations by given proportion.

Modeling Traffic Control

VISSIM uses conflict areas, priority rules, and stop-signs to model un-signalised traffic control, where the user can define Right of Way (ROW). Conflict areas can be used in case of un-signalized crossing, merging and diverging (Figure 4.3b). ROW can either be decided by the user or can be set to undecided ROW e.g. in cases like diverging lanes. Conflict areas are usually preferred over priority rules as it allows more tactical driving behavior (PTV 2015b). However, priority rules come in handy when certain situations demand. An example of such situations can be to keep intersection clear from the blockage (Figure 4.3a) or to model permissive right turns at a traffic signal.

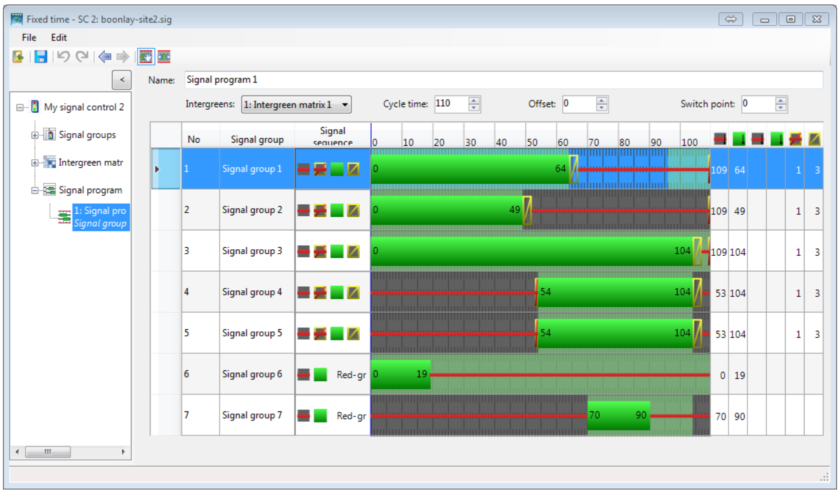
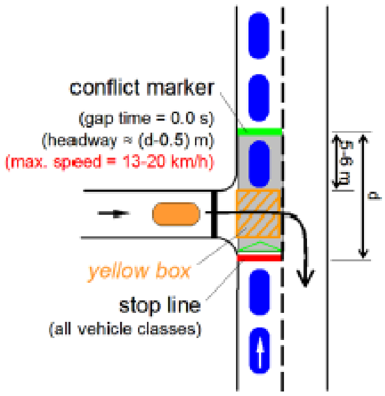
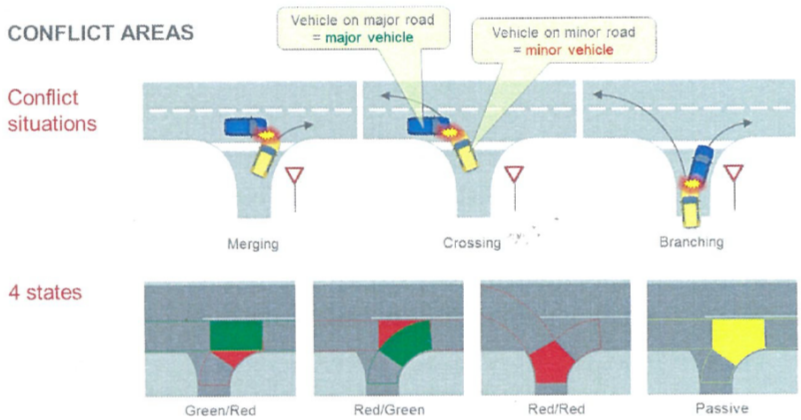


Figure 4.4.: Signal program of a fixed time traffic controller in VISSIM, Source: (PTV 2015b)

Fixed time traffic signal can be designed in VISSIM by defining signal groups in intersections, their inter-green times and green splits (Figure 4.4). Optimization of fixed time controllers is also possible by utilizing built-in algorithms of VISSIM. With additional add-on VISVAP, a programming tool, the user can design traffic-actuated signals using data from detectors during simulation. VISSIM also provides support for famous third-party traffic adaptive controllers such as SCATS, SCOOT,



(a) Priority rules



(b) Conflict areas

Figure 4.3.: Conflict modeling at un-signalized intersection

and Siemens VA and so on.

4.1.3. Simulation and Evaluation

VISSIM can simulate the model in both 2D and 3D modes. While 3D is used for presentation purpose, 2D simulation is enough to visualize all the operations and collect required data. For evaluation of the model, travel time measurement, queue length, and vehicle counters can be used to generate an output at predefined points. Moreover, node and link evaluation can be used to collect data like vehicle delays, average speed etc. VISSIM stores all outputs in its result lists and provides aggregated results with basic statistical analysis. Alternatively, these results can be exported as a database for further analysis.

4.2. Limitation of the Software License

1. **Network Size**: The maximum allowed network in the license was of 10 km X 10 km.
2. **Pedestrian Modeling**: It was not allowed to model pedestrian flow.
3. **Signal Controllers**: The maximum of ten signal controllers were allowed to be used.

4.3. Assumptions

- All the vehicles from every zone started to depart at the same time, as explained in section 2.5.5. High preparation time of inland areas and more time required to make a decision in inland areas, lead to similar departure time from home.
- Vehicles were assumed to take the shortest path to the nearest main highway (with one exception as explained in section 5.5, vehicle were rerouted from few zones in Kenner and Metairie.
- Since the traffic signal module was not included in the software license, it is beyond the scope of the study to have exact cycle-time of signals. It is also assumed that during the evacuation the signals can be turned off to normal traffic priority rules to ease the outbound traffic.
- At the intersection, 5% of the cars would choose the non-evacuation route in each direction. The reason behind this is that people often run some errands, like picking up a friend, or going to the supermarket or petrol pump. But, the buses will follow only the defined evacuation route as drivers can be informed of the destinations.
- At the intersection, with two equidistant roads to the main highway, the route choice is equally distributed.
- All the vehicles entering the main network are assumed to enter with slow speed: (1) for cars: max. 30 kmph and (2) for buses: max. 25 kmph.
- The warm-up time of 600 seconds i.e. 10 minutes is used in the model, to allow it to come to the real world state.
- The maximum speed of the cars is 50 kmph and of buses is 40 kmph in the normal traffic.
- The inputs and outputs are given and recorded on an hourly basis.

- The supply of traffic infrastructure is same as in real world. Some with and lanes of the roads were modeled, same number of public transportation supply and private cars were considered for vehicular input.
- Since the scale of the modeling is mesoscopic and not microscopic, therefore the maximum number of simulations runs were at least three for the scenarios 1 and 3, and at least two for the scenario 2, mainly because of the time constraints as single simulation took on an average 3-4 hours but simulation of scenario 2 took more than 9 hours.

4.4. Approach

The defined shock (see section 3.2) was simulated in two regions (see section 3.3) of different land use structure (see section 2.7) and different modal share of transport (see section 3.3.2) to positively prove the defined hypothesis (see section 1.2.1).

5. Quantitative Analysis and Results

The evacuation was modeled in the VISSIM 7 software for both the regions as defined in study area. According to the scenarios explained in section 5.2, the traffic flow was input in the network and following evaluation results were generated:

- Data collection: to count cars and buses traveling to the desired destination, and to know when the last vehicle left the network
- Queue length: to see how long is the queue due to congestion
- Vehicle travel time: to measure the average travel time of the vehicles
- Network performance parameters: average delay time and average speed of the vehicles were collected to analyze the performance of the network.

5.1. Vehicular Input

In order to calculate the vehicular flow, different population zones were created, based upon the residence, both for Louisiana and Singapore. The population in the zones was converted to vehicular flow based on the collected data and using statistical tools. Further details, are elaborated in the respective sections 5.1.1 and 5.1.2.

5.1.1. Louisiana

In total, 16 population zones were created for the combined region of Kenner and Metairie, Louisiana (ArcGIS 2012). Seven zones, K1 to K7, fall in the Kenner and nine zones, M8 to M16, fall in Metairie as shown in figure 5.1. Table A.1 illustrates the population in every zone of the selected study area. The car riders in the modal split are assumed to be in the age group of 18 to 64. Using the data in figure 3.4 and figure 3.7, and the average car ownership data of Kenner (DataUSA 2014a), the share of people evacuating in cars and buses is shown in table B.2. The number of persons evacuating in cars and buses, and the number of cars that are used in Kenner is shown in table B.3. The same calculation results for the city of Metairie are shown in table C.4 and table C.5.

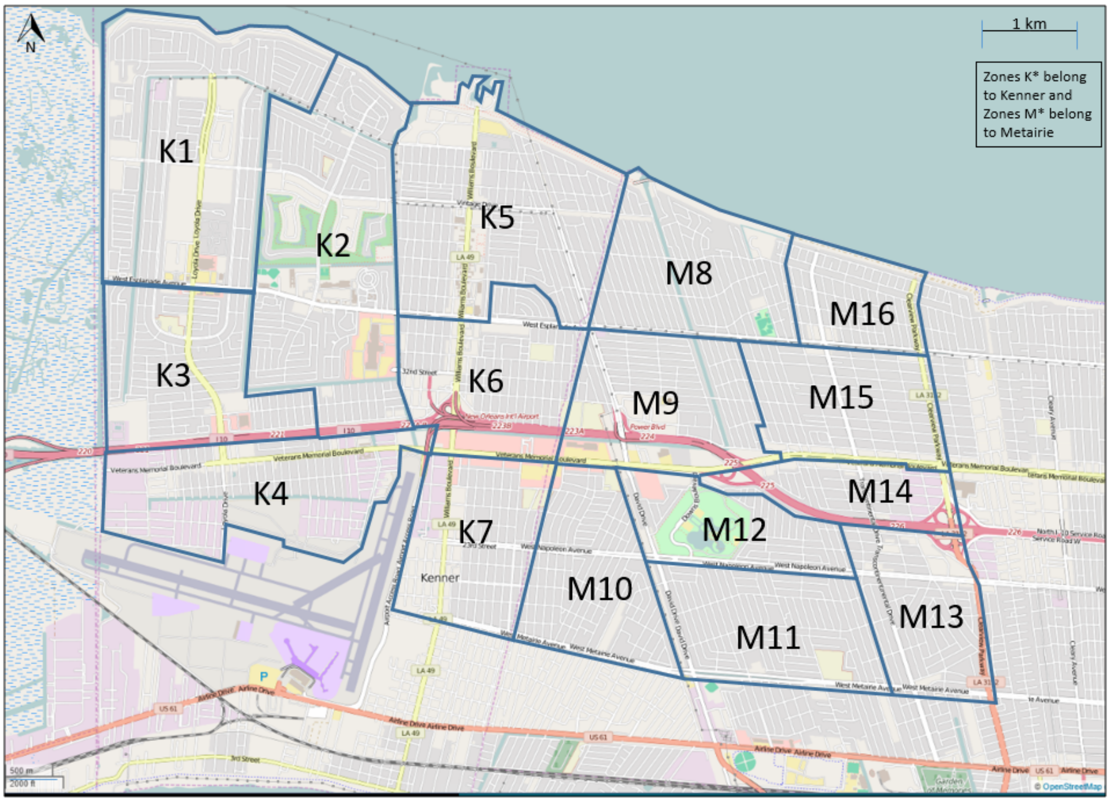


Figure 5.1.: Signal program of a fixed time traffic controller in VISSIM; Source: (ArcGIS 2012)

5.1.2. Singapore

As per the maximum allowable length of the software license, ten zones of West Singapore lies in the study area. They are shown in figure 5.2 and respective populations are shown in table D.6. Due to non-availability of the population of all zones (DOS 2015), the study zones were modified based on the coherent data and connections of zones to the roads. The population in every study zone is shown in table D.7. Similar to Louisiana the car riders in the modal split are assumed to be in the age group of 18 to 64. Using the data in figure 3.6 and figure 3.9, and the average car ownership data of Singapore (Menon and Kuang 2006), the share of people evacuating in cars and buses is shown in table E.8. The number of persons evacuating in cars and buses, and number of cars that are used in Singapore is shown in table E.9 (LTA 2015).

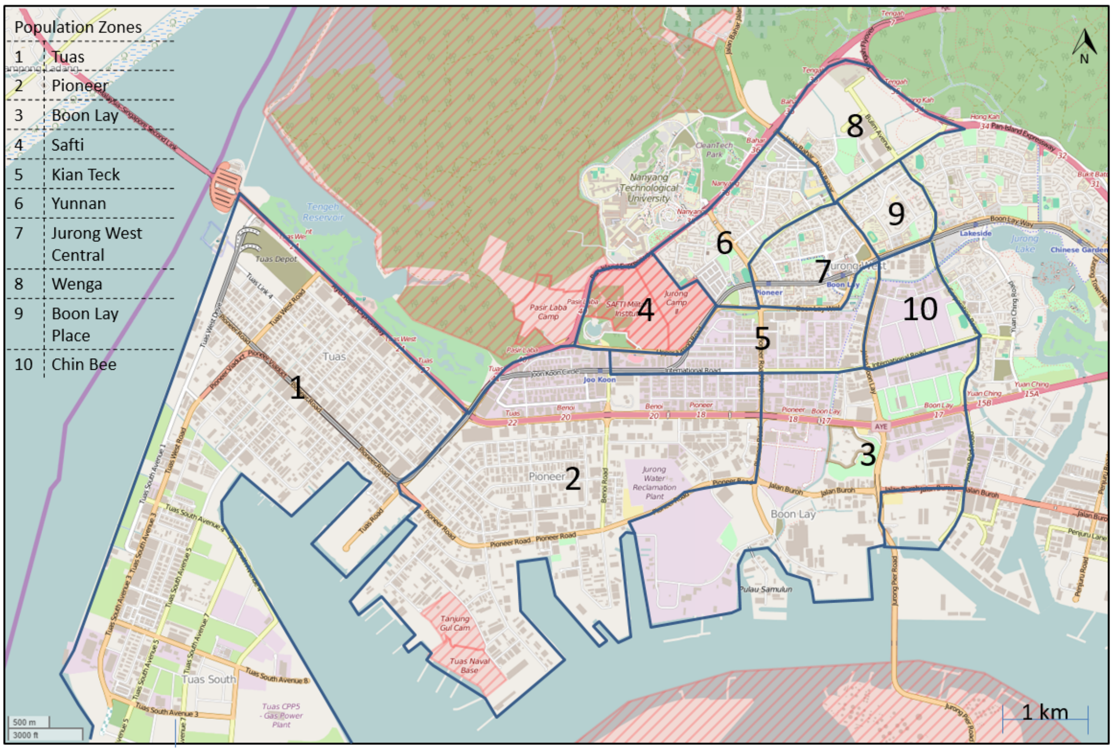


Figure 5.2.: Signal program of a fixed time traffic controller in VISSIM; Source: (URA 2010a)

5.2. Scenario Definition

The evacuation in both the study areas, region of Louisiana and Singapore, was studied under following scenarios.

5.2.1. Scenario 1

During hurricane Floyd, the warning was issued two days prior to the landfall. As mentioned in the results of the survey (Dow and Cutter 2002), 61% of the people left two days prior to the landfall. Out of which 25.4% of the people left between 9 a.m. and noon, 22.6% left between noon and 3 p.m., and the rest left on other hours of the day. It was assumed that rest of the evacuation was also carried out in the next three-hour window i.e. 3 p.m. to 6 p.m. Besides, it was assumed for the modeling that, after 6 p.m. households chose not to leave because of the issues mentioned in section 2.4.2. This leads to the total evacuation time of 9 hours on that particular day. After the 9th hour, no vehicles were added to the network.

The input flows are calculated using the ratio of evacuating cars and buses for the city of Kenner (see table: B.3) and Metairie (see tableC.5) and the population of each zone(see tableA.1). Since the number of persons evacuating two days prior are 61%, this day's vehicular flow is inserted into the network (values are shown in table F.10). Table 5.1 shows the input flow of cars and buses per hour.

Table 5.1.: Louisiana, Scenario 1, hourly vehicular flow

	9 a.m. - noon			**noon - 3 p.m.**			**3 p.m. - 6 p.m.**		
Zones	**Cars**	**Buses**	**Veh inp**	**Cars**	**Buses**	**Veh inp**	**Cars**	**Buses**	**Veh inp**
K1	304	1	305	270	1	271	156	1	157
K2	393	1	394	349	1	350	201	1	202
K3	253	1	254	226	1	227	130	1	131
K4	171	1	172	152	1	153	88	1	89
K5	404	1	405	359	1	360	207	1	208
K6	184	1	185	164	1	165	95	1	96
K7	142	1	143	127	1	128	73	1	74
M8	183	1	184	163	1	164	94	1	95
M9	194	1	195	173	1	174	100	1	101
M10	193	1	194	172	1	173	99	1	100
M11	194	1	195	172	1	173	99	1	100
M12	120	1	121	107	1	108	62	1	63
M13	205	1	206	182	1	183	105	1	106
M14	74	1	75	66	1	67	38	1	39
M15	189	1	190	168	1	169	97	1	98
M16	99	1	100	88	1	89	51	1	52

Using the similar approach as discussed in section 5.2.1, table 5.2 shows the vehicular flow per hour in the network of Singapore.

Table 5.2.: Singapore, Scenario 1, hourly vehicular flow

	9 a.m. - noon			noon - 3 p.m.			3 p.m. - 6 p.m.		
Zones	**Cars**	**Buses**	**veh inp**	**Cars**	**Buses**	**veh inp**	**Cars**	**Buses**	**veh inp**
Boon Lay	1	1	2	1	1	2	1	1	2
Pioneer	1	1	2	1	1	2	1	1	2
Tuas	1	1	2	1	1	2	1	1	2
Boon Lay Place_1	110	10	120	98	9	107	57	5	62
Boon Lay Place_2	110	10	120	98	9	107	57	5	62
Jurong West Central_1	240	21	261	214	19	233	123	11	134
Jurong West Central_2	240	21	261	214	19	233	123	11	134
Kian Teck	1	1	2	1	1	2	1	1	2
Wenya_1	31	3	34	27	3	30	16	2	18
Wenya_2	31	3	34	27	3	30	16	2	18
Yunnan_1	125	11	136	111	10	121	64	6	70
Yunnan_2	125	11	136	111	10	121	64	6	70
Yunnan_3	125	11	136	111	10	121	64	6	70
Yunnan_4	125	11	136	111	10	121	64	6	70

Since the evacuation duration is of nine hours irrespective of any fixed time, it do not necessitate that the VISSIM model is only applicable from the 9 a.m. to 6 p.m. time window; it is the same as 10 a.m. to 7 p.m. time window or so on.

5.2.2. Scenario 2

The second scenario aimed to check the network performance if the warning is given only one day prior to the landfall and the whole population has to evacuate on the same day. Since it is a single day evacuation, the vehicular input was calculated for twelve hours for both the study areas. The proportion of vehicles was based on the result of Hurricane Floyd survey (Dow and Cutter 2002). The additional three-hour window, between 6 a.m. to 9 a.m was added. As mentioned earlier in section 5.2.1, the 12-hour window is independent of real clock time.

The vehicular input calculations are similar to the scenario 1, but for the whole population and period of 12 hours. The vehicular input data of Louisiana and Singapore are shown in table 5.3 and table 5.4.

Table 5.3.: Louisiana, Scenario 2, hourly vehicular flow

	6 a.m. - 9 a.m. & 3 p.m. to 6 p.m.			9 a.m. - noon			noon - 3 p.m.		
Zones	**Cars**	**Buses**	**Veh inp**	**Cars**	**Buses**	**Veh inp**	**Cars**	**Buses**	**Veh inp**
K1	402	1	403	612	2	614	545	1	546
K2	519	1	520	791	2	793	704	2	706
K3	335	1	336	511	1	512	454	1	455
K4	226	1	227	345	1	346	307	1	308
K5	533	1	534	813	2	815	724	2	726
K6	243	1	244	371	1	372	330	1	331
K7	188	1	189	287	1	288	255	1	256
M8	242	1	243	369	1	370	328	1	329
M9	257	1	258	391	1	392	348	1	349
M10	255	1	256	388	1	389	346	1	347
M11	256	1	257	390	1	391	347	1	348
M12	158	1	159	241	1	242	214	1	215
M13	271	1	272	413	1	414	367	1	368
M14	98	1	99	148	1	149	132	1	133
M15	249	1	250	380	1	381	338	1	339
M16	131	1	132	200	1	201	178	1	179

Table 5.4.: Singapore, Scenario 2, hourly vehicular flow

	6 a.m. - 9 a.m. & 3 p.m. to 6 p.m.			9 a.m. - noon			noon - 3 p.m.		
Zones	**Cars**	**Buses**	**Veh inp**	**Cars**	**Buses**	**Veh inp**	**Cars**	**Buses**	**Veh inp**
Boon Lay	1	1	2	1	1	2	1	1	2
Pioneer	1	1	2	2	1	3	2	1	3
Tuas	1	1	2	1	1	2	1	1	2
Boon Lay Place_1	145	13	158	221	19	240	197	17	214
Boon Lay Place_2	145	13	158	221	19	240	197	17	214
Jurong West Central_1	318	27	345	484	42	526	431	37	468
Jurong West Central_2	318	27	345	484	42	526	431	37	468
Kian Teck	1	1	2	1	1	2	1	1	2
Wenya_1	41	4	45	62	6	68	55	5	60
Wenya_2	41	4	45	62	6	68	55	5	60
Yunnan_1	165	15	180	252	22	274	224	20	244
Yunnan_2	165	15	180	252	22	274	224	20	244
Yunnan_3	165	15	180	252	22	274	224	20	244
Yunnan_4	165	15	180	252	22	274	224	20	244

5.2.3. Scenario 3

Scenario 3 is a theoretical scenario which assumes that the modal split of the study area in Louisiana is the same as the modal split of the Singapore. The evacuation is carried out in one day. The procedure to calculate the vehicular input is the same as defined in scenario 1 (see section 5.2.1). The evacuation period is assumed to be of 12 hours as in scenario 2 (see section 5.2.2). Table 5.5 shows the vehicular input for this scenario.

Table 5.5.: Louisiana, Scenario 3, hourly vehicular flow

	6 a.m. - 9 a.m. & 3 p.m. to 6 p.m.			**9 a.m. - noon**			**noon - 3 p.m.**		
Zones	**Cars**	**Buses**	**veh inp**	**Cars**	**Buses**	**veh inp**	**Cars**	**Buses**	**veh inp**
K1	95	8	103	144	13	157	128	11	139
K2	122	11	133	186	16	202	165	15	180
K3	79	7	86	120	11	131	107	10	117
K4	53	5	58	81	7	88	72	7	79
K5	125	11	136	191	17	208	170	15	185
K6	57	5	62	87	8	95	78	7	85
K7	44	4	48	68	6	74	60	6	66
M8	59	5	64	90	8	98	80	7	87
M9	63	6	69	95	9	104	85	8	93
M10	62	6	68	95	9	104	84	8	92
M11	62	6	68	95	9	104	85	8	93
M12	39	4	43	59	5	64	52	5	57
M13	66	6	72	101	9	110	90	8	98
M14	24	3	27	36	4	40	32	3	35
M15	61	6	67	93	8	101	83	7	90
M16	32	3	35	49	5	54	44	4	48

5.2.4. VISSIM Models

It is difficult to show the detailed VISSIM model (with conflict points, vehicle input points, routing decisions,etc.) on an A3 page size. However, a network model for respective study areas with following information is created:

- main links/roads
- vehicle input links
- location of queue counters
- location vehicle counters or data collection points
- location of speed and travel time measurement counters

The VISSIM model for Louisiana is shown in figure 5.3 and for Singapore is shown in figure 5.4.

The location where data collection is shown, is assumed to be the desired exit point or *destination link*. All the vehicles would exit the respective study zones from this location.

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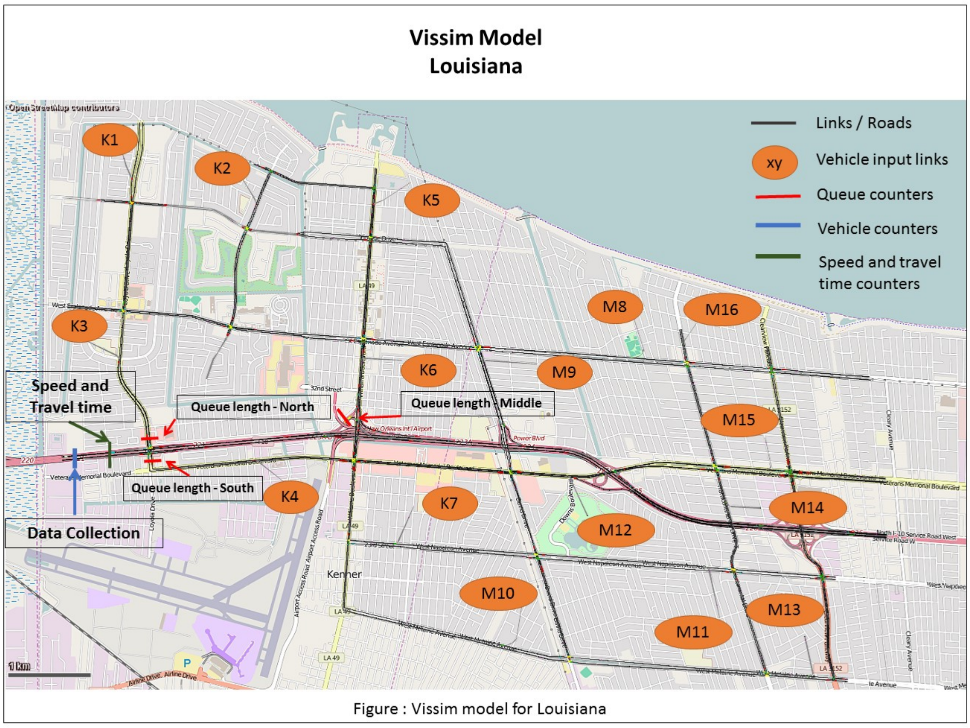

Figure 5.3.: Vissim Model for Louisiana

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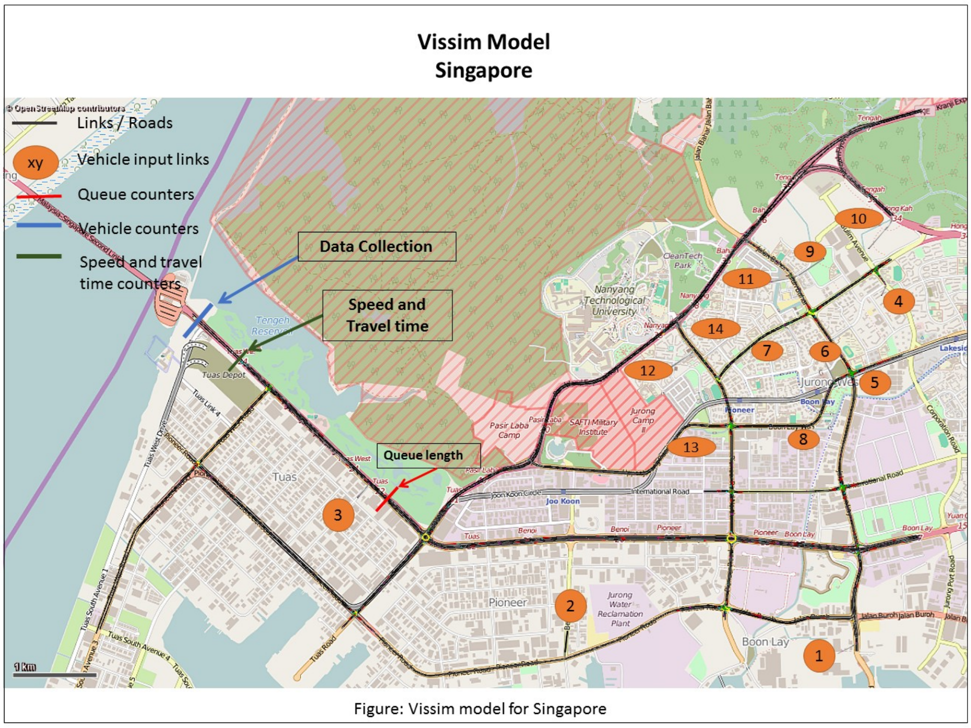

Figure 5.4.: Vissim Model for Singapore

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5.3. Scenario 1 Results

The vehicular input for scenario 1 is discussed in section 5.2.1. Based on this input VISSIM model has generated the following results. The model has been created with the aim to replicate the existing transport infrastructure, for all the major roads. The simulations are run several times to check for inconsistencies. The microscopic travel characteristics are defined in chapter 4.

5.3.1. Data Collection

The data collection results inform about the time when the last vehicle left the system, and also count the number of vehicles. As mentioned in section 5.2.1, the vehicles entered the network for 9 hours (9 a.m. to 6 p.m.) and it can easily be seen in figure 5.5 that the last vehicle that left Louisiana study area at the 13th hour and the 11th hour in Singapore. Although the length of the study area is same for both cases, i.e. 10 km; and the maximum direct distance from the main highway in Louisiana is 2.87 km and 4.07 km in Singapore.

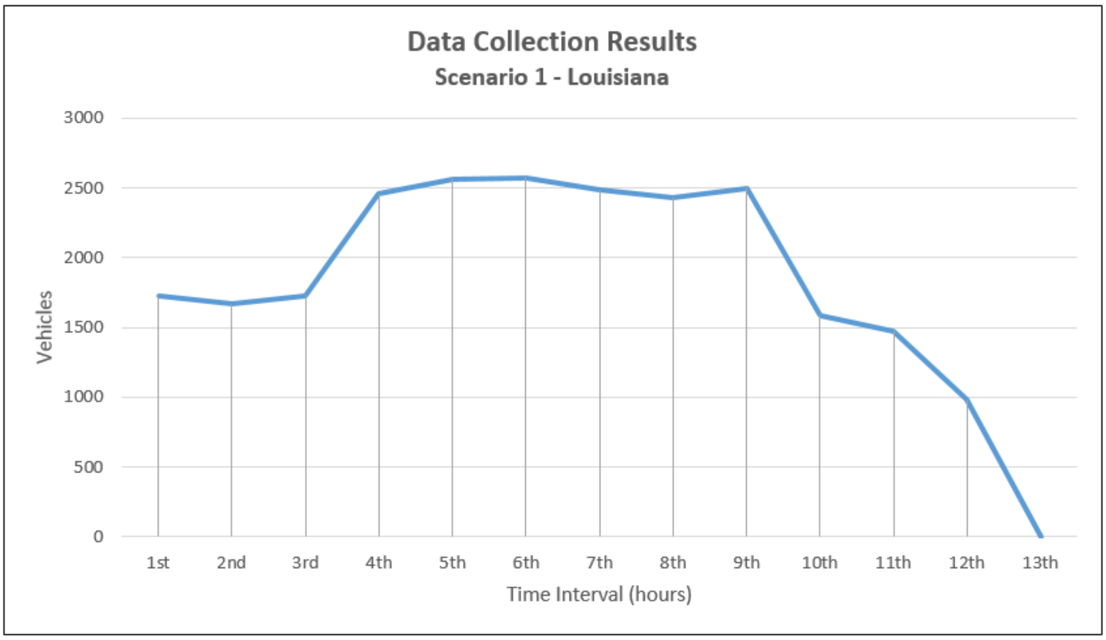

Figure 5.5.: Data collection results- Louisiana

The last vehicle left the system within 4 hours after the last vehicle entered in Louisiana (see figure: 5.5) and the last vehicle left the system within 2 hours after the last vehicle entered the system in Singapore (see figure: 5.6).

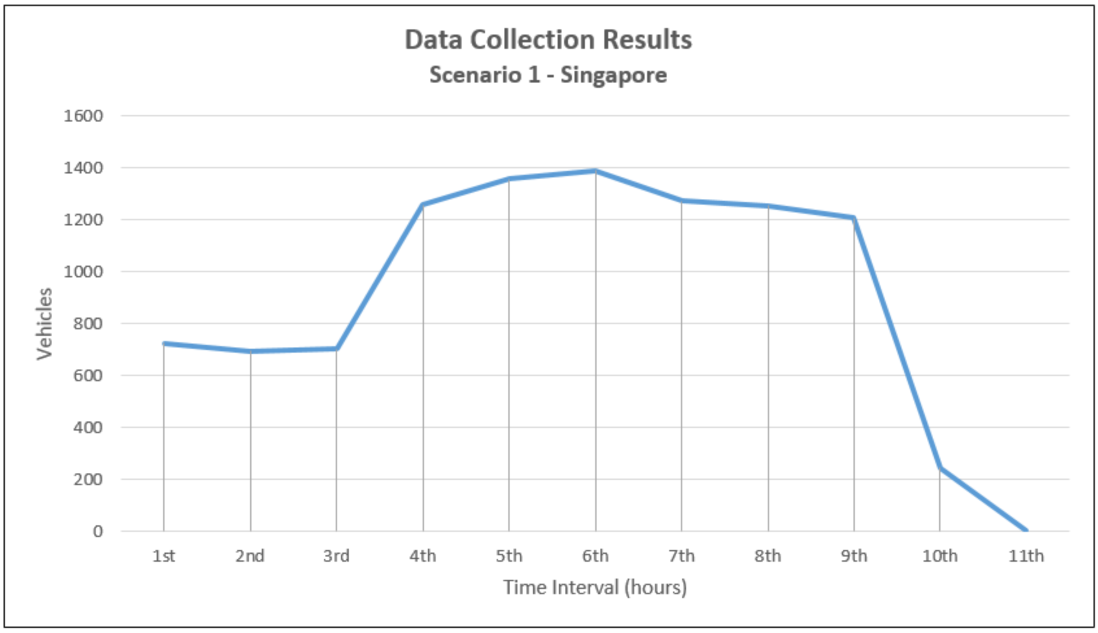

Figure 5.6.: Data collection results- Singapore

5.3.2. Queue Length Results

A significant number of vehicles were stuck in congestion and that led to the long queue length. The longest queue with 4709 meters was observed at the 10th hour, at the ‘North’ queue counter (see figure 5.7) and of 3632 meters at the 7th hour at the ‘South’ queue counter (see figure 5.8). The position of ‘North’ and ‘South’ queue counter is shown in figure 5.3. At the 13th hour, there is no vehicle in the network and hence the queue length is *zero*.

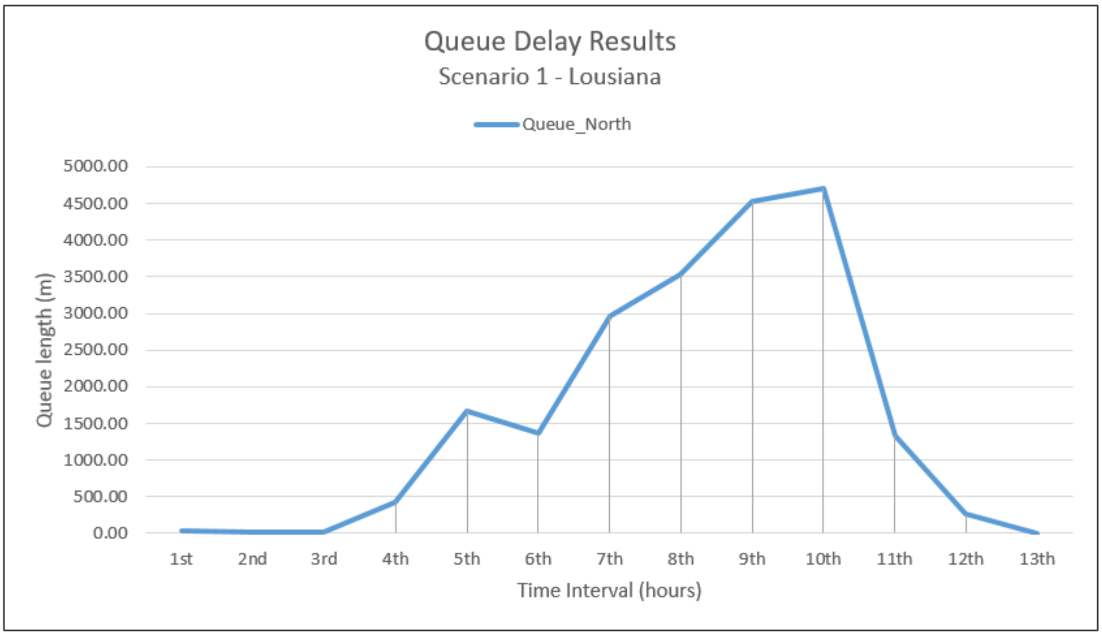

Figure 5.7.: Queue length result (North)- Louisiana

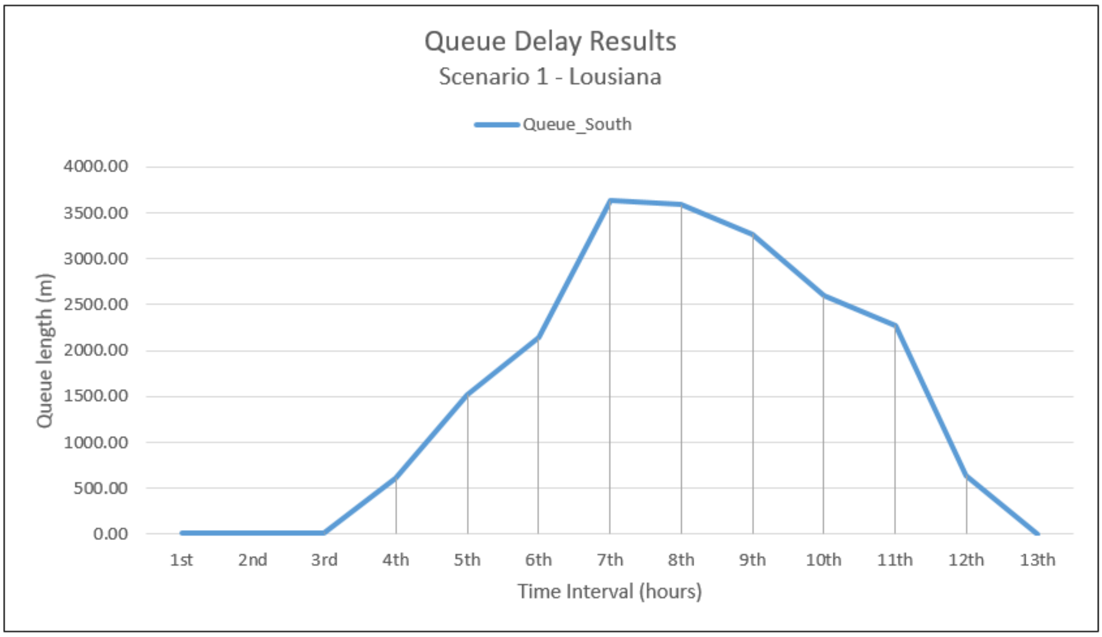

Figure 5.8.: Queue length result (South)- Louisiana

In the case of Singapore, no congestion was seen under scenario 1.

5.3.3. Vehicle Travel Time Results

The vehicle travel time results with respect to population zones (as shown in figure 5.1) for Kenner and Metairie are depicted in figures 5.9 and 5.10.

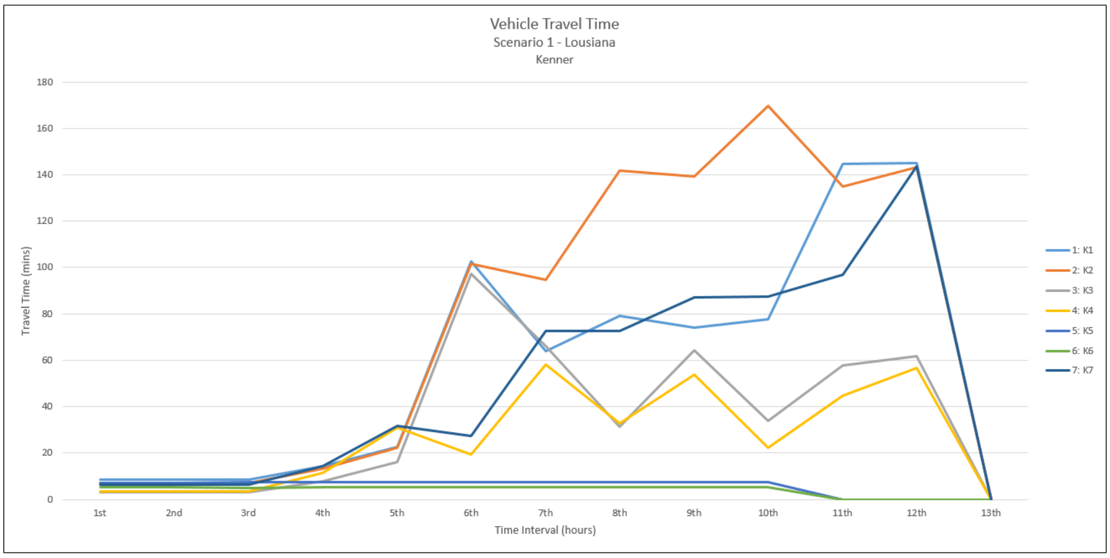

Figure 5.9.: Vehicle travel time results - Kenner, Louisiana

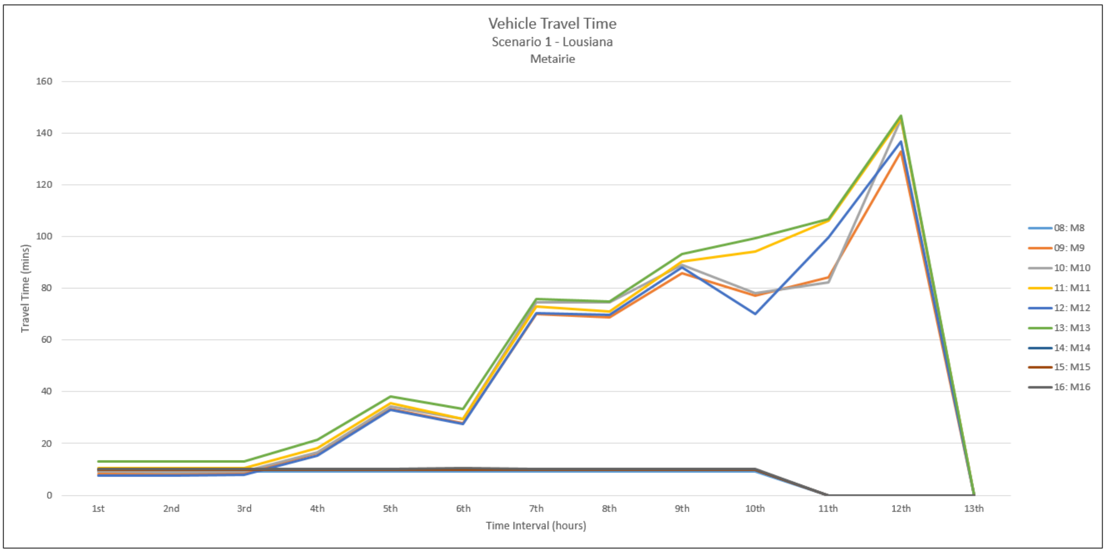

Figure 5.10.: Vehicle travel time results - Metairie, Louisiana

It can be easily observed that the vehicle travel times are increasing with time because of the observed queue lengths. It is also interesting to see that the vehi-

cles that are entering the main highway from the nearby links have much less and constant travel time. The main reason is the unrestricted and un-signalized smooth traffic flow. At the 13th hour, since the last vehicle is out of the network, hence the vehicle travel time is *zero*.
Vehicle travel times in case of Singapore, as shown in figure 5.11, are comparatively constant, mainly because of the smooth flow of traffic and no observed congestion. Zones closer to the main highway and destination link (see figure 5.2)have less vehicle travel time and it increases as the distance from the destination link increases.

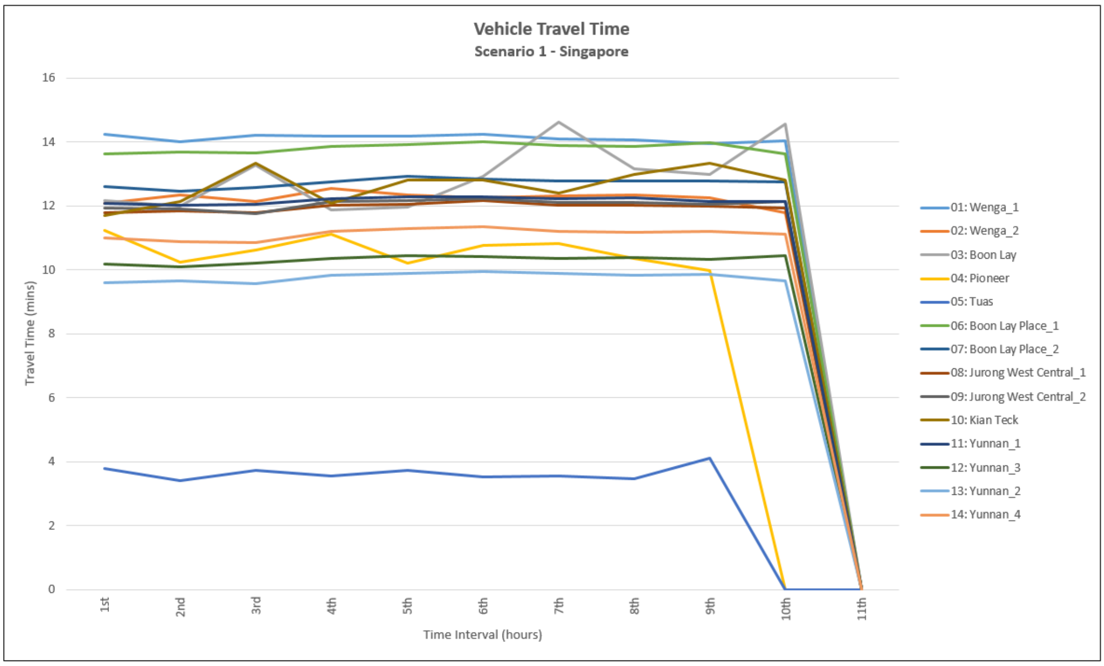

Figure 5.11.: Vehicle travel time results - Singapore

5.3.4. Network Performance Results

The performance of the network is measured in terms of the following:

- Average delay time (per vehicle)
- Average speed (per vehicle)

Average Delay Time

The average delay time variation per vehicle for Louisiana, shown in figure 5.12. IT has the maximum average delay of 39.04 mins observed at the 10th hour. At 13th hour there is no vehicle in the network; hence the delay is *zero*.

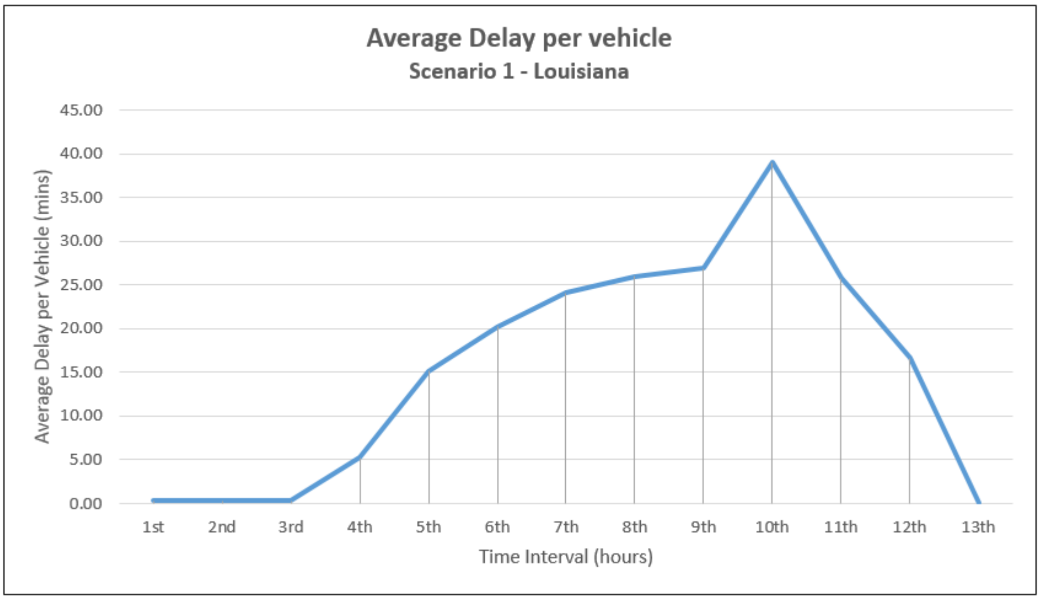

Figure 5.12.: Average delay time - Louisiana

The average delay time variation per vehicle for Singapore, shown in figure 5.13. It has the maximum average delay of 24 seconds observed at the 6th hour. With average delay per vehicle less than one minute, the performance was significantly good. At the 11th hour there is no vehicle in the network, hence the delay is *zero.*

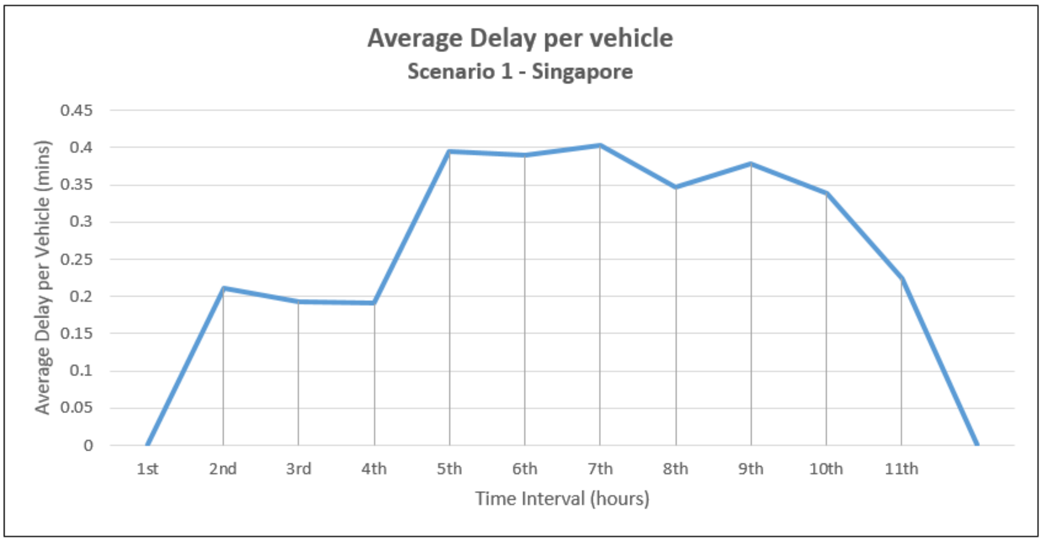

Figure 5.13.: Average delay time - Singapore

Average Speed

The reducing or negative trend of average speed per vehicle in Louisiana is shown in figure 5.14. It is clearly understood that the congestion has resulted in the reduced average speed with time. At the 13th hour, there is no vehicle in the network and hence the speed is *zero*.

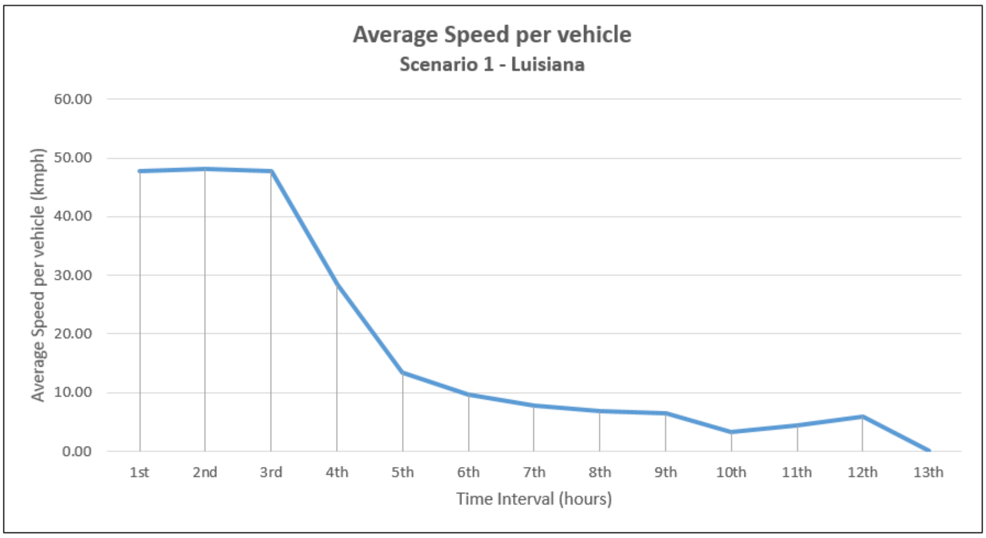

Figure 5.14.: Average speed - Louisiana

It is clear that the average speed per vehicle, as shown in figure 5.15, is constant because of no observed congestions. At the 11th hour, there is no vehicle in the network and hence the speed is *zero*.

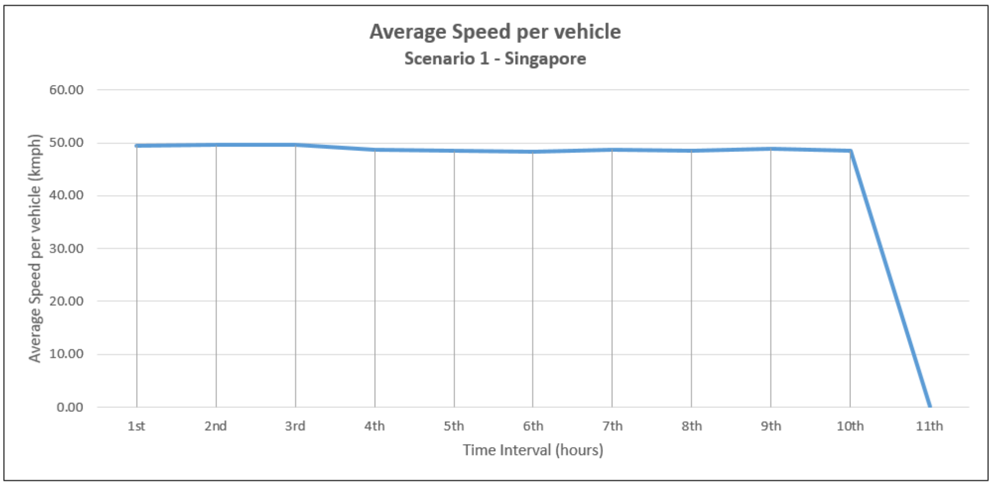

Figure 5.15.: Average speed - Singapore

5.4. Scenario 2 Results

5.4.1. Data Collection

As mentioned in section 5.2.2, the vehicles entered the network for 12 hours (6 a.m. to 6 p.m.) and it can easily be seen in figure 5.16 that the last vehicle could not leave the network even at the 28th hour or 100,000 seconds (the maximum simulation time in VISSIM 7).

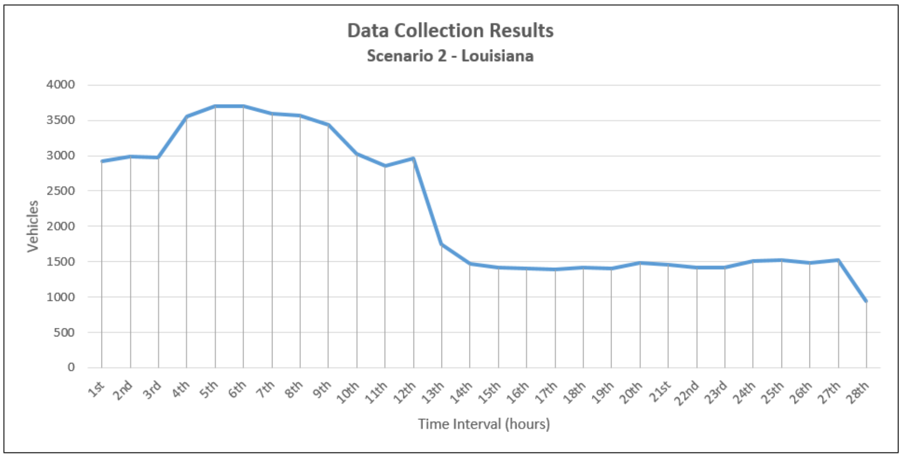

Figure 5.16.: Data collection results- Louisiana

However, the last vehicle left the Singapore network at the 14th hour, as shown in figure 5.17, i.e. two hours after the last input vehicle.

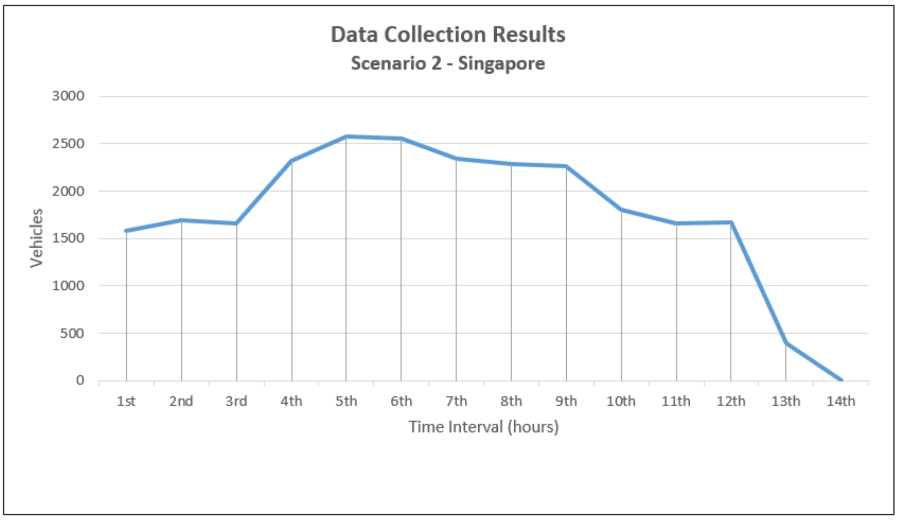

Figure 5.17.: Data collection results- Singapore

5.4.2. Queue Length Results

A significant number of vehicles were stuck in congestion and that led to the long queue length of approximately 5000 meters at the 'North' queue counter (see figure 5.18). While, from 5th to 23rd hour it was constant which means that the traffic came to standstill and reached highest vehicle density. The condition of the 'South' queue counter (see figure 5.19) was worse compared to 'North' queue counter, the same with maximum queue length reaching up to 12204 meters. The position of 'North' and 'South' queue counter is shown in figure 5.3.

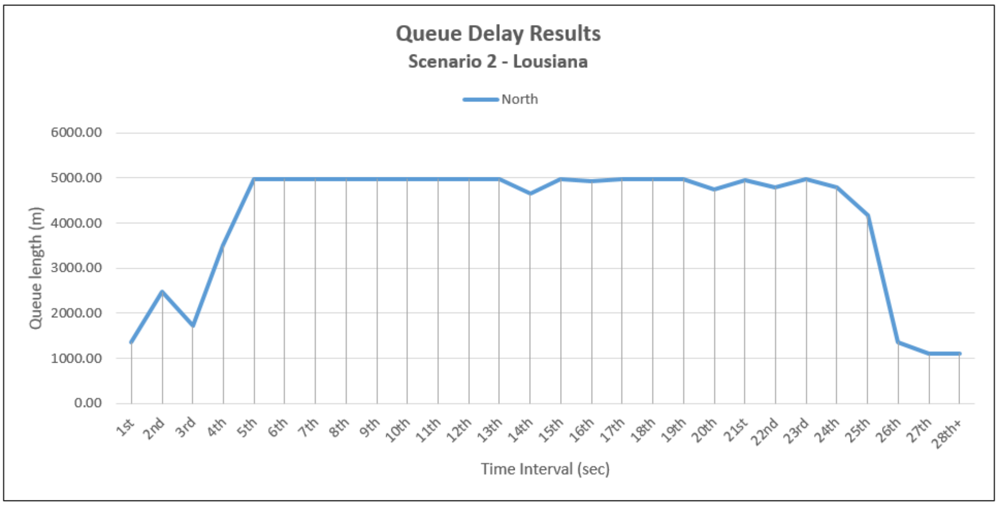

Figure 5.18.: Queue length result (North)- Louisiana

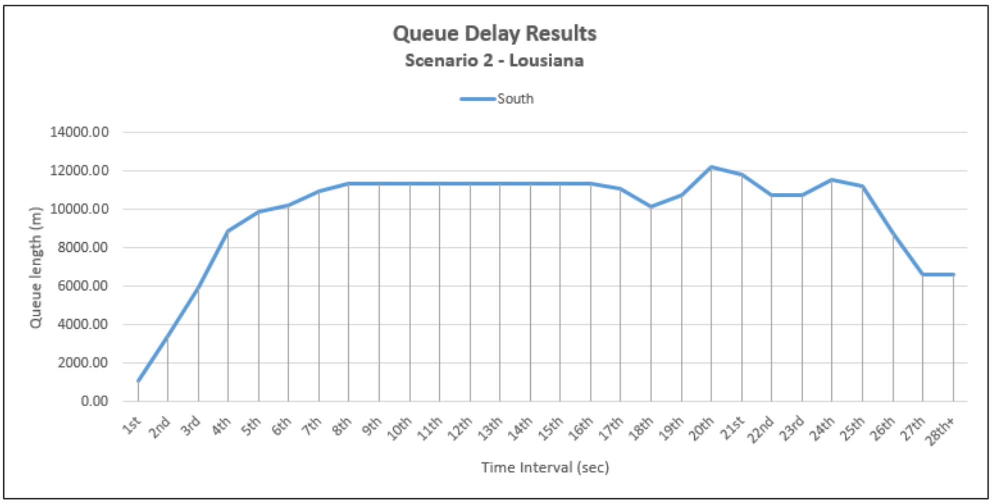

Figure 5.19.: Queue length result (South)- Louisiana

No significant congestion was observed in Singapore, also evident from the figure 5.20, where maximum queue length is 0.23 meter and the location of the queue counter is shown in figure 5.4.

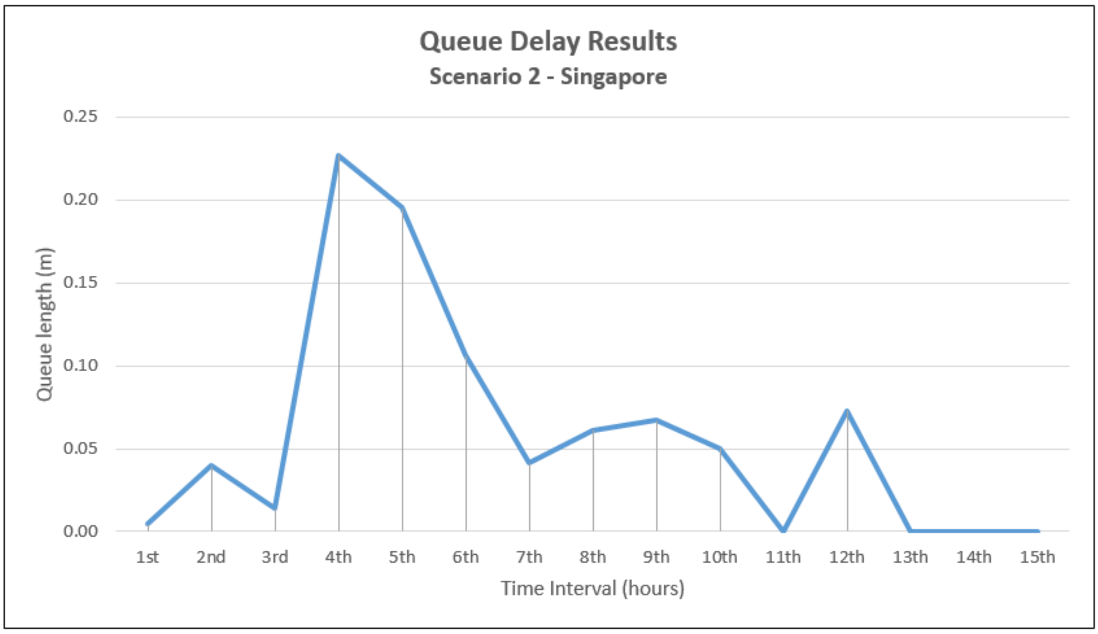

Figure 5.20.: Queue length result - Singapore

5.4.3. Vehicle Travel Time Results

The results of the vehicle travel times are the most interesting. With reference to the figure 5.21 of the results of Kenner, it can be noticed that for several zones and at many points the travel time drops to zero and rises again. The zero travel time point signifies the case when no vehicle can enter the main network because of the complete jam and stand still traffic. Hence the vehicle never reached the *speed and travel time counter* (see figure 5.3). It is also seen that few vehicles from the zone K3 were not able to exit in the maximum allowable simulation time.

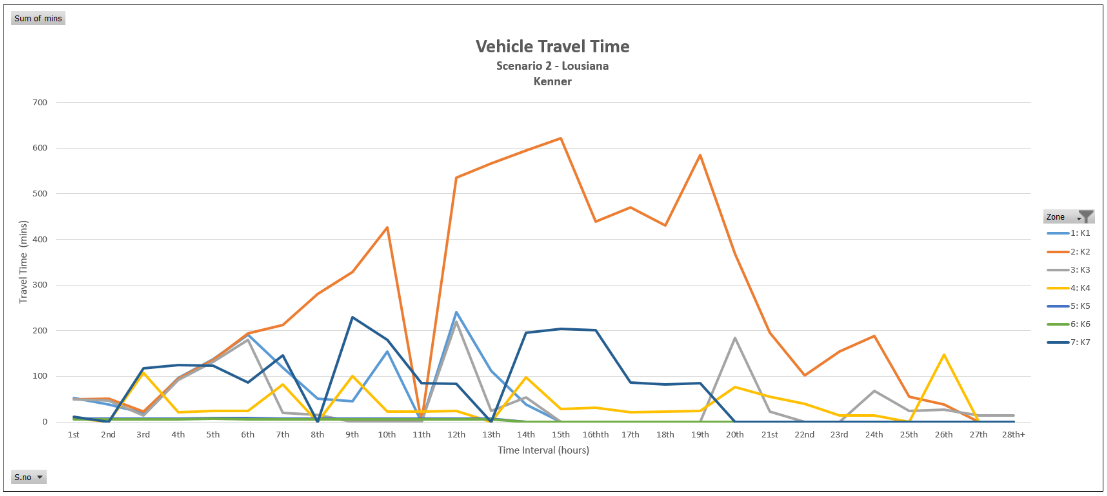

Figure 5.21.: Vehicle travel time results - Kenner, Louisiana

Similar outcomes were seen in Metairie, as shown in figure 5.22. However the last vehicle was able to exit at the 24th hours from Metairie.

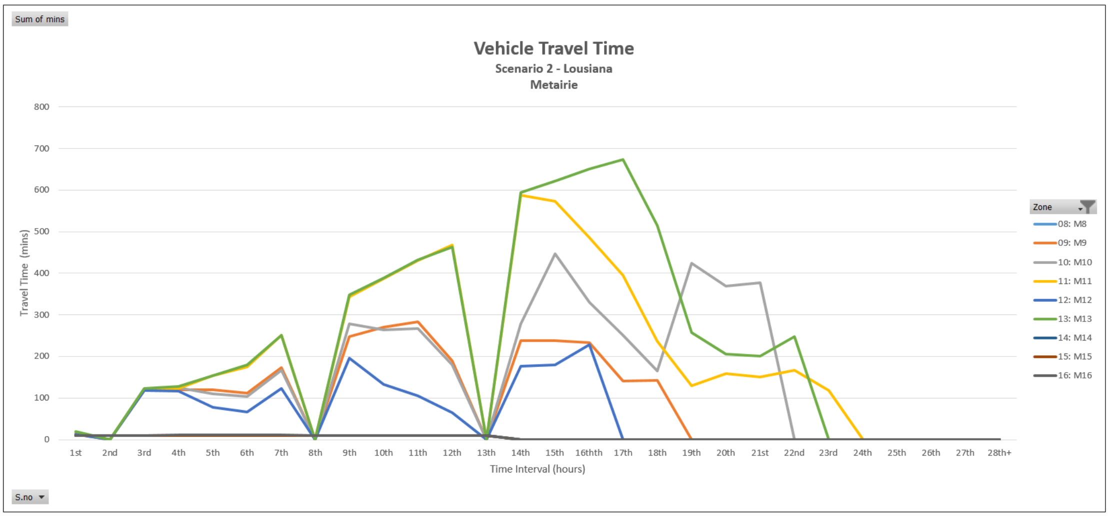

Figure 5.22.: Vehicle travel time results - Metairie, Louisiana

Similar to the scenario 1, vehicles from most of the zones reflected constant and smooth traffic flow, as shown in figure 5.23. The irregularities that were seen in the results of Pioneer and Kian Tech are because of the few number of vehicles and less number of simulation runs, which can help in averaging out these variations.

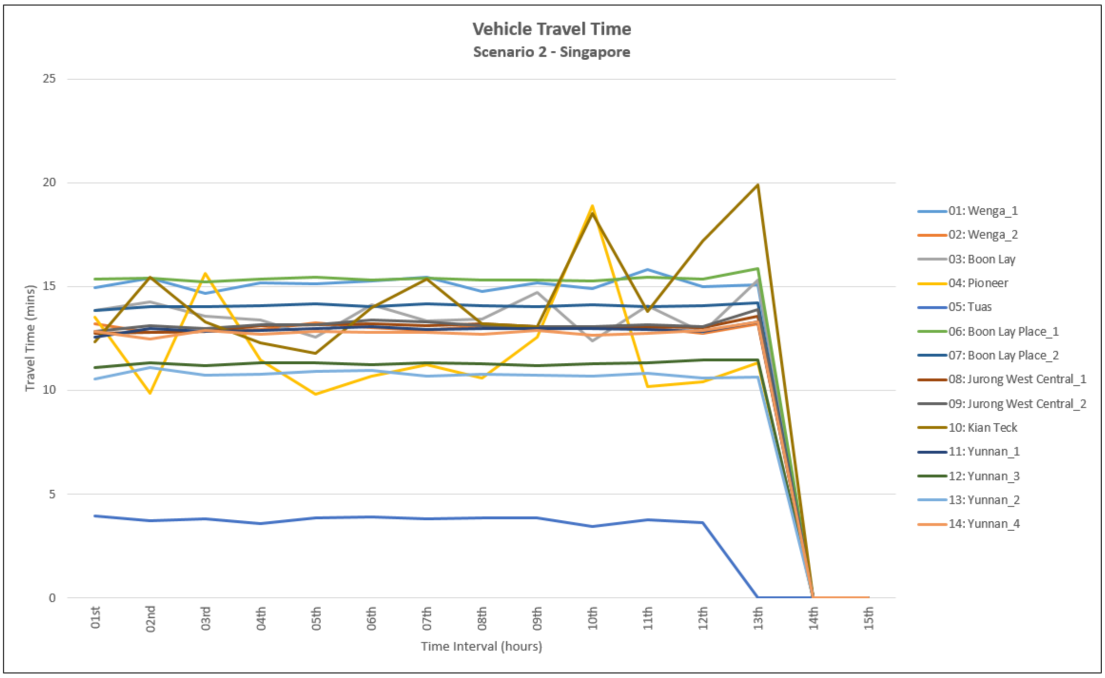

Figure 5.23.: Vehicle travel time results - Singapore

5.4.4. Network Performance Results

The performance of the network is measured in terms of the following:

- Average delay time (per vehicle)
- Average speed (per vehicle)

Average Delay Time

The average delay time variation per vehicle for Louisiana, shown in figure 5.24, has a maximum average delay of 49.74 mins observed at the 13th hour.

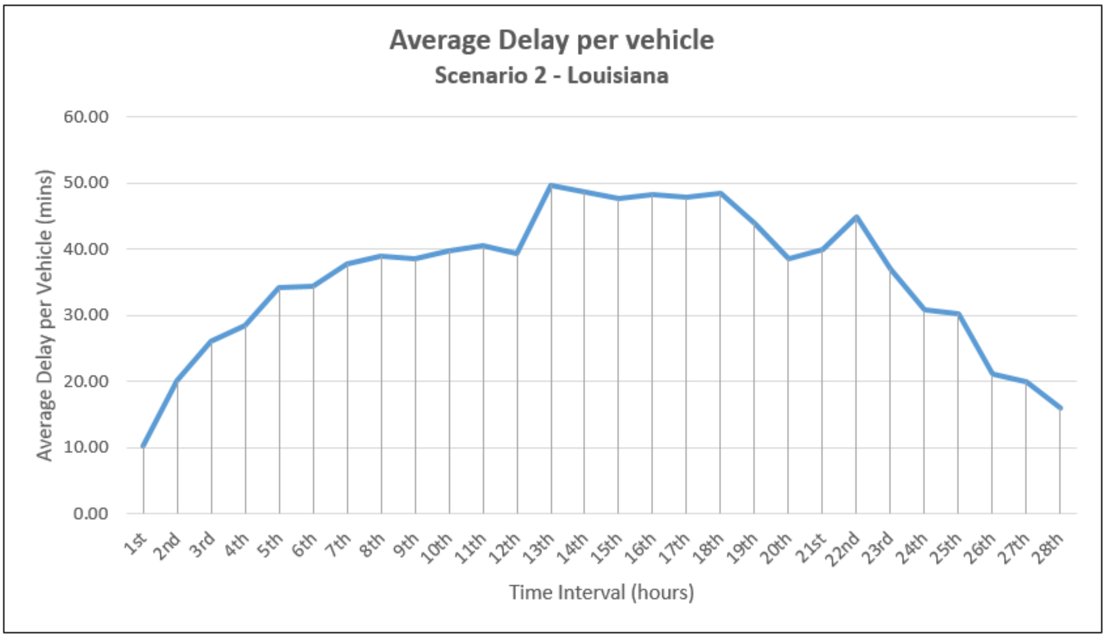

Figure 5.24.: Average delay time - Louisiana

The average delay time variation per vehicle for Singapore, shown in figure 5.25, has a maximum average delay of less than a minute. At the 15th hour there is no vehicle in the network and hence the average delay is *zero*.

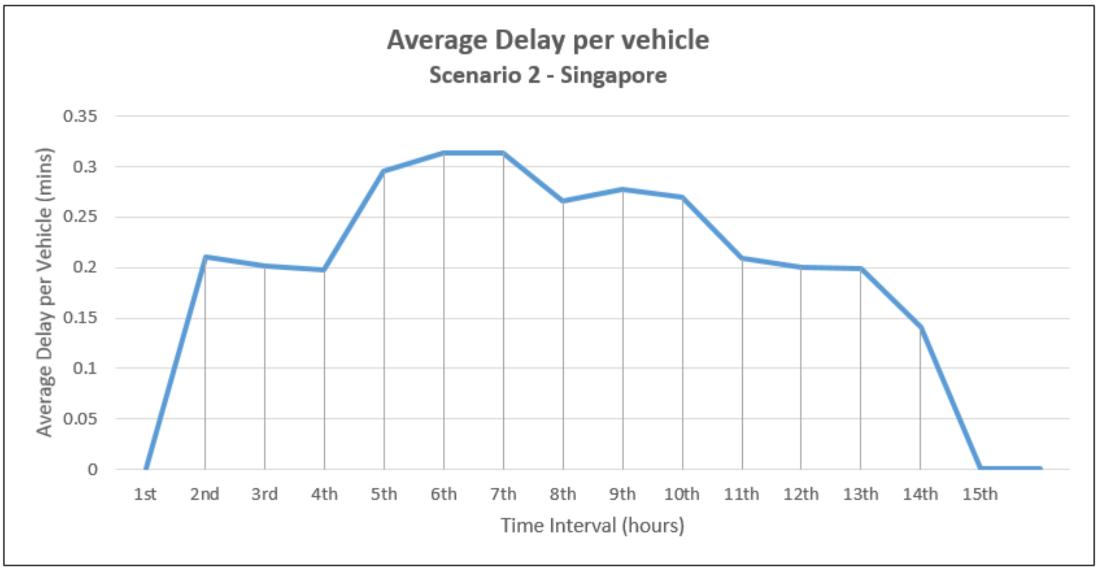

Figure 5.25.: Average delay time - Singapore

Average Speed

The negative trend of average speed per vehicle in Louisiana is shown in figure 5.26. It is clearly understood that the congestion has resulted in the reduced average speed with time. After the 13th hour, the increase in speed is due to the relief of congestion and the fact that no vehicle entered the network after the 12th hour.

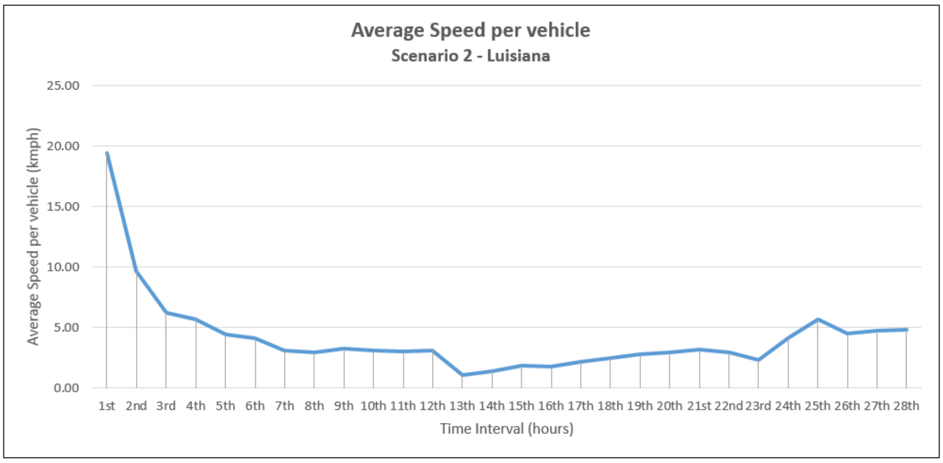

Figure 5.26.: Average speed - Louisiana

It is clear that the average speed per vehicle, as shown in figure 5.27, is constant because of no observed congestions. At 14th hour, there is no vehicle in the network and hence the speed is *zero.*

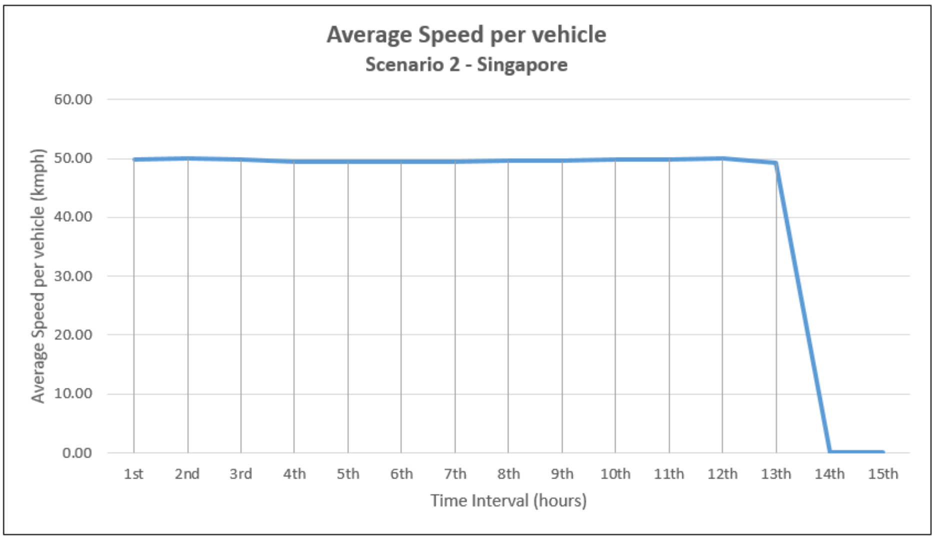

Figure 5.27.: Average speed - Singapore

5.5. Modified Scenario 2 Results

Because of long congestions in Louisiana under scenario 2, it was decided to modify the route choice in Louisiana for scenario 2 vehicle input. A contradiction to the defined assumption (see section 4.3) has been made for zones M8, M11, M13 and M16; the vehicles instead of following the shortest path had followed a little longer but a faster path and spent more time on congestion free main highway. Following results were seen as the consequence.

5.5.1. Data Collection

As mentioned in section 5.2.2, the vehicles entered the network for 12 hours (6 a.m. to 6 p.m.) and it can easily be seen in figure 5.28 that the last vehicle could now leave the network at the 21st hour.

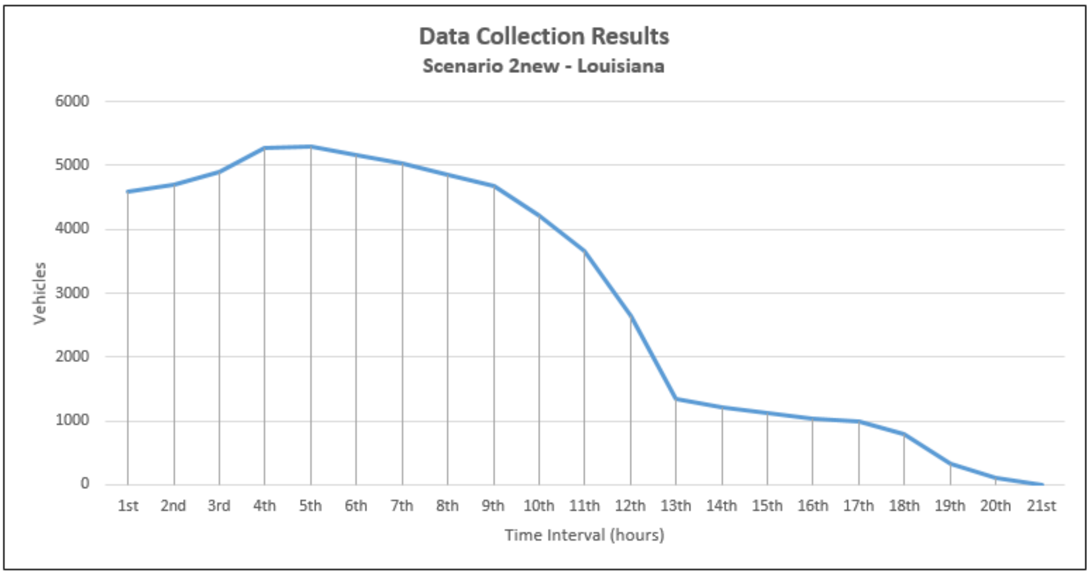

Figure 5.28.: Data collection results- Louisiana

5.5.2. Queue Length Results

A significant number of vehicles were stuck in congestion and that led to the long queue length as high as 5637 meters at the 'North' queue counter (see figure 5.29). Additionally, and because of new route assignment the queue length at 'South' queue counter (see figure 5.30) was reduced to the maximum of 7404 meters.

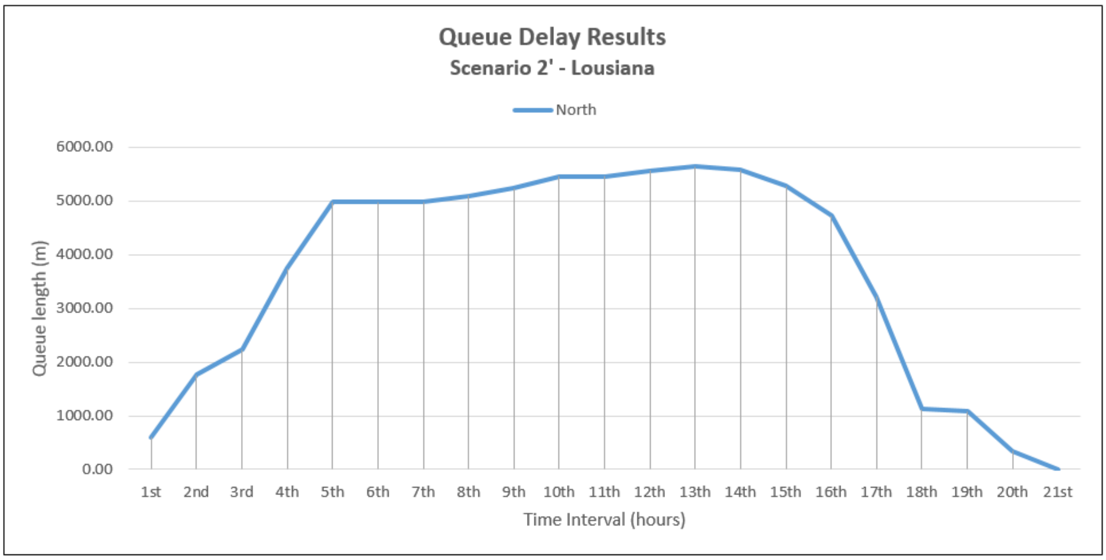

Figure 5.29.: Queue length result (North)- Louisiana

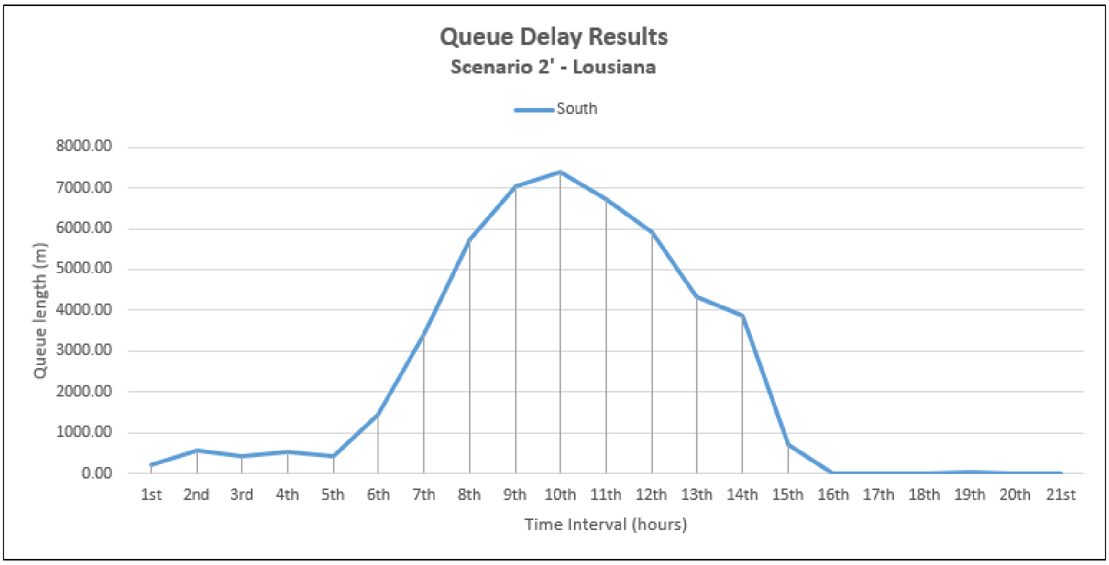

Figure 5.30.: Queue length result (South)- Louisiana

Also, a new congestion location was generated called ‘Middle’ queue counter which had a queue length of as high as 9003 meters, as shown in figure 5.31. The position of ‘North’, ‘South’ and ‘Middle’ queue counter is shown in figure 5.3.

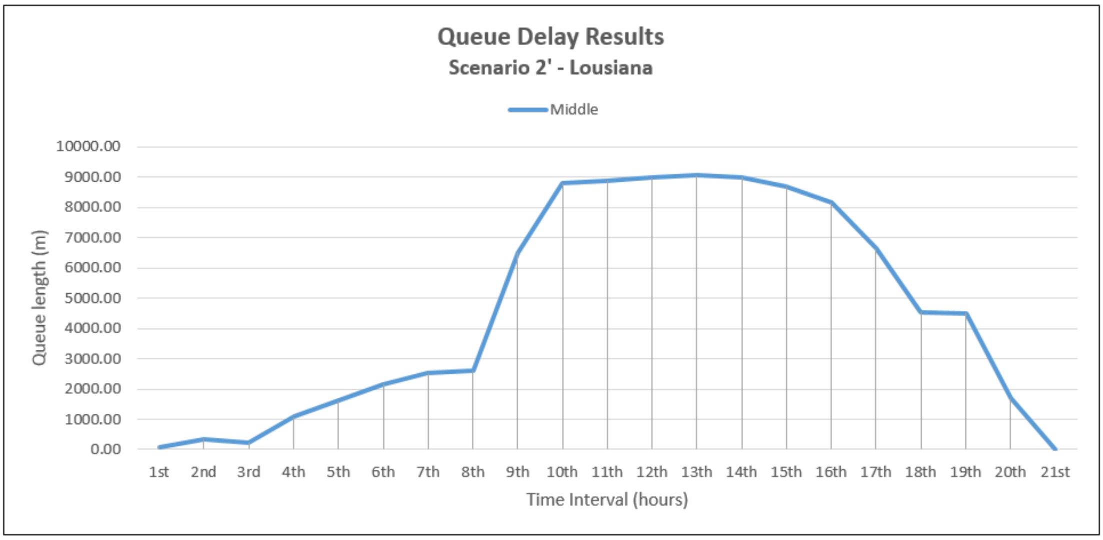

Figure 5.31.: Queue length result (Middle)- Louisiana

5.5.3. Vehicle Travel Time Results

The vehicle travel time in the modified scenario followed the same trend of increase in vehicle travel time with every passing hour. The variation is shown in figure 5.32. Since the last vehicle came out of the network at the 21st hour, the vehicle travel time reduced to *zero.*

Similar outcomes are shown by Metairie but with last vehicle exiting the network at the 18th hour as shown in figure 5.33.

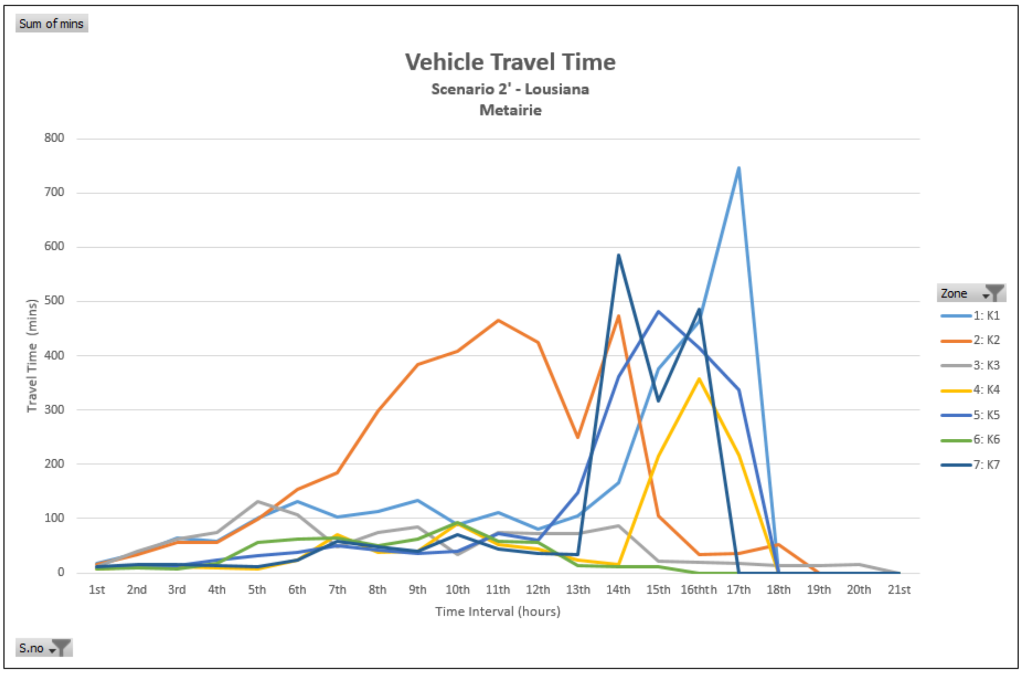

Figure 5.32.: Vehicle travel time results - Kenner, Louisiana

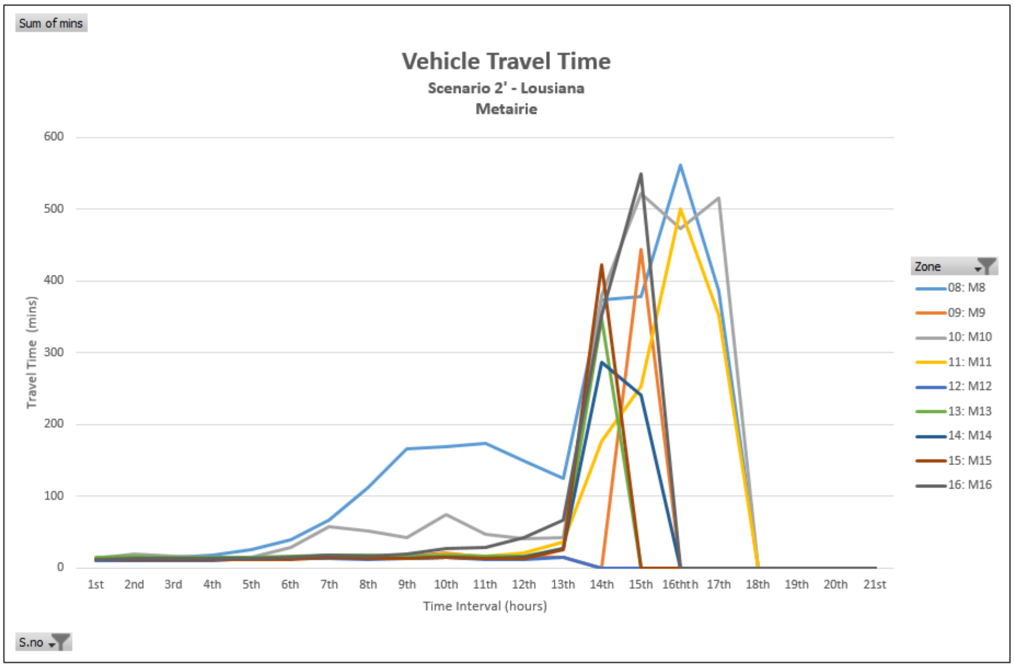

Figure 5.33.: Vehicle travel time results - Metairie, Louisiana

5.5.4. Network Performance Results

Average Delay Time

The average delay time variation per vehicle for Louisiana, shown in figure 5.34. It has a maximum average delay of 28.97 mins observed at the 10th hour. Average delay per vehicle has been significantly reduced from 49.74 mins to 30 mins.

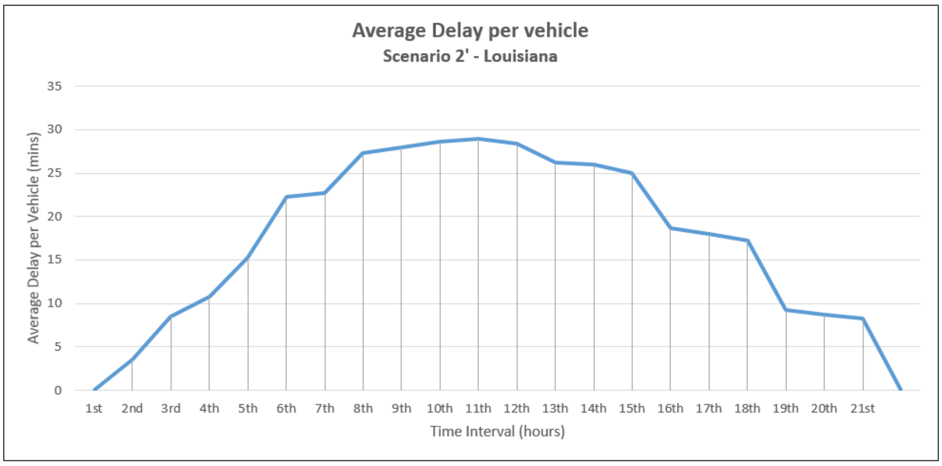

Figure 5.34.: Average delay time - Louisiana

Average Speed

As shown in figure 5.35, the average speed first decreased with increasing congestion and then started to increase as there was a relief of congestion till the 21st hour, when the last vehicle left the network.

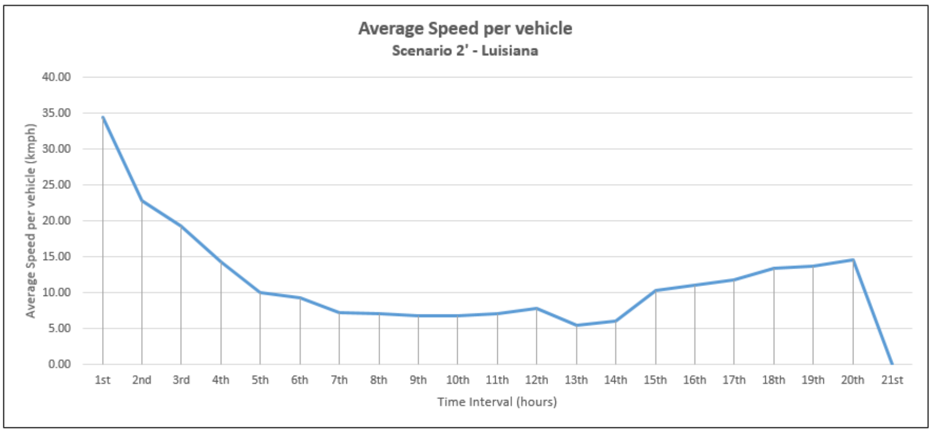

Figure 5.35.: Average speed - Louisiana

5.6. Scenario 3 Results

As already discussed in section 5.2.3, this scenario is more of a theoretical scenario where the modal split of Singapore is applied in Louisiana.

5.6.1. Data Collection

It is interesting to observe that with new modal share, all the residents can evacuate in one day within 14 hours, as shown in figure 5.36. The vehicle input is given for 12 hours. The volume of vehicles is reduced because of higher capacities of buses to take more people, hence reducing the number of evacuating cars.

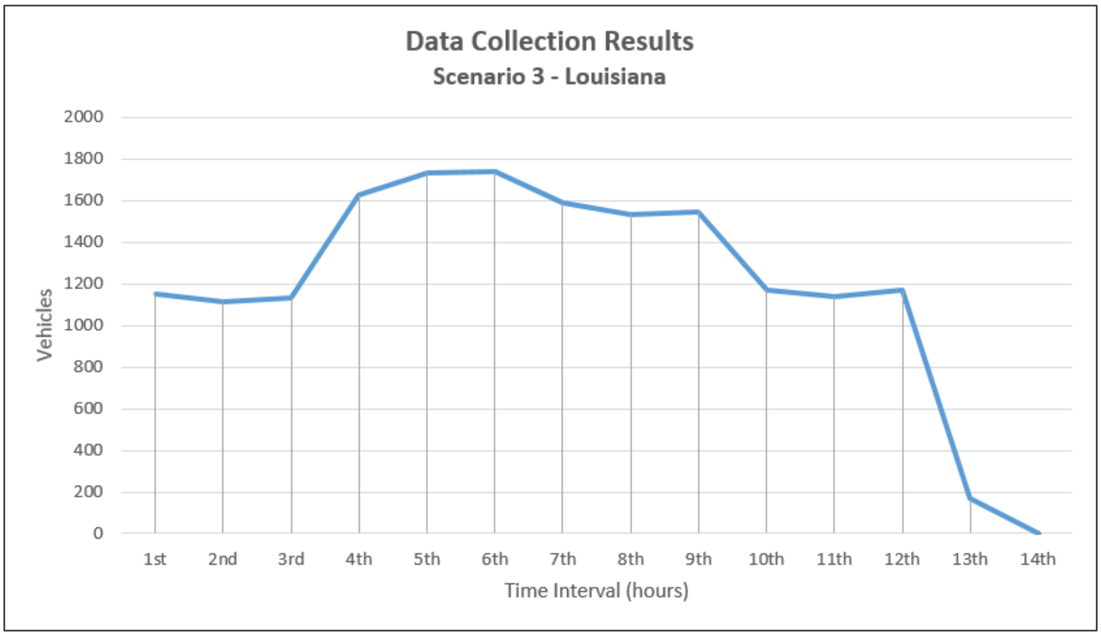

Figure 5.36.: Data collection results- Louisiana

5.6.2. Queue Length Results

The congestion was significantly reduced with new modal share. The maximum queue lengths at ‘North’ and ‘South’ queue counters are 37.29 and 80.26 meters respectively and shown in figure 5.37 and figure 5.38.

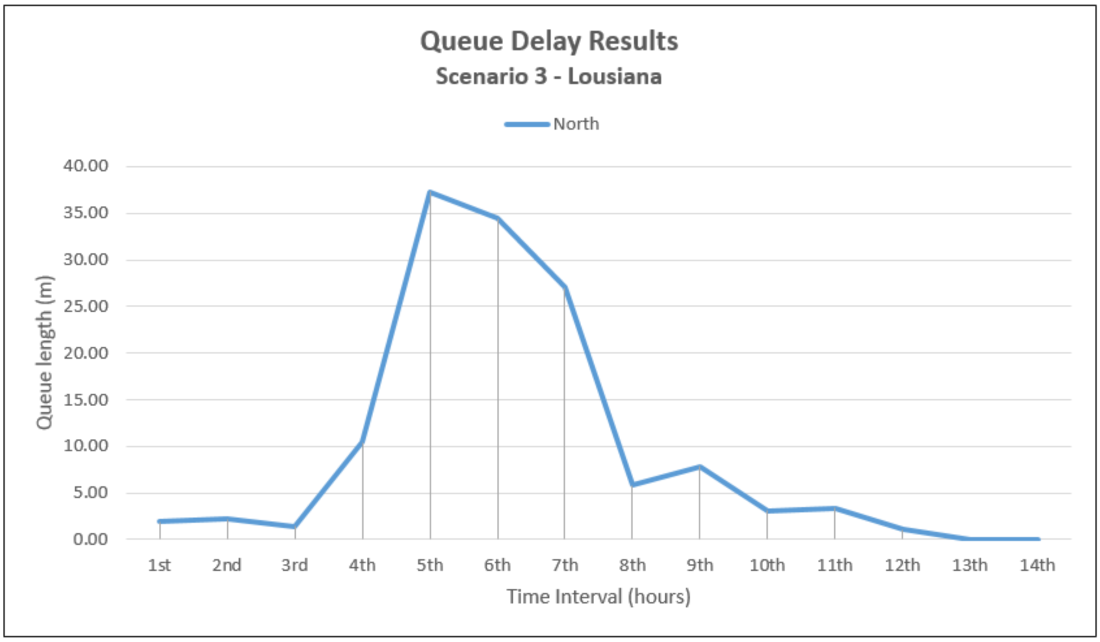

Figure 5.37.: Queue length result (North)- Louisiana

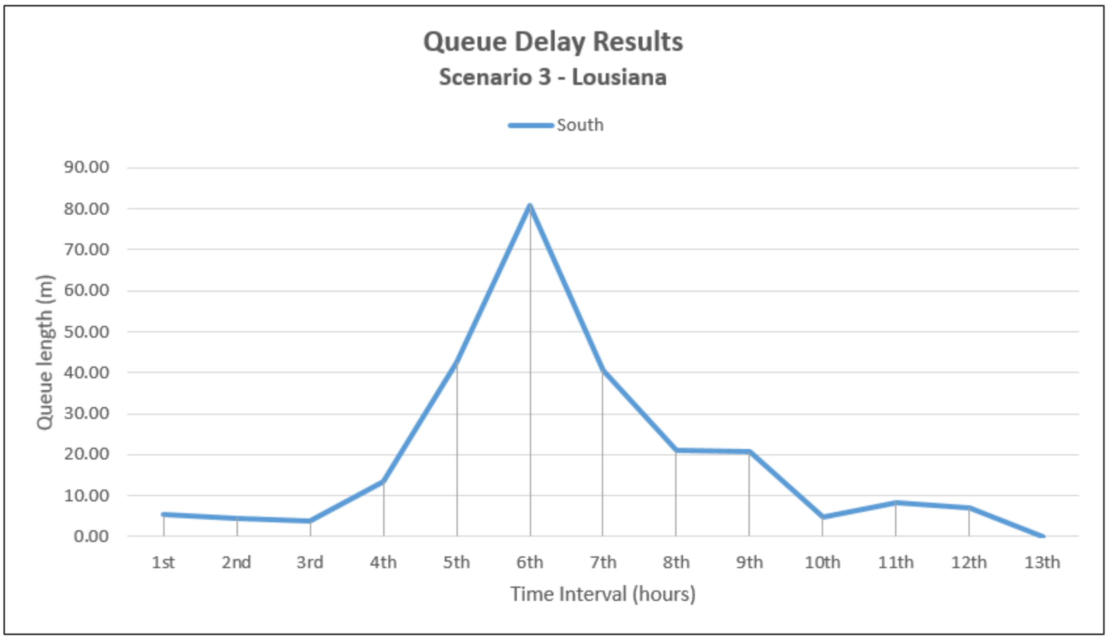

Figure 5.38.: Queue length result (South)- Louisiana

5.6.3. Vehicle Travel Time Results

The result in figure 5.39 displays the constant and unobstructed flow of vehicles. All the vehicles exited the network at the 14th hour. The zone farthest to the destination link (see figure 5.1) has the maximum travel time and vice versa.

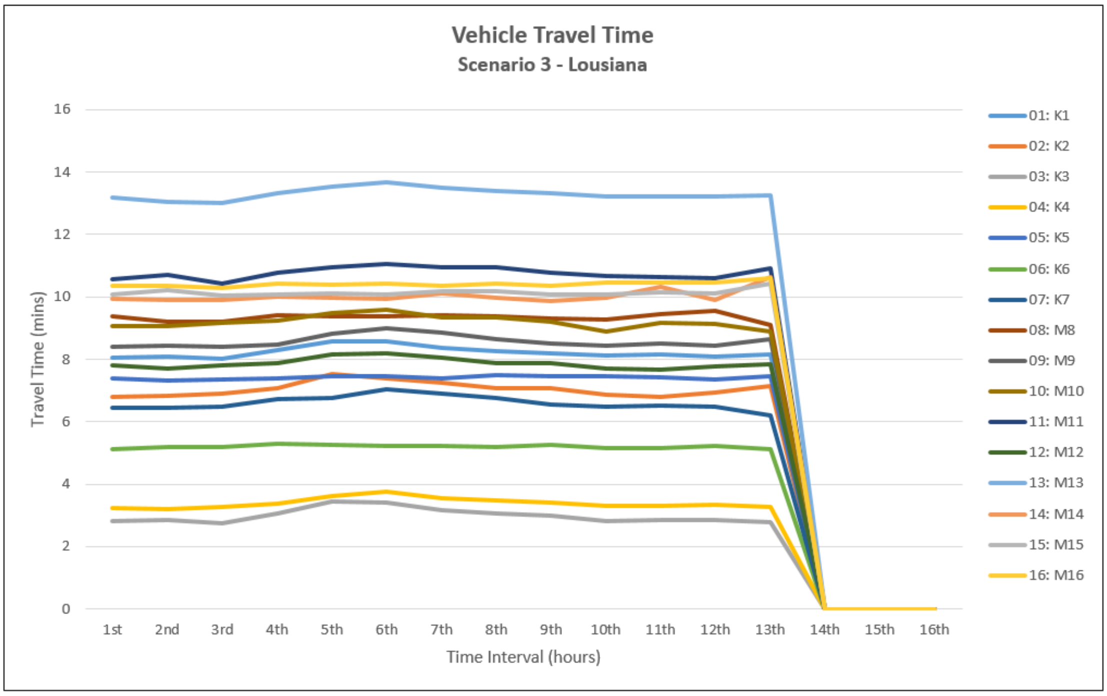

Figure 5.39.: Vehicle travel time results - Kenner, Louisiana

5.6.4. Network Performance Results

There has been a significant improvements in the network performance.

Average Delay Time

The average delay time per vehicle has been significantly reduced to less than a minute as shown in figure 5.40. This implies a free flow of traffic without any significant congestion.

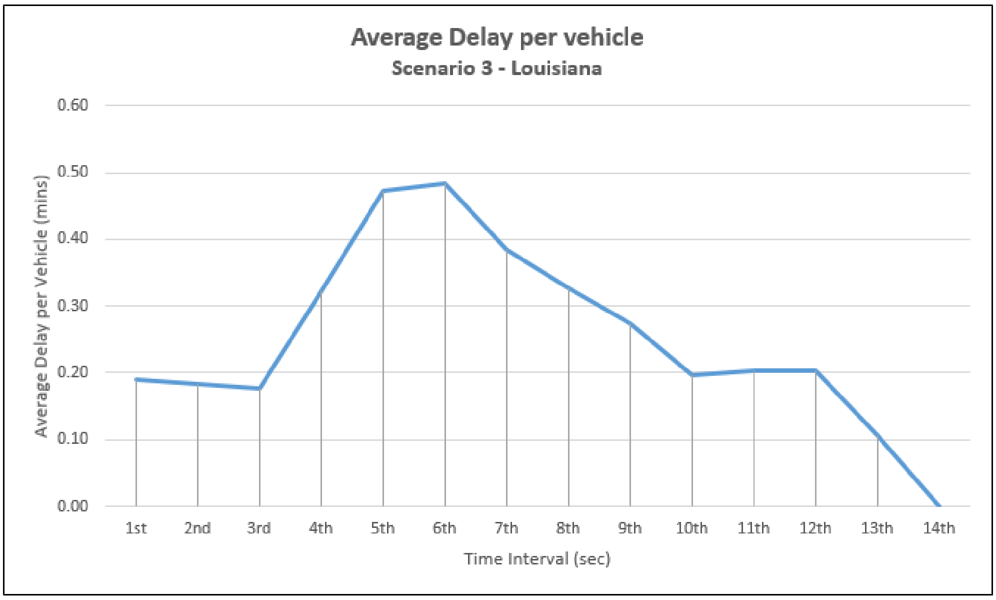

Figure 5.40.: Average delay time - Louisiana

Average Speed

That no significant congestion or delays have been observed, is reflected clearly by the average speed per vehicle, which is almost constant with time, see figure 5.41. The speed of zero indicates that there were no more vehicles in the network.

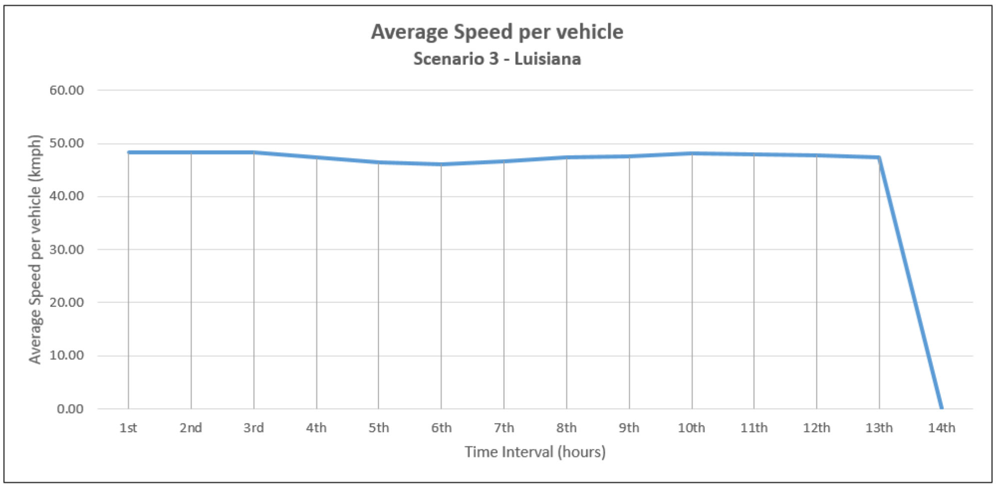

Figure 5.41.: Average speed - Louisiana

6. Qualitative Analysis and Discussions

The detailed quantitative analysis was explained in chapter 5. This chapter tries to prove the defined hypothesis (see section 1.2.1) qualitatively. In section 2.7.1, the characteristics of TOD and neighborhood mobility are elaborated; and the positive link between the TOD and social capital has already been established (Kamruzzaman et al. 2014). The qualitative analysis aims to establish a positive link of learning from previous shocks to the characteristics of TOD or neighborhood mobility. Within the scope of this study, the establishment of this connection assumes the acceptance of the stated hypothesis. A qualitative survey was beyond the scope of this study time-frame.

6.1. 1995 Chicago Heat Waves

On July 12, 1995, Chicago endured a devastating hot weather system: temperature reached 106 degrees Fahrenheit, heat index increased to 126; the energy grid failed, roads buckled, bridges locked, train trails warped, school buses full of children dangerously overheated, hospitals filled up and city's response crumbled from the over-stress. This incident claimed 739 lives (Klinenberg 2015).

Klinenberg (2015) noticed that three of the ten neighborhoods with lowest death rates were predominantly poor, African-American communities, places that should have been far deadlier than they were. It was discovered that the places with a social infrastructure - the sidewalks, community centers, parks, and commercial establishments- that encouraged local social life and contact between neighbors were far less likely to have multiple heat deaths. Whereas the places with broken streets, sidewalks and unattractive public places were far more likely to see death rates soar (Klinenberg 2015).

The observations clearly mentions that the features which helped in reducing causalities are all the characteristics of transit oriented development. Although it is not mentioned cogently that car dependent development would have reacted otherwise. Hence in partial response to the hypothesis it can be said that:

Areas or cities with transit oriented development if experienced with a shock, perform better than they were expected to.

6.2. Superstorm Sandy

A survey to explore resilience of people and neighborhood directly affected by the Superstorm Sandy was conducted by Associated Press-NORC Center for Public Affairs Research (AP-NORC). The aim was to learn more about how neighborhood characteristics and social factors relate to recovery and resilience (Coleman 2013).

It was noticed that “neighborhoods lacking in social cohesion and trust, more generally are having a difficult time recovering from Sandy”. Individuals in slowly recovering neighborhoods were less likely to believe that people can be trusted. Immediately after storm, the neighborhoods lacking social cohesion reported greater levels of hoarding food and water, looting and stealing, and vandalism (Coleman 2013).

As described in section 2.7.1,TOD tends to increase social capital (which includes social cohesion as one of the components); and in support of partial proof of hypothesis, it can be stated that:

Areas or cities with transit oriented development if experienced with a shock, perform better than they were expected to.

7. Conclusion & Future Work

7.1. Conclusions

The intention of this thesis was to invest time and resources to understand the concept of resilience in urban areas, review ongoing research and attempt to establish a link between urban planning and urban resilience. Last six months have been full of a lot of learnings; it has provided many answers and raised some further questions.

The quantitative analysis been elaborated in chapter 5 has positively confirmed the stated hypothesis which is "transit oriented developments if faced with a shock, perform better than car dependent developments." Not only was the main objective fulfilled but also this thesis offered a proposal on how to think and achieve urban resilience from transport planning perspective. Along with the quantitative analysis, the qualitative dimension was also investigated, although it was not the part of research objectives. The qualitative analysis as well affirms the stated hypothesis partially.

Since the aim was to use same transportation infrastructure and supply as in real world, the results are relatively closer to real situations. Despite the fact that the population of the study area in Singapore is 60% more than the population of the study area of Louisiana (see tables A.1 and D.6), the evacuation was much faster and smoother in the case of Singapore. In the case of scenario 2, which has only one-day warning, the situation was worst in the case of Louisiana. First results show more than 28 hours of evacuations, which means it's not possible to evacuate within one day and night. The modified routes had improved the condition marginally, but still the evacuation took 21 hours, which is 33% longer as compared to 14 hours in the case of Singapore. The theoretical scenario 3, highlighted the ease of evacuation if the modal split of Singapore is used in Louisiana area.

To make the process of evacuation faster one has to opt for high occupancy vehicles. It is for the fact that training the bus drivers and other public transport operators about the routes and destinations is much easier than training every car on the street. Moreover, a trained person often makes fewer mistakes than distressed drivers. The risks associated with standing in long queues can increase the vulnerability of the people, mechanical failure of cars, discomfort and sickness. Moreover people may remain stuck in the congestion.

The goal was not only to have a concrete conclusion, but also to contribute to the discussions in the scientific communities in the field of transport planning and urban resilience.

7.2. Recommendations and Discussions

Two very different urban structures were chosen in this research, mainly because conditions in many developing cities are somewhere in between these two kinds of urban structures. Despite the fact that; not just more people evacuated in Singapore than Louisiana area, but also in lesser time. This evidence shows that if a city is planned with the feature of TOD, it has an intrinsic property of urban resilience in addition to other benefits like efficient daily transport, reduced emissions, fewer private vehicles, etc.

The analysis of this thesis has highlighted that TOD offers much faster and smoother response to emergency evacuations than car oriented developments. The evaluation results serves as a decision making tool for new developing cities. It is imperative now for developing nations to make judgment calls on which direction to choose.

The mathematical tools can help planners analyze the situation during the disaster and facilitates them to prepare better so as to avoid the life or property losses. With recent increasing frequency of shocks (mostly man-made) and less warning times, transport planners have to play a bigger role in improving the resilience of the transportation systems to respond better and to increase the capacity of the city to absorb and recover, thereby making a city more resilient.

Learnings from several Hurricanes have attested the importance of the good governance. With proper preparedness the individuals, communities and cities can recover much faster. The preparation of evacuating maps is not enough, also testing the implementation is a must to check the real performance. Unprecedented traffic from shadow evacuation and tourism has to be taken into consideration.

7.3. Future Works

- Lane reversal decision could be modeled to see the response during evacuation. It is one of the important decisions which can increase the capacity of the transportation network and help reduce the evacuation time. It is important to take into account the necessary inbound traffic (related to refueling trucks, hospitals, medical vehicles, etc.).

- Evacuation model with the dedicated lanes for High Occupancy Vehicles (HOV) and buses can allow these vehicles to make multiple trips.

- If the study area has a train network, the evacuation with trains as one mode of transportation can reveal interesting results.

- More research is needed to evaluate the social capital associated with different urban structures.

The commencement of this thesis indicated a vast scope of further research in the unexplored aspects of urban resilience.

Appendix

A. Populations in Different Zones of Louisiana

Table A.1.: Populations in different zones of Louisiana; Source: (ArcGIS 2012)

City	**Zone Name**	**Population (2012)**
Kenner	K1	10111
Kenner	K2	13067
Kenner	K3	8430
Kenner	K4	5686
Kenner	K5	13433
Kenner	K6	6125
Kenner	K7	4729
Metairie	M8	6305
Metairie	M9	6686
Metairie	M10	6640
Metairie	M11	6665
Metairie	M12	4115
Metairie	M13	7052
Metairie	M14	2533
Metairie	M15	6500
Metairie	M16	3412
Total		**111489**

B. Calculation of Vehicular Share of Kenner

Table B.2.: Proportion of people using cars(C) and buses(P)

Mode of transport	**Number of adults**	**Share of people using cars and buses (C:P)**
Bicycle	282	80C:20P
Carpooled	5625	C
Drove alone	34361	C
Work from home	963	80C:20P
Motorcycle	45	80C:20P
Other	354	80C:20P
Bus	570	P
Taxi	185	C
Walked	1075	80C:20P

Table B.3.: Calclulation of number of cars, and people using cars and buses

The city of Kenner	
People using cars	42344
Number of cars used for evacuation	**38884**
People using buses	1114
Dependent evacuating in cars	22867
Dependent evacuating in buses	601
Total persons evacuating in cars	65211
Total persons evacuating in buses	1715
Number of available cars	38884
Average car occupancy during evacuation	1.677
Daily average car occupancy (USF 2000)	1.089

C. Calculation of Vehicular Share of Metairie

Table C.4.: Proportion of people using cars(C) and buses(P)

Mode of transport	**Number of adults**	**Share of people using cars and buses (C:P)**
Bicycle	460	84C:16P
Carpooled	9681	C
Drove alone	71829	C
Work from home	2348	84C:16P
Motorcycle	40	84C:16P
Other	1490	84C:16P
Bus	933	P
Taxi	222	C
Walked	1293	84C:16P

Table C.5.: Calculation of number of cars, and people using cars and buses

The city of Metairie	
People using cars	85584
Number of cars used for evacuation	**78589**
People using buses	2713
Dependent evacuating in cars	50186
Dependent evacuating in buses	1591
Total persons evacuating in cars	135769
Total persons evacuating in buses	4305
Number of available cars	78589
Average car occupancy during evacuation	1.728
Daily average car occupancy (USF 2000)	1.089

D. Population in Different Zones of Singapore

Table D.6.: Population in different zones of Singapore; Source: (DOS 2015)

Zones	Population	
1	Tuas	70
2	Pioneer	100
3	Boon Lay	30
4	Safti	-
5	Kian Teck	50
6	Yunnan	70890
7	Jurong West Central	68200
8	Wenga	8619
9	Boon Lay Place	31100
10	Chin Bee	-
	Total	**179059**

Table D.7.: Population in different study zones of Singapore

Study Zones	Residential Population	
1	Boon Lay	30
2	Pioneer	100
3	Tuas	70
4	Boon Lay Place_1	15550
5	Boon Lay Place_2	15550
1	Jurong West Central_1	34100
7	Jurong West Central_2	34100
8	Kian Teck	50
9	Wenya_1	4305
10	Wenya_2	4305
11	Yunnan_1	17723
12	Yunnan_2	17723
13	Yunnan_3	17723
14	Yunnan_4	17723

E. Calculation of Vehicular Share of Singapore

Table E.8.: Proportion of people using cars(C) and buses(P)

Mode of transport	**Number of adults**	**Share of people using cars and buses (C:P)**
Public buses only	36584	P
Metro only	25031	P
Metro + Bus	44286	P
Private vehicles	55839	P
Cycle	1925	90P:10C
Taxi	3851	C
Two wheeler	3851	90P:10C
Private bus only	7702	P
Walking	9627	90P:10C
Car+Metro(park and ride)	3851	50P:50C

Table E.9.: Calculation of number of cars, and people using cars and buses

West Singapore	
Adult Population	192548
People using cars	63156
People using buses	129392
Dependent evacuating in cars	26280
Dependent evacuating in buses	53842
Total persons evacuating in cars	89436
Total persons evacuating in buses	183234
Number of cars used for evacuation	**37150**
Average car occupancy during evacuation	2.407
Daily average car occupancy	1.7

F. Calculation of People Evacuating under Scenario 1 in Louisiana

Table F.10.: Calculation of people evacuating under scenario 1 in Louisiana

Zones	Zone population	Day 1 evacuees	People evacuating in cars	Number of cars evacuating	People evacuating in buses	Number of buses evacuating
K1	10111	6168	6010	3583	158	6.3
K2	13067	7971	7767	4631	204	8.2
K3	8430	5142	5011	2988	132	5.3
K4	5686	3468	3380	2015	89	3.6
K5	13433	8194	7984	4761	210	8.4
K6	6125	3736	3640	2171	96	3.8
K7	4729	2885	2811	1676	74	3.0
M8	6305	3846	3728	2158	118	4.7
M9	6686	4078	3953	2288	125	5.0
M10	6640	4050	3926	2272	124	5.0
M11	6665	4066	3941	2281	125	5.0
M12	4115	2510	2433	1408	77	3.1
M13	7052	4302	4170	2413	132	5.3
M14	2533	1545	1498	867	47	1.9
M15	6500	3965	3843	2225	122	4.9
M16	3412	2081	2017	1168	64	2.6
Total	111489	68008	66110	38905	1898	76

The names of the zones are shown in figure 5.1.

List of Abbreviations

AP-NORC	Associated Press-NORC Center for Public Affairs Research.
HOV	High Occupancy Vehicles.
NHC	National Hurricane Center.
ROW	Right of Way.
TAD	Transit Adjacent Development.
TOD	Transit Oriented Development.

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