2020-09

AN OPERATIONAL MODEL OF THE CRITICAL SUPPLY CHAIN FOR ST. THOMAS AND ST. JOHN

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https://hdl.handle.net/10945/66134

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

AN OPERATIONAL MODEL OF THE CRITICAL SUPPLY CHAIN FOR ST. THOMAS AND ST. JOHN

by

Robert D. Routley

September 2020

Thesis Advisor:	David L. Alderson Jr.
Second Reader:	Daniel Eisenberg

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REPORT DOCUMENTATION PAGE				*Form Approved OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.				
1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** September 2020	**3. REPORT TYPE AND DATES COVERED** Master's thesis		
4. TITLE AND SUBTITLE AN OPERATIONAL MODEL OF THE CRITICAL SUPPLY CHAIN FOR ST. THOMAS AND ST. JOHN				**5. FUNDING NUMBERS**
6. AUTHOR(S) Robert D. Routley				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000				**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A				**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution is unlimited.				**12b. DISTRIBUTION CODE** A

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The purpose of this thesis is to assess the surface road transportation and supply chain network on the islands of St. Thomas and St. John in the U.S. Virgin Islands (USVI). Following two Category 5 hurricanes in 2017 that devastated the islands' road transportation network with mudslides and washouts, the Federal Emergency Management Agency, the Virgin Islands Territorial Emergency Management Agency, and the USVI territorial government embarked on a mission to improve the resilience of the USVI's surface road transportation network. This thesis works in support of those agencies by (1) developing and curating a dataset of the surface road transportation and supply chain network for St. Thomas and St. John and (2) analyzing how the surface road transportation and supply chain network operates under normal, flooded, and worst-case conditions within a six-hour post-disaster curfew window. This analysis found that both islands' residents were able to reach critical supplies and return home within the six-hour window in normal and flooded conditions. However, under the worst-case scenario, both St. Thomas and St. John have residents who were unable to reach critical supplies within the curfew window. Additionally, St. John's port was cut off from the supply chain, rendering resupply of stores impossible.

14. SUBJECT TERMS supply chain, transportation, network flow, optimization, U.S. Virgin Islands, USVI, hurricane, Hazard Mitigation Plan			**15. NUMBER OF PAGES** 127
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

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AN OPERATIONAL MODEL OF THE CRITICAL SUPPLY CHAIN FOR ST. THOMAS AND ST. JOHN

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

NAVAL POSTGRADUATE SCHOOL
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ABSTRACT

The purpose of this thesis is to assess the surface road transportation and supply chain network on the islands of St. Thomas and St. John in the U.S. Virgin Islands (USVI). Following two Category 5 hurricanes in 2017 that devastated the islands' road transportation network with mudslides and washouts, the Federal Emergency Management Agency, the Virgin Islands Territorial Emergency Management Agency, and the USVI territorial government embarked on a mission to improve the resilience of the USVI's surface road transportation network. This thesis works in support of those agencies by (1) developing and curating a dataset of the surface road transportation and supply chain network for St. Thomas and St. John and (2) analyzing how the surface road transportation and supply chain network operates under normal, flooded, and worst-case conditions within a six-hour post-disaster curfew window. This analysis found that both islands' residents were able to reach critical supplies and return home within the six-hour window in normal and flooded conditions. However, under the worst-case scenario, both St. Thomas and St. John have residents who were unable to reach critical supplies within the curfew window. Additionally, St. John's port was cut off from the supply chain, rendering resupply of stores impossible.

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List of Acronyms and Abbreviations

BPR Bureau of Public Roads

BVI British Virgin Islands

CRS Coordinate Reference System

DOE Department of Energy

DPW Virgin Islands Department of Public Works

EPSG European Petroleum Research Group

FEMA Federal Emergency Management Agency

GPS Global Positioning System

KML Keyhole Markup Language

LPG liquified petroleum gas

MPH miles per hour

NPS Naval Postgraduate School

OSM OpenStreetMap

SHRP2 Second Strategic Highway Research Program

STJ St. John

STT St. Thomas

STX St. Croix

USCB U.S. Census Bureau

USNPS U.S. National Park Service

USVI U.S. Virgin Islands

UVI University of the Virgin Islands

VIPA Virgin Islands Port Authority

VITEMA Virgin Islands Territorial Emergency Management Agency

VPH vehicles per hour

WAPA U.S. Virgin Islands (USVI) Water and Power Authority

WSG84 World Geodetic System 84

Executive Summary

During a two-week period in September 2017, the Category 5 Hurricanes Maria and Irma struck and devastated the U.S. Virgin Islands (USVI). Both storms severely damaged the critical infrastructure systems that provide lifeline services including electricity, water, transportation, and telecommunications. This damage adversely impacted local communities and delayed disaster response. The damage wrought by these hurricanes motivated U.S. federal agencies, the USVI territorial government, local public utilities, universities, philanthropic organizations, and other stakeholders to work to return normalcy to the territory and plan for future events.

The USVI relies on its road network and transportation infrastructure to drive its economic development, facilitating the movement of tourists, goods, resources, and allowing its residents to access those goods and resources. The island's remote geographic location forces it to rely on its surface road network to facilitate movement of goods from its ports to where the goods are needed. The hurricanes inflicted severe damage on that important road network.

The thesis considers the capacity of the USVI surface roadway transportation network to support delivery of critical supplies to communities. We define critical supplies as food, fuel, and hardware. Our goal is to assess how the USVI supply chain network and transportation system performs under normal, flooded, and worst-case conditions. We seek to see which communities are hardest hit by adverse conditions, and whether or not the supply chain network can withstand adversity. We measure this capacity via travel time during curfew travel windows experienced after major disasters.

This thesis performs four tasks:

1. *Data Curation and Network Construction:* We develop a geospatial dataset use for analysis of traffic flows and congestion on the islands of St. Thomas and St. John.
2. *Program Development:* We develop a faster, easier, and more user-friendly computer model program to enable this analysis and beyond.
3. *Model Formulation and Implementation:* We implement a four-step traffic model that measures roundtrip travel times between population centers and sources of supply.

We model these travel times for scenarios with under normal conditions, flooded conditions, and worst-case conditions.

4. *Analysis:* Using the results generated from the model, we determine the capability of surface roads on St. Thomas and St. John to withstand the usage required prior to and after disaster scenarios. We assess which communities will be the most affected by congestion and have the greatest difficulty in reaching sources of supply under the three scenarios.

We address several questions.

Under normal conditions, what are the roundtrip travel times and congestion between population locations and the port? The road networks of both St. Thomas and St. John are able to allow all populations to reach critical supplies and return home within a six-hour curfew window. All stores are able to be resupplied from each island's respective ports within the curfew window.

Under flooded conditions, what are the roundtrip travel times and congestion between population locations and the port? Considering flood-prone locations provided by the University of the Virgin Islands, we model how flooded roads impact the ability of populations to reach critical supplies. We find that the road networks of both St. Thomas and St. John are able to support the ability of all populations to reach critical supplies and return home within the six-hour curfew window. All stores are also able to be resupplied within the curfew window.

Under worst-case conditions, what are the roundtrip travel times and congestion between population locations and the port? Assuming a worst-case scenario where roads are washed-out or otherwise disrupted, we analyze how losing those roads affects the network. We find that some population centers on both St. Thomas and St. John are rendered unable to reach critical supplies. We find the port on St. John is unable to resupply the island's stores because of road disruption in and around the port. We also find that some stores on St. Thomas are cut off from the road network, and also unable to be resupplied.

Acknowledgments

I extend my deepest gratitude to my thesis advisor, Dr. David L. Alderson, and my second reader, Dr. Daniel Eisenberg. I truly appreciate the mentoring and guidance that you both provided during the entire process. It would not have been possible without you both keeping the important things at the forefront of my mind. I hope that the work we put into the data process and model execution will pay dividends down the road.

To my lovely wife, Tauni, and our two children, Alistair and Devon, thank you for all of your support and patience as I navigated this process. I would not have been able to succeed in this program or with this thesis without you. I look forward to what the future brings.

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CHAPTER 1: Introduction

During a two-week period in September 2017, the Category 5 Hurricanes Maria and Irma struck and devastated the U.S. Virgin Islands (USVI). Both storms severely damaged the critical infrastructure systems that provide lifeline services like electricity, water, transportation, and telecommunications impacting local communities and delaying disaster response. The damage wrought by these hurricanes motivated U.S. federal agencies, the USVI territorial government, local public utilities, universities, philanthropic organizations, and other stakeholders to work to return normalcy to the territory and plan for future events.

This thesis is in support of a large effort led by the Federal Emergency Management Agency (FEMA), the Naval Postgraduate School (NPS), the Department of Energy (DOE), and the University of the Virgin Islands (UVI) among others to assess and improve the resilience of critical infrastructure in the USVI. This work focuses on assessing the capacity of surface roads and supply chain infrastructure to ensure territorial communities can access critical supplies after major disasters. The work presented in this thesis is intended to inform territorial resilience for the next-generation USVI Hazard Mitigation and Resilience Plan (University of the Virgin Islands 2020), and it is intended to complement additional studies that were also completed towards this goal. For supporting and related studies on USVI critical infrastructure systems, we direct the reader to the following work:

- Transportation and Supply Chains: Good (2019), Bengigi (2020);
- Electricity: Wille (2019), Bunn (2018);
- Water: Borgdorff (2020), Wille (2019), Bunn (2018); and
- Telecommunications: Moeller (2020), Wine (2020).

1.1 The U.S. Virgin Islands

The USVI is a collection of islands located approximately 1,100 miles southeast of Florida and 40 miles east of Puerto Rico in the Virgin Islands, an archipelago in the Caribbean Sea (Figure 1.1). The USVI is comprised of three primary islands; St. Thomas (STT), St. John (STJ), and St. Croix (STX), and two minor islands, Water Island and Hassel Island

Source: Central Intelligence Agency (2020).

Figure 1.1. The USVI in relation to the Caribbean.

(Figure 1.2). As of 2010, 106,405 people lived in the USVI, with 51,634 residing on STT, 50,601 on STX, and 4,170 on STJ. The islands constitute 133.7 square miles of landmass with STT residing three miles west of STJ in the northern portion of the territory, immediately west of the British Virgin Islands (BVI). STX is approximately 40 miles south of STT and resides in the southern portion of the territory. Due to their small size and few inhabitants, the remainder of this work will not discuss Water Island and Hassell Island.

Though bound by a common heritage, language and government, the three primary islands have their own unique cultures and topography.

1.1.1 St. Thomas

STT is the administrative heart of the USVI. Charlotte Amalie serves as the seat of government and capital of the territory. Charlotte Amalie's deep water harbor cemented its role as the commercial, financial, and tourist base of the USVI (USVI Department of Public Works 2014). STT consists of mountainous terrain and more than 80% of the island's population live on the eastern half of the island opposite Charlotte Amelie. This leads to significant daily traffic to commute across the island despite its relatively small geographic area (32 mi^2).

Source: Central Intelligence Agency (2020).

Figure 1.2. The USVI.

1.1.2 St. John

STJ is the least populous of the islands and is located three miles east of STT. STJ is also highly mountainous, with a geographic area of 22 mi^2. Approximately 70% of STJ is owned by the U.S. National Park Service (USNPS) and designated as national park land. Since so much of the island is national park land, much of the island is undeveloped in terms of industry or agriculture. This lack of development, however, is a boon for the tourism industry, and has led to development of luxury housing (USVI Department of Public Works 2014).

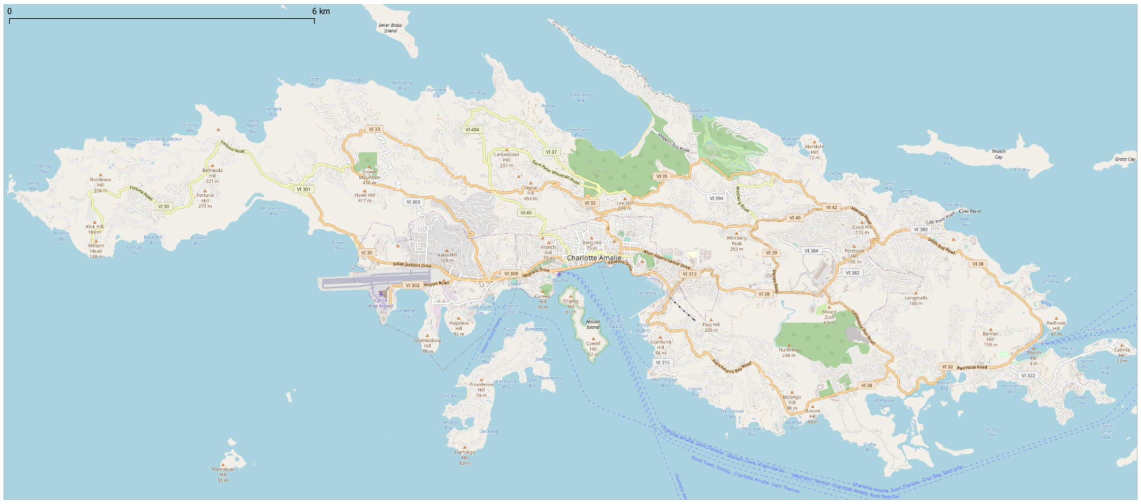
1.1.3 St. Croix

STX is the second most populous of the three islands. Unlike STT and STJ, coral formed STX and the island is mostly flat, with two mountain ranges in the north and east of the island. The island has two major cities, Christiansted in the east and Frederiksted in the west, with the majority of the population living between them. The STX economy was originally agricultural, yet changed in the 1960s to focus on tourism, light industry, and oil production. Previously, STX had the third-largest oil refinery in the world, which closed in 2012 and caused severe economic ramifications to the territory. Recently, the refinery has reopened as Limetree Bay Refining.

1.1.4 Road Infrastructure in the USVI

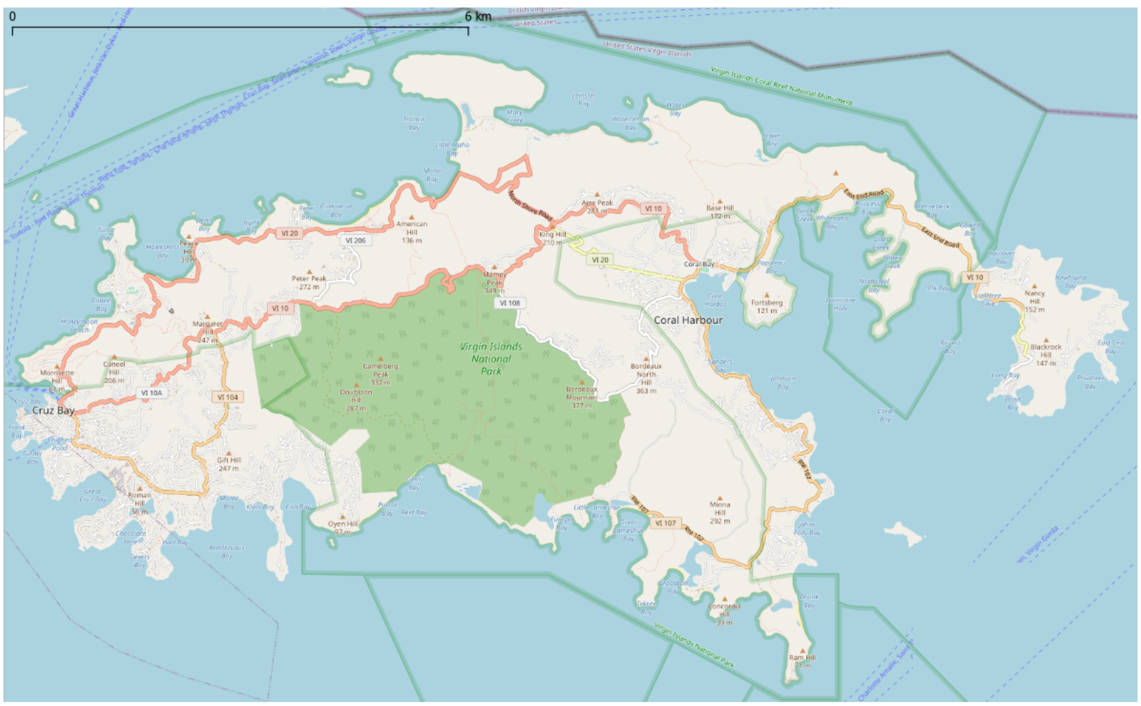
The USVI relies on its road network and transportation infrastructure to drive its economic development, facilitating the movement of tourists, goods, resources, and allowing its residents to access those goods and resources. The island's roads are planned, constructed and maintained by the Virgin Islands Department of Public Works (DPW). However, the surface road network in the USVI suffers from age and insufficient maintenance, exacerbated by frequent disasters such as earthquakes, heavy rainfall, and hurricanes (USVI Hurricane Recovery and Resilience Task Force 2018). For example, the island's roads were never designed to withstand the force of Category 4 and 5 hurricanes (USVI Hurricane Recovery and Resilience Task Force 2018), but the USVI has experienced several over the last few decades.

The USVI road network consists of 1,230 miles roads across STT, STJ, and STX (see Figures 1.3, 1.4, and 1.5). Of these, 340 miles are classified as federal routes, 410 miles are classified as local routes, and 480 miles are private routes (USVI Hurricane Recovery and Resilience Task Force 2018).



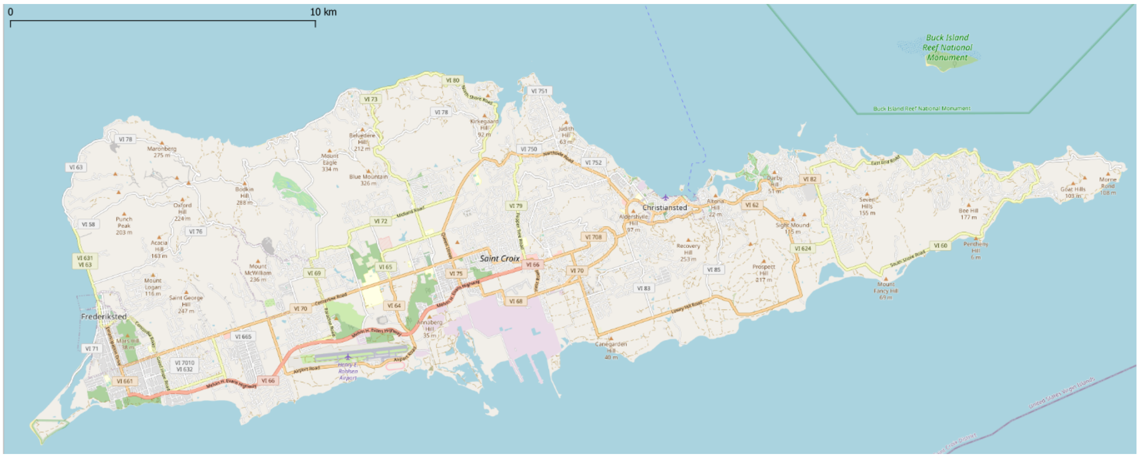
Source: OpenStreetMap contributors (2020).

Figure 1.3. STT road network.



Source: OpenStreetMap contributors (2020).

Figure 1.4. STJ road network.



Source: OpenStreetMap contributors (2020).

Figure 1.5. STX road network.

1.1.5 Critical Supply Chains in the USVI

The purpose of the surface roads on the USVI is to enable mobility for both daily economic production and access to critical services such as food, gasoline, water, hardware, and other items. These critical services include critical supplies, such as food and water, necessary for life. Gasoline and other fuels are also critical supplies, though not required for life, does power vehicles and generators that allow access to food and water.

The USVI relies on its seaports and airports to provide access to critical supplies and its major source of income, tourism (USVI Department of Public Works 2014). The seaports act as the first step in the supply chain of the islands, feeding the island's distributors and stores. The island's seaports are operated by Virgin Islands Port Authority (VIPA). Additionally, the island's power provider, USVI Water and Power Authority (WAPA), imports fuel oil and liquified petroleum gas (LPG) for its primary generators (USVI Hurricane Recovery and Resilience Task Force 2018). The Limetree Bay refinery provides gasoline and diesel for STX and has an agreement with the USVI government to maintain a 30-day supply. However, the geographical distance of STT and STJ from STX renders it more effective to procure fuel from Puerto Rico. Fuel shipped to STT is then passed onto STJ (USVI Hurricane Recovery and Resilience Task Force 2018). Critical supplies other than fuel emanate from the global supply chain (e.g., Puerto Rico, the U.S. mainland, and other locations).

Functioning seaports and airports are vital for continued economic growth in the islands. The hospitality industry provides 17% of the island's jobs, mainly to support tourism (USVI Department of Public Works 2014). On STT and STJ, 76% of visitors arrived by cruise ship, the rest by air (USVI Hurricane Recovery and Resilience Task Force 2018). Seaports also provide mobility between the islands. Visitors to STJ typically arrive at STT first, then travel via ferry to STJ. Ferries between STT and STJ are essential for the movement of goods and people. For example, STJ does not have either a junior or senior high school, and students must transit to STT daily for their education (USVI Hurricane Recovery and Resilience Task Force 2018). Lack of services on STJ can be alleviated by travel to STT.

1.2 The Impact of Hurricanes Irma and Maria

On 6 September 2017, the Category 5 Hurricane Irma struck STT and STJ with wind speeds exceeding 180 miles per hour (MPH). In response, agencies and communities on STX sent emergency supplies to STT and STJ to help manage damages and recover failed systems. Two weeks later, on 20 September 2017, Hurricane Maria struck STX as a Category 5 storm. Together, the storms left behind a trail of destruction that included over 660,000 tons of debris and detritus that blocked roads, neighborhood access, and limited the ability of residents to access necessary supplies.

Because of the impact to infrastructure, including washed out roads and downed power lines, car travel was limited following the storms. Across each major island, the government instituted a six-hour travel window to allow residents to travel and access relief supplies (USVI Hurricane Recovery and Resilience Task Force 2018). Anecdotal evidence experience suggested that the six-hour window was insufficient for residents to make the roundtrips from their homes to relief supplies and then back home.

Another major issue following the storms were road washouts caused by significant flooding and erosion. Local drainage systems were overwhelmed by rain and storm surge, causing underground utilities including water distribution and sewage pipelines to fail. The failure of water distribution and drainage systems further impeded disaster recovery efforts and community access to supplies by flooding and washing out roads.

1.3 Thesis Goals

The thesis considers the capacity of the USVI surface roadway transportation network to support delivery of critical supplies to communities. The main goal is to assess the capacity of the USVI supply chains and roadway transportation system during normal and post-hurricane conditions. We measure this capacity via travel time during curfew travel windows experienced after major disasters.

This work is an extension of the previous resilience study completed by Good (2019), who assessed the capacity of the STX surface roadway and supply chain transportation system to serve communities during curfew. We build on this past work to complete a similar assessment of roadway capacity for STT and STJ. Toward this end, this thesis makes the following contributions:

1. Develops and presents a geospatial data set for STT and STJ surface roads. These data sets will support analysis by FEMA and Virgin Islands Territorial Emergency Management Agency (VITEMA) and other stakeholders to assess community mobility by car and access to critical supplies during curfews;
2. Refactors computer models and code to enable surface roadway assessment of systems besides STX;
3. Extends previous models to consider the mountainous geography found on STT and STJ that affects travel time and ability for disaster supplies to reach communities; and,
4. Assesses the impacts of possible roadway flooding on community access to supplies using projected flood maps developed for the territory.

In Chapter 2, we present a review of past work relevant to Good (2019) and proposed data, computation, and modeling extensions. In Chapter 3, we present methods that build on Good (2019) to enable roadway network capacity assessment in STT and STJ. We measure the capacity of STT and STJ road networks via travel time for communities to reach critical supplies during normal and disaster situations. Overall, this work presents new data, computational methods, models, and analyses relevant to assess the resilience of transportation systems in the USVI. In Chapter 4, we apply the model presented in Section 3.3 to assess the critical supply chains and transportation networks of STT and STJ.

CHAPTER 2:
Background

This chapter discusses research on critical supply chain and transportation infrastructure. There is a great deal of literature discussing surface road transportation infrastructure and network models for predicting traffic flows. Unfortunately, the vast majority of these studies focus on urban traffic for large-scale metropolitan areas during normal traffic scenarios (e.g., rush hour). There is limited research on data development and modeling of last-mile supply chains during disasters. Furthermore, there are few studies that inform roadway congestion and traffic for islands like those in the USVI that feature remote locations, varied geography, have a large variation of road types (e.g., dirt and unincorporated roads), and have many small, isolated communities that require roadway access.

2.1 Traffic Models and Last-Mile Supply Chains

The design and operation of roadway infrastructure systems is a historically difficult problem. This is due to the fact that roadway location, connectivity, capacity, maintenance, and funding requires predicting human behavior such as driving patterns, choice of living location, and choice of destination. Despite the complexity of these problems, transportation and traffic engineering rely on standard models to measure travel time from a given origin (e.g., a household) to a series of destinations (e.g., a store, workplace). The most common approach is using "four-step" models that integrate four key stages to determine roadway traffic:

1. Trip Generation,
2. Trip Distribution,
3. Mode Choice or Modal Split, and
4. Traffic Assignment.

These are discussed in depth in Section 3.2.

2.2 Review of Previous Work on the USVI

The first in-depth look and attempt at modeling the USVI critical supply chain was performed in Good (2019). His work centered on STX, and focused on answering five questions:

1. What are the roundtrip travel times and congestion when travelers pick destinations "selfishly"?
2. What are the roundtrip travel times and congestion when travelers pick destinations in a "coordinated" fashion?
3. What are the resulting travel times from ports under the above traffic patterns?
4. Which blocked road segments would crate the most congestion and hardships?
5. What other analysis could be conducted utilizing his model?

To answer these questions, Good made several assumptions about traffic demands and routing. First, he assumed that 40% of travelers would travel to gas stations, 40% would travel to grocery store, and the final 20% to hardware or other miscellaneous stores. His second assumption was that a vehicle would only make a single trip to one store before returning home. The total roundtrip time would include the travel to the the destination store, followed by the travel time back home. Time shopping is not modeled. Finally, calculating the roundtrip time from ports involved only a single delivery to each supply access point.

2.2.1 Results

In Good (2019), modeling of the STX transportation network found that "under 'normal' circumstances, the road network for the island of STX has sufficient capacity to support the entire population." Utilizing the "selfish" model, most trips were under 50 minutes, with the longest taking 150 minutes. The average travel time was 17.27 minutes with a standard deviation of 19.81 minutes. All trips were within a notional six-hour travel window outside of curfew hours. The "coordinated" model lowered the number of trips under 50 minutes, although the longest travel time increased to over 175 minutes. The average travel time was 18.99 minutes with a standard deviation of 25.98 minutes.

2.2.2 Limitations

Good (2019) was only able to model STX, leaving STT and STJ without valuable information. Additionally, only single roundtrips were modeled; if a household required food and fuel, the model forced them to return home prior for leaving for fuel. That situation would not be wholly realistic. Additionally, time spent shopping was not incorporated. It would take time to purchase necessary supplies in supply access points that would undoubtedly be inundated by other shoppers.

The interdiction model he performed could only simulate one disruption to the road network at a time. Unfortunately, if one segment of a road was washed out or flooded, then the chances are there are more road segments that are also out of commission. This was alleviated somewhat by disrupting only the most important road segments; losing the Melvin H. Evans highway on STX is dramatically more devastating than a dirt road to a single house, at least for the population on the whole, but unfortunate for that single house.

Nevertheless, while not a perfect representation of reality, the analysis in Good (2019) was an excellent starting point in the quest to model the critical supply chain and transportation network of the USVI. This paper hopes to expand and improve upon that beginning.

2.2.3 The Differences between STX, STT and STJ

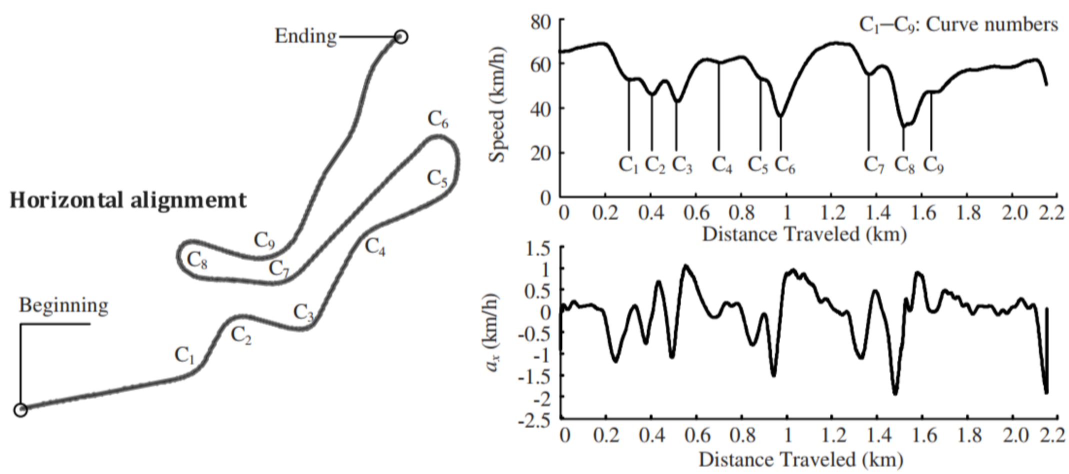
Whereas STX has primarily flat terrain with relatively curve-free roads, STT contains some hilly and mountainous terrain, while STJ is almost wholly comprised of rolling hills and mountainous terrain. The differences in terrain understandably creates differences in their transportation network designs in terms of speed and capacity. Owing to topography, the territory's only divided highway, or road, lies on STX. All roads on STT and STJ are either single-lane or two-lane without dividers. This, in turn, reduces the possible maximum capacity of the roads.

Two key factors that are relevant to surface transportation in STJ and STT include the following.

1. *Winding Roads.* The American Association of State Highway and Transportation Officials (2018) discusses roads with "horizontal" and "vertical" alignment. For our purposes, we will refer to these roads as "winding" or "hilly." Although portions

of STX have roads that are "curvy" and/or "hilly," roads on the island are largely flat and/or straight. In contrast, both STJ and STT are dominated by roads that both "winding" and "hilly." The travel speed and throughput capacity of these winding and hilly roads tend be to be considerably less. Figure 2.1 presents an example from Xu et al. (2017) on the effects of horizontal curvature on vehicle speed.

2. *Flooded Roads.* Due to hilly nature of STJ and STT, the roads on these islands are more prone to flooding. Flooded roads can be traversed by vehicles, but the travel speeds are significantly affected. Figure 2.2 presents a graph from Pregnolato et al. (2017) that shows the effect of flood water depth on on the speed of vehicles.



Source: Xu et al. (2017)

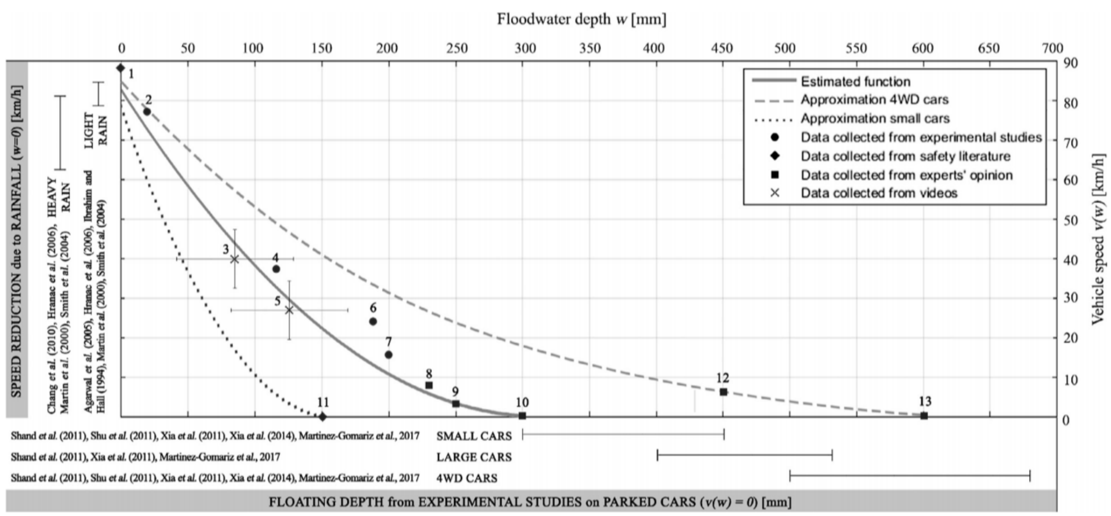
Figure 2.1. Effects of horizontal alignment on vehicle speed. C_1 through C_9 on the left portion show different turns in the road which correlate to reductions in speed and acceleration in the right portion of the figure.

2.3 Roadway Design

The industry standard for the design of highways and roads is "A Policy on Geometric Design of Highways and Streets" (American Association of State Highway and Transportation Officials 2018), also known as the "Green Book." From that, other governmental organizations and departments of transportation derive their design and planning guidance.

The key factor from which the design of a roadway is derived is the "design speed." That is the

> Selected speed used to determine the various geometric design features of the roadway. The selected design speed should be a logical one with respect to the anticipated operating speed, topography, the adjacent land use, modal mix, and the functional classification of the roadway. In selection of design speed, every effort should be made to attain a desired combination of safety, mobility, and efficiency within the constraints of environmental quality, economics, aesthetics, and social or political impacts (American Association of State Highway and Transportation Officials 2018, p. 2-23).



Source: Pregnolato et al. (2017).

Figure 2.2. Effects of floodwater depth on vehicle speed. The solid line in the middle represents the estimated function of floodwater depth on speed. As water depth increases vehicle speed decreases. At three-and-a-half inches of water, speed is roughly reduced by half.

The primary factors in the design of a roadway include:

- Sight Distance: the distance a driver can see ahead of their car for the safe and efficient operation of the vehicle.
- Horizontal Alignment: The design of roadway curves based on the relationship between design speed and curvature and their relationships with superelevation (roadway

banking) and side friction.

- Vertical Alignment: The topography of the land that has an influence on the vertical grade of the road, and impacts the selection of a design speed.
- Combinations of Horizontal and Vertical Alignment: Dramatically impacts the selection of road sites and design speed.

Once a design speed is selected, the suggested minimums of which are listed in table 2.1, a geometric design of the roadway can begin. Attributes of the roadway such as grades, superelevation, topography, and curvature of the road can be designed.

Table 2.1. Minimum design speeds for local roads in rural areas. Source: American Association of State Highway and Transportation Officials (2018).

	Design Speed (MPH) for Specified Design Volume (vehicle/day)				
Type of Terrain	Under 50	50 to 250	250 to 400	400 to 2000	2000 and over
Level	30	30	40	50	50
Rolling	20	30	30	40	40
Mountainous	20	20	20	30	30

2.3.1 Types of Terrain

There is no transportation industry definition on what constitutes a “winding” or “meandering” road as a seasoned driver would classify it while driving, but rather classifications of the terrain types themselves, for which road systems are then designed to conform. The first of three different terrain types is level terrain, where “highway sight distances, as governed by both horizontal and vertical restrictions, are generally long or can be made to be so without construction difficulty or major expense” (American Association of State Highway and Transportation Officials 2018, p. 3-122). The second is rolling terrain, where “natural slopes consistently rise above and fall below the road or street grade, and occasional steep slopes offer some restriction to normal horizontal and vertical roadway alignment” (American Association of State Highway and Transportation Officials 2018, p. 3-122). Finally, mountainous terrain is where “longitudinal and transverse changes in the elevation of the ground with respect to the road or street are abrupt, and benching and side hill excavation are frequently needed to obtain acceptable horizontal and vertical alignment" (American Association of State Highway and Transportation Officials 2018, p. 3-122).

Alignment of the road is derived from its topography. There are two types of alignment, horizontal and vertical. A heavy preponderance of either leads to "winding" alignment, where low design speeds are applicable because of the rolling or mountainous terrain, or where other environmental concerns dictate low speeds (American Association of State Highway and Transportation Officials 2018, p. 5-2).

2.3.2 Road Design in the USVI and its Impact on Modeling

Unfortunately, road design in the USVI has not properly incorporated best practices in its transportation network. Many roads were established during a colonial period that predates modern transportation engineering. The condition of most roads in STT and STJ is poor, while "most roads are narrow, two lanes with no or narrow shoulders. Because of the topography, there are many blind corners. Pavement markings are mostly faded and on many facilities, guardrails are damaged or non-existent" (USVI Department of Public Works 2014, p. 49).

With the above in mind, the question becomes how can travel times be estimated accurately in roadways with "winding" alignment, and therefore be modeled correctly. To expand on that, how can speed and congestion be modeled properly? The Highway Capacity Manual (Transportation Research Board 2016, p. 15-6) does not hold the exact answer for roadways of "winding" alignment with no or narrow shoulders, but it states that "lanes narrower than 12 ft and shoulders narrower than 6 ft have been shown to reduce speeds." Good (2019, p. 35) used speeds of 25 MPH, 35 MPH, and 55 MPH for dirt and urban, rural, and highways, respectively. For the topography of STJ and the more "winding" areas of STT, those values are probably not the right answer.

2.3.3 Possible Answers

The "Green Book" provides a possible answer in Table 2.2. A two-lane local road in mountainous terrain yields a design speed of 20 MPH. This speed is obviously lower than even the dirt road speed of STX. Creating a new road type for the model called "winding" using a lower speed and smaller capacity than used in Good (2019) could be used to represent the longer travel times that a "winding" journey may entail.

Table 2.2. Design speeds for resource recovery and local service roads. Source: American Association of State Highway and Transportation Officials (2018).

	Design Speed (MPH)	
Type of Terrain	Single Lane	Two Lanes
Level	30	40
Rolling	20	30
Mountainous	10	20

Another possible solution is to modify the BPR function found in Peeta et al. (2015). Adjusting the function to model an increase in congestion as cars slow to go uphill, or slow to navigate a blind curve, and so on, could represent the increase in travel time based on congestion inherent in "winding" roadways.

2.3.4 Other Work on Road Curvature

Pratt et al. (2019) used data from the Second Strategic Highway Research Program (SHRP2) to evaluate and build on their previous models to predict speeds through horizontal curves. They found that their models can accurately predict speeds through curves, and that speed and safety can be predicted by properties of the curves, combined with driver familiarity with the road and superelevation differential. Xu et al. (2018) develops a model based on the sight distance on drivers, a combination of a "speed control pattern" combining minimum travel time, maximum, or other objectives. Cafiso and Cerni (2012) use sampled Global Positioning System (GPS) data to collect continuous speed data to study actual acceleration an deceleration behavior through curves. They develop a model to predict operating speed through various curves using horizontal curvature and vertical grade as weighted values.

Dell'Acqua (2015) develops a statistically significant regression model to determine the operating speeds on roads involving curves based on the curvature radius and width of the lane. Findley et al. (2012) looked beyond individual curves as a factor in road speed and safety, but at the roadway as a whole. They found that curves in succession resulted in fewer crashes than curves separated by longer straightaways; drivers expected and anticipated curves on curvier roads. Long straight roads punctuated by unexpected curves lead to more accidents.

Other studies on curve safety include Fatemi et al. (2014), who used a radar and camera-based system to look at road signs to estimate the next 200 meters of road. Hamzeie (2016) developed a "naturalistic" model utilizing speed at the time of incidents, variation in speed over a period, the age of drivers, and weather conditions. In Karaduman et al. (2016), cameras on test vehicles are used to determine curvature and bend angle of roadways, data which is used to perform a risk estimation, with potential use in autonomous cars and driver assist systems.

2.4 Modeling Flooding and Road Washouts

Hurricanes Irma and Maria flooded and washed out roads. Is it possible to model that without simply eliminating the arcs from the network? Pregnolato and Ford (2017) found that once flood water reached 11.8 inches, driving over a road became impossible, and vehicles started to float. A mere 3.5 inches of water halved the speed of vehicles traveling over a road with a normal traveling speed of 50 MPH. With the already slow speeds based on the "winding" roads of STJ, even modest flooding could lead to a crippling of the road system, especially if any of the main cross-island arteries were flooded or washed out. Pregnolato and Ford (2017) also present a function to model the effects on speed of amounts of rainfall on typical and four-wheel drive vehicles.

Choo et al. (2020) uses the "Spatial Runoff Assessment Tool" and the "Flood Inundation Model" to calculate flooding in urban areas, and its resultant effects on road speed and traffic disruption. Evans et al. (2020) look at Barcelona, Spain, and Bristol, England, and the methods used to assess the impact of rainfall flooding events on traffic within urban environments. The study found that impacts of flooding on a road network extend past the duration of the event.

2.5 Our Contribution

We build on the work of Good (2019) to model the transportation infrastructure of STT and STJ using the same multi-commodity equilibrium model of congestion based on the territory's road network and destination and origin pairings. However, we intend to model the predominant "winding" nature of STJ's roads, while blending the "winding" roads and level roads of STT to calculate roundtrip times between households and supply access points, with an emphasis on government mandated curfews in the aftermath of a disaster. Additionally, we estimate roundtrip travel time from ports of origin to supply access points to calculate how much volume can arrive to supply access points.

CHAPTER 3:
Model

This chapter provides an overview of the methods used to develop the transportation and critical supply chain model for STT and STJ.

Throughout this project, we use Coordinate Reference System (CRS) 4326 as defined by the European Petroleum Research Group (EPSG), most often referred to as EPSG:4326. EPSG:4326 utilizes the World Geodetic System 84 (WSG84) as its coordinate reference, the same coordinate system as utilized by the Global Positioning System (National Geospatial-Intelligence Agency 2020).

3.1 Data Curation and Network Construction

Although Good (2019) was able to generate a dataset for STX data for STT and STJ was still lacking. Therefore, the first step in the modeling process involves generating a dataset to support research into STT and STJ. Figure 3.1 depicts the software and workflow utilized throughout the process.

Figure 3.1. Diagram of the project's workflow. We develop and curate a geospatial dataset using QGIS. We then use Pyomo to solve the optimization model detailed in Section 3.3. Finally, we plot the resultant maps and graphs using Folium and matplotlib, respectively.

3.1.1 Ports and Supply Access Points

The initial step in data acquisition involves using Google Maps to export Keyhole Markup Language (KML) files of vital points of interest (e.g., ports, grocery and hardware stores, and fueling points) to the model, formatting and parsing the data via Geopandas (GeoPandas

Development Team 2020), and finally exporting the resultant file as a GeoJSON. The resultant GeoJSONs are then loaded into QGIS (QGIS Development Team 2020) and overlaid on an OpenStreetMap OpenStreetMap (OSM) (OpenStreetMap contributors 2020) street map. Figure 3.2 and Figure 3.3 show the resultant points on STT and STJ, respectively.

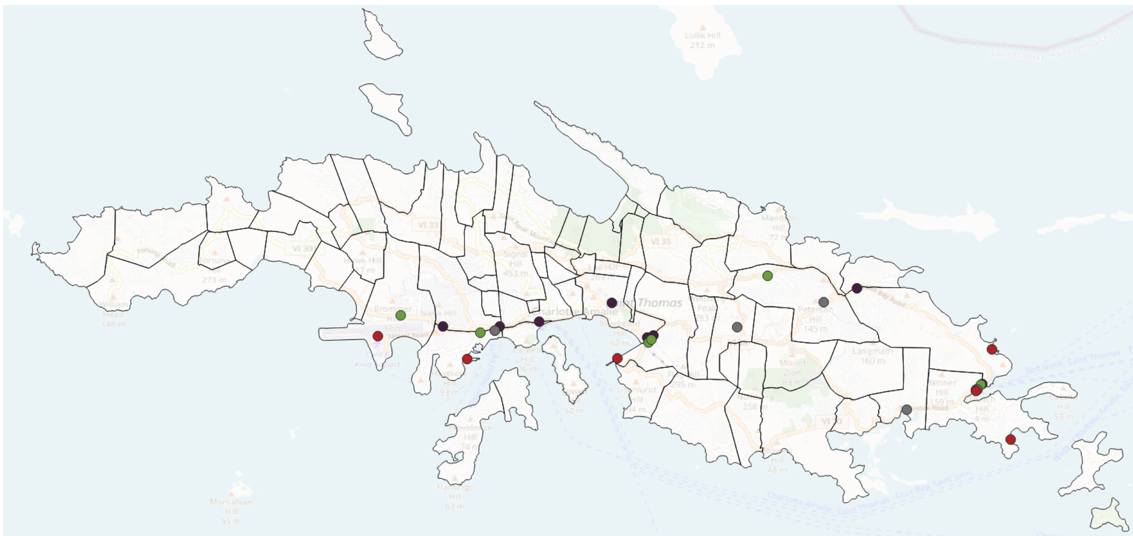


Figure 3.2. STT Ports and Supply Access Points plotted in QGIS using CRS EPSG:4326. Ports are represented by red points, gas stations in purple, grocery stores in green, and hardware stores in grey.

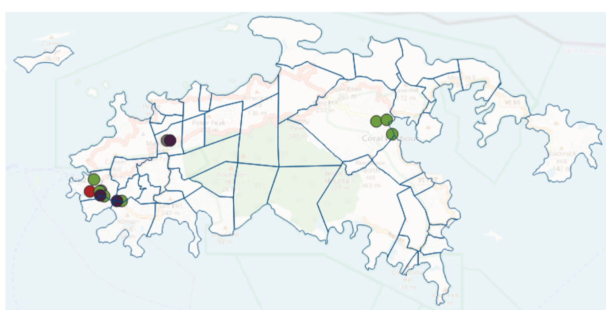


Figure 3.3. STJ ports and supply access points plotted in QGIS using CRS EPSG:4326. Ports are represented by red points, gas stations in purple, grocery stores in green, and hardware stores in grey. The points appear larger because of the smaller land mass.

3.1.2 Estates and Population Centers

The USVI uses *estates* for the purposes of census tracking. These estates are generally smaller than traditional census subdistricts, but serve the same role. The U.S. Census Bureau maintains the database of estates and their associated population counts as shape files. To initially define the population nodes, we import the shape files from the U.S. Census Bureau into QGIS, then create "centroids" in each estate. We lay these points over a "Google Satellite Hybrid" allowing for visual inspection and movement of the points over appropriate neighborhoods. For nodes with distinct surface road access points, we split the nodes were and distribute the population count uniformly over all of the population nodes in a given estate. Figure 3.4 and Figure 3.4 show the resultant estate boundaries and population nodes on STT and STJ, respectively.

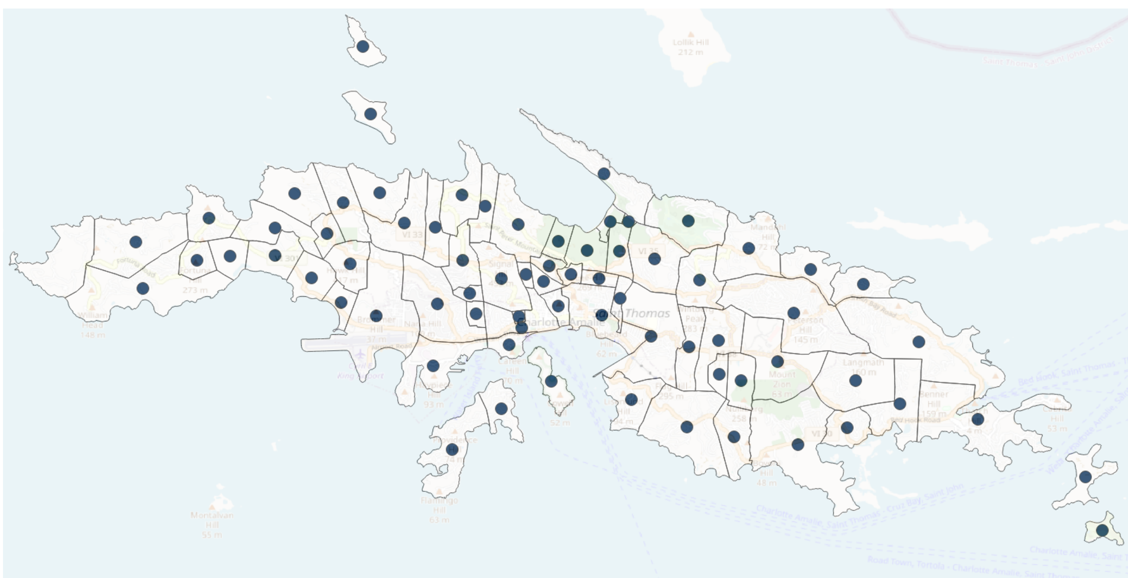


Figure 3.4. Estate boundaries and population nodes on STT. U.S. Census Bureau (USCB) estate boundaries shown in back. Population nodes are shown in blue.

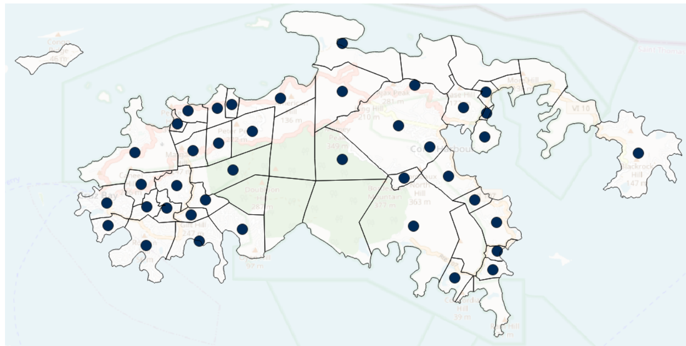


Figure 3.5. Estate boundaries and population nodes on STJ. USCB estate boundaries shown in back. Population nodes are shown in blue.

3.1.3 Transshipment Nodes

We create initial transshipment nodes by placing OSM features corresponding to highways and residential roads on an OSM overlay. Using the QGIS intersect tool, we place points on each intersection between a highway and a residential road. We place intermediate transshipment nodes along long stretches of highways and residential roads, as well as the more "winding" roads to increase the accuracy of the network. Figure 3.6 and Figure 3.7 show the resultant transshipment nodes on STT and STJ, respectively.

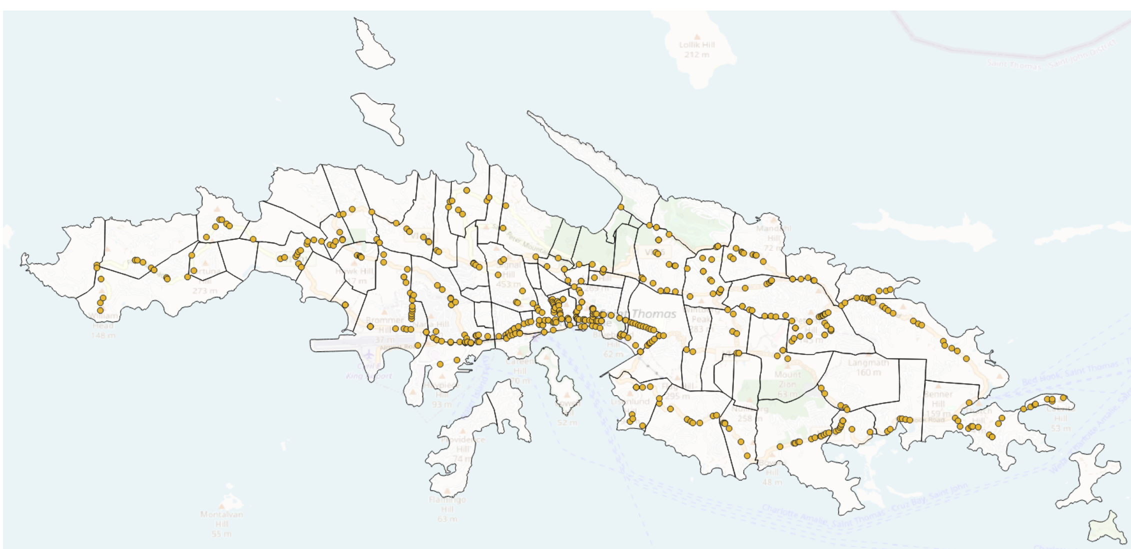


Figure 3.6. STT transshipment nodes.

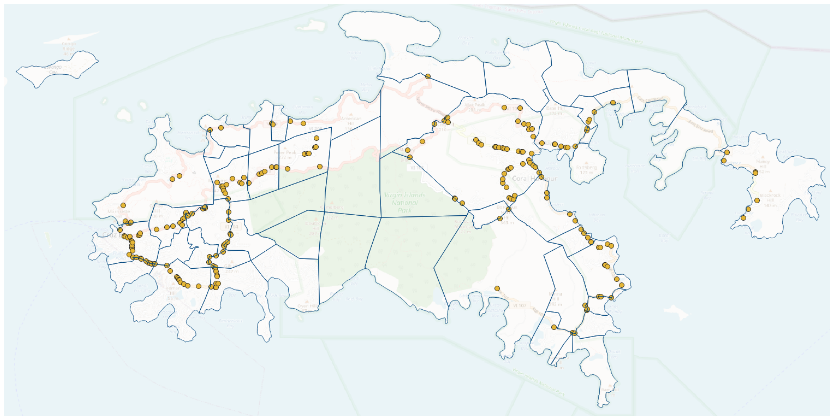


Figure 3.7. STJ transshipment nodes.

3.1.4 Network Construction

We construct the network by placing all previous nodes in QGIS over an OSM overlay of roads, then using a new vector layer, manually drawing lines between nodes with the line drawing tool that snaps to each point. After generating an accurate network of lines, we create the first "from-to" arc layer by using the QGIS "merge by location (summary)" tool, with the origin node as the minimum and the destination node as the maximum. We generate the second arc layer in the same manner, with the minimum and the maximum reversed. We then merge the two layers. The resultant arcs layer includes every arc required for the model. For each pair of nodes in the model, there are two corresponding arcs, representing an arc out and an arc in. We employ a Python script that uses the arcs GeoJSON generated by this method to create an adjacency list. This method proved significantly faster and more accurate than the manual method of adjacency list generation used by Good (2019). The arcs representing the road networks of STJ and STT are displayed in Figure 4.1 and Figure 5.1, respectively.

3.2 Four-Step Traffic Assignment

We follow the four-step modeling process used by Good (2019) and discussed by Maerivoet and De Moor (2005).

3.2.1 Step 1: Trip Generation

Trip generation begins by assigning origins and destinations. For our purposes, ports and population centers serve as origins, while stores and other supply access points serve as destinations. Because we are concerned with the number of vehicles on the road completing roundtrips from an origin to a destination, this necessitates determining the expected number of cars for each origin.

Population Center Vehicle Count

Based on 2010 census data, the average household size for STT is 2.35 persons per household and STJ is 2.18 persons per household. The distribution of these vehicles per household can be found in Table 3.1 (USVI Department of Public Works 2014).

Table 3.1. Vehicle distribution per household on STT and STJ. Source: USVI Department of Public Works (2014).

Vehicles Per Household	STT Count	STJ Count	STT Percent of Total	STJ Percent of Total
None	5000	380	23%	20%
1	9920	870	46%	46%
2	4860	520	23%	27%
3 or more	1770	130	8%	6%

From this data, we can calculate the number of households for each population node by dividing by the population of that node on STT by 2.35 and on STJ by 2.18 (USVI Department of Public Works 2014) and rounding up to the nearest integer. We then use Table 3.1 to calculate the proportion of households in a node that own zero, one, two, or three vehicles, rounding down to the nearest integer. Households in the "more" portion of "3 or more" are considered to only own three vehicles for the model.

3.2.2 Step 2: Trip Distribution

After generating trips, we connect origins to destinations by generating an origin-destination table. The full origin-destination full table for STT consists of 40 rows representing possible destinations, 109 columns representing possible origins, and values reflecting a vehicle count for each origin. STJ consists of 12 rows, 49 columns, and values reflecting a vehicle count for each origin node.

3.2.3 Step 3: Mode Choice or Modal Split

On STT, 16.7% of the population utilizes public transportation, while 62.7% drive alone (USVI Department of Public Works 2014). On STJ, 8.2% of the population utilizes public transportation, while 65.7% drive alone (USVI Department of Public Works 2014). With these numbers in mind, we assume that all trips exercised by car utilize the maximum vehicles at an origin node.

3.2.4 Step 4: Traffic Assignment

The last step is to determine which routes are followed between origins and destinations. At first, population centers are restricted to their nearest supply point using a 40/40/20 split between grocery stores, gas stations, and hardware stores, respectively. We assign only a single trip to any one vehicle leaving a population center based on accounts given to Good (2019) after the 2017 hurricanes. Additionally, we assume only one delivery is made to each supply access point from the port.

Lastly, we assume that individuals will make their decision on which supply access point to travel to based on a "selfish" or "coordinated" decision. A "selfish" decision involves no cooperation between individuals, and only self-interest is considered. A "selfish" decision will embark an individual to the nearest supply access point that serves their requirement. A "coordinated" decision involves information sharing between individuals, where the best outcome for the group is considered. This "coordinated" decision allows individuals to travel to the supply access point with the shortest travel time, which—depending on roadway congestion—may not be the nearest supply access point.

3.3 Model Formulation

We adopt the transportation model from Good (2019), which we repeat here for completeness.

Indices and Sets

$i \in N$	nodes (alias j, s, t)
$(i, j) \in A \subseteq N \times N$	arcs
$(s, t) \in D \subseteq N \times N$	set of all origin and destination pairs

$r \in R$	sections for piece-wise linear approximation
	($\bar{r}$ = total number of sections)
$Out_i \subset A$	set of all outbound arcs from node i
$In_i \subset A$	set of all inbound arcs to node i

Data [units]

b_{st}	supply rate at node s destined for node t
	($b_{st} < 0$ represents demand) [vehicles per hour (VPH)]
u_{ij}	nominal capacity of arc (i, j) [VPH]
s_{ij}	unrestricted speed of arc (i, j) [MPH]
d_{ij}	length of arc (i, j) [miles]
$avail_{ij}$	1 if arc (i, j) is available for use, 0 otherwise
q	maximum intended travel window for all
	origin-destination roundtrips [hours]

Calculated Data [units]

λ_{ij}	interval width on arc (i, j) for calculating piecewise linear congestion
	$\lambda_{ij} = 2u_{ij}/\bar{r}$
h_{ijr}	total travel time for all vehicles traversing segment r on arc (i, j)
	$h_{ijr} = \left(r\lambda_{ij}\right)\left(\frac{d_{ij}}{s_{ij}}\right)\left(1 + 0.15\left(\frac{r\lambda_{ij}}{u_{ij}}\right)^4\right)$
$slope_{ijr}$	slope of segment r for arc (i, j)
	$slope_{ijr} = \frac{h_{ijr} - h_{ijr-1}}{\lambda_{ij}}$
$intercept_{ijr}$	y intercept of line section r for arc (i, j)
	$intercept_{ijr} = -slope_{ijr}(r\lambda_{ij}) + h_{ijr-1}$

Decision Variables [units]

Y_{stij}	flow rate of supply originating at node s destined for node t
	transiting arc (i, j) [VPH]
Y_{ij}	total flow rate transiting arc (i, j) [VPH]
Z_{ij}	travel time on arc (i, j) [vehicle hours]
$Dropped_{st}$	dropped quantity of supply originating at node s destined for

node t [vehicles]

$Excess_{st}$ excess quantity of demand originating at node s destined for node t [vehicles]

Formulation

$$\min_{Y,Z,Dropped,Excess} \quad \sum_{(i,j)\in A} Z_{ij} + \sum_{(s,t)\in D, s\neq t} \frac{q}{2} \cdot Dropped_{st} \tag{3.1}$$

$$\text{s.t.} \quad \sum_{(i,j)\in Out_i} Y_{stij} - \sum_{(j,i)\in In_i} Y_{stji} + Dropped_{st} = b_{st} \quad \forall i \in N, (s,t) \in D, i = s \tag{3.2}$$

$$\sum_{(i,j)\in Out_i} Y_{stij} - \sum_{(j,i)\in In_i} Y_{stji} - Excess_{st} = -b_{st} \quad \forall i \in N, (s,t) \in D, i = t \tag{3.3}$$

$$\sum_{(i,j)\in Out_i} Y_{stij} - \sum_{(j,i)\in In_i} Y_{stji} = 0 \quad \forall i \in N, (s,t) \in D, i \neq s, i \neq t \tag{3.4}$$

$$Y_{stij} \leq b_{st} \quad \forall (s,t) \in D, (i,j) \in A \tag{3.5}$$

$$Y_{ij} = \sum_{s,t\in D} Y_{stij} \quad \forall (i,j) \in A \tag{3.6}$$

$$Y_{ij} \leq 2u_{ij}avail_{ij} \quad \forall (i,j) \in A \tag{3.7}$$

$$Z_{ij} \geq intercept_{ijr} + slope_{ijr} \cdot Y_{ij} \quad \forall (i,j) \in A, \forall r \in R \tag{3.8}$$

$$Excess_{st} = Excess_{ts} \quad \forall (s,t) \in D \tag{3.9}$$

$$Dropped_{st} = Dropped_{ts} \quad \forall (s,t) \in D \tag{3.10}$$

$$Y_{stij}, Y_{ij}, Z_{ij}, Dropped_{st}, Excess_{st} \geq 0 \quad \forall (i,j) \in A, (s,t) \in D \tag{3.11}$$

Discussion

The objective function value (3.1) of the formulation provides the total cost in terms of vehicle hours of assigning traffic along each arc (i, j) and enforces a penalty if there is any dropped flow. The penalty enforced by dropped flow is a combination of the number of vehicles that do not travel because of road congestion weighted by half of the maximum roundtrip travel time. Constraints (3.2) enforces balance of flow for supply nodes. Constraints (3.3) enforces balance of flow for demand nodes. Constraint (3.4) enforces balance of flow for transshipment nodes. Constraints (3.5) enforces the capacity of flow of supply (s, t) over arc (i, j). Constraints (3.6) calculates the intermediate value for total flow over each arc. Constraints (3.7) requires total flow over arc (i, j) to be less than the arc's capacity. Constraints (3.8) requires that the travel time over an arc (i, j) be lower-bounded by the piece-wise sections $r \in R$. Constraints (3.9) and (3.10) enforce symmetry for the elastic variables. Constraint (3.11) enforces non-negativity on the other decision variables.

This model analyzes the *rate* of traffic. The model assumes that all traffic will leave from their origin in the first hour they are able. This provides a worst-case supply rate at any given location to be equal to the number of vehicles at a location. Since we are modeling travel under the effects of a curfew, we assume a three-hour window for a one-way trip from a supply location to a destination. This approximates the six-hour curfew ($q = 6$) that was implemented in the USVI. We assume that a family will decide to remain home if a one-way trip will exceed six hours in length.

Roundtrip travel times can exceed six hours because of non-linear congestion. This is expected only as $\lambda_{ij} = 2u_{ij}$ is approached.

Travel Time Function using a Piecewise Linear Approximation

Given a total flow of Y_{ij} an average travel time over an arc (i, j) is given by the Bureau of Public Roads (BPR) function (Good 2019; Peeta et al. 2015), which is defined by $f_{ij}(Y_{ij}) = \frac{d_{ij}}{s_{ij}}\left(1 + 0.15\left(\frac{Y_{ij}}{u_{ij}}\right)^4\right)$. Thus, the total travel time in vehicle hours, or the "cost" on an arc (i, j) is the product of total flow Y_{ij} and the non-linear travel time $f_{ij}(Y_{ij})$. We bound Z_{ij}, the total travel time, by a sequence of linear approximations $r \in R$ as defined by constraint (3.8). We follow the convention in Alderson et al. (2014) and use $\bar{r} = 40$, yielding a suitable approximation.

3.4 Computation and Post-processing

We implement and solve the model on a custom Windows computer with an AMD Ryzen 3600 processor and 16GB of RAM. Both networks took under 15 minutes to run to completion.

Removal of Artificial Flows

As the formulation above is an equilibrium model, it attempts to balance the objective function across all of the routes. It is possible, in that case, that small flows along routes may not follow the shortest path by either time or distance. Cycles in flow are also not explicitly prevented. To correct this, after the model is run, we conduct post-processing to remove artificial flows. As in Good (2019) for each (s,t) commodity, we extract the flows as a standalone network and first make sure that the traffic properly makes its way from origin to destination, and second, removes any artificial flows, including cycles. After this post-processing, the resultant network flows are ready for analysis.

3.5 Demonstrating the Effects of Winding and Flooded Roads with a Simple Road Network

We present a simple network to demonstrate the structure and model in Figure 3.8. The network uses geospatial data from STJ, but is not an accurate representation of the island's road network.

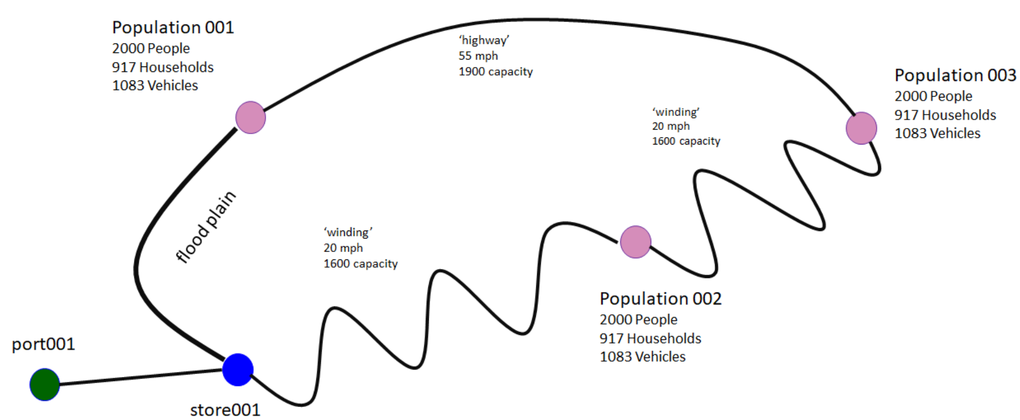


Figure 3.8. Simple road network. A simple road network to demonstrate the model. There are four origin nodes, consisting of one port and three population nodes. The sole destination node is "store001." There are two road types modeled: a northern highway, and a southern winding road. The arcs are labeled with their type, speed, and capacity. Population nodes are labeled with their total population, and household and vehicle proportions derived from STJ totals from Table 3.1.

This small network contains three population nodes having the characteristics shown in Table 3.2. Traffic originating from these three nodes travel to the sole destination in the network, "store001."

Table 3.2. Simple model population nodes.

Name	Population	Households	Vehicles
population001	2000	917	1083
population002	2000	917	1083
population003	2000	917	1083

The three population nodes have the choice of taking the highway or the winding road. Speed and capacities for the road types are found in Table 3.3.

Table 3.3. Flow capacity for road types. Winding was created for our purposes. Other speeds and capacities were used by Good (2019) and derived from Zegeer et al. (2008)

Road Type	Speed (MPH)	Capacity (VPH)	Flooded Speed (MPH)	Flooded Capacity (VPH)
Highway	55	1900	27.5	950
Urban	25	1700	12.5	850
Rural	35	1600	17.5	800
Winding	20	1600	10	800
Dirt	10	1000	5	500

3.5.1 Traffic under Normal Conditions

We first consider the model under normal conditions (Figure 3.9), normal meaning no flooding or impassable roads. We solve the model for the optimum flow (Y_{ij}) through the network to meet demand requirements while minimizing total travel time. We use the flow results to calculate flow-to-capacity ratios ($\frac{Y_{ij}}{u_{ij}}$), and the resulting reduction in arc transit speeds ($\frac{d_{ij}}{f_{ij}(Y_{ij})}$). These results are found in Table 3.4, where we use it display the resultant congestion in the system seen in Figure 3.9. The darker the color, the more congestion over the arc.

We find the most congestion in the system over arc (population001, store001). This is because only 80 vehicles from population003 travel the winding road to their destination, while the remaining vehicles take the longer distance, but faster highway. The remaining

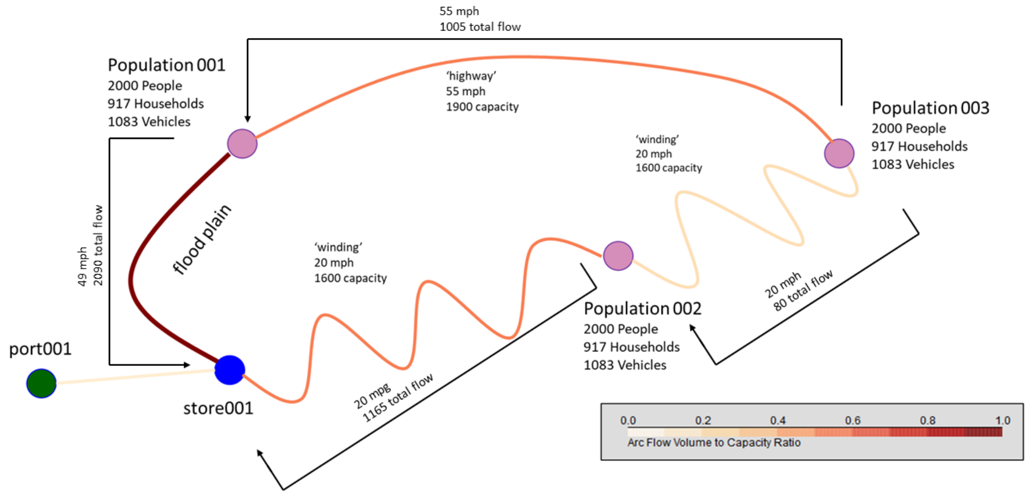


Figure 3.9. Winding road network. The majority of population003 takes the highway to population001. We also see congestion in arc (population001, store001) resulting in a 6 MPH speed reduction.

vehicles from population003 meet the vehicles from population002 where flow exceeds capacity and the system congests. We see a decrease in actual speed on arc (population001, store001) from 55 MPH to 49 MPH.

Table 3.4. Winding road network flow capacity. Traffic flows and travel speed for simple network under normal conditions.

i	j	Y_{ij}	u_{ij}	$\frac{Y_{ij}}{u_{ij}}$	s_{ij}	$\frac{d_{ij}}{f_{ij}(Y_{ij})}$
population003	population001	1005	1900	0.529	55	55
population003	population002	80	1600	0.050	20	20
population002	store001	1165	1600	0.728	20	20
population001	store001	2090	1900	1.100	55	49

3.5.2 Traffic under Flooded Conditions

Next, we consider the model under flooded conditions (Figure 3.10). We "flood" arc (population001, store001), activating the "flooded speed" and "flooded capacity" from Table 3.3 to see how the model solution changes. These results are found in Table 3.5.

We find that where only 80 vehicles traversed the winding road under normal conditions,

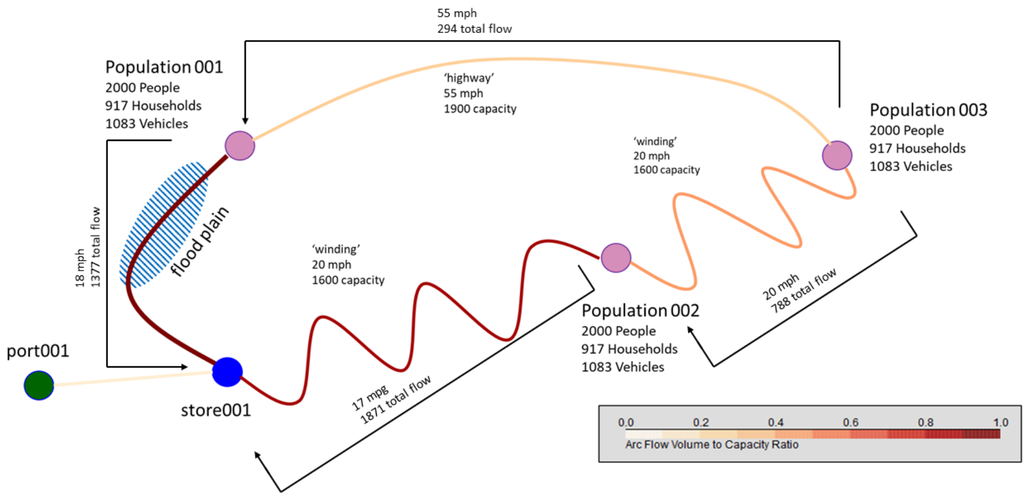


Figure 3.10. Winding road network under flooded conditions. We see fewer vehicles from population003 take the highway to population001. As a result, we see congestion form in arcs (population002, store001) and (population001, store001) where speeds are reduced to 17 MPH and 18 MPH respectively.

Table 3.5. Traffic flows and travel speed for simple model under normal conditions

i	j	Y_{ij}	u_{ij}	$\frac{Y_{ij}}{u_{ij}}$	s_{ij}	$\frac{d_{ij}}{f_{ij}(Y_{ij})}$
population003	population001	294	1900	0.155	55	55
population003	population002	788	1600	0.050	20	20
population002	store001	1871	1600	1.170	20	17
population001	store001	1377	950	1.45	27	18

788 now make the journey since arc (population001, store001) is flooded. With this added flow, arc (population002, store001) exceeds its capacity and begins to congest. Speed over arc (population001, store001) falls to 18 MPH. Speed over arc (population002, store001) falls to 17 MPH. We see that the model can account for changes in road condition caused by flooding and changing circumstances.

3.5.3 Discussion

This is a highly simplified network. However, it does demonstrate some of the key tensions at work in the real-world road network of the USVI where flooding and winding roads are endemic. We next consider behavior for the real systems on both STT and STJ.

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CHAPTER 4:
Analysis and Results for St. John

We apply the model from Section 3.3 to the of island STJ. We consider 49 origins (48 population nodes and one port) and 12 destinations (seven grocery stores, three gas stations, and two hardware stores) connected by a network of 684 road segments. Figure 4.1 demonstrates the network.

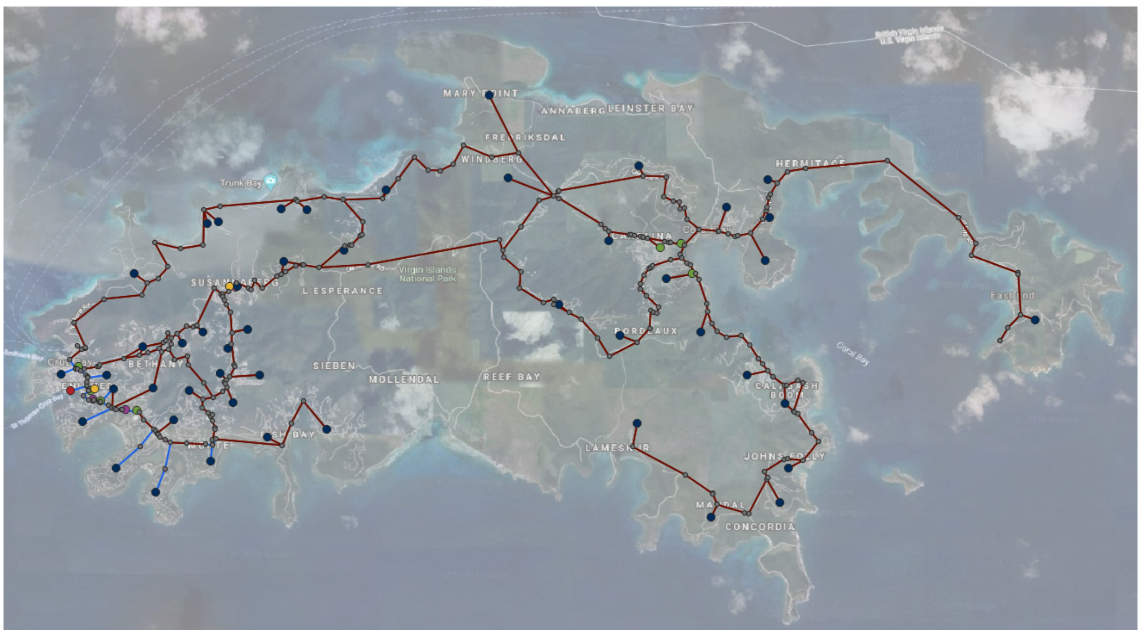

Figure 4.1. STJ model road network. "Urban" roads are in blue. "Winding" roads are in burgundy. Created using QGIS Development Team (2020) on 18 September 2020.

We address several questions.

1. Under normal conditions, what are the roundtrip travel times and congestion between population locations and the port?
2. Under flooded conditions, what are the roundtrip travel times and congestion between population locations and the port?
3. Under worst-case conditions, what are the roundtrip travel times and congestion between population locations and the port?

Good (2019) looked at traveler destination choices based on either “selfish routing,” where travelers travel to their closest destination regardless of circumstances, or “coordinated routing” where a central authority such as VITEMA or FEMA determines ahead of time the most efficient destination for any given traveler. For our analysis, we assume routing is being coordinated by an authority. To simulate this, we add a “supersink” to each type of destination, as well as arcs connecting each destination to its corresponding “supersink.” This allows the model to determine which destination should be traveled to. Some travelers may have to travel further than they would have under their own myopic decisions, but the resultant roundtrip time could be faster.

Following the convention in Good (2019), we assume that from each population center, 40% travel to grocery stores, 40% travel for fuel, and the remaining 20% travel to hardware stores. In addition, we assume that each traveler makes only one roundtrip per curfew period. Roundtrips only include time on the road and do not include time spent at destinations. Lastly, for the purposes of calculations, we include only a single delivery from the port to each supply access point.

4.1 Travel under Normal conditions

Figure 4.2 shows the resulting traffic flows on STJ. We assume there are no road blockages and the maximum allotted travel time is six hours ($q = 6$). Road segments are displayed according to their flow-to-capacity ratios. A darker color indicates a higher ratio, indicating higher congestion. We can see that the roads are not nearing their maximum capacity. Not surprisingly, the two most heavily traveled road segments are Centerline Rd. and Highway 104.

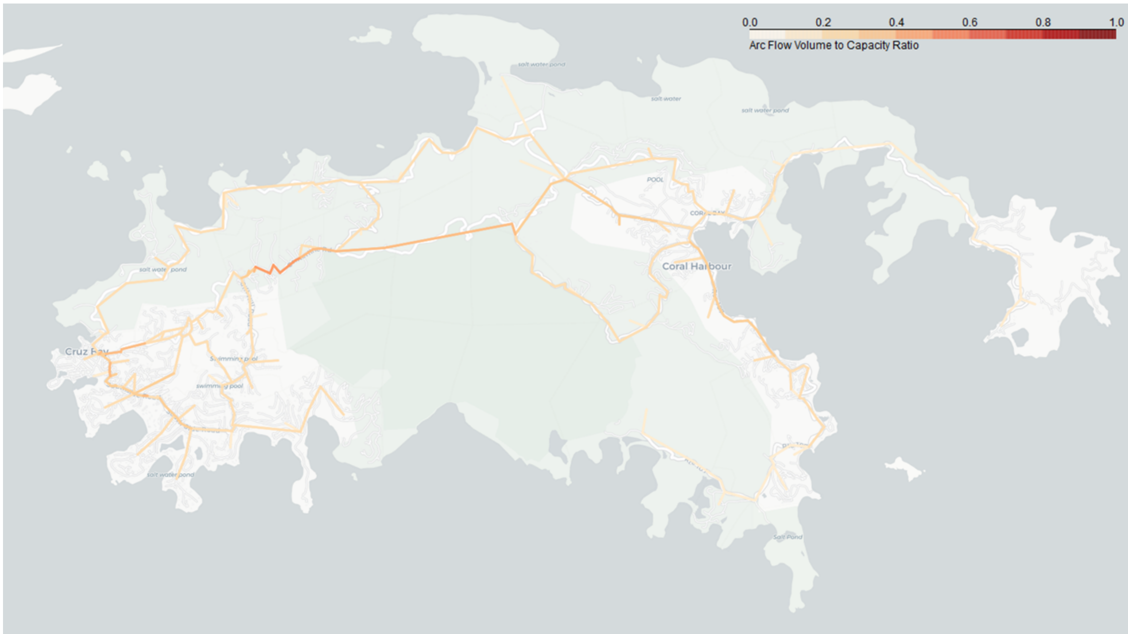

Figure 4.2. STJ traffic flows under normal conditions. Arcs are displayed according to their flow-to-capacity ratios. Higher ratios are depicted by darker colors. Created using QGIS Development Team (2020) on 14 September 2020.

Though not displayed in a figure, we find that there is no dropped demand on STJ under normal conditions. This means that all travelers can reach their intended destination and return home within a six-hour curfew window.

Figure 4.3 shows the roundtrip travel time distributions to each store type. We are interested in which populations are most affected by the limited stores on the eastern side of the island and the potential long travel times through the "winding" roads of the center of the island.

We find that roundtrip times generally remain under an hour, with the exception of some hardware stores. This is not wholly unexpected as residents have to make the aforementioned trip through the mountains to reach the western side's hardware stores.

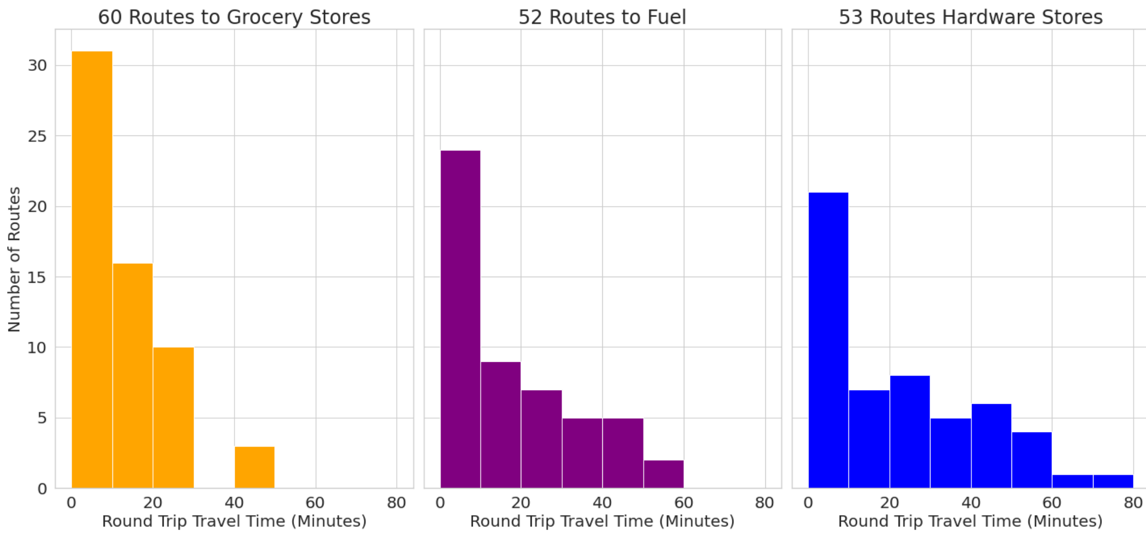

Figure 4.3. STJ roundtrip travel times under normal conditions. While most trips are under one hour, some roundtrips to hardware stores exceed that.

Table 4.1 shows the averages and standard deviations for all roundtrip travel times. We see that only hardware stores exceed 20-minute roundtrips.

Table 4.1. STJ average roundtrip times under normal conditions.

Destination Type	Average (minutes)	Standard Deviation (minutes)
All	17.40	16.07
Grocery	12.66	10.62
Fuel	17.45	15.51
Hardware	22.71	19.89

Figure 4.4 displays the longest roundtrip travel times for all destinations. Unsurprisingly, the longest travel times are experienced by residents of the eastern population centers attempting to reach hardware stores and fuel on the western side of the island. Population center "population041-Calabash Boom" faces the longest travel times on the island, needing approximately 70 minutes to reach a hardware store and return home.

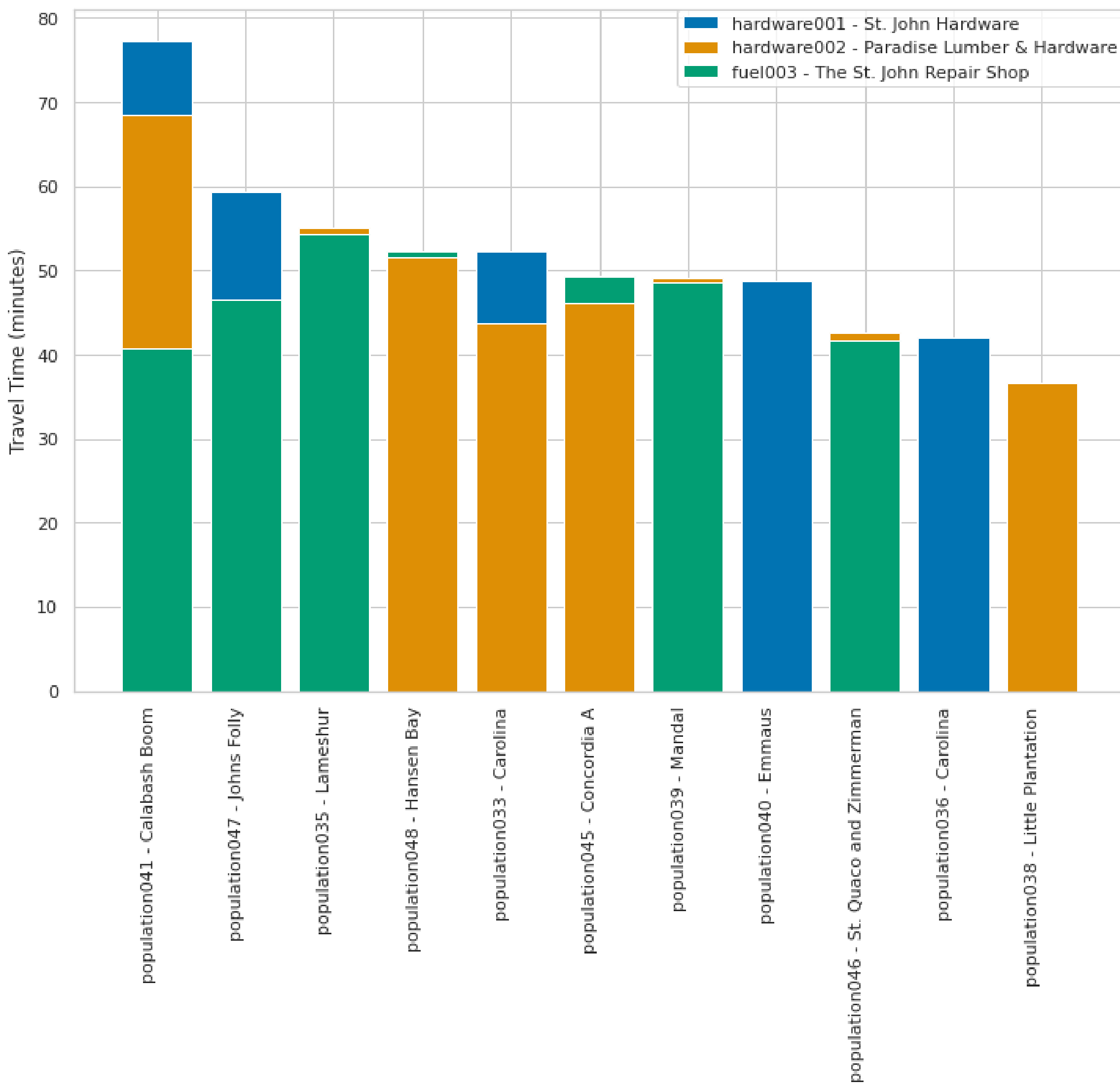

Figure 4.4. STJ roundtrip travel times for all store types under normal conditions. The height of the bar indicates the total travel time from a particular origin to a given store. Color of bar indicates the store. In cases where an origin has more than one longest round trip, the bars are superimposed with one color per store.

Figure 4.5 displays the longest roundtrips to grocery stores. No trip exceeds 30 minutes. Since there are three grocery stores on the eastern side of the island, residents of the eastern population centers do not need to travel as far they would have to for fuel or hardware. Interestingly, the longest roundtrip time belongs to “population025-Adrian,” a population center in the center of the island. While nearly next door to fuel and hardware, its central location combined with grocery stores being on the island’s periphery result in a comparatively long roundtrip.

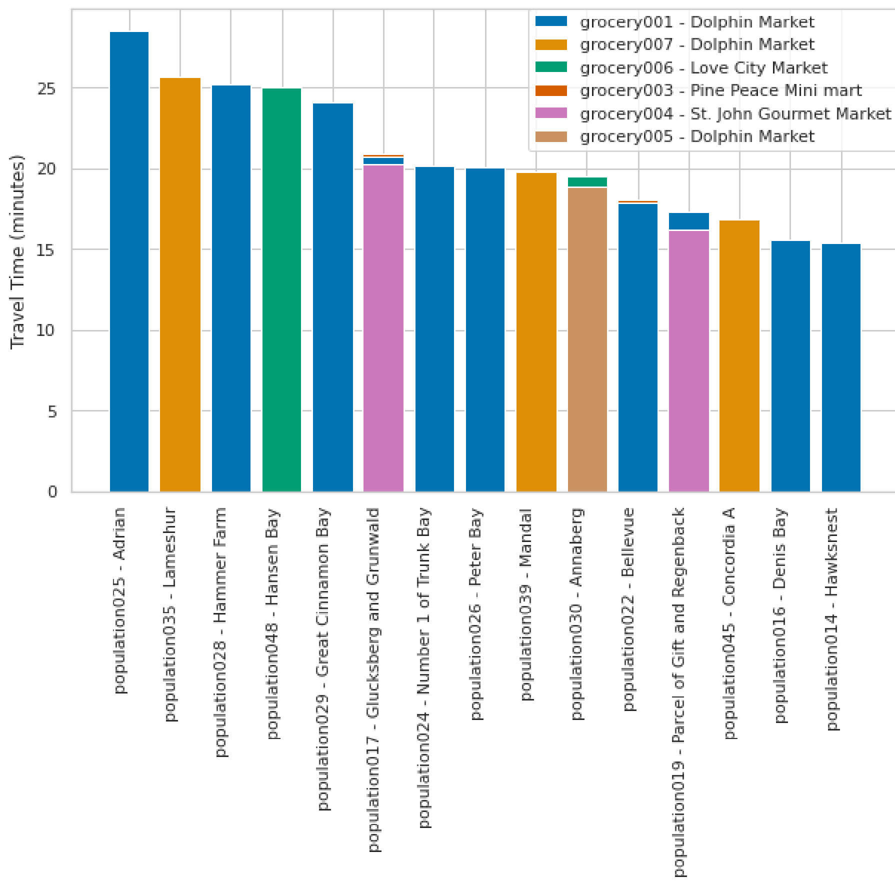

Figure 4.5. STJ roundtrip travel times for grocery stores under normal conditions. The height of the bar indicates the total travel time from a particular origin to a given store. Color of bar indicates the store. In cases where an origin has more than one longest round trip, bars are superimposed with one color per store.

Figure 4.6 displays the longest roundtrips for fuel. We observe that the entire eastern side of the island travels to “fuel003-The St. John Repair Shop” for fuel. That trip can take as long as an hour for the furthest population centers. We see that “population035- Lameshur” and “population048-Hansen Bay,” two of the most remote population centers, exceed 50 minute roundtrips for fuel. A concern is that with only three sources of fuel on the island, and “fuel003-The St. John Repair Shop” being the fuel supply for the eastern side of the island, service times may be excessive. Additionally, depending on fuel supply available, there is a possibility that one or more of the fueling points may run out of product.

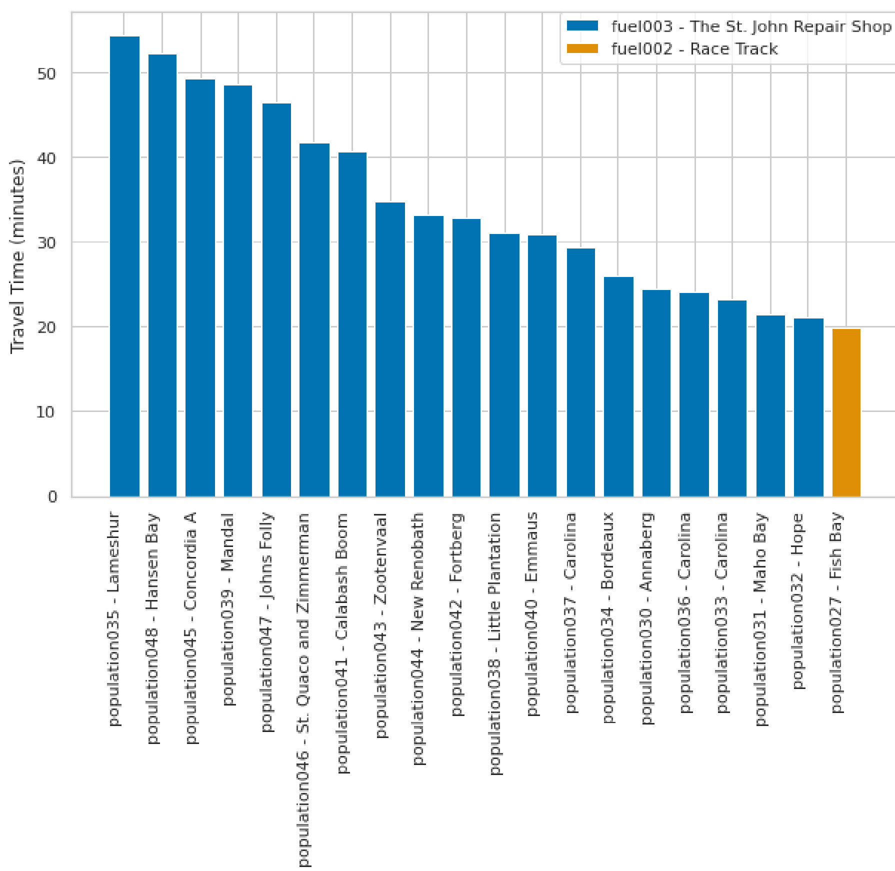

Figure 4.6. STJ roundtrip travel times for fuel under normal conditions. The height of the bar indicates the total travel time from a particular origin to a given store. Color of bar indicates the store. In cases where an origin has more than one longest round trip, bars are superimposed with one color per store.

Figure 4.7 displays the longest roundtrips to hardware stores. Every trip is under one hour except "population041-Calabash Boom" to "hardware001-St. John Hardware," which takes over 75 minutes. This is slightly longer than the time it takes "population041-Calabash Boom" takes to reach the other hardware store "hardware002-Paradise Lumber & Hardware." Interestingly, population centers further out than "population041-Calabash Boom" such as "population035-Lameshur" take less time to reach hardware stores. This is because the model is routing "population041-Calabash Boom" differently than "population035-Lameshur." Routing "population041-Calabash Boom" over a longer route reduces the total amount of time travellers are on the road as a whole.

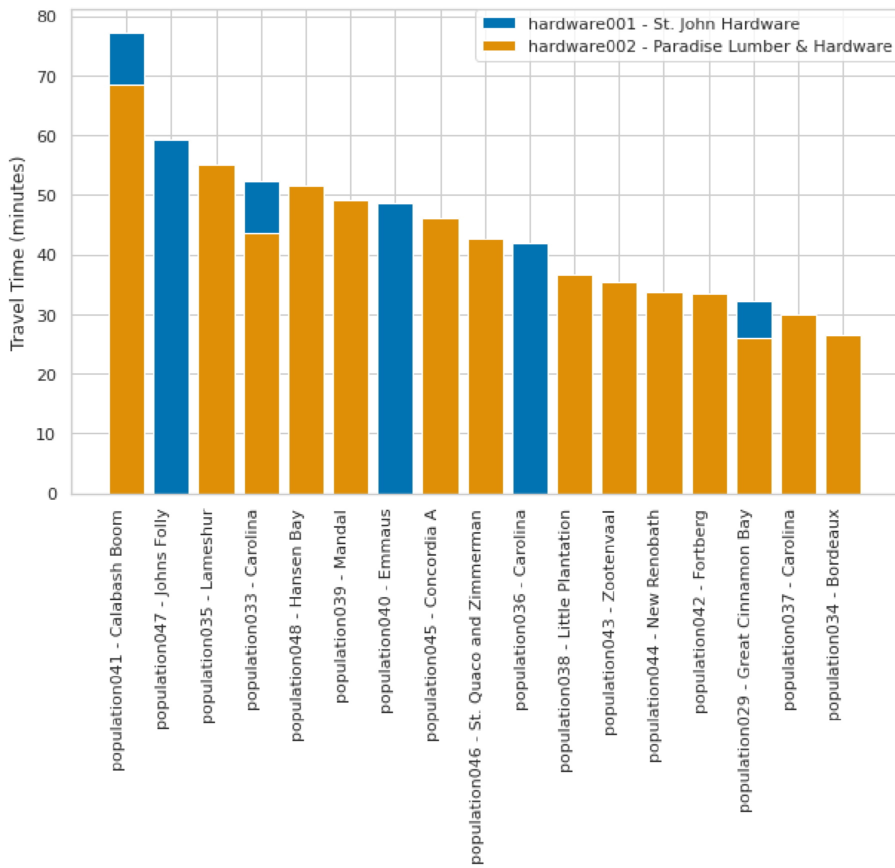

Figure 4.7. STJ roundtrip travel times for hardware stores under normal conditions. The height of the bar indicates the total travel time from a particular origin to a given store. Color of bar indicates the store. In cases where an origin has more than one longest round trip, bars are superimposed with one color per store.

In terms of travel from the Theovald Eric Moorehead Dock and Terminal at Enighed Pond, Figure 4.8 displays the longest roundtrips to resupply supply sources. Unsurprisingly, the longest times are for the grocery stores on the eastern side of the island; “grocery005-Dolphin Market,” “grocery006-Love City Market,” and “grocery005-Dolphin Market.” All three trips take in excess of 40 minutes. Two stores, “fuel003-The St. John Repair Shop” and “hardware002-Paradise Lumber & Hardware” exceed 10 minutes. All other stores are under five minutes.

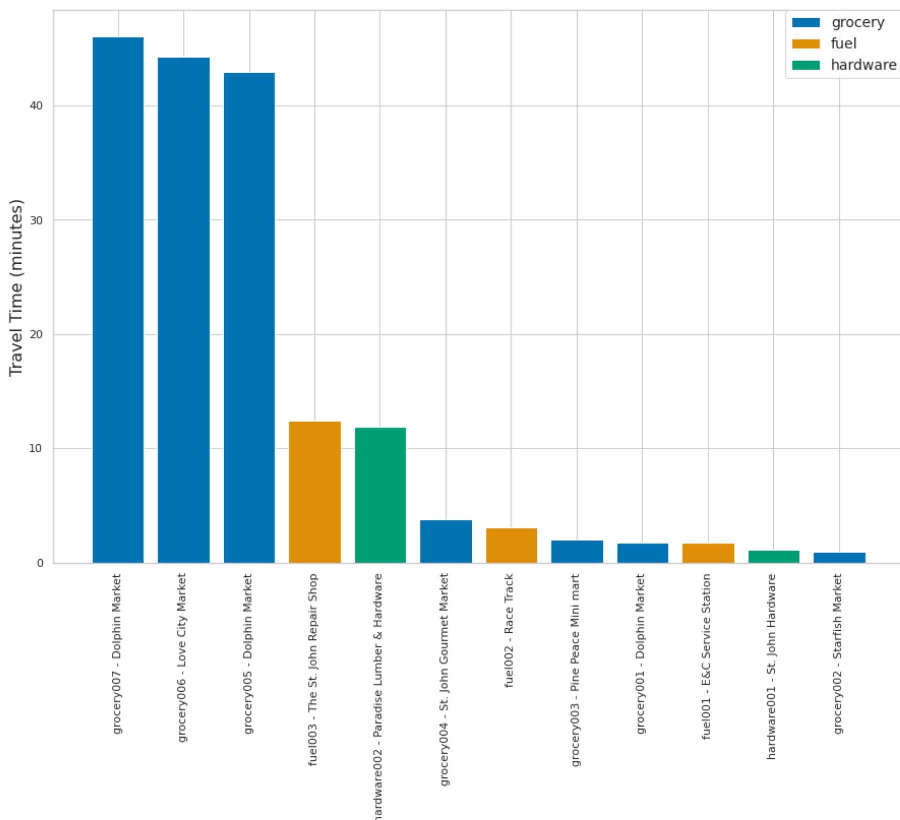

Figure 4.8. STJ travel time from the port under normal conditions. Roundtrip travel times in minutes from the Theovald Eric Moorehead Dock and Terminal at Enighed Pond to all stores. Color of bar indicates the store type.

Figure 4.9 depicts the longest routes from population centers to sources of supply on the island. The key point is that all of the longest trips belong to population centers on the eastern end of the island. In order to procure hardware or fuel, they have to traverse the entire island. If travel between ends of the island was disrupted, they would be entirely cut off from hardware and fuel.

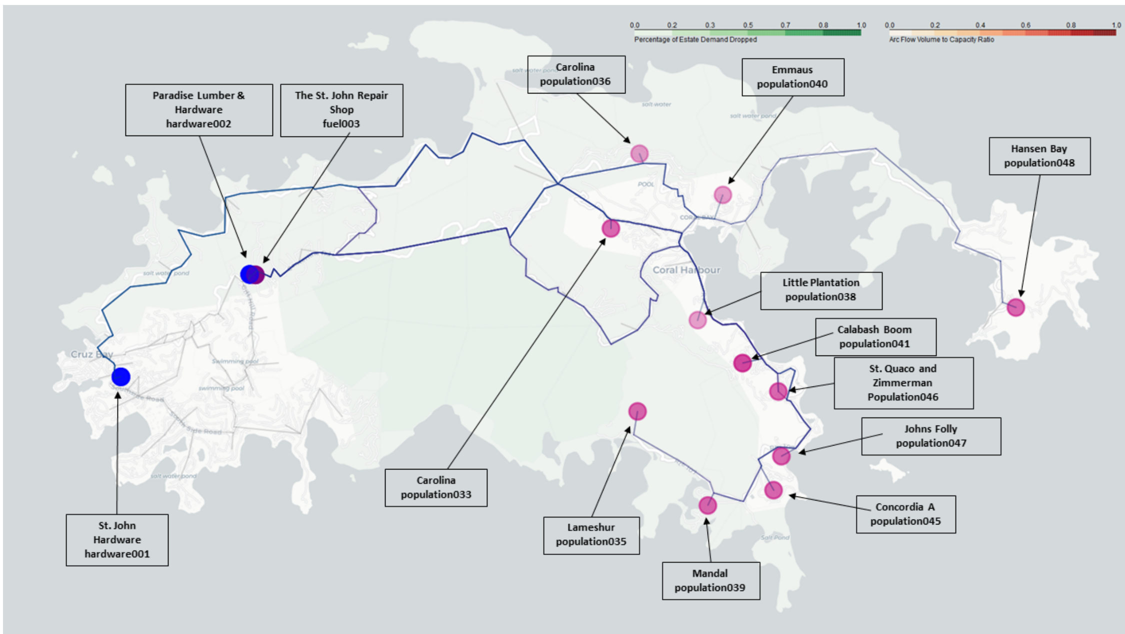

Figure 4.9. STJ longest trips under normal conditions. Route colors indicate the destination store type: blue for hardware stores, orange for grocery stores, and purple for gas stations. The remaining arcs are rendered in grey. Created using QGIS Development Team (2020) on 14 September 2020.

4.2 Travel under Flooding

We now look at potential flooding and its effects on the road network. Dr. Greg Guannel, from UVI, provided maps of areas prone to flooding and storm surge. Figure 4.10 shows these areas with flooding up to three inches in bright blue. Roads flooded by three inches of water were found by Pregnolato et al. (2017) to reduce speed by half. Roads that are considered "flooded" for the purposes of the model are indicated in red and have had their speed and capacity halved.

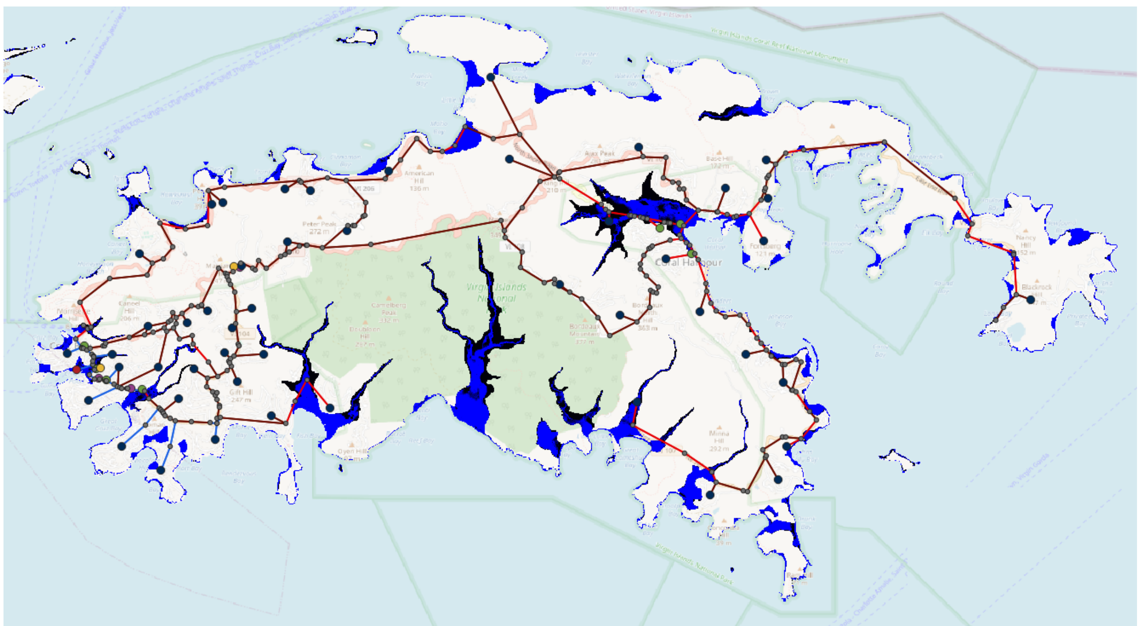

Figure 4.10. STJ areas prone to flooding and storm surge. Bright blue areas indicated flooding. Roads in red indicated roads considered "flooded" for the model. Created using QGIS Development Team (2020) on 14 September 2020.

Figure 4.11 shows the flows under flooded conditions. We see that there is additional congestion in the Cruz Bay area on the western end of the island, in the area west of Coral Bay, and in the inland route through the middle of the island. Though, the increase in flow does reach the capacity of the roads.

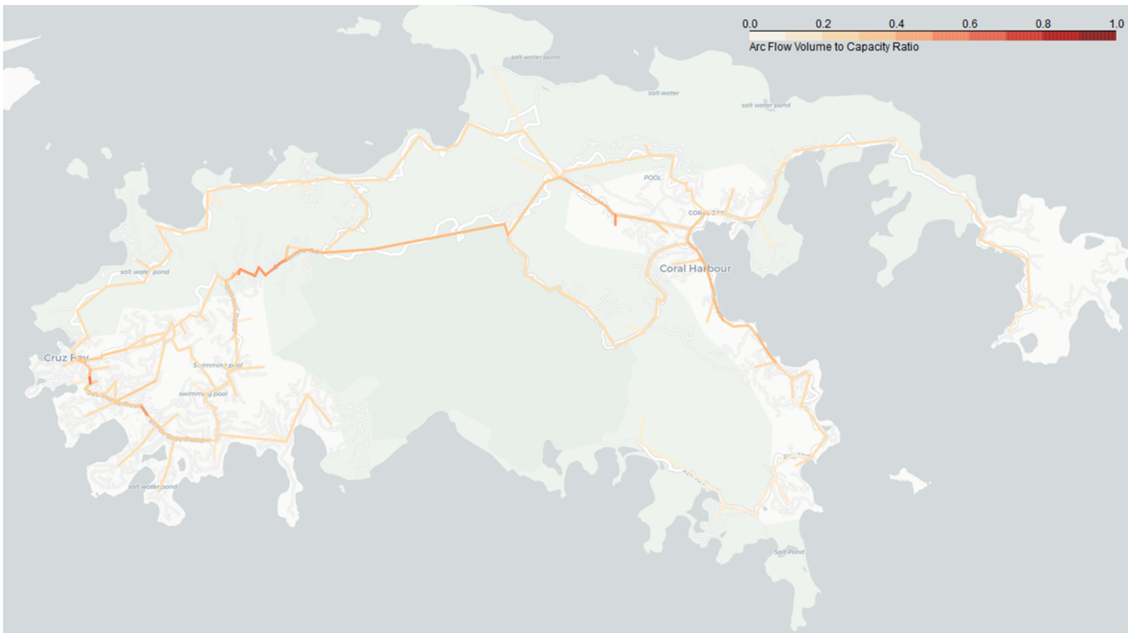

Figure 4.11. STJ traffic flows under flooded conditions. Arcs are displayed according to their flow-to-capacity ratios. Higher ratios are depicted by darker colors. Created using QGIS Development Team (2020) on 14 September 2020.

Figure 4.12 shows the roundtrip travel time distributions to each store type. We see increases in roundtrip travel times for each store type. Most population nodes retain their relatively short travel times, but some others, mostly those with the highest travel times, increase. The maximum grocery store roundtrip travel time increases from under 50 minutes to over an hour. The maximum fuel roundtrip travel time increases from under an hour to over 70 minutes. The maximum hardware store roundtrip time increases from 80 minutes to over 90.

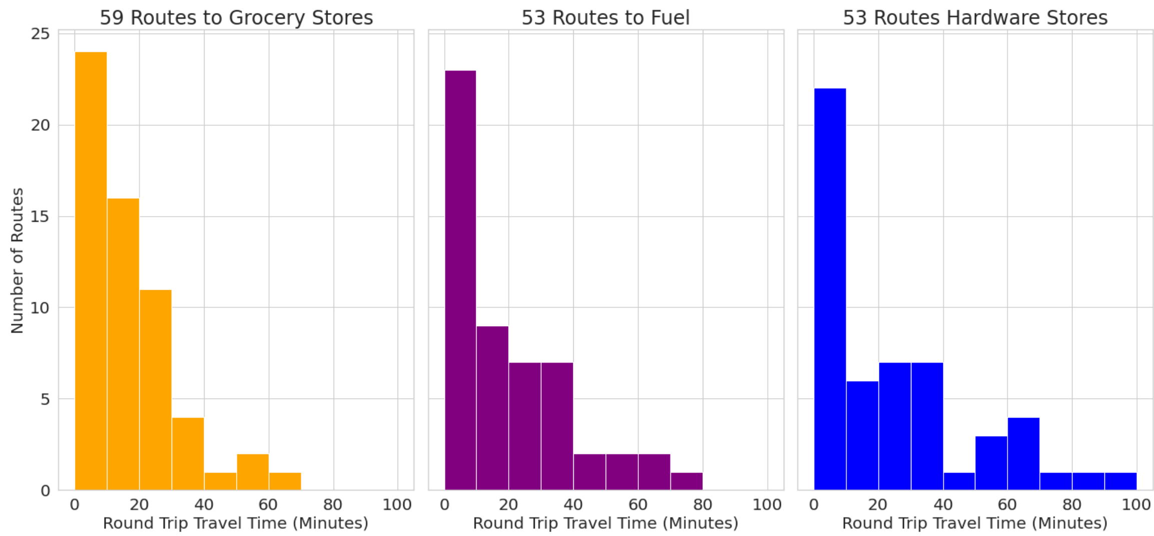

Figure 4.12. STJ roundtrip travel times under flooded conditions. We see an increase in roundtrip travel times across all store types.

Table 4.2 shows the averages, standard deviations, and change in average for all roundtrip travel times. Whereas before only hardware stores had roundtrip travel times in excess of 20 minutes, that time is now exceeded by the average of all stores and fuel. We see the smallest change in travel time to hardware stores.

Table 4.2. STJ average roundtrip times under flooded conditions.

Destination Type	Average (minutes)	Change in Average (minutes)	Standard Deviation (minutes)
All	20.26	2.86	19.80
Grocery	16.10	3.44	14.28
Fuel	20.23	2.78	19.12
Hardware	24.95	2.24	24.54

Figure 4.13 displays the longest roundtrip travel times for all destinations. Population “population041-Calabash Boom” again suffers the most here, with the longest travel time approaching 100 minutes. Population “population035-Lameshur” overtakes “population047-Johns Folly” as holder of the second longest travel time, increasing from 55 minutes to 70 minutes. We see the first appearance of a grocery store in the form of “grocery001-Dolphin Market,” where it takes “population025-Adrian” over 40 minutes roundtrip.

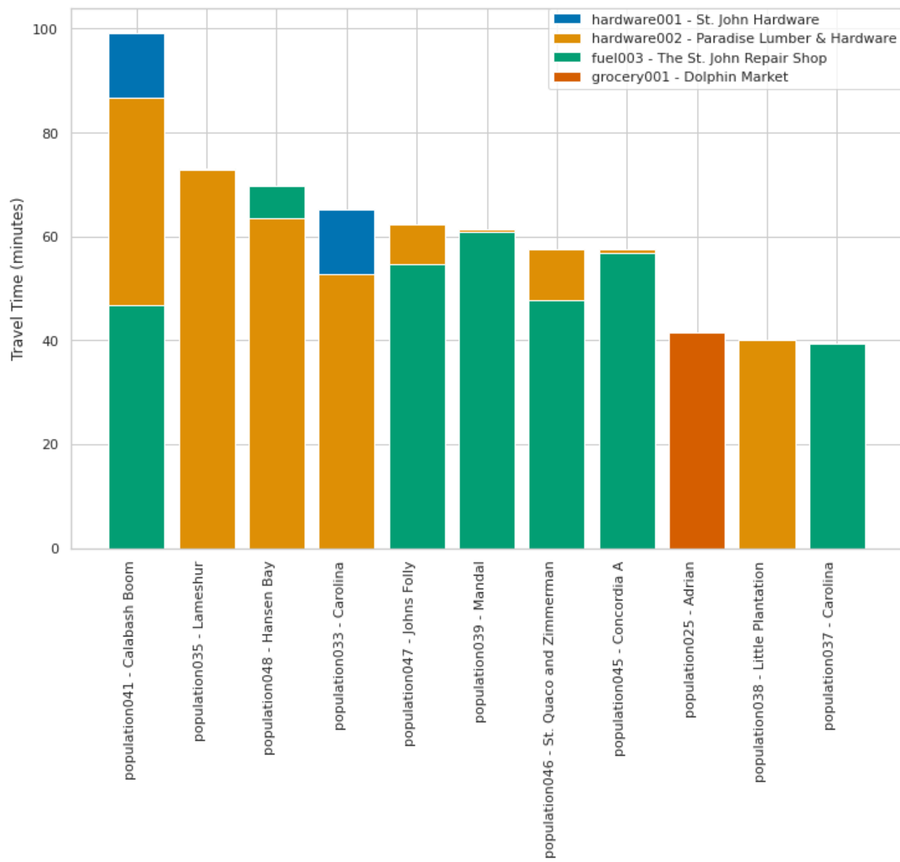

Figure 4.13. STJ roundtrip travel times for all store types under flooded conditions. The height of the bar indicates the total travel time from a particular origin to a given store. Color of bar indicates the store. In cases where an origin has more than one longest round trip, the bars are superimposed with one color per store.

Figure 4.14 displays the longest grocery travel times. Population “population025-Adrian” sees an increase of more than 15 minutes in its trip to “grocery001-Dolphin Market.” In addition to the highest overall, it has the fourth-highest roundtrip travel time over in its trip to “grocery003-Pine Peace Mini Mart.” During flooding, “population025-Adrian” would have the most difficulty quickly reaching groceries, though it would be well within the six-hour curfew window.

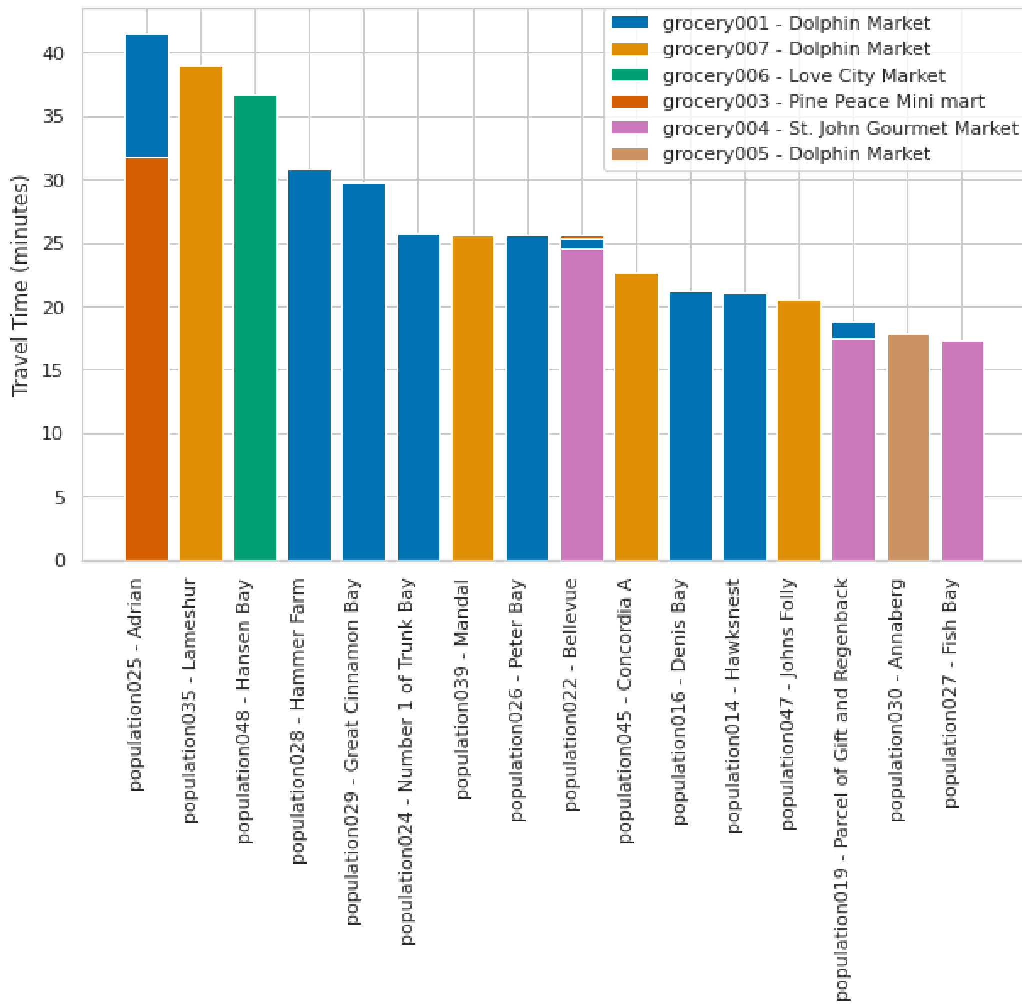

Figure 4.14. STJ roundtrip travel times for grocery stores under flooded conditions. The height of the bar indicates the total travel time from a particular origin to a given store. Color of bar indicates the store. In cases where an origin has more than one longest round trip, bars are superimposed with one color per store.

Figure 4.15 displays the longest fuel travel times. Population "population035-Lameshur" sees the largest increases in its trip to "fuel003-The St. John Repair Shop," increasing by over 20 minutes. Again, all roundtrips are within the six-hour curfew window, not including potentially high service times.

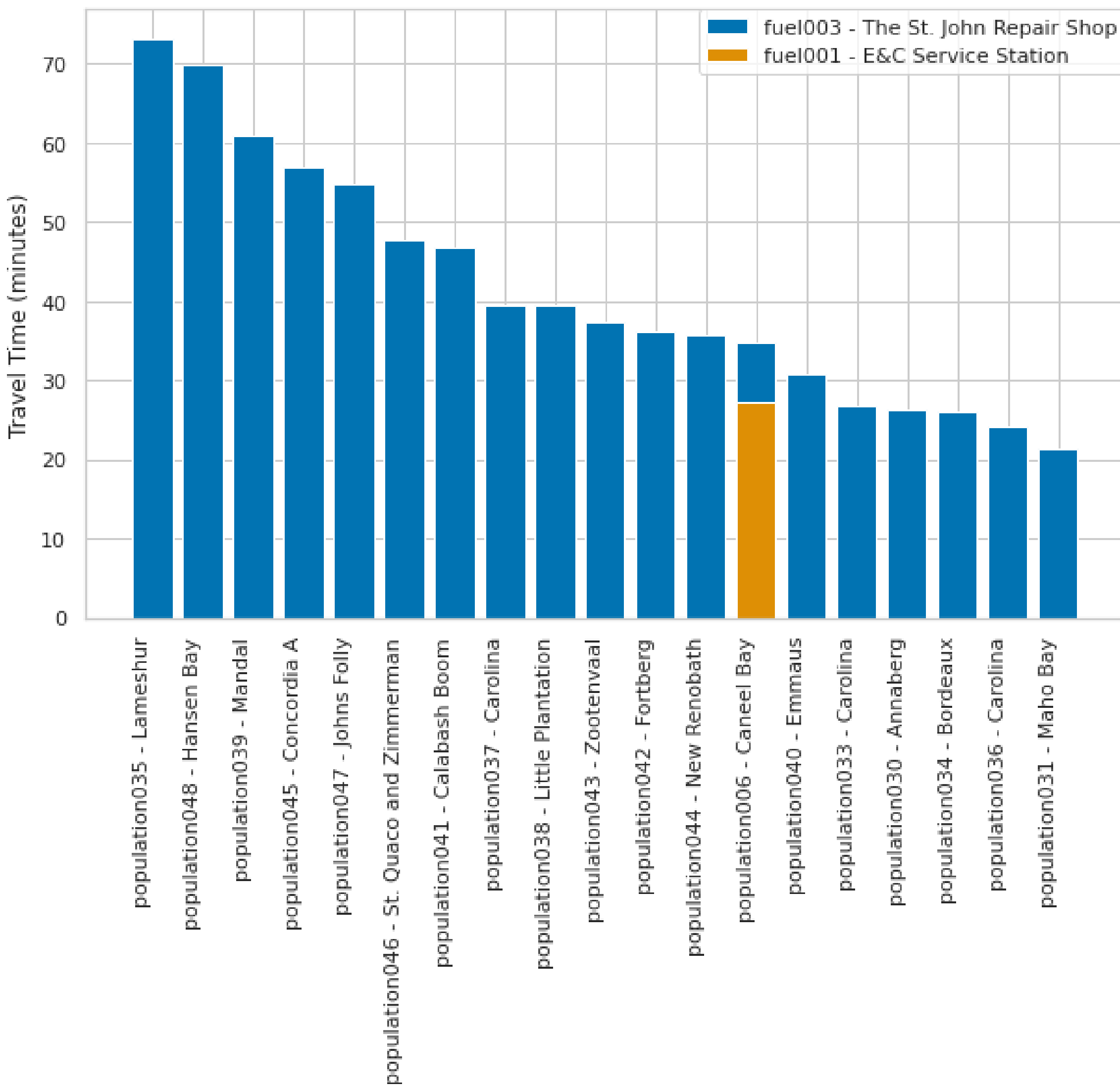

Figure 4.15. STJ roundtrip travel times for fuel under flooded conditions. The height of the bar indicates the total travel time from a particular origin to a given store. Color of bar indicates the store. In cases where an origin has more than one longest round trip, bars bars are superimposed with one color per store.

Figure 4.16 displays hardware roundtrip times. Population "population041-Calabash Boom" remains as the longest trip, seeing a 20 minute increase. The previous second longest time, "population047-Johns Folly," sees a minimal increase and falls to fourth. Population "population035-Lameshur" increases by 20 minutes and rises to second.

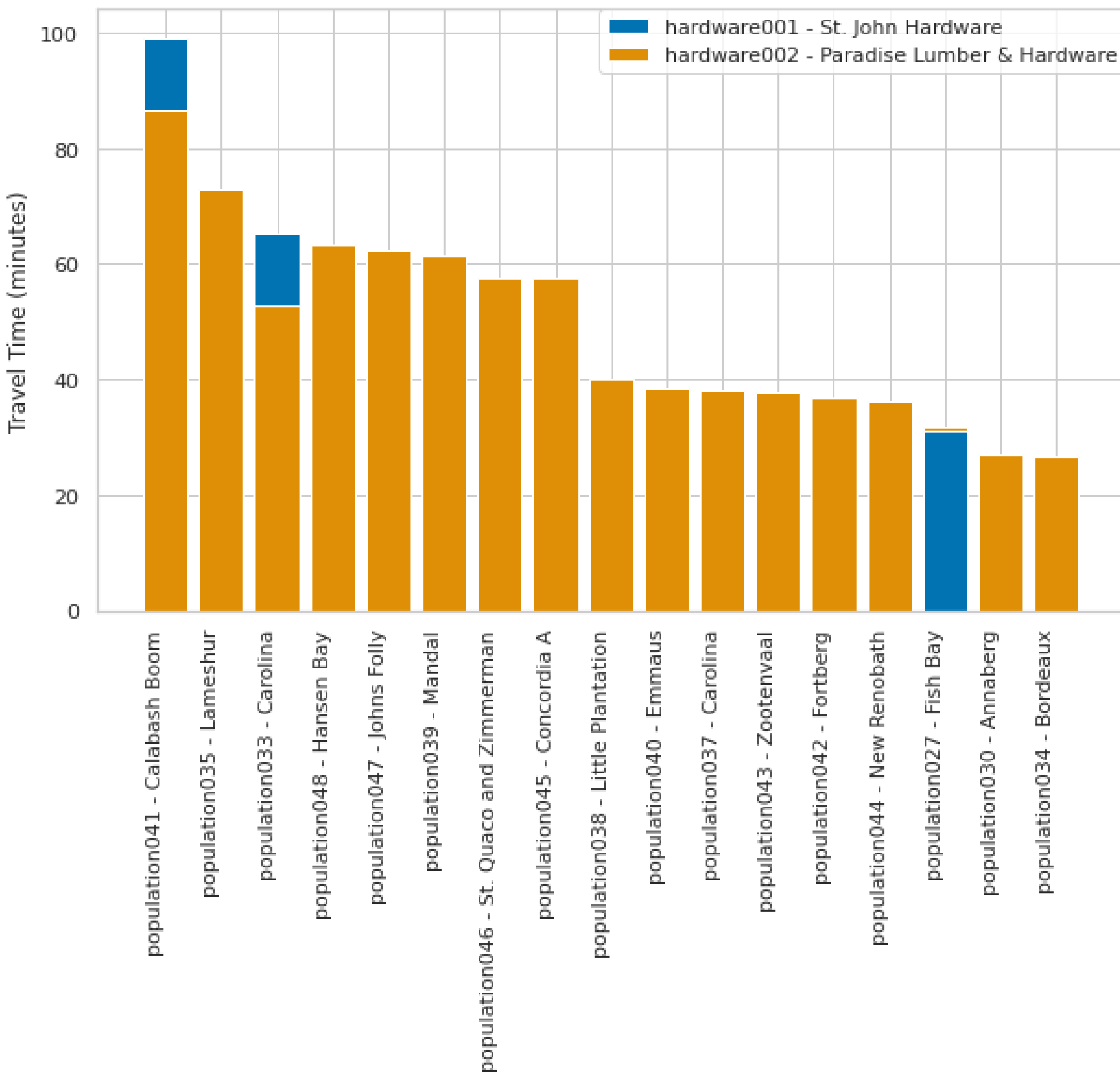

Figure 4.16. STJ roundtrip travel times for hardware stores under flooded conditions. The height of the bar indicates the total travel time from a particular origin to a given store. Color of bar indicates the store. In cases where an origin has more than one longest round trip, bars bars are superimposed with one color per store.

The general shape of port travel times remains the same in Figure 4.17. The three grocery stores on the eastern side the island remain the longest haul for delivery trucks, but only increase from 45 minutes to an hour.

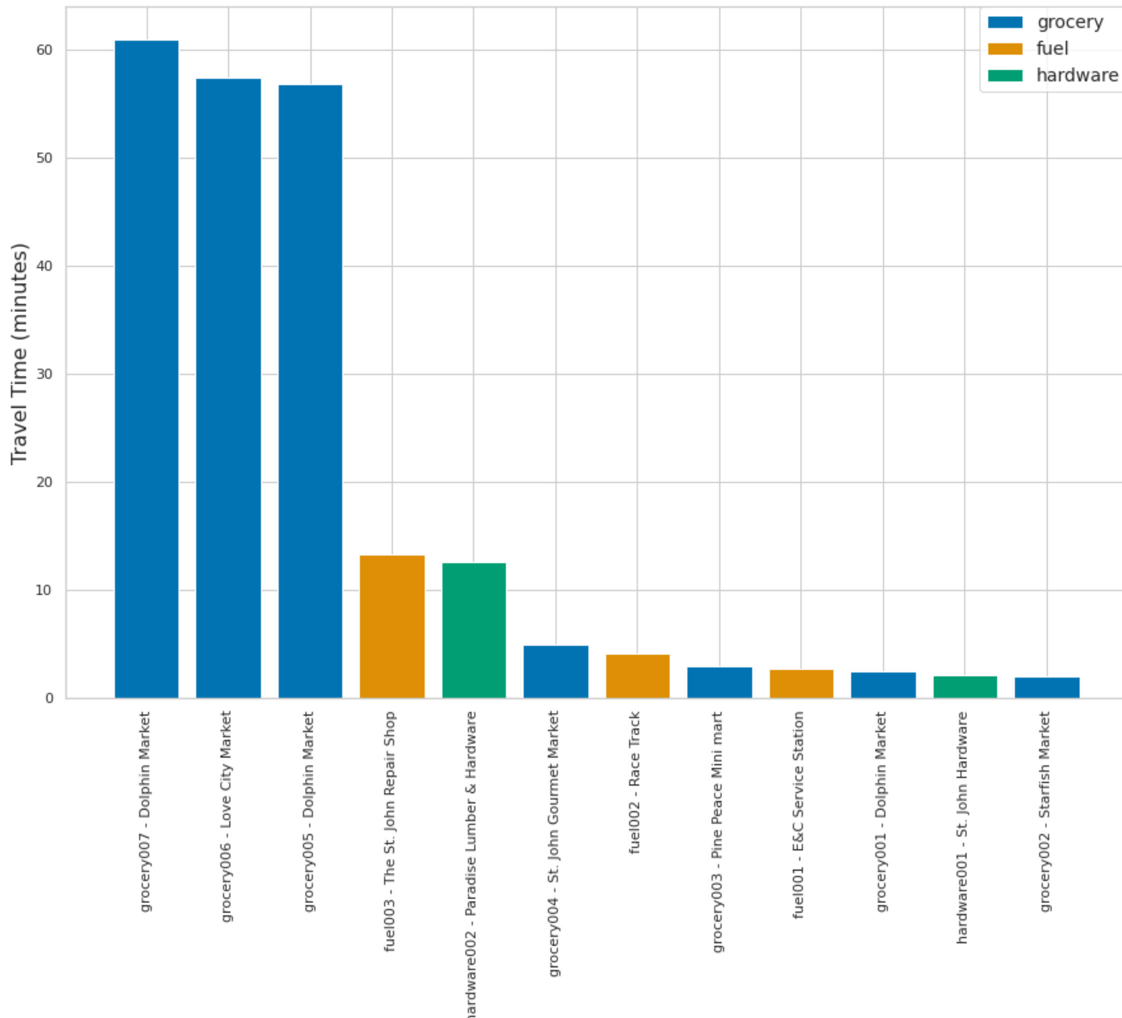

Figure 4.17. STJ travel time from the port under flooded conditions. Roundtrip travel times in minutes from The Theovald Eric Moorehead Dock and Terminal at Enighed Pond to all stores. Color of bar indicates the store type.

Figure 4.18 depicts the island's longest travel times under flooded conditions. The longest travel times are in the eastern population centers with the exception of "population 025-Adrian" who travels east, then north, then back west along the coast to reach a grocery store. We see that flooding has affected the road network enough that the model sends "population 025-Adrian" on a longer, but potentially faster route, to reach groceries.

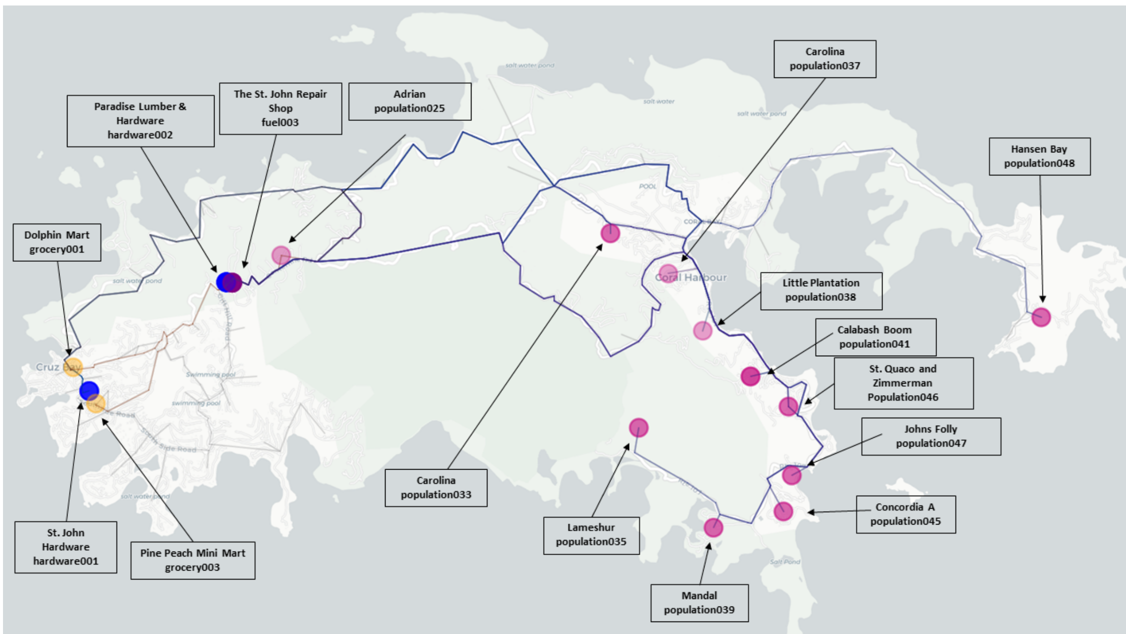

Figure 4.18. STJ longest trips under flooded conditions. Route colors indicate the destination store type: blue for hardware stores, orange for grocery stores, and purple for gas stations. The remaining arcs are rendered in grey. Created using QGIS Development Team (2020) on 14 September 2020.

4.3 Worst-Case Disruptions

We now look at worst-cast scenarios where flooding and storm surge renders roads impassable. Figure 4.19 shows flood water and storm surge up to 12 inches in bright blue. At 12 inches, per Pregnolato et al. (2017), roads become unusable by most vehicles. Roads that "flooded" still have their speeds and capacity halved. "Impassable" roads are switched off by the model and ignored. This results in traffic rerouting around those roadways.

It is important to note that the area surrounding Cruz Bay has two of its three access roads cut off. The northern and southern routes are rendered impassable, only leaving an eastern access road.

Along with cutting off the northern and southern route, extreme flooding renders the Theovald Eric Moorehead Dock and Terminal at Enighed Pond inaccessible. If the cargo port were to become inaccessible, stores would have to rely on whatever they had in stock until such a time as access was restored. Priority should be placed on ensuring goods and supplies can flow from the port to stores.

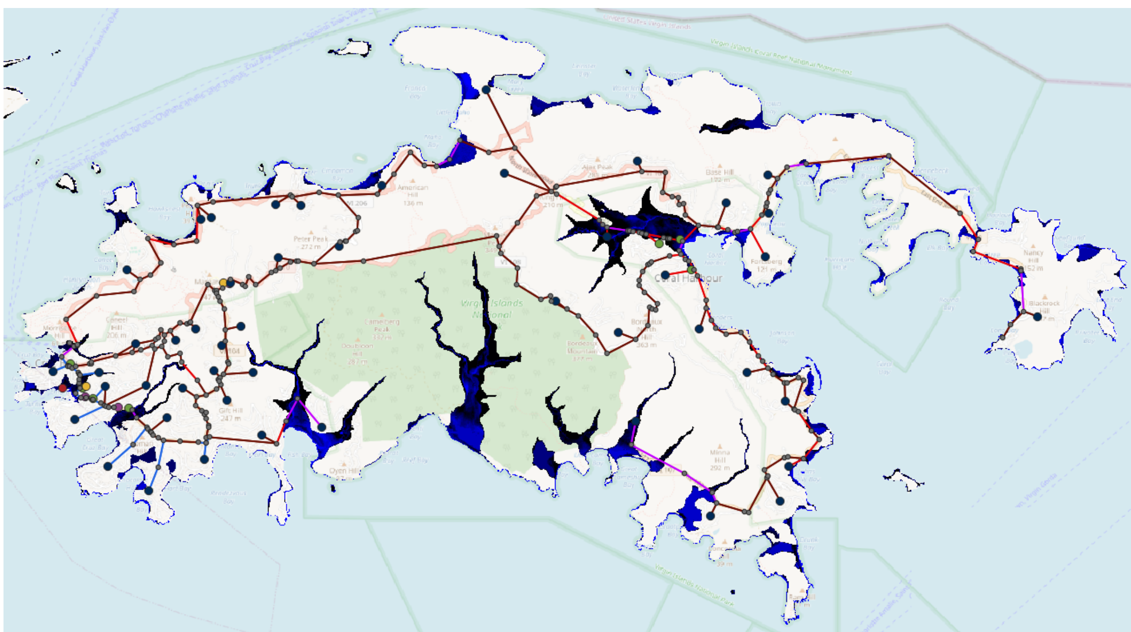

Figure 4.19. STJ areas made impassable. Bright blue areas indicated flooding. Roads in purple indicate roads considered "impassable" for the model. Roads in red are considered "flooded." Created using QGIS Development Team (2020) on 14 September 2020.

Figure 4.20 shows the traffic flow under worst-case conditions. We do not see much in the way of increased congestion. However, in Figure 4.21, we see our first evidence in dropped demand. We see completely dropped demand in the estates of Fish Bay, Lameshur, Zootenvaal, Fortberg, and Hansen Bay. Access roads to these estates are blocked by floodwater and storm surge and cannot allow people to leave their homes to procure supplies.

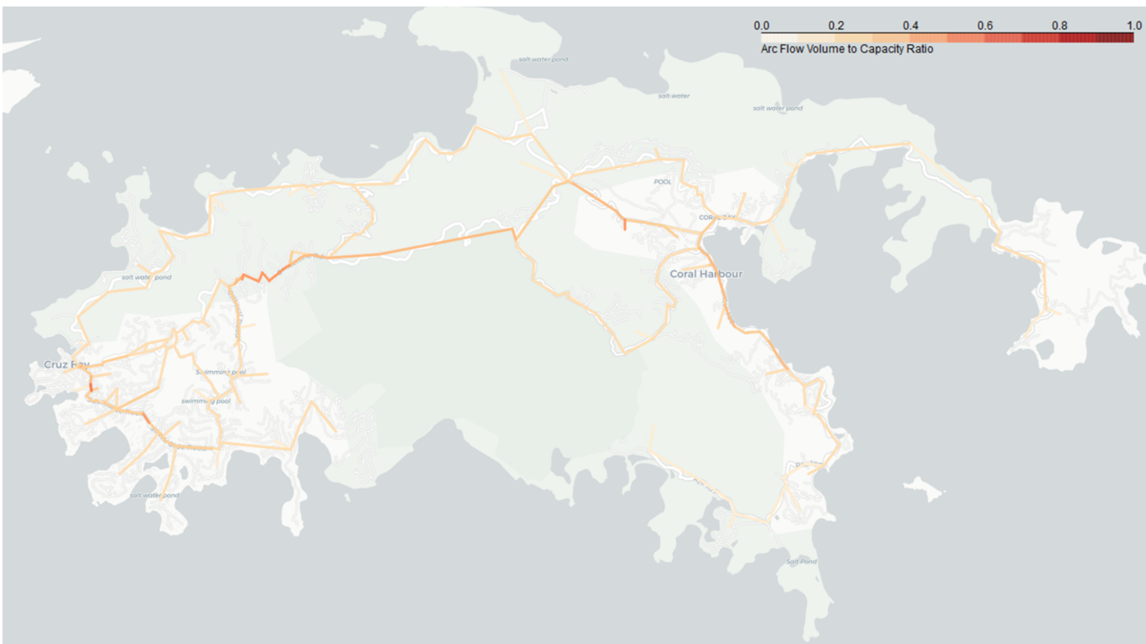

Figure 4.20. STJ traffic flows under worst-case conditions. Arcs are displayed according to their flow-to-capacity ratios. Higher ratios are depicted by darker colors. Created using QGIS Development Team (2020) on 14 September 2020.

Figure 4.21 shows our first dropped estates under this model. Roads becoming impassable remove five estates from the road network: Fish Bay, Lameshur, Zootenvaal, Fortberg, and Hansen Bay. All told, 250 people are removed from the road network and are unable to access supplies.

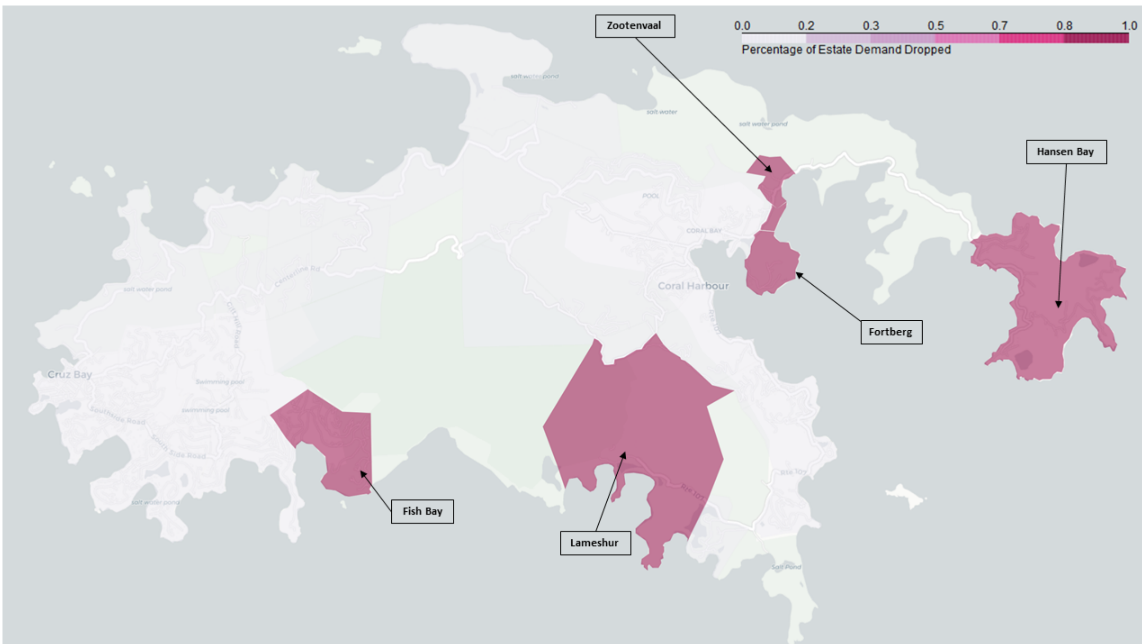

Figure 4.21. STJ dropped demand from estates. The darker the color the more demand was dropped. Created using QGIS Development Team (2020) on 14 September 2020.

In Figure 4.22 we see a general reduction in overall travel times. When estates such as Lameshur are eliminated from model because of being cutoff, the removal of their long travel times brings down the average. Table 4.3 shows these reductions in travel times.

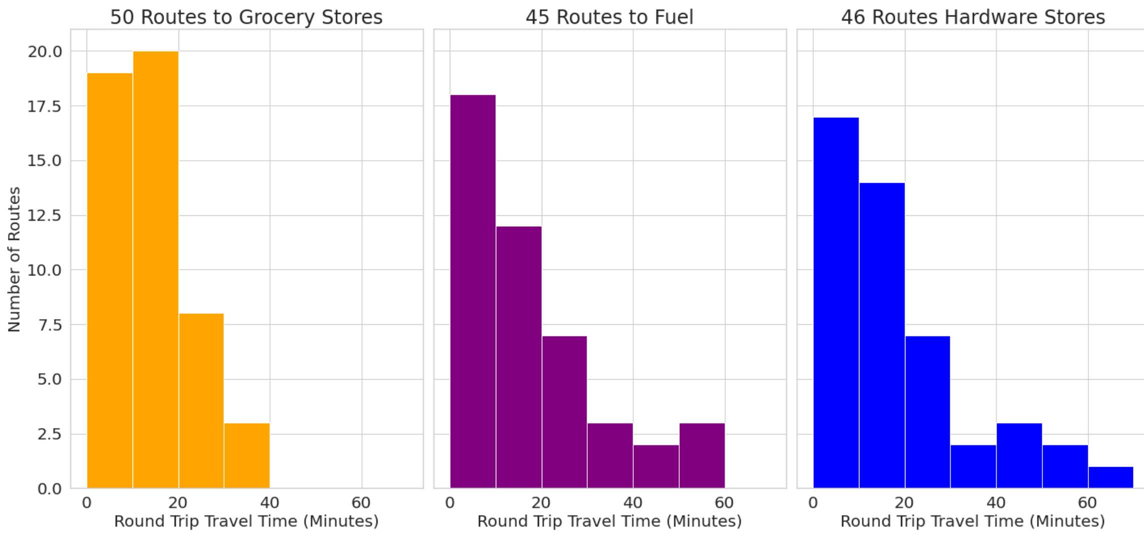

Figure 4.22. STJ roundtrip travel times under worst-case conditions. While most trips are under one hour, some roundtrips to hardware stores and fuel meet or exceed one hour.

Table 4.3. STJ average roundtrip times under worst-case conditions.

Destination Type	Average (minutes)	Change in Average (minutes)	Standard Deviation (minutes)
All	16.10	-4.16	14.57
Grocery	12.74	-3.36	10.16
Fuel	17.59	-2.64	16.35
Hardware	18.34	-6.61	16.35

Figure 4.23 shows that while some population centers are now without paths to supplies, the remaining population centers see minimal increases in travel times over flooded conditions. Again, the majority of the eastern side of the island congregates at “hardware002-Paradise Lumber & Hardware” and “fuel003-The St. John Repair Shop.”

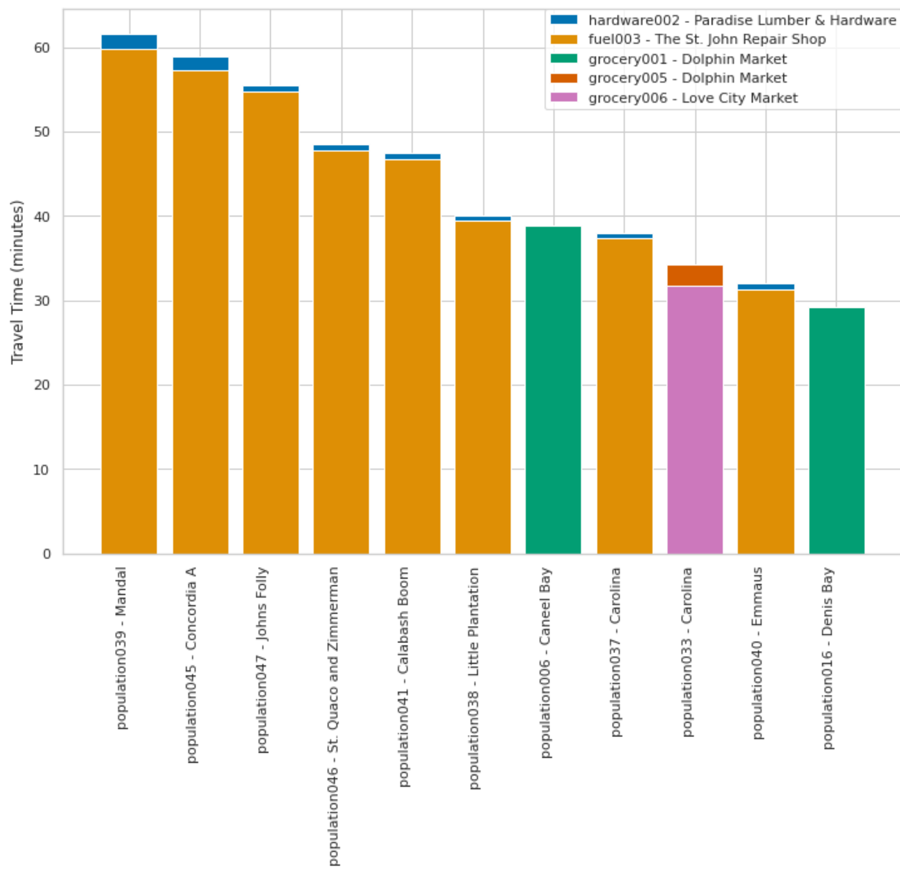

Figure 4.23. STJ roundtrip travel times for all store types under worst-case conditions. The height of the bar indicates the total travel time from a particular origin to a given store. Color of bar indicates the store. In cases where an origin has more than one longest round trip, the bars are superimposed with one color per store.

Figure 4.24 depicts grocery store roundtrip travel times. Population “population025-Adrian” falls from highest under flooded conditions to last on the graph. Its travel time fell from over 40 minutes to under 15. The longest time now belongs to population “population006-Caheel Bay,” which did not appear in Figure 4.14, with a travel time in excess of 35 minutes.

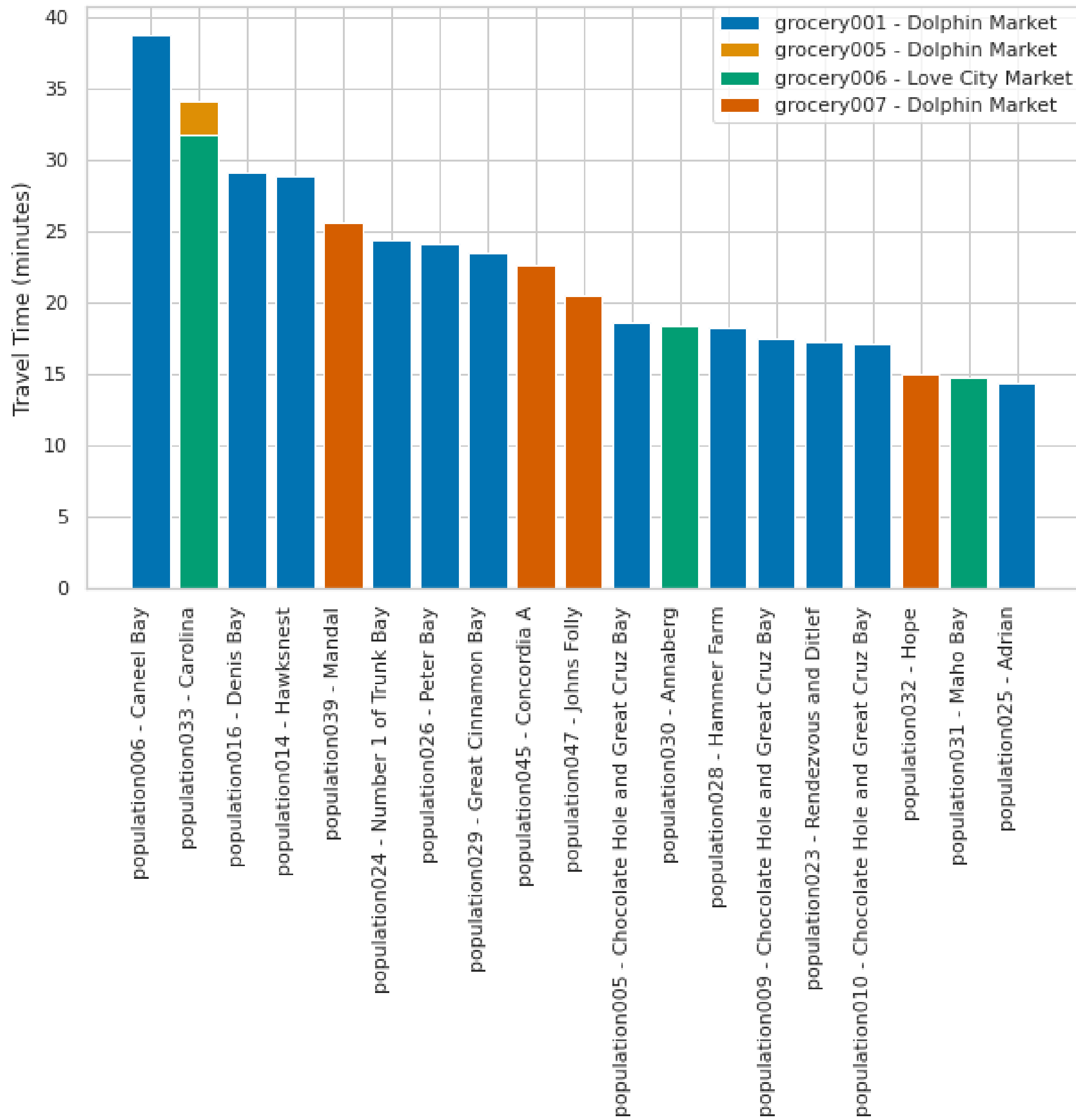

Figure 4.24. STJ Roundtrip travel times for grocery stores under worst-case conditions. The height of the bar indicates the total travel time from a particular origin to a given store. Color of bar indicates the store. In cases where an origin has more than one longest round trip, bars are superimposed with one color per store.

Figure 4.25 shows that nearly the entire island converges on "fuel003-The St. John Repair Shop." Since Cruz Bay is cut off from the north and south, the easiest and shortest route to take to procure fuel is at "fuel003-The St. John Repair Shop." This will potentially have severe service times and impact the availability of the fuel supply. The longest travel time of is population "population039-Mandal" with a one hour travel time. This time is unchanged from the flooded scenario, and only takes the top spot because populations "population035-Lameshur" and "population048-Hansen Bay" became inaccessible.

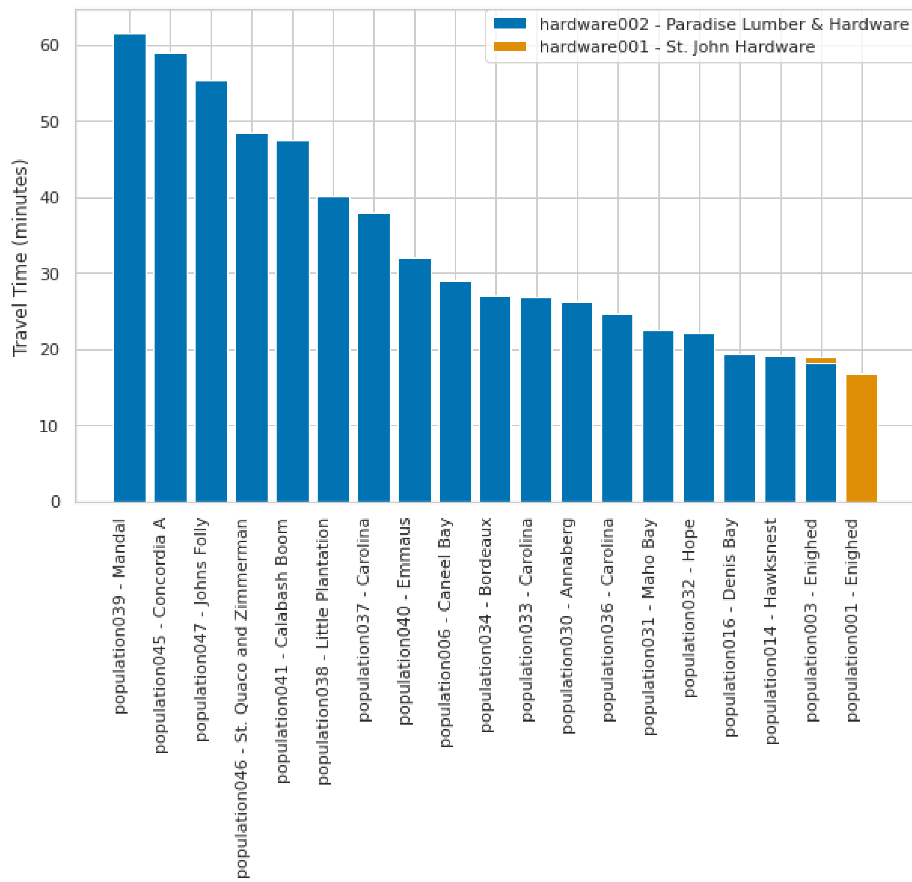

Figure 4.25. STJ roundtrip travel times for hardware stores under worst-case conditions. The height of the bar indicates the total travel time from a particular origin to a given store. Color of bar indicates the store. In cases where an origin has more than one longest round trip, bars bars are superimposed with one color per store.

Figure 4.26 shows the same phenomena as with Figure 4.25. The majority of the island converges on “hardware002-Paradise Lumber & Hardware.” Population “population039-Mandal” also retains the longest travel time of one hour, as it did with fuel. The previous longest travel time was “population041-Calabash Boom,” which fell from nearly 100 minutes to under 50.

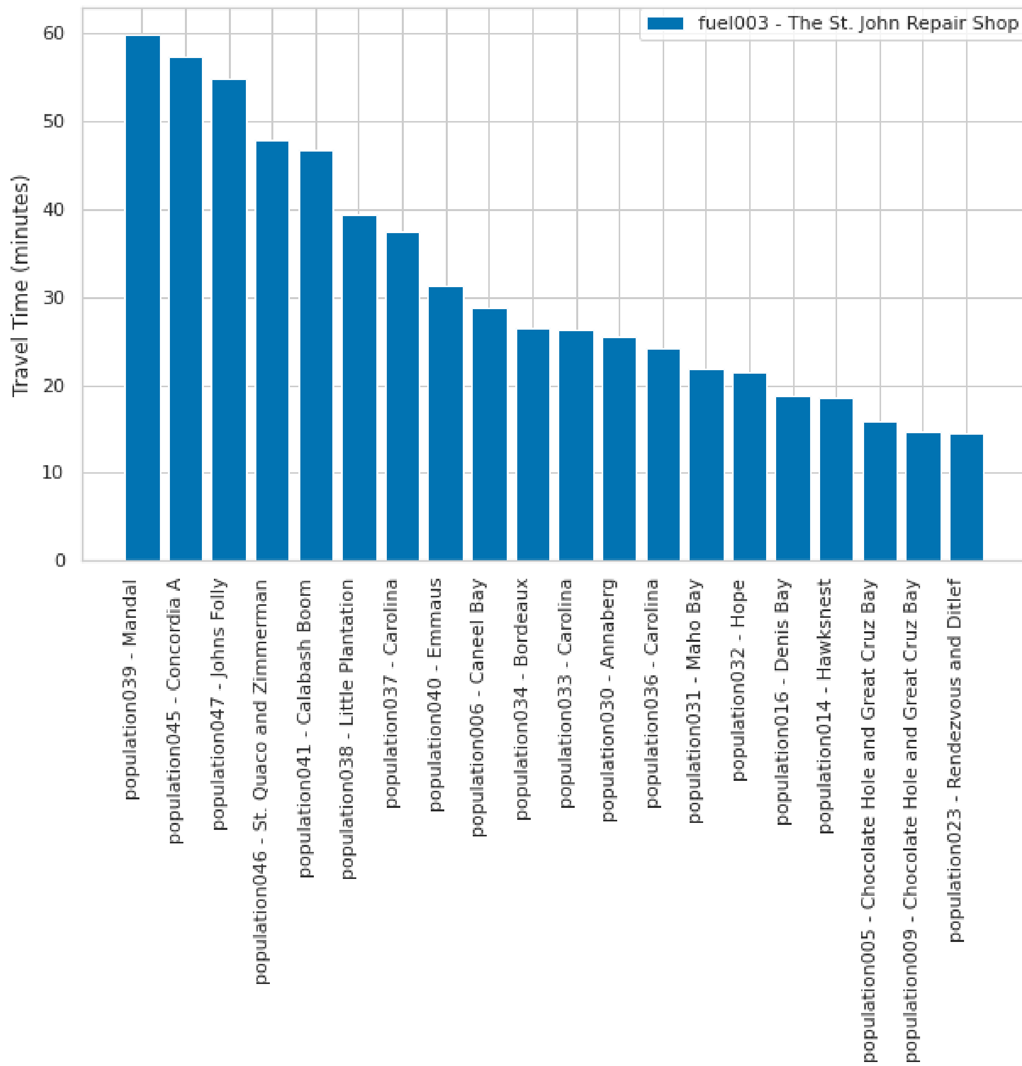

Figure 4.26. STJ roundtrip travel times for fuel under worst-case conditions. The height of the bar indicates the total travel time from a particular origin to a given store. Color of bar indicates the store. In cases where an origin has more than one longest round trip, bars bars are superimposed with one color per store.

Figure 4.27 shows the longest trips under impassable conditions. We again see the eastern side of the island with the longest trips towards hardware and fuel. One interesting note is that population "population006-Caheel Bay" drives the long way around the coast to reach "grocery001-Dolphin Mart" since the more direct northern route into Cruz Bay has been blocked.

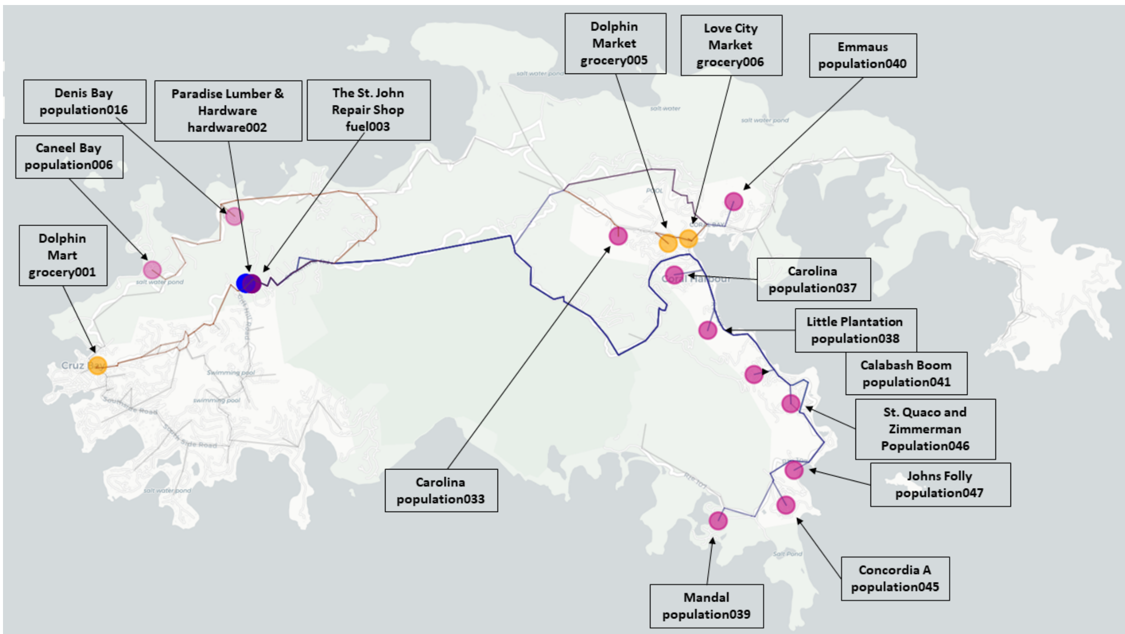

Figure 4.27. STJ longest trips under worst-case conditions. Route colors indicate the destination store type: blue for hardware stores, orange for grocery stores, and purple for gas stations. The remaining arcs are rendered in grey. Created using QGIS Development Team (2020) on 14 September 2020.

4.4 Discussion

Table 4.4 summarizes the different STJ scenarios. Total vehicle-hours increase as the conditions worsen from normal to flooded, but decrease during the worst-case scenario because five estates and 250 people are stranded behind impassable roads. Additionally, the Theovald Eric Moorehead Dock and Terminal at Enighed Pond is rendered inaccessible during the worst-case scenario, keeping cargo trucks off of the road.

Table 4.4. Comparison of disaster scenarios for STJ.

Scenario	Total Vehicle-Hours	Mean Travel Time (Ports)	Total Dropped (Stores)	Mean Travel Time (Estates)	Total Dropped (People)
Normal	158.97	14.32	0	17.40	0
Flooding	213.62	18.49	0	20.26	0
Worst-Case	172.20	-	12	16.10	250

There are constants across all of the scenarios:

- The port is located near hardware stores and fuel, but far from at least three grocery stores. This renders resupply of hardware store and fuel easier than that of the eastern grocery stores. Conversely, those eastern population centers have short travel times to these grocery stores, but longer travel times to hardware stores and fuel.
- Resupply of stores will prove difficult during flooded scenarios, and almost impossible during worst-case scenarios. The three eastern grocery stores will be the most impacted by flooded roads, while every store will be impacted during the worst-case scenario.
- The travel time of specific estates and STJ communities will be more impacted by flooding disasters than others. Importantly, communities located in the southeastern coastline such as Carolina, Little Plantation, and Mandal among others have the longest travel times to critical supplies.
- Communities most impacted by flooding are in the east and southern regions of STJ. The national forest on STJ bifurcates the road network across the center of the island, separating the west and east coasts. Unfortunately, worst-case flooding can impact communities on both sides of the island. Examples include the Fish Bay community connected to the western portion of the road network and Lameshur, Fortberg, Zootenval, and Hansen Bay connected to the eastern road network. These communities may be unable to reach critical supplies. Overall, the eastern communities are most impacted by flooding and storm surge.

Can we think of any possible solutions?

- Communities: The STJ road network does not appear to be constrained by capacity. The roads appear sufficient to support current populations to travel within set curfew periods. This is true even with “winding” roads that slow traffic. However, there are several key locations within the road network that appear vulnerable to flooding and storm surge. Those locations can isolate communities and prevent them from accessing critical supplies. Specifically, major intersections in Coral Bay that link east coast communities to the western side of the island are all physically near each other and in a flood zone. This creates a “bottleneck” that isolates these eastern communities.

- Despite this bottleneck on roadway traffic, it does not make sense to necessarily build a new road that connects eastern and western STJ. There are several redundant paths already and locating a new road far from Coral Bay would cause significant damage to the National Park. Instead, it may make sense to develop more ferry and ocean-based capacity and routes that can reach communities that are isolated during storms. In particular, it would be beneficial to develop docks that support the shipping of enough supplies to serve communities with dropped traffic.
- Ports: Additional ports that enable the movement of supplies to the eastern side of STJ may also benefit the island as a whole. Currently, it is difficult for food supplies reaching the Theovald Eric Moorehead Dock and Terminal at Enighed Pond to reach grocery stores on STJ. In fact, when roads become impassable, many do not receive any supplies whatsoever. These roads may become impassable because the port resides in a flooding zone that is susceptible to storm surge. Expanding the facilities in Coral Bay to allow for limited cargo access may help alleviate these issues.

CHAPTER 5:
Analysis and Results for St. Thomas

We apply the model from Section 3.3 to the island of STT. We consider 109 origins (108 population nodes and one port) and 40 destinations (20 grocery stores, 14 gas stations, and six hardware stores connected by a network of 1670 road segments. Figure 5.1 displays the network.

As in Chapter 4, we address several questions.

1. Under normal conditions, what are the roundtrip travel times and congestion between population locations and the port?
2. Under flooded conditions, what are the roundtrip travel times and congestion between population locations and the port?
3. Under worst-case conditions, what are the roundtrip travel times and congestion between population locations and the port?

We use the same assumptions for routing, destination choice, and single deliveries from the port.

Figure 5.1. STT model road network. "Urban" roads are in blue. "Winding" roads are in burgundy. Created using QGIS Development Team (2020) on 14 September 2020.

5.1 Travel under Normal conditions

Figure 5.2 shows the resulting traffic flows on STT during normal conditions. We assume there are no road blockages and the maximum allotted travel time is six hours ($q = 6$). Road segments are displayed according to their flow-to-capacity ratios. A darker color indicates a higher ratio, indicating higher congestion. We see that some roads are nearing their maximum capacities even under normal conditions. Table 5.1 shows the road segments carrying the most traffic flow.

Though not displayed in a figure, we find that there is no dropped demand on STT under normal conditions. This means that all travelers can reach their intended destinations and return home within a six-hour curfew window.

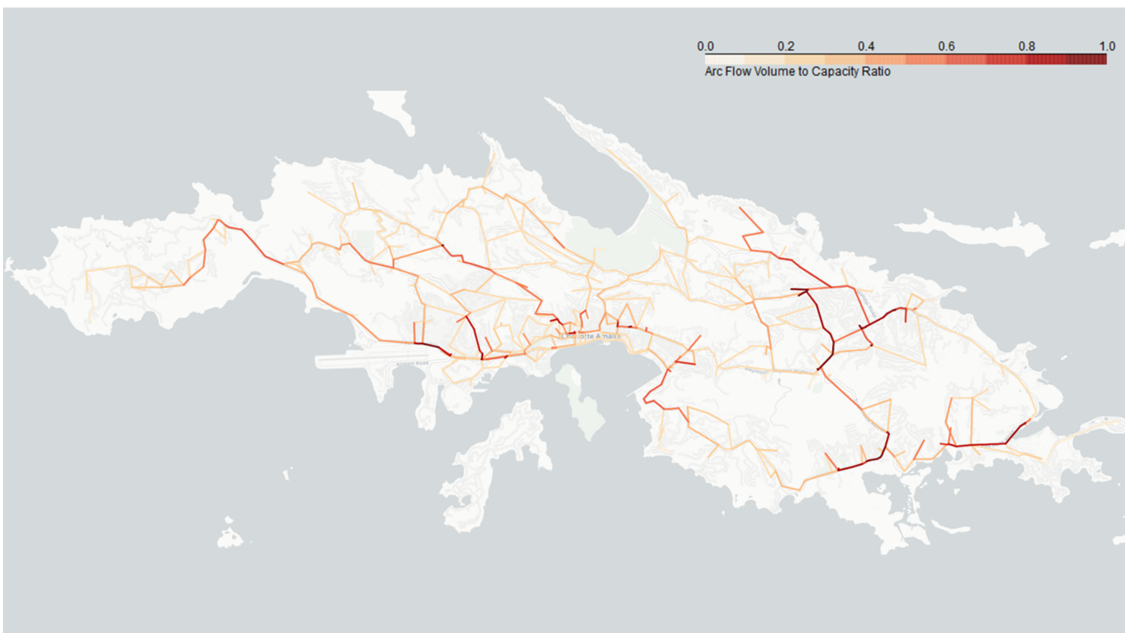

Figure 5.2. STT traffic flows under normal conditions. Arcs are displayed according to their flow-to-capacity ratios. Higher ratios are depicted by darker colors. Created using QGIS Development Team (2020) on 14 September 2020.

Table 5.1. Most-traveled STT road segments.

Estate	Road Segment	Flow (VPH)
Annas Retreat	Highway 40 near Hometown Grocery	1768
Lindbergh Bay	Julian Jackson Dr. near the Airport	1715
Annas Retreat	Smith Bay Rd. near East End Lumber	1568
Charlotte Amalie	Raphune Hill near Total Gas Station	1473
Bovoni	Bovoni Rd. between Mariendahl Rd. and Rosa Lima Rd.	1319
Kings Quarter	Dronningens Gade near Puma Gas Station	1280
Crown and Hawk	Lime St. and Highway 386	1280
Bovoni	Bovoni Rd. near Puma Gas Station	1172
Annas Retreat	Flambouyant Ave.	1151
Nisky	Veterans Dr. near Sea Chest ACE Hardware	1130
Solberg	Theodore Boscheulte Rd. near Builders Emporium	1051

Figure 5.3 shows the roundtrip travel time distributions to each store type. We are interested in which populations are most affected by their remoteness, such as the western and northern portions of the island. We find that roundtrip travel tines generally remain under 50 minutes. We also find that the more than 80% of all roundtrips take fewer than 20 minutes to complete.

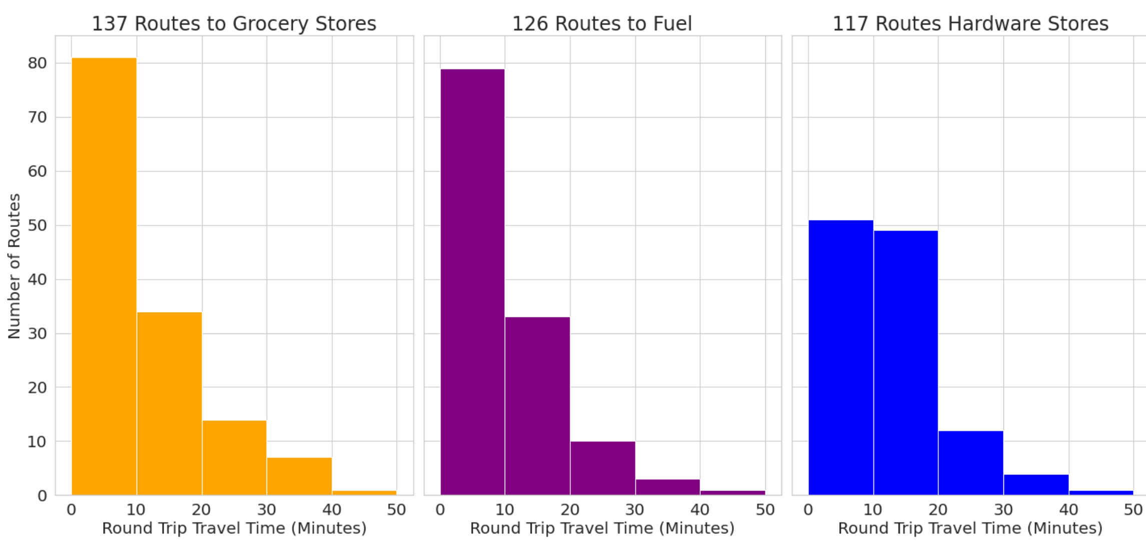

Figure 5.3. STT roundtrip travel times under normal conditions. While most trips are under 50 minutes. 80% of all trips take fewer than 20 minutes.

Table 5.2 shows the averages and standard deviations for all roundtrip travel times. Unlike STJ, there is no one store type that takes generates the largest roundtrips.

Table 5.2. STJ average roundtrip times under normal conditions.

Destination Type	Average (minutes)	Standard Deviation (minutes)
All	11.23	8.45
Grocery	11.26	9.00
Fuel	9.89	7.78
Hardware	12.66	8.33

Figure 5.4 displays the longest roundtrip travel times for all destinations. The longest trips belong to the population centers on the western side of the island who to have to traverse "winding" roads to reach Charlotte Amalie. However, population "population079-Lovenlund," located on the north-eastern portion of the island also has a long travel time, requiring more than 25 minutes to reach a hardware store and return.

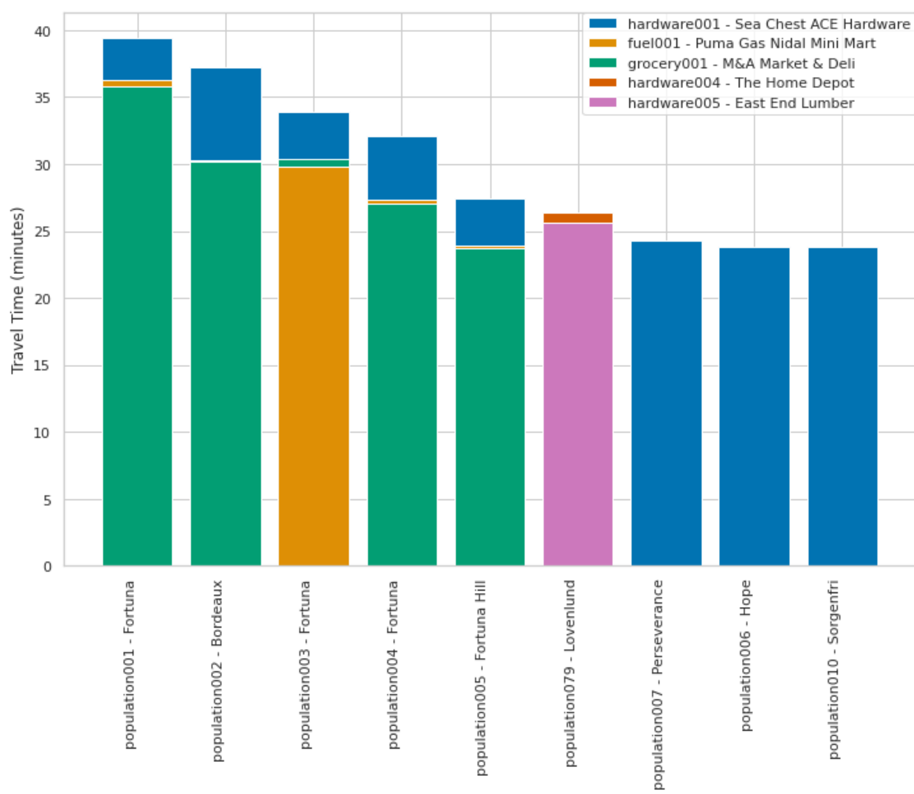

Figure 5.4. STT roundtrip travel times for all store types under normal conditions. The height of the bar indicates the total travel time from a particular origin to a given store. Color of bar indicates the store. In cases where an origin has more than one longest round trip, the bars are superimposed with one color per store.

Figure 5.5 displays the longest roundtrips to grocery stores. We again find the western side of the island having the longest trips to reach stores, ranging from 24 minutes to more than 35 minutes. Population "population001-Fortuna" has the distinction of being the furthermost west population center, with an accordingly long roundtrip. After the western population centers, the northernmost population center "population056-Peterborg" takes the longest roundtrip.

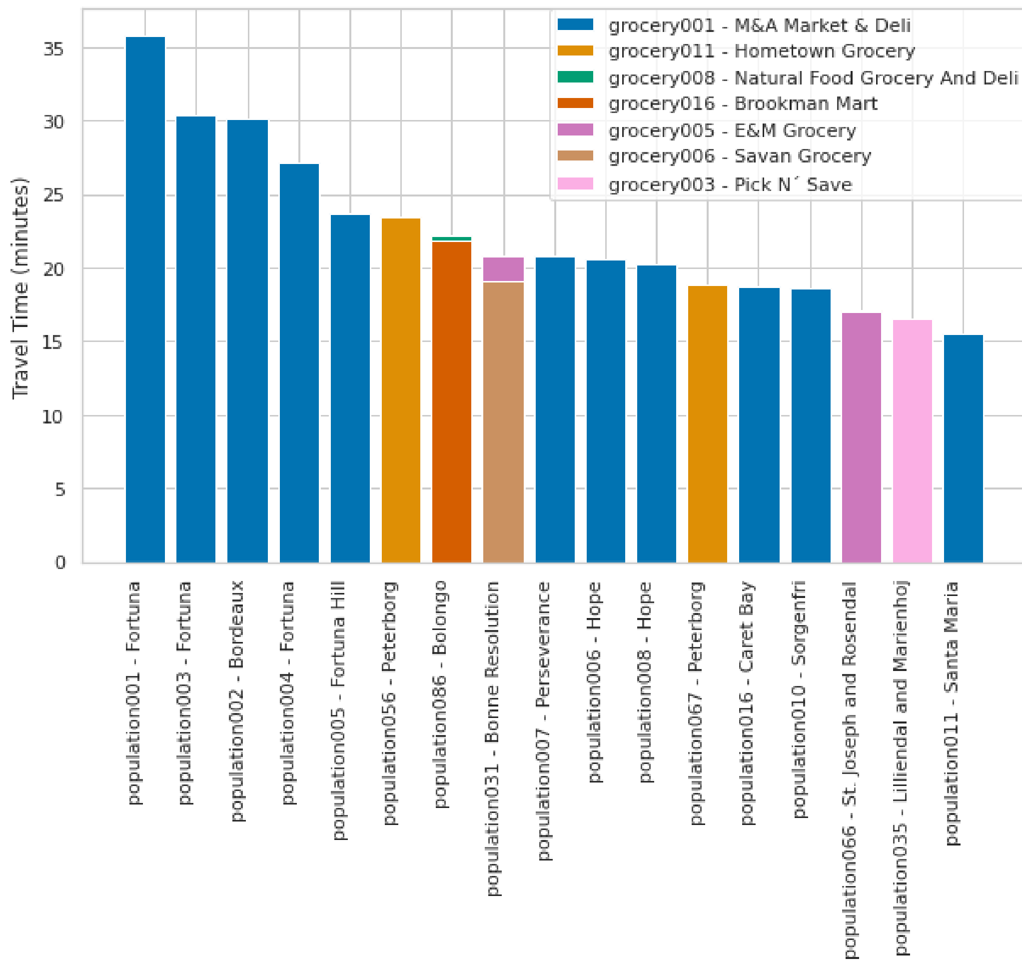

Figure 5.5. STT roundtrip travel times for grocery stores under normal conditions. The height of the bar indicates the total travel time from a particular origin to a given store. Color of bar indicates the store. In cases where an origin has more than one longest round trip, bars are superimposed with one color per store.

Figure 5.6 displays the longest roundtrips for fuel. Most trips are 30 minutes or less, with the exception of population “population001-Fortuna.” We observe that the western communities travel to “fuel001-Puma Gas Nidal Mini Mart” for fuel. Again, after the western communities, population “population056-Peterborg” has the longest roundtrip. We observe that Figure 5.5 and Figure 5.6 are similar in their distribution. The clustering of store types on STT means most population centers do not have to make disparate trips to different locations for different store types.

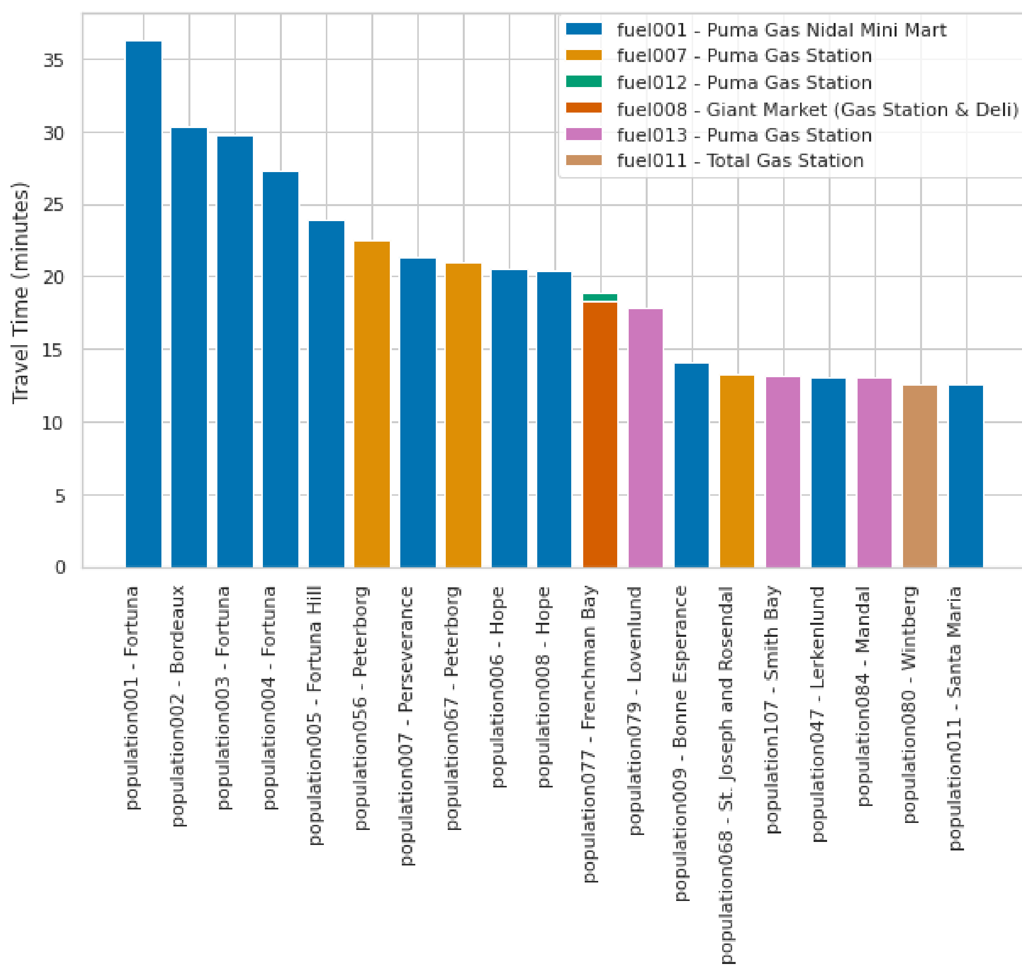

Figure 5.6. STT roundtrip travel times for fuel under normal conditions. The height of the bar indicates the total travel time from a particular origin to a given store. Color of bar indicates the store. In cases where an origin has more than one longest round trip, bars are superimposed with one color per store.

Figure 5.7 displays the longest roundtrips to hardware stores. Every trip is under 40 minutes. Again, as with grocery stores and fuel, the western communities have the longest roundtrip times. Contrary to the previous stores, the next longest trip belongs to population "population079-Lovenlund," which has a shorter trip to "hardware004-The Home Depot" than "population056-Peterborg."

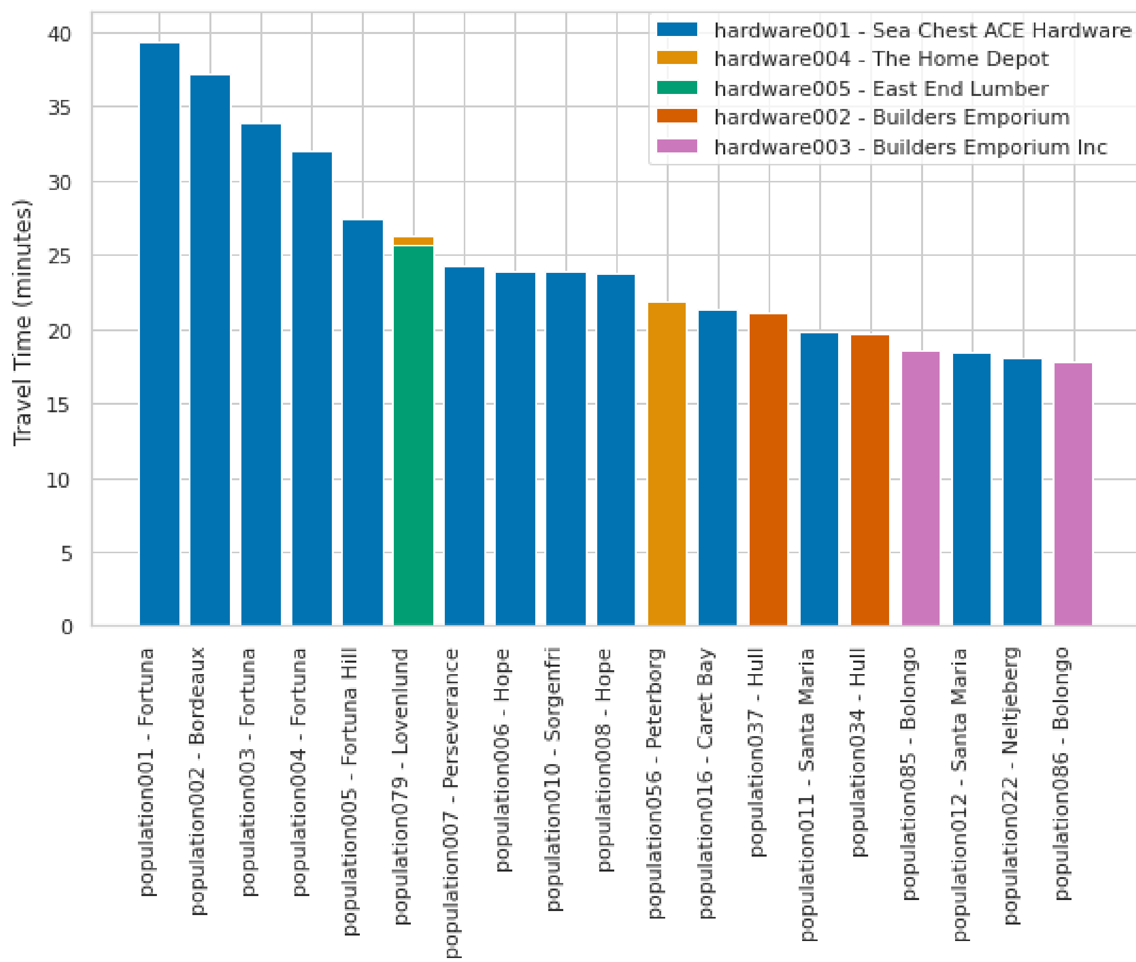

Figure 5.7. STT roundtrip travel times for hardware stores under normal conditions. The height of the bar indicates the total travel time from a particular origin to a given store. Color of bar indicates the store. In cases where an origin has more than one longest round trip, bars are superimposed with one color per store.

Figure 5.8 displays the longest roundtrips from the Crown Bay Cargo Port to resupply supply sources. As with STJ, the longest times are for the stores on the eastern side of the island; "hardware006-Island Marine Outfitters," "grocery020- Moe's Fresh Market Redhook," and "fuel014-Total Gas Station." Figure 5.13 shows that stores on STT are usually clustered together, with fuel and groceries near each other. This is good, because if communities are rendered isolated by road disruptions, they will generally have sources of groceries and fuel.

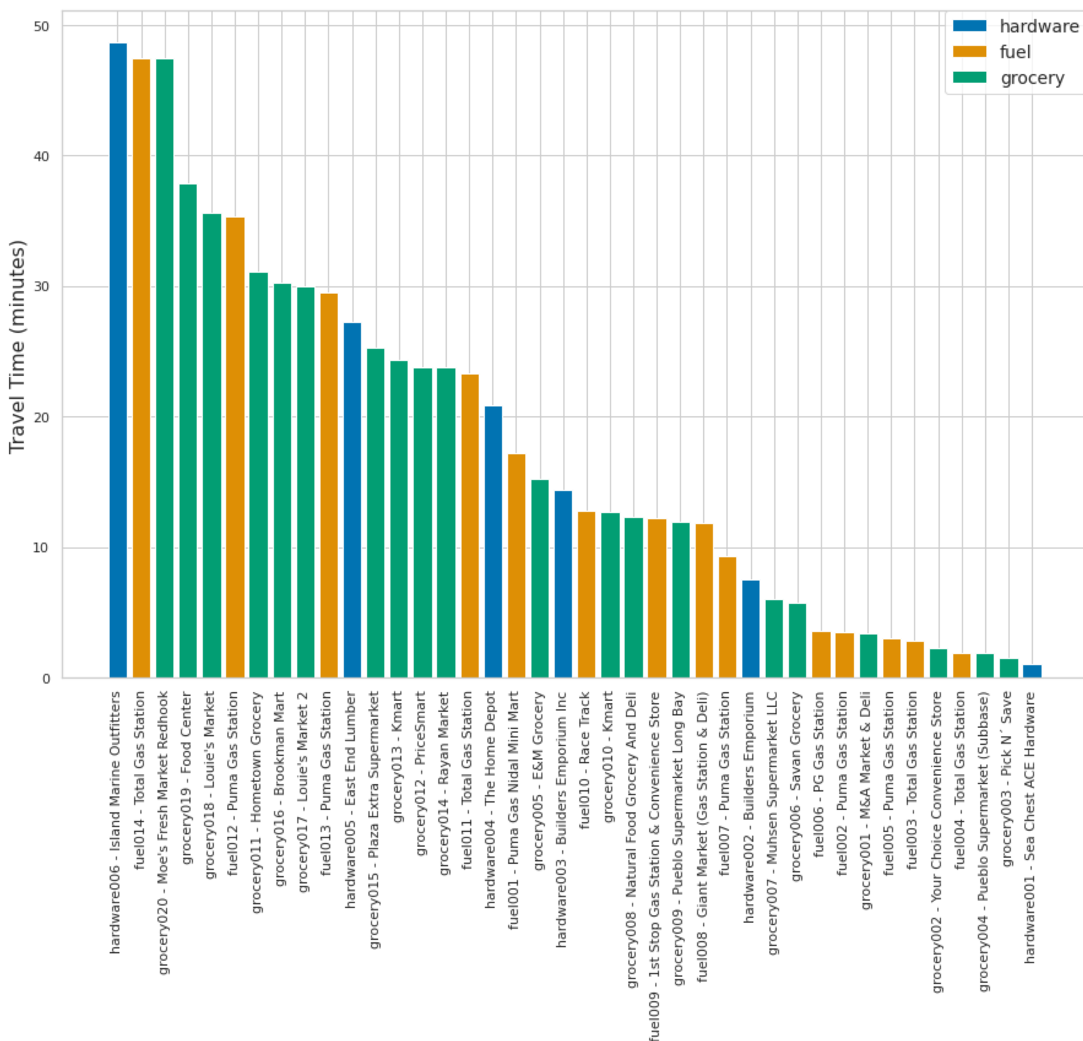

Figure 5.8. STT travel time from the port under normal conditions. Roundtrip travel times in minutes from Crown Bay Cargo Port to all stores. Color of bar indicates the store.

Figure 5.9 depicts the longest routes from population centers to sources of supply on the island. We observe a cluster of population centers on the western part of the island have long routes. If the main road artery from the western cluster were to become disrupted, they would become cut off. Population "population079-Lovenlund," is the lone population center not part of the western cluster that has a longest travel time.

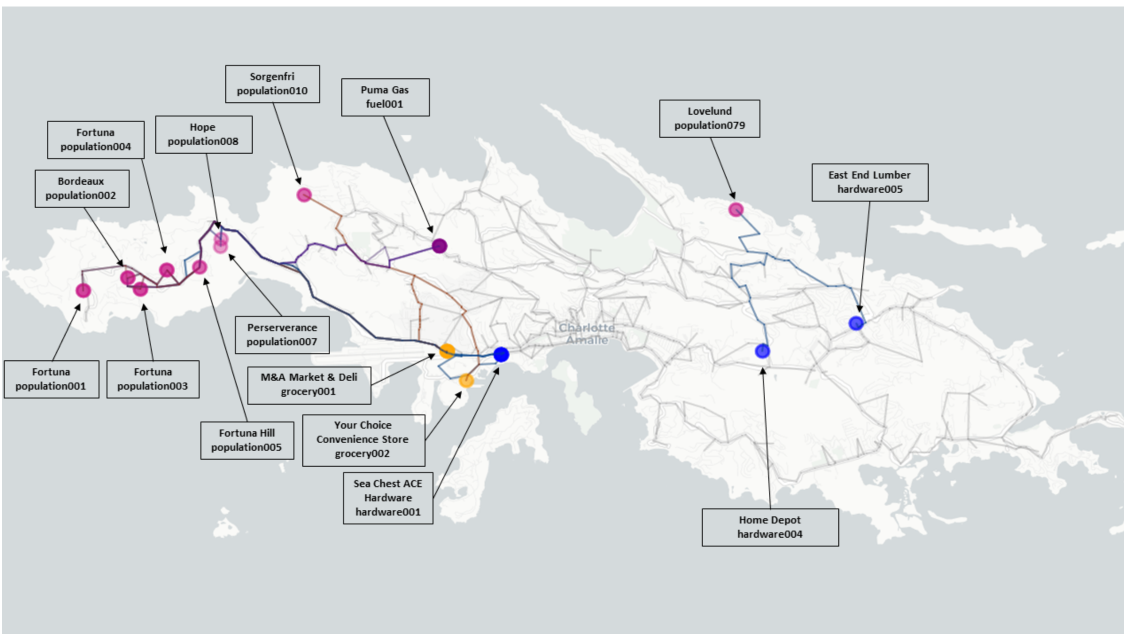

Figure 5.9. STT longest trip under normal conditions. Route colors indicate the destination store type: blue for hardware stores, orange for grocery stores, and purple for gas stations. The remaining arcs are rendered in grey. Created using QGIS Development Team (2020) on 14 September 2020.

5.2 Travel under Flooding

We now look at potential flooding and its effects on the road network. We use the same maps as in Section 4.2 provided by Dr. Greg Guannel from UVI. Figure 5.10 shows in bright blue the areas with flooding up to three inches. Roads flooded by three inches of water were found by Pregnolato et al. (2017) to reduce speed by half. Roads that considered "flooded" for the purposes of the model are indicated in red and have had their speed and capacity halved.

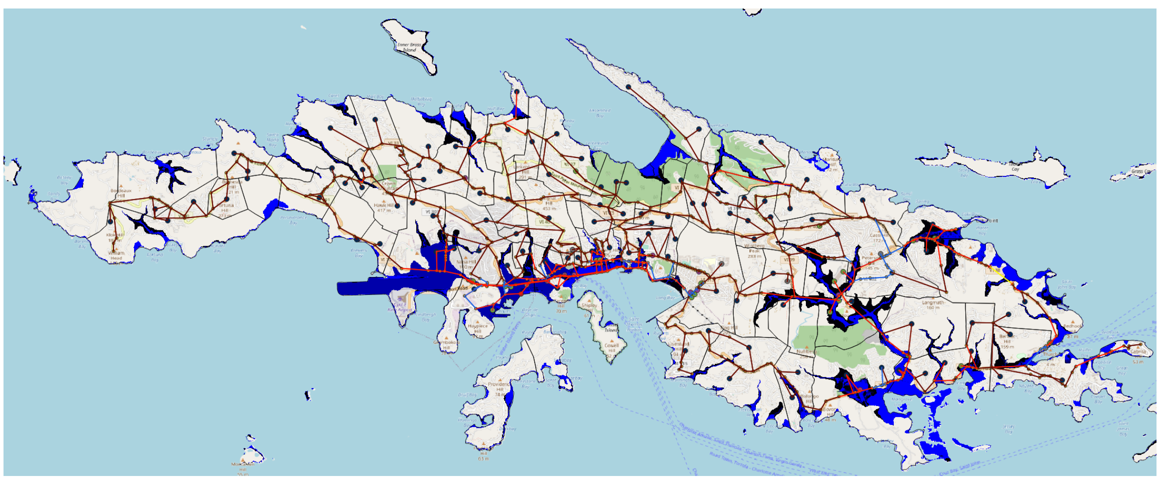

Figure 5.10. STT areas prone to flooding and storm surge. Bright blue areas indicated flooding. Roads in red indicated roads considered "flooded" for the model. Created using QGIS Development Team (2020) on 14 September 2020.

Figure 5.11 shows the flows under flooded conditions. We observe marked increases in congestion over most the island's roads. Charlotte Amalie is especially hard hit by flooding. As a major artery of the island, flooding there has a significant impact. We also see a marked increase in congestion in the Red Hook area on the eastern side of the island.

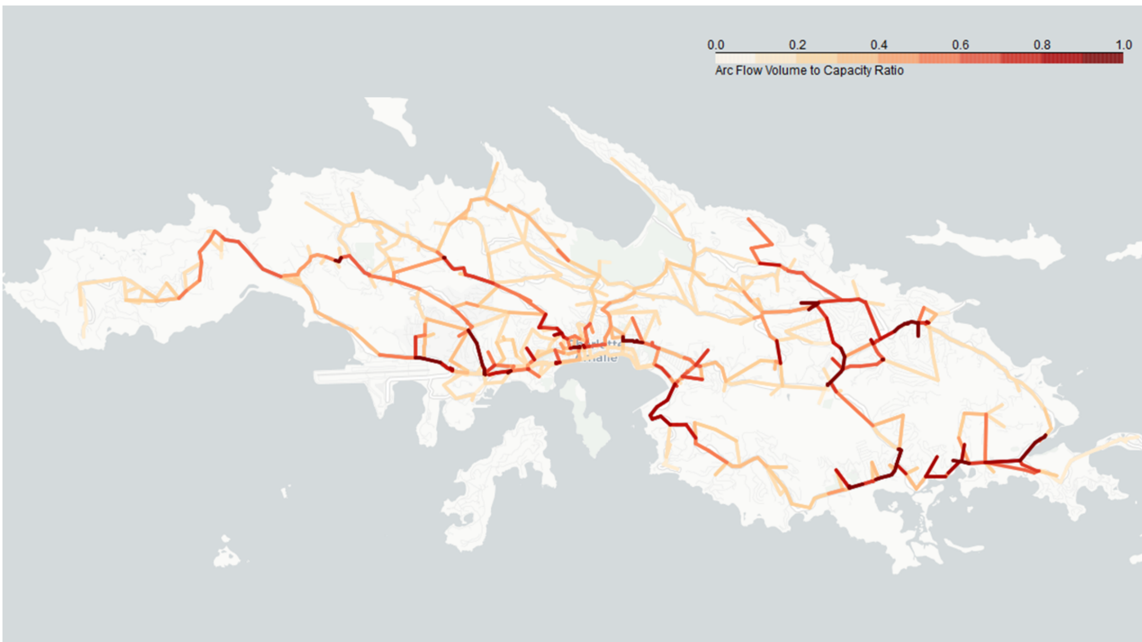

Figure 5.11. STT traffic flows under flooded conditions. Arcs are displayed according to their flow-to-capacity ratios. Higher ratios are depicted by darker colors. Created using QGIS Development Team (2020) on 14 September 2020.

Figure 5.12 shows the roundtrip travel time distributions to each store type. We see increases in roundtrip travel times for most stores on the island. The three longest roundtrips under normal conditions see increases of over 15 minutes in travel time. Not unsurprisingly, the further a store is from the port, the greater the change in travel time. Even small differences in congestion between normal and flooded conditions compound upon each other.

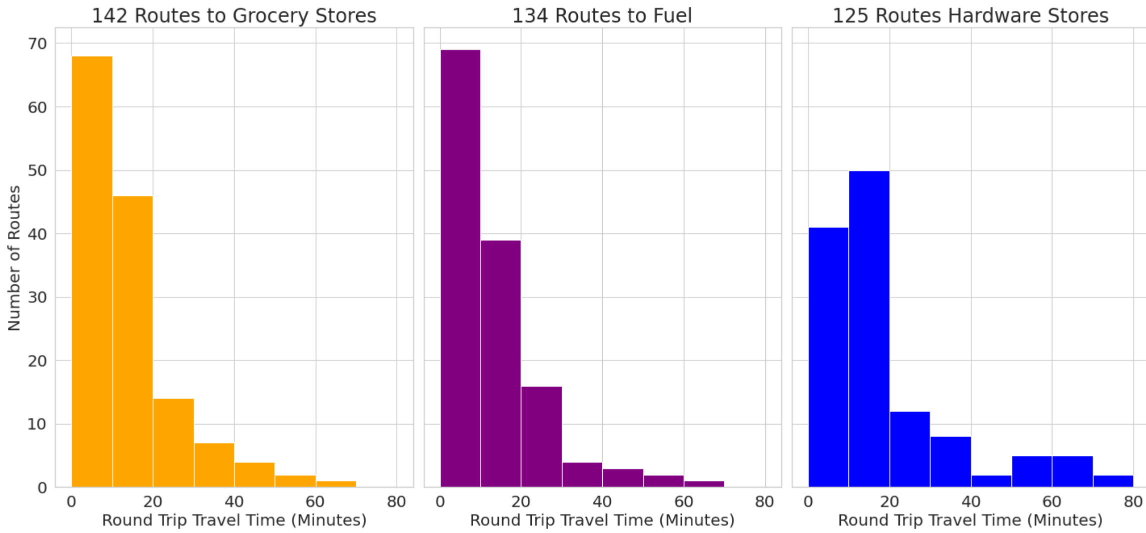

Figure 5.12. STT roundtrip travel times under flooded conditions. While most trips are under one hour, some roundtrips to hardware stores exceed that.

Table 5.3 shows the averages, standard deviations, and change in average for all roundtrip travel times.

Table 5.3. STT average roundtrip times under flooded conditions.

Destination Type	Average (minutes)	Change in Average (minutes)	Standard Deviation (minutes)
All	15.23	4.00	13.40
Grocery	13.89	2.63	11.51
Fuel	13.37	3.48	11.19
Hardware	16.58	3.92	16.58

Figure 5.13 displays the longest roundtrip travel times for all destinations. The western side of the island again suffers the most. Population "population001-Fortuna," "population002-Bordeaux," and "population003-Fortuna" have one hour roundtrip travel times to hardware stores. Population "population079-Lovenlund" continues to be the non-western population center with the worst travel times.

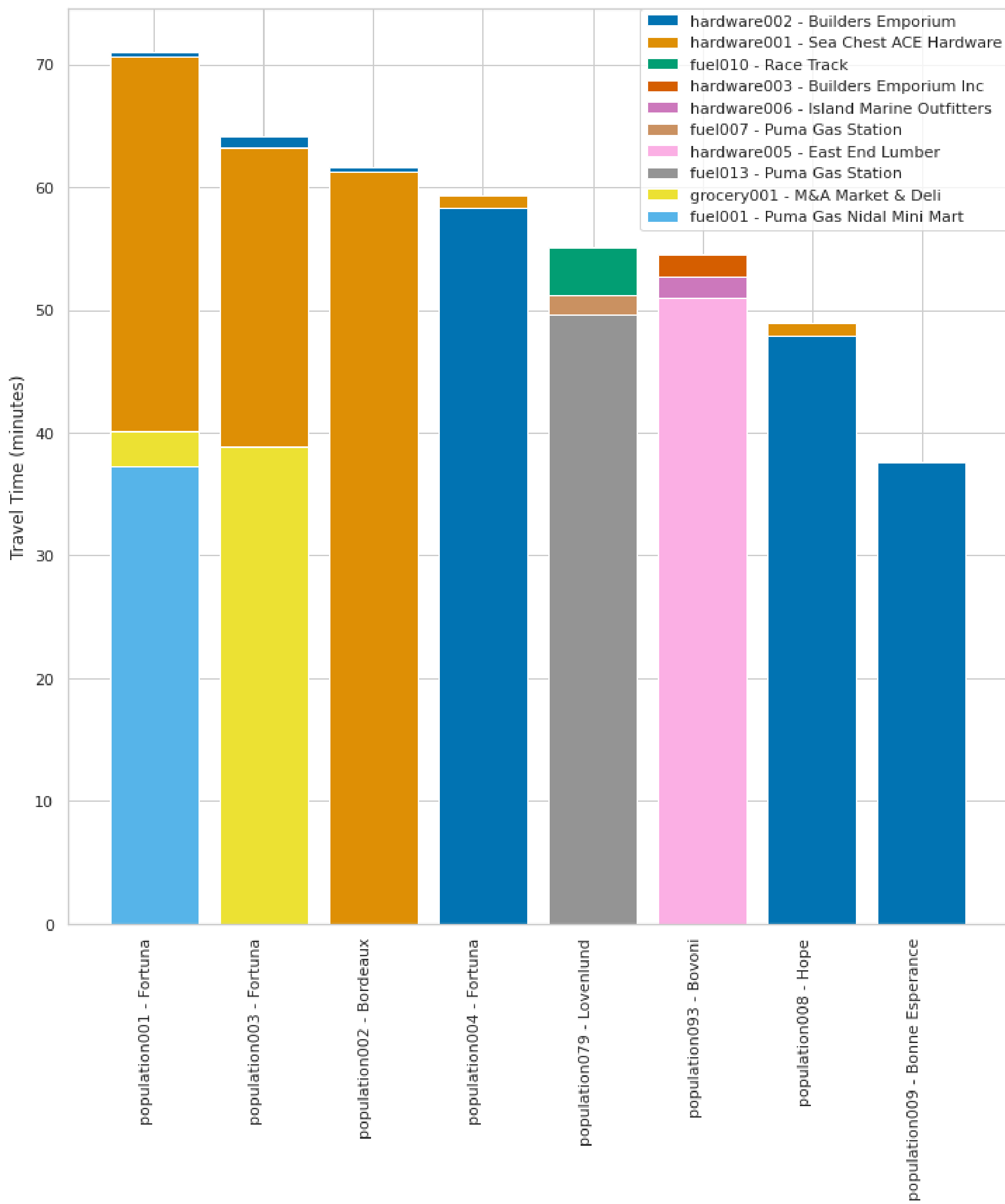

Figure 5.13. STT roundtrip travel times for all store types under flooded conditions. The height of the bar indicates the total travel time from a particular origin to a given store. Color of bar indicates the store. In cases where an origin has more than one longest round trip, the bars are superimposed with one color per store.

Figure 5.14 displays the longest grocery travel times. The western populations face the longest travel times, ranging from 25 minutes at the shortest to 40 minutes for the longest. The next longest other than the west again belonged to “population056-Peterborg” in the north.

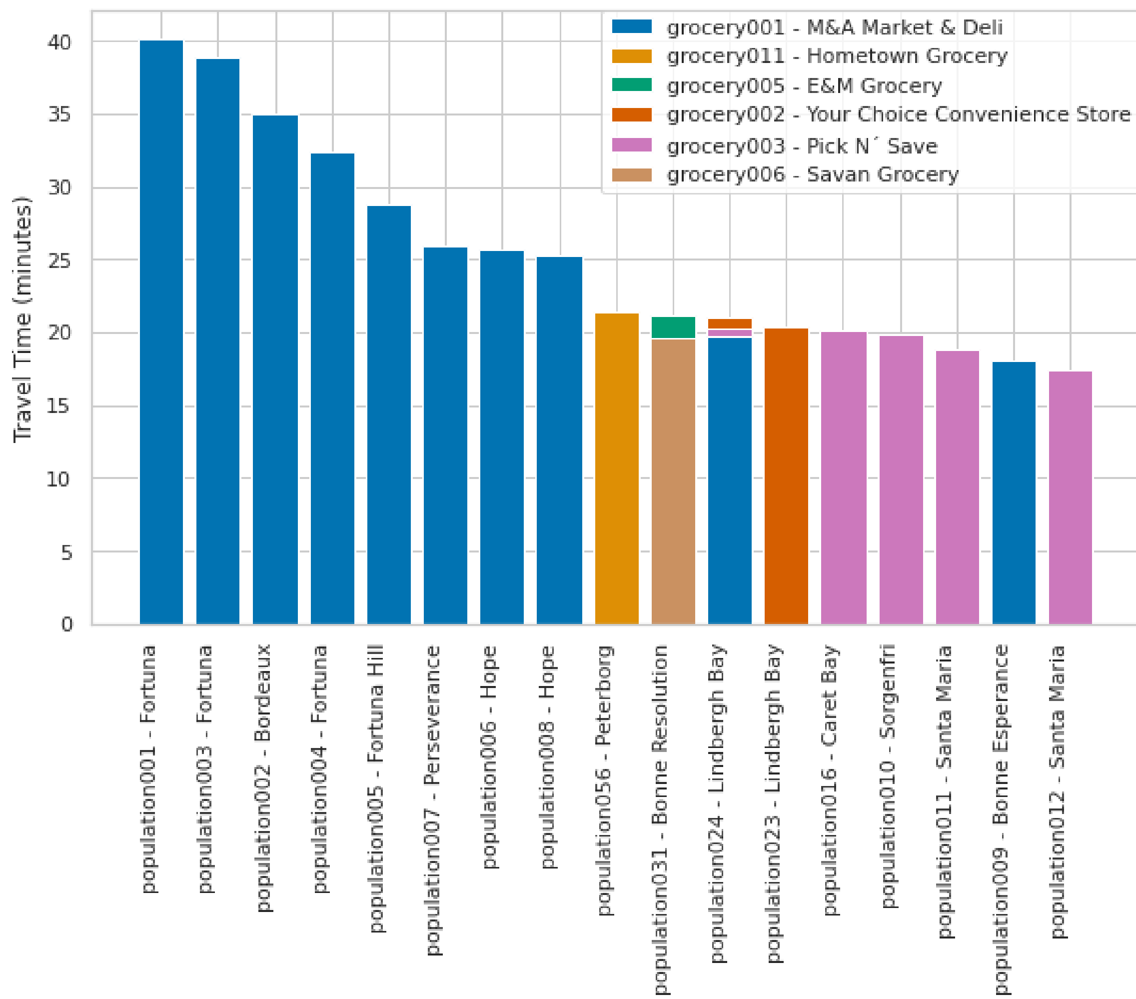

Figure 5.14. STT roundtrip travel times for grocery stores under flooded conditions. The height of the bar indicates the total travel time from a particular origin to a given store. Color of bar indicates the store. In cases where an origin has more than one longest round trip, bars are superimposed with one color per store.

Figure 5.15 displays the longest fuel travel times. Here, “population079-Lovenlund” takes the longest roundtrips of over 55 minutes, nearly 15 minutes more than the furthest most west population center “population001-Fortuna.” We see nine different fueling points, indicating that there is a wide variety of places to procure fuel from on the island. STT can avoid the issue where the majority of the island goes to one single fueling point.

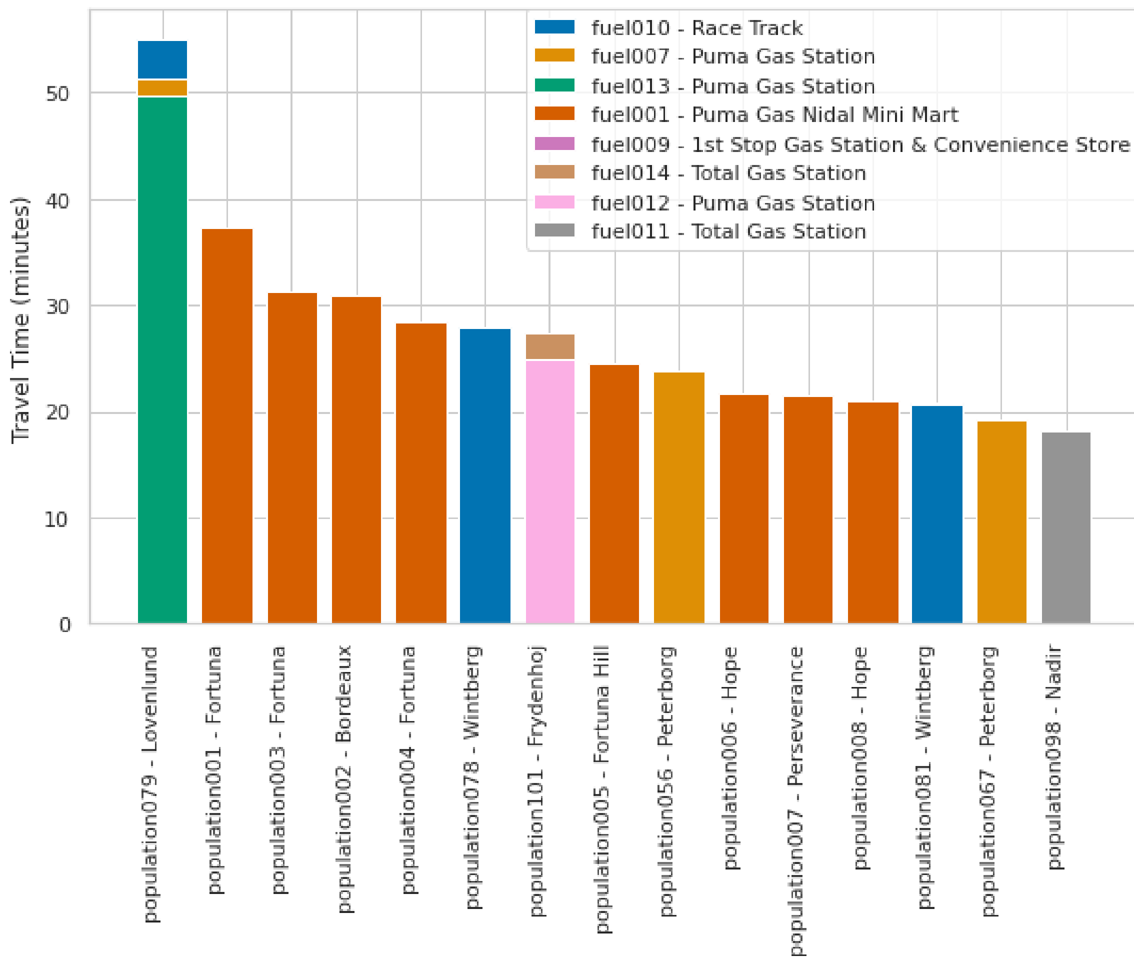

Figure 5.15. STT roundtrip travel times for fuel under flooded conditions. The height of the bar indicates the total travel time from a particular origin to a given store. Color of bar indicates the store. In cases where an origin has more than one longest round trip, bars are superimposed with one color per store.

Figure 5.16 displays hardware roundtrip times. Not surprisingly, the travel times from western populations were affected. Notably, population “population093-Bovoni” on the southern portion of the island increased its roundtrip time from under 25 minutes to more than 55 minutes.

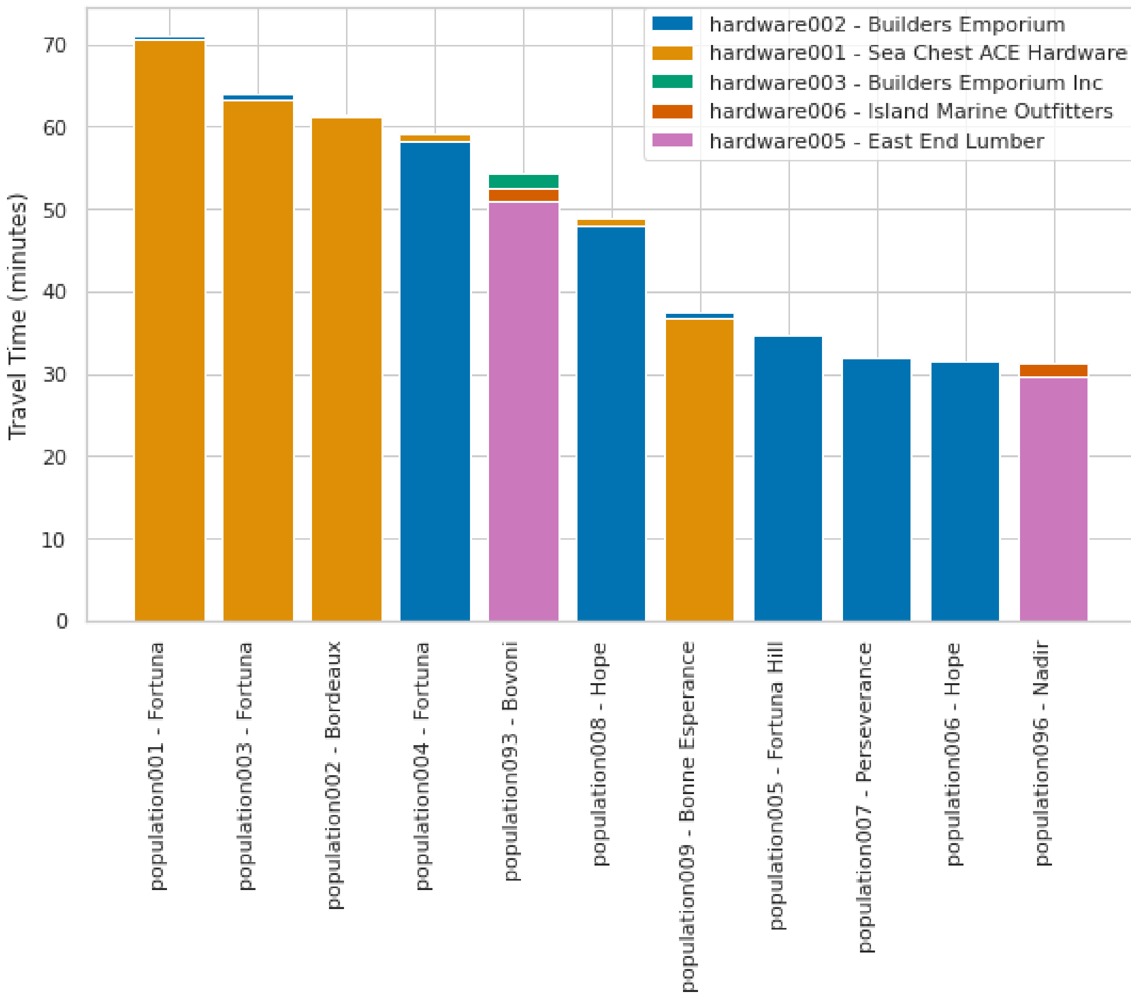

Figure 5.16. STT roundtrip travel times for hardware stores under flooded conditions. The height of the bar indicates the total travel time from a particular origin to a given store. Color of bar indicates the store. In cases where an origin has more than one longest round trip, bars bars are superimposed with one color per store.

Figure 5.17 displays the longest roundtrips from the Crown Bay Cargo Port to resupply supply sources. The longest times remain “hardware006-Island Marine Outfitters,” “grocery020- Moe’s Fresh Market Redhook,” and “fuel014-Total Gas Station.” Flooded conditions add approximately 10 minutes to the roundtrip travel time. Otherwise, the general shape of the travel times remain similar to the times under normal conditions.

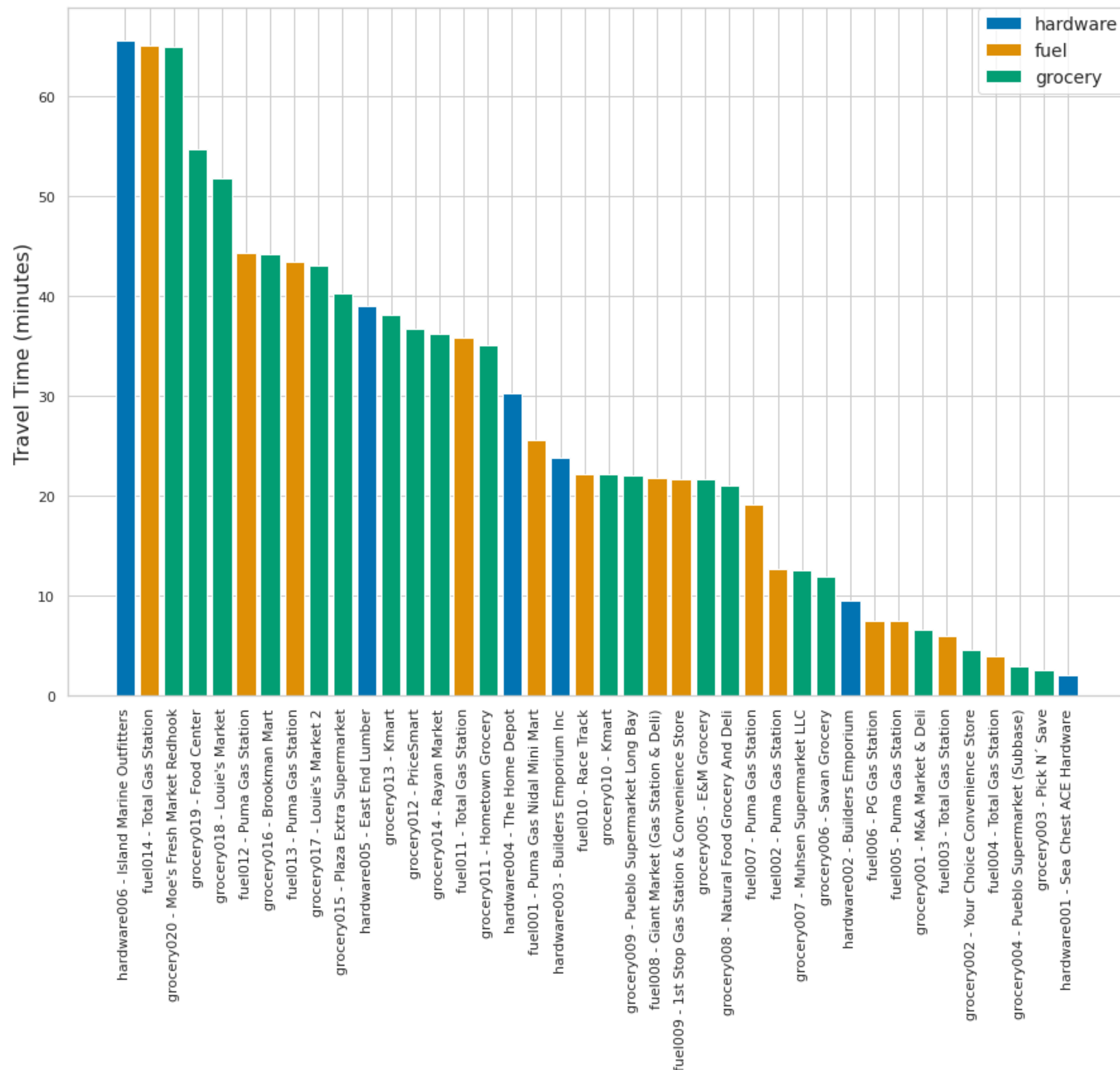

Figure 5.17. STT travel time from the port under flooded conditions. Roundtrip travel times in minutes from Crown Bay Cargo Port to all stores. Color of bar indicates the store.

Figure 5.18 depicts the longest routes from population centers to sources of supply on the island. We continue to observe the western population centers and population "population079-Lovenlund" having the longest travel times. However, population "population093-Bovoni" appears because of its 55 minute travel time to three separate hardware stores.

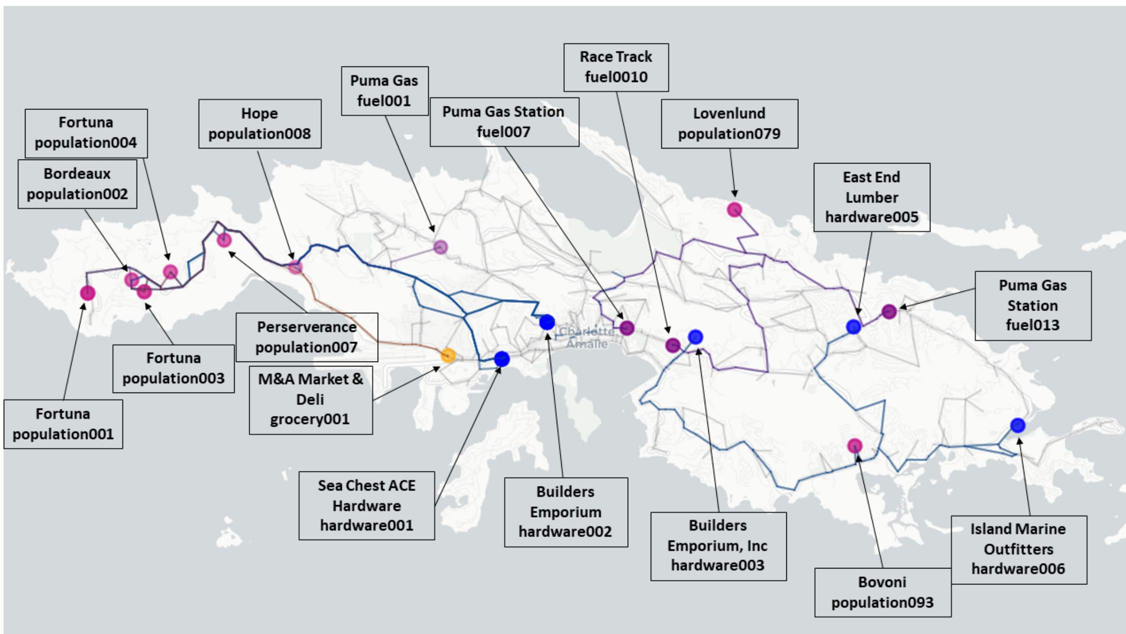

Figure 5.18. STT longest trips under flooded conditions. Route colors indicate the destination store type: blue for hardware stores, orange for grocery stores, and purple for gas stations. The remaining arcs are rendered in grey. Created using QGIS Development Team (2020) on 14 September 2020.

5.3 Worst-Case Disruptions

We now look at worst-case scenarios where flooding and storm surge renders roads impassable. Figure 5.19 shows flood water and storm surge up to 12 inches in bright blue. At 12 inches, per Pregnolato et al. (2017), roads become unusable by most vehicles. Roads that "flooded" still have their speeds and capacity halved. "Impassable" roads are switched off by the model and ignored. This results in traffic rerouting around those roadways.

We note that the Red Hook area on the western end of the island becomes cut off from the rest of the island. We also note that parts of the main road through Charlotte Amalie become impassable. We also note that populations "population037-Hull" and some parts of "population108-Nazareth" become cut off.

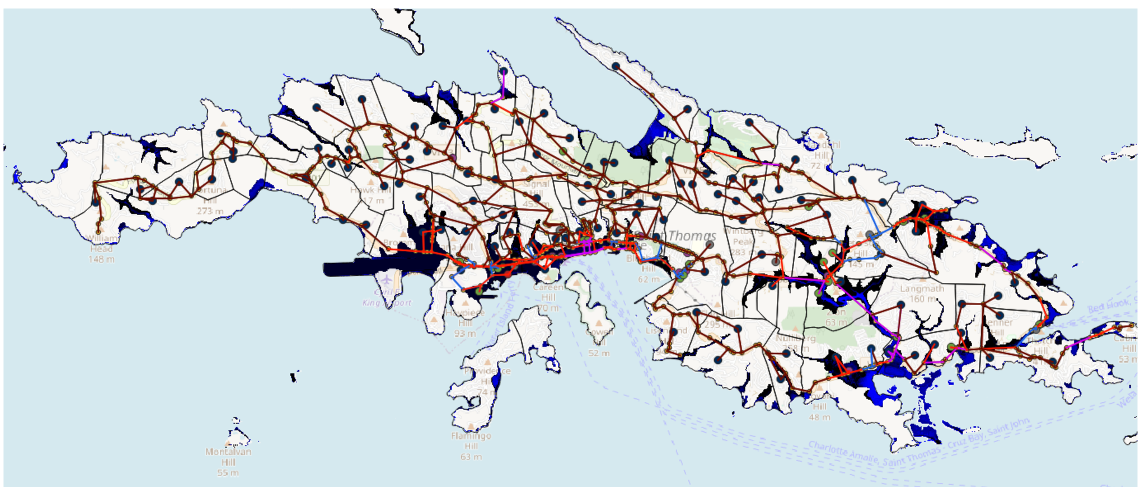

Figure 5.19. STT areas made impassable. Bright blue areas indicated flooding. Roads in purple are considered "impassable." Roads in red indicated roads considered "flooded." Created using QGIS Development Team (2020) on 14 September 2020.

Figure 5.20 shows the traffic flow under "worse-case" conditions. We observe significant differences over the flooded model. First, Red Hook's congestion essentially disappears because it is now cut off from the rest of the island. We see traffic that would flow to Red Hook instead goes south and then west along the coast line to reach what it can in Charlotte Amalie East. Congestion in central Charlotte Amalie is reduced as the roads become impassable and stores become inaccessible.

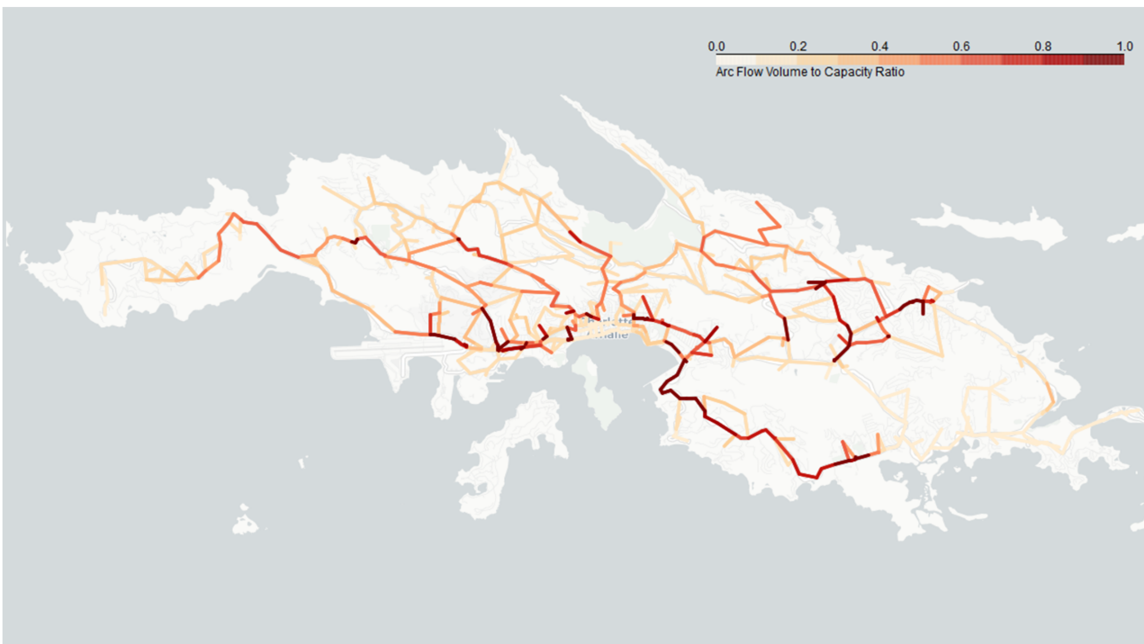

Figure 5.20. STT traffic flows under worst-case conditions. Arcs are displayed according to their flow-to-capacity ratios. Higher ratios are depicted by darker colors. Created using QGIS Development Team (2020) on 14 September 2020.

Figure 5.21 shows our first dropped estates under this model. Roads become impassable, hampering five estates from accessing the road network: Hull, Nadir, Langmath Mariendal, Frydenhoj, and Nazareth. All of these communities, except Hull, are on the eastern side of the island near Red Hook. All told, 4,656 people become isolated from the rest of the island, and are unable to access supplies.

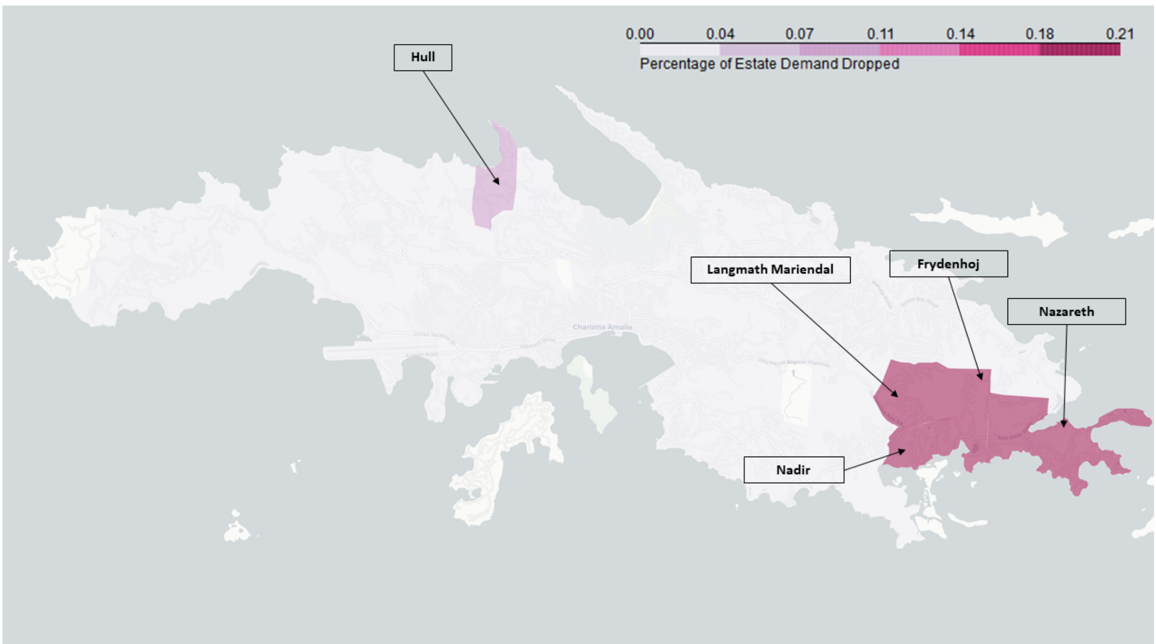

Figure 5.21. STT dropped demand from estates. The darker the color the more demand was dropped. Created using QGIS Development Team (2020) on 18 September 2020.

In Figure 5.22 we see the same phenomenon as on STJ. There is a general reduction in overall travel times. With approximately 10% of the population now cut off from the network, the travel times improve for other population centers on the island. Table 5.4 shows these reductions in travel times.

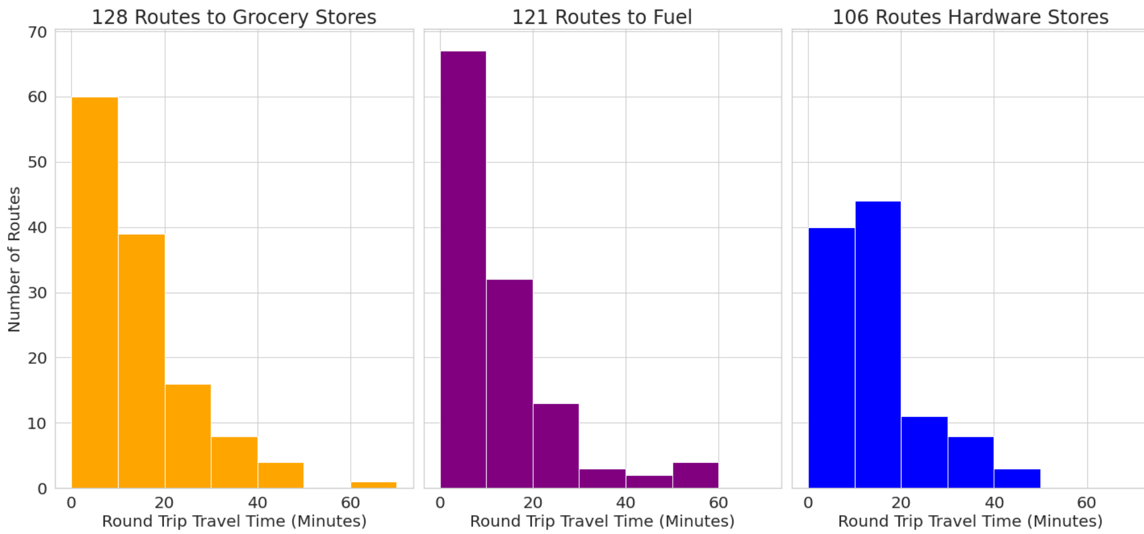

Figure 5.22. STT roundtrip travel times under worst-case conditions. While most trips are under one hour, some roundtrips to hardware stores exceed that.

Table 5.4. STT average roundtrip times under worst-case conditions.

Destination Type	Average (minutes)	Change in Average (minutes)	Standard Deviation (minutes)
All	13.72	-1.51	10.85
Grocery	13.78	-0.11	11.16
Fuel	13.03	-0.34	11.42
Hardware	14.41	-2.17	9.80

Figure 5.23 shows that while some population centers are now without paths to supplies, the remaining population centers see minimal increases in travel times over flooded conditions. The travel times for the western end of the island improved over flooded conditions. Population "population079-Lovenlund" shows the longest travel times, nearing a one hour trip to reach any source of fuel.

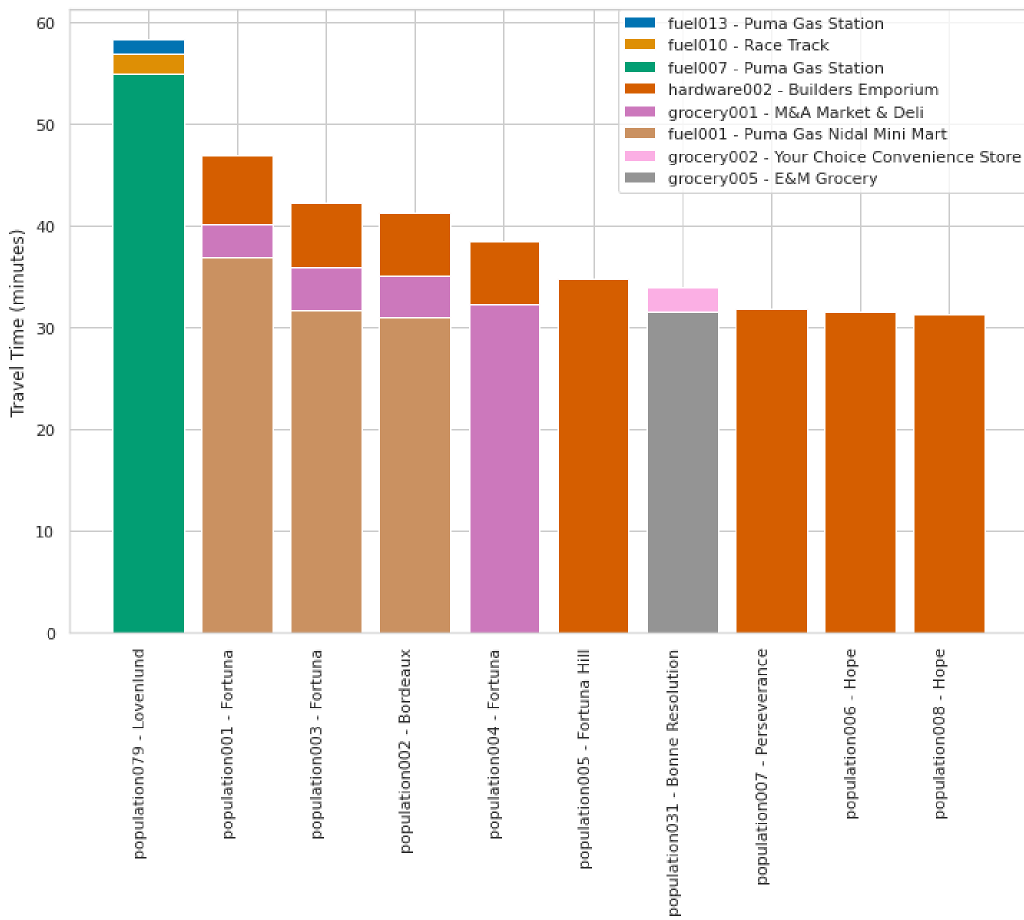

Figure 5.23. STT roundtrip travel times for all store types under worst-case conditions. The height of the bar indicates the total travel time from a particular origin to a given store. Color of bar indicates the store. In cases where an origin has more than one longest round trip, the bars are superimposed with one color per store.

Figure 5.24 depicts grocery store roundtrip travel times. Roundtrip travel times generally remain the same. The western side of the island still fairs the worst in terms of longest travel times. One significant changes involve population “population031-Bonne Resolution” increasing from 20 minutes to 35 minutes. Another change is that after not appearing on Figure 5.14, population “population093-Bovoni” and “population090-Bovoni” appear on the graph with travel times above 25 minutes.

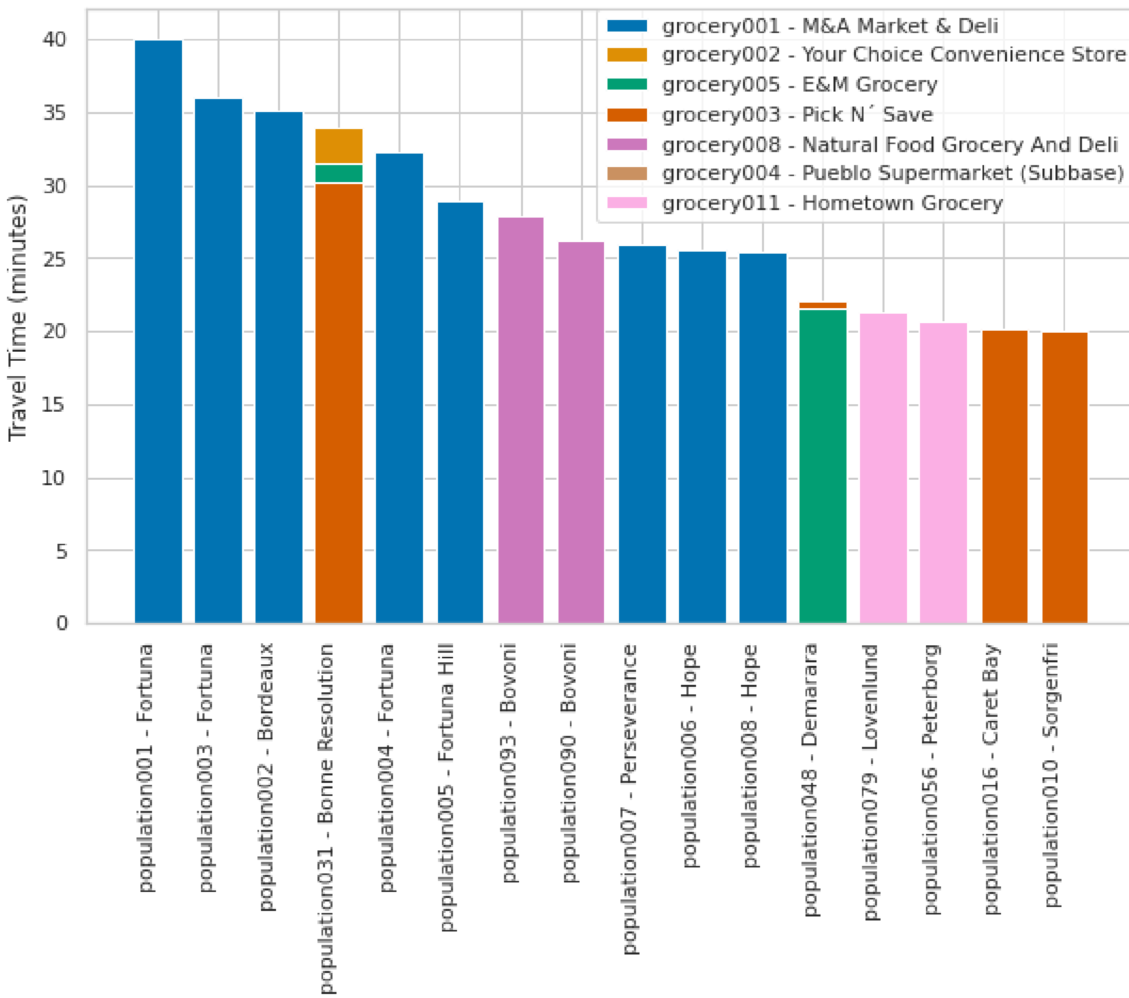

Figure 5.24. STT roundtrip travel times for grocery stores under worst-case conditions. The height of the bar indicates the total travel time from a particular origin to a given store. Color of bar indicates the store. In cases where an origin has more than one longest round trip, bars are superimposed with one color per store.

Figure 5.25 shows a dramatic improvement in the fortunes of population "population079-Lovenlund," which sees it's 55 minute roundtrip fall to barely over 20 minutes. Populations "population093-Bovoni" and "population090-Bovoni" appear after not appearing in Figure 5.15. Other than those changes, the western side of the islands continues to display long roundtrip travel times.

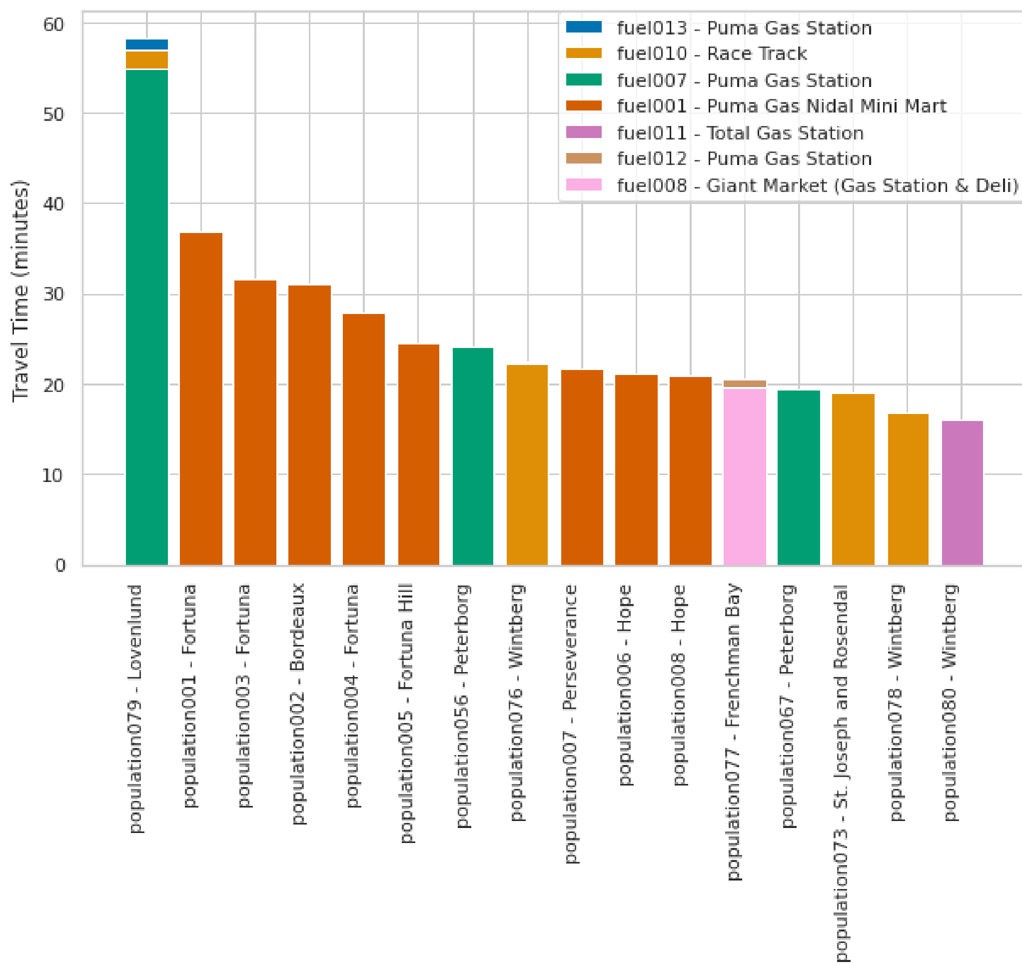

Figure 5.25. STT roundtrip travel times for fuel under worst-case conditions. The height of the bar indicates the total travel time from a particular origin to a given store. Color of bar indicates the store. In cases where an origin has more than one longest round trip, bars are superimposed with one color per store.

Figure 5.26 shows a dramatic reduction in roundtrip travel times to hardware stores. Population "population001-Fortuna" sees a 15-minute decrease in travel times. All other population centers see equivalent or better drops. However, the west coast converges on hardware store "hardware002-Builders Emporium," which will probably see significant service time delays.

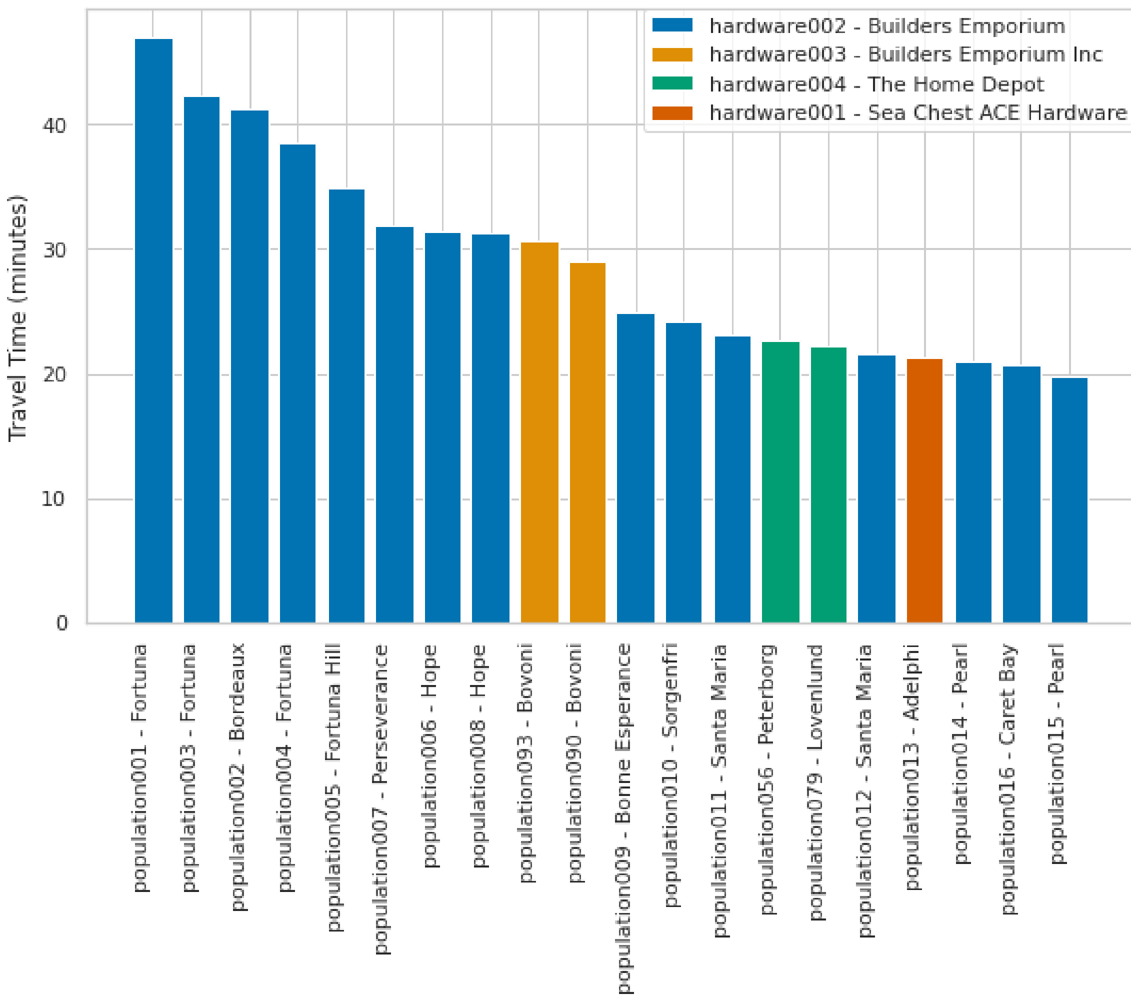

Figure 5.26. STT roundtrip travel times for hardware stores under worst-case conditions. The height of the bar indicates the total travel time from a particular origin to a given store. Color of bar indicates the store. In cases where an origin has more than one longest round trip, bars bars are superimposed with one color per store.

Figure 5.27 shows estates with stores that are unable to receive resupply. We see that the road disruptions on the eastern part of the island near Red Hook are the worst hit. Additionally, several stores in Charlotte Amalie are cut off from the network.

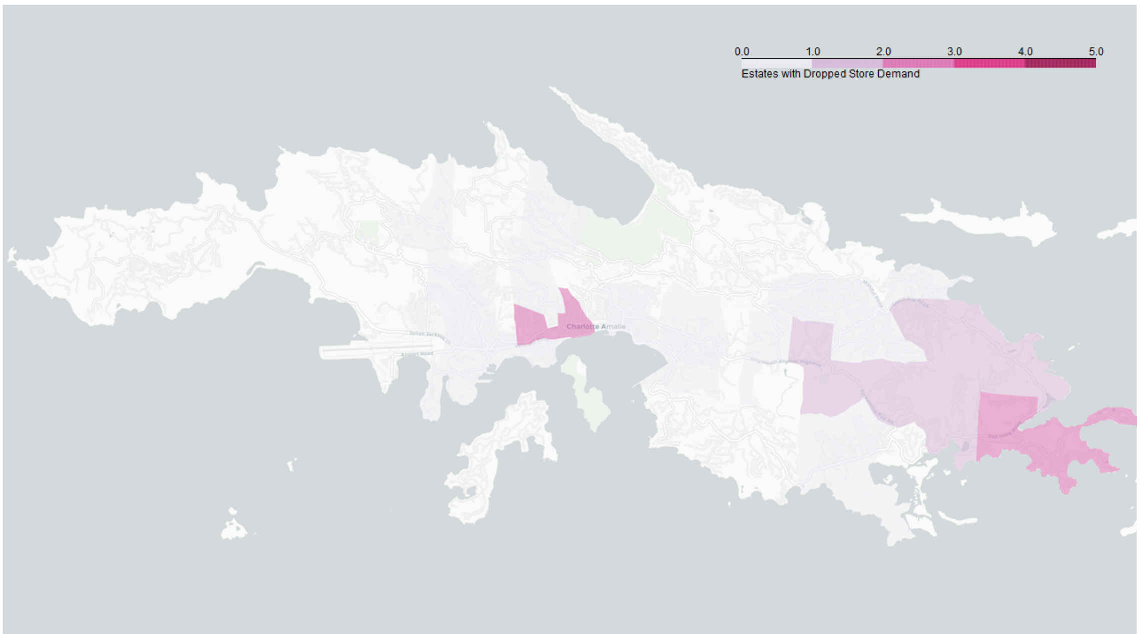

Figure 5.27. STT dropped stores during worst-case conditions. Any estates containing stores that drop demand are depicted in red with darker colors indicating higher levels of dropped demand. Created using QGIS Development Team (2020) on 14 September 2020.

Figure 5.28 shows these dropped stores in more detail. We observe one hardware store, one fuel location, and six grocery stores. Not coincidentally, these dropped stores had the previously highest roundtrip travel times from the port. Now, however, they are cut off. The biggest increase in roundtrip is that of grocery store "grocery013-Kmart," which sees an increase from 25 minutes to nearly 65 minutes. Fuel location "fuel012-Puma Gas Station," second on the graph, sees its roundtrip time nearly double.

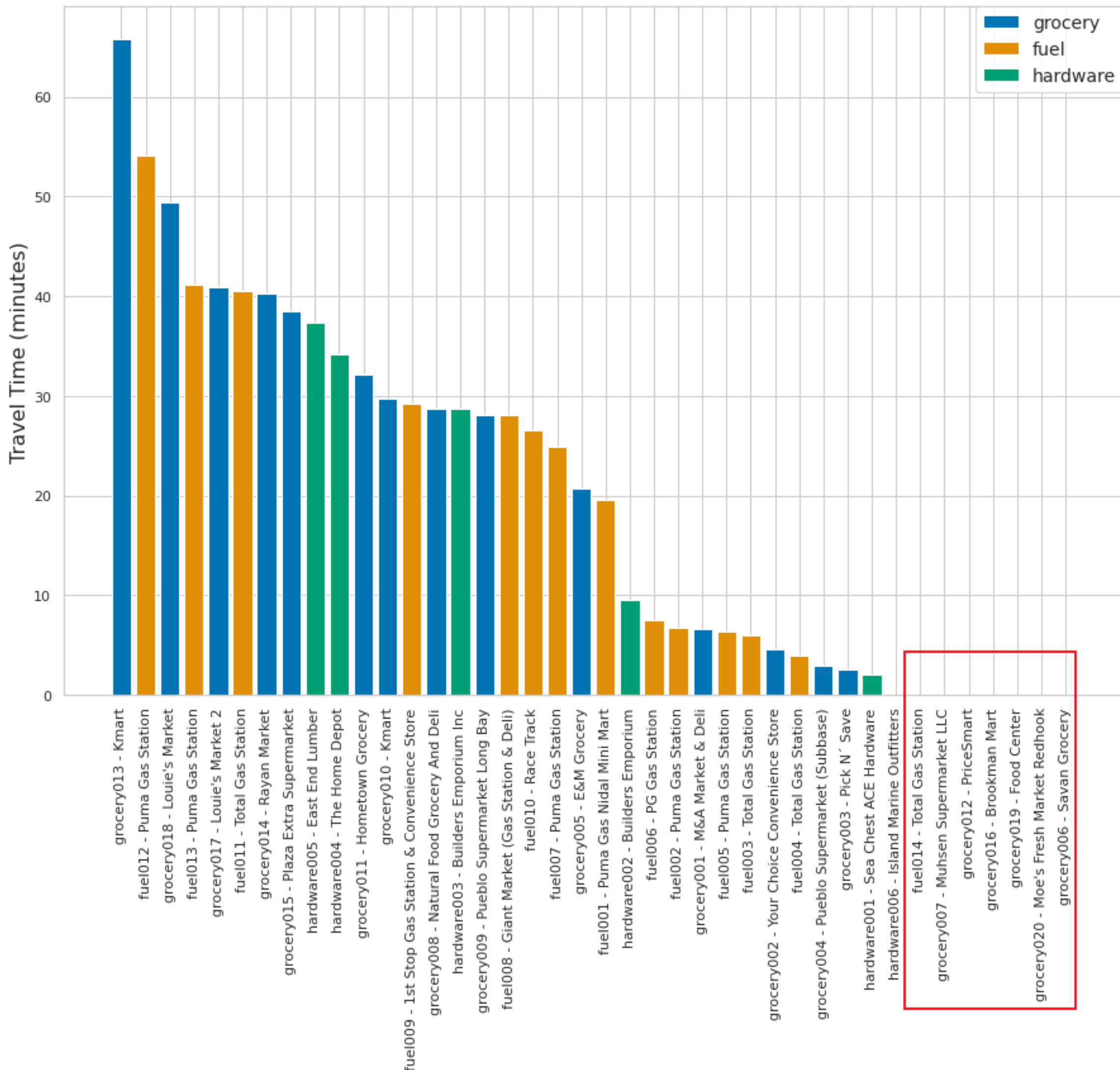

Figure 5.28. STT travel time from the port under worst-case Conditions. Roundtrip travel times in minutes from Crown Bay Cargo Port to all stores. Color of bar indicates the store. The red box indicates stores that are unable to receive resupply because of impassable roads.

Finally, Figure 5.29 shows the longest trips under worst-case conditions. We see little change from flooded conditions. Population "population010-Sorgenfi" is exchanged from flooded conditions for population "population031-Bonne Resolution" on the impassable map. We see that "population09-Lovenlund" has exchanged its longest trips to hardware stores to longest trips to fuel locations.

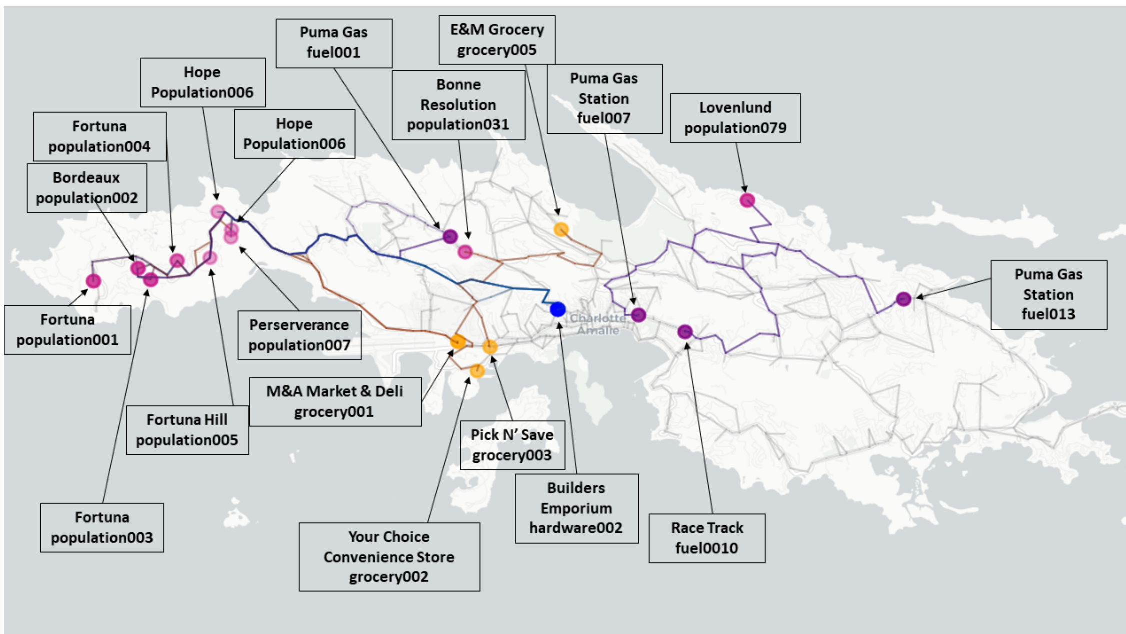

Figure 5.29. STT longest trips under worst-case conditions. Route colors indicate the destination store type: blue for hardware stores, orange for grocery stores, and purple for gas stations. The remaining arcs are rendered in grey. Created using QGIS Development Team (2020) on 14 September 2020.

5.4 Discussion

Table 4.4 summarizes the different STT scenarios. As on STJ, total vehicle-hours increase as the conditions worsen from normal to flooded, but decrease during the worst-case scenario because of the dropped demand and population stranded behind impassable roads. The largest impact during the worst-case scenario is the complete isolation of the Red Hook area on the eastern side of the island.

Table 5.5. Comparison of disaster scenarios for STT.

Scenario	Total Vehicle-Hours	Mean Travel Time (Ports)	Total Dropped (Stores)	Mean Travel Time (Estates)	Total Dropped (People)
Normal	2229.50	19.93	0	17.40	0
Flooding	3016.63	26.99	0	20.26	0
Worst-Case	2869.82	19.93	8	13.72	4,656

There are constants across all of the scenarios:

- The western communities including Fortuna and Bordeaux consistently face the longest travel times under all scenarios. Further, Fortuna Road is the only road out of the area. Although the road was not affected under any of scenarios, an unforeseen disruption would prove harmful to the communities.
- Red Hook stores require the longest time to resupply under normal and flooded scenarios. The populations that rely on Red Hook will face the most difficulty once supplies run low or out.
- Further, Red Hook bears the brunt of dropped demand for population and stores under worst-case conditions.
- Lovenlund, on the northern coast, faces the longest travel times on the island after the western communities. While it can reach grocery stores relatively fast, it faces issues reaching fuel and hardware.

Can we think of any possible solutions?

- Communities: Because we only consider a curfew scenario, we do not see the daily congestion on STT that is a mainstay of daily life on the island. During curfew events, he STT road network does not appear to be constrained by capacity. Meaning the roads appear sufficient to support current populations to travel within the set six-hour curfew window. Roads may be at or above capacity during daily commute traffic causing congestion and slow downs. This is true even with "winding" roads that slow traffic. However, there are several key locations within the road network that appear vulnerable to flooding and storm surge. Those locations can isolate communities and prevent them from accessing critical supplies. Specifically, major roads leaving Red Hook that link the western coast to the rest of the island show. Though these roads are geographically separate from each other, their combined disruptions cause significant dropped demand for both population centers and stores.

- Ports: The ability to offload cargo in Red Hook bay, even in limited amounts, could alleviate the supply disruptions felt by Red Hook during disasters. Unfortunately, outside of Charlotte Amalie and the Red Hook area, there are no developed wharves or docks that could be used to offload cargo in an emergency.

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CHAPTER 6: Summary and Conclusions

We conclude with a summary of this work, along with a discussion of potential future work.

6.1 Summary

This purpose of this work is to assist our USVI partners in assessing the capacity of surface roads and supply chain infrastructure on STT and STJ. We assess these capabilities to assist in development of the next-generation USVI Hazard Mitigation and Resilience Plan (University of the Virgin Islands 2020). This work is one of many conducted by NPS, listed in Chapter 1, in conjunction with UVI and other USVI partners. We perform three modeling and analysis tasks; (1) we construct a useful dataset for both STT and STJ for the analysis of traffic congestion and resupply shipments on their surface roads, (2) we utilize a multi-commodity flow model first developed by Good (2019) that measures the roundtrip travel times for resupply shipments and residents to reach distribution locations during normal, flooded, and "worst-case" traffic conditions, and (3) we measure the capability of surface roads on both STT and STJ to support access to disaster relief supplies, and identify which communities may have difficulty accessing supply locations during normal, flooded, and worst-case scenarios.

In support of this objective, we improve the data curation techniques and computational process. We implement automated processes to build our dataset of the islands. We reduce the number of input files required for model execution from 15 to three. Instead of generating arc adjacency lists and geospatial data by hand, the model executable automatically generates the required information. Overall, we create a simpler and more user-friendly interface to more easily allow USVI stakeholders and others to utilize our process.

We find that certain geographic communities have the most difficulty to reach supplies. These communities include the STT communities of Fortuna and Bordeaux on the western end, and Red Hook on the eastern end. On STJ, all eastern communities have to traverse the length of the island to the west for fuel and hardware.

We find that under normal conditions, the road networks on both STT and STJ have enough capacity to meet demand during a six-hour curfew window. However, some communities descend en masse on one destination, such as the eastern half of STJ converging on "fuel002- The St. John Repair Shop." Service times under those circumstances could increase well beyond the curfew window, in shades of the lines at gas stations during the oil crises of the 1970s.

We find that under flooded conditions, communities are still able to access required supplies within curfew windows. This finding assumes that communities follow directions and coordinated movement plans of FEMA and VITEMA.

However, we also find that during worst-case scenarios, communities can be cut off from sources of supply. We find that the entirety of the supply chain on STJ will shut down under "worst-case" conditions because of the isolation of the cargo port from the rest of the network.

6.2 Future Work

There are a number of ways that this line of inquiry can be improved or expanded. As noted by Good (2019), there remains an opportunity to identify the best locations for emergency relief locations, assessing emergency response times (e.g., medical, fire, police), and assessing the performance of the road network for non-standard, traffic patterns (e.g., evacuation). Moreover, in the immediate aftermath of a disaster, there are a number of other important places—the airport, the landfill, the port, the hospital—for which it makes sense to study the accessibility by roads. For each of these applications, there remains interest in the potential impact of congestion or blocked roads.

The model can also be adapted to plan for new road construction, seeing how those new roads could improve travel times or lower congestion. The model could also be expanded to take into account the ferries that regularly travel between the islands, and whether for instance stranded Red Hook residents could take the ferry to STJ instead of remaining at home without required supplies.

Incorporating economic data in terms of potential disparities in equity is also an important topic for future work.

While the surface road network itself is important, it is a larger part of the interconnected infrastructure of the islands. One part of that infrastructure is the water delivery system. Since a large portion of consumer water use is provided by water delivery trucks (Borgdorff 2020), we could look at the impact of road disruptions on the distribution of fresh water.

In all these applications, we recommend that the model remain focused on supporting USVI organizations and stakeholders in their future designs of hazard mitigation and response planning frameworks.

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