An Operational Model of the Critical Supply Chain for the U.S. Virgin Islands

M.S. Thesis in Operations Research (Sept. 2019, expected),
Naval Postgraduate School, Monterey, CA

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Partners

FEMA

U.S. DEPARTMENT OF ENERGY

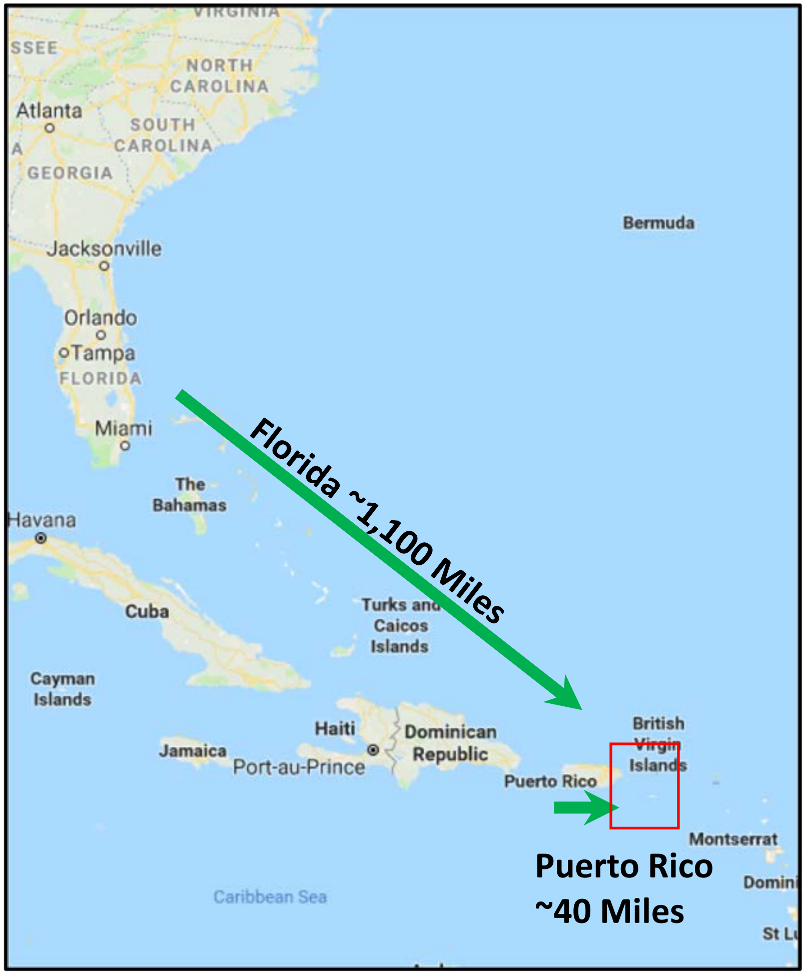
NPS PRAESTANTIA PER SCIENTIAM 1909

NAVAL POSTGRADUATE SCHOOL

University of the Virgin Islands

Territory Characteristics

FL → PR



Puerto Rico
~40 Miles

Territory Characteristics

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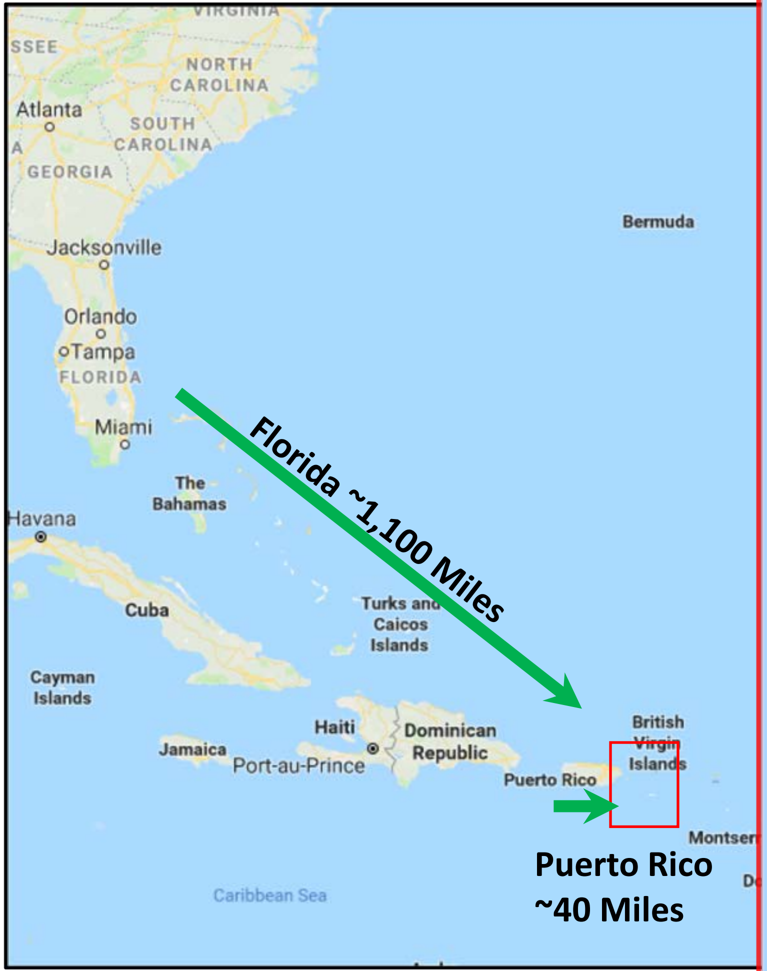
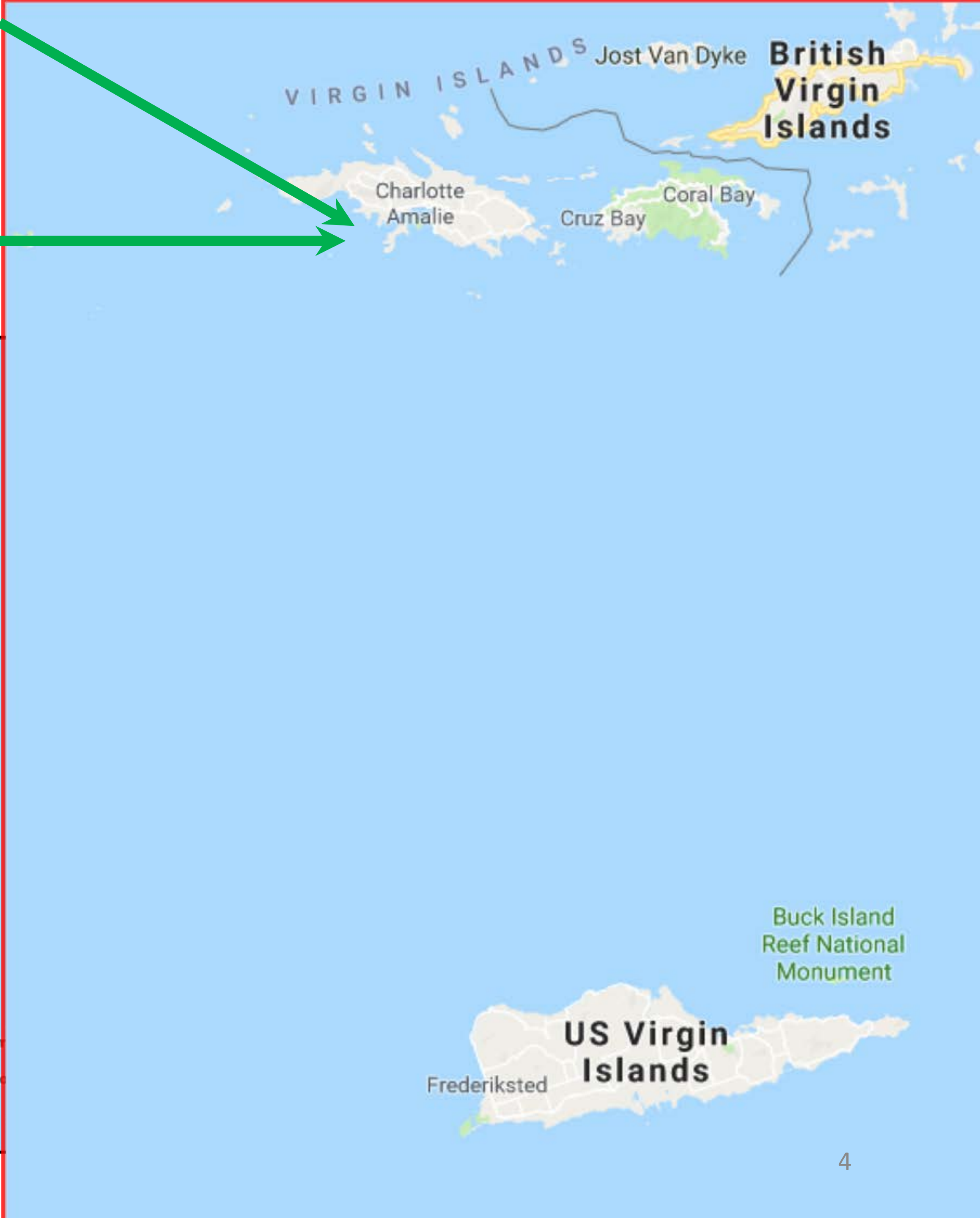


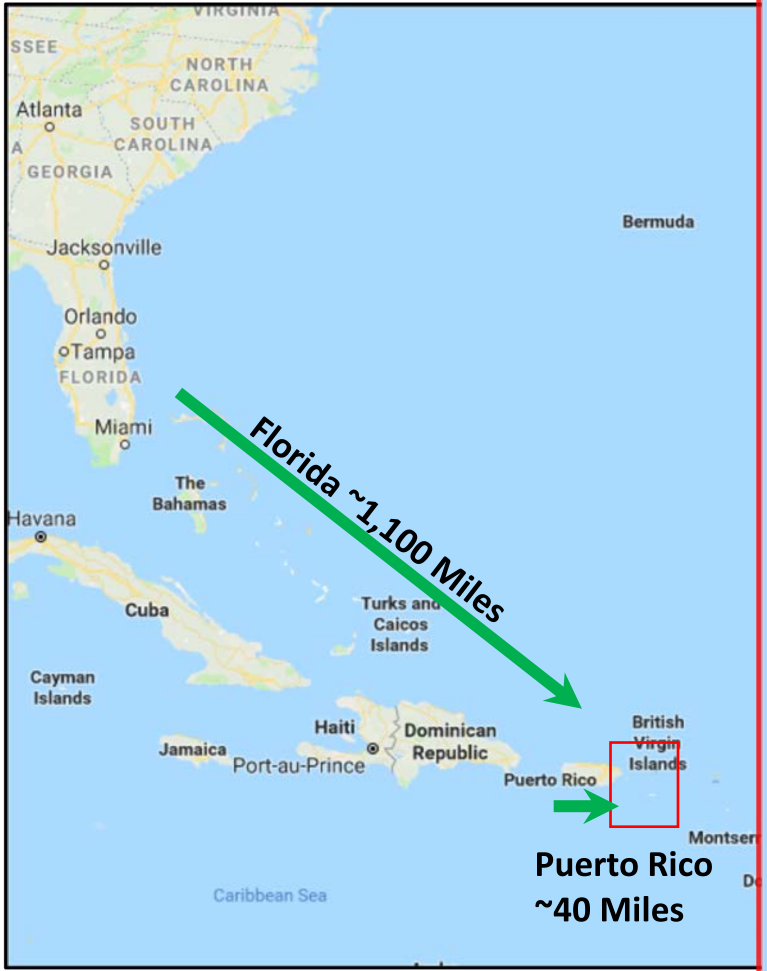
Florida ~1,100 Miles

Puerto Rico ~40 Miles



Territory Characteristics

FL→PR→STT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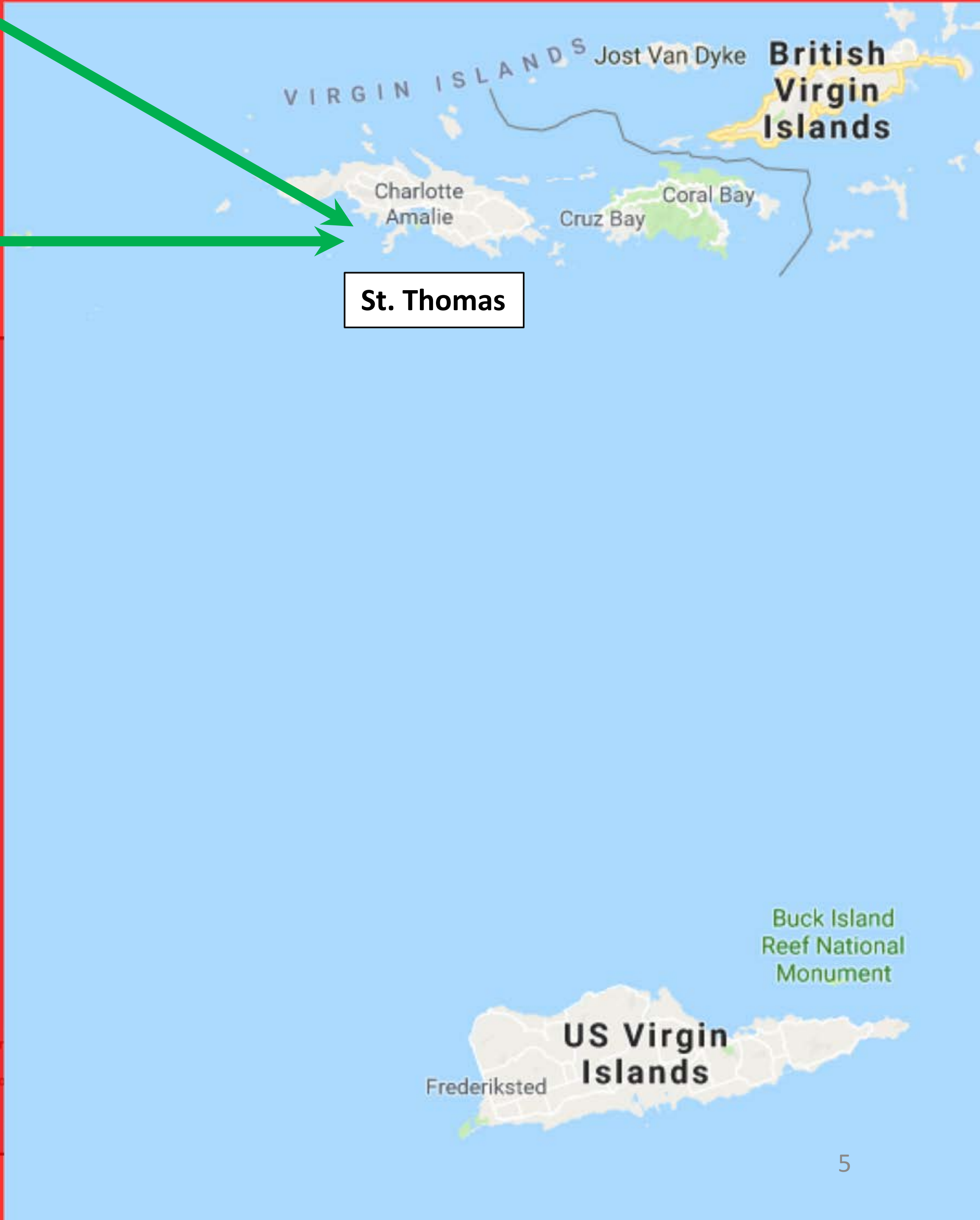
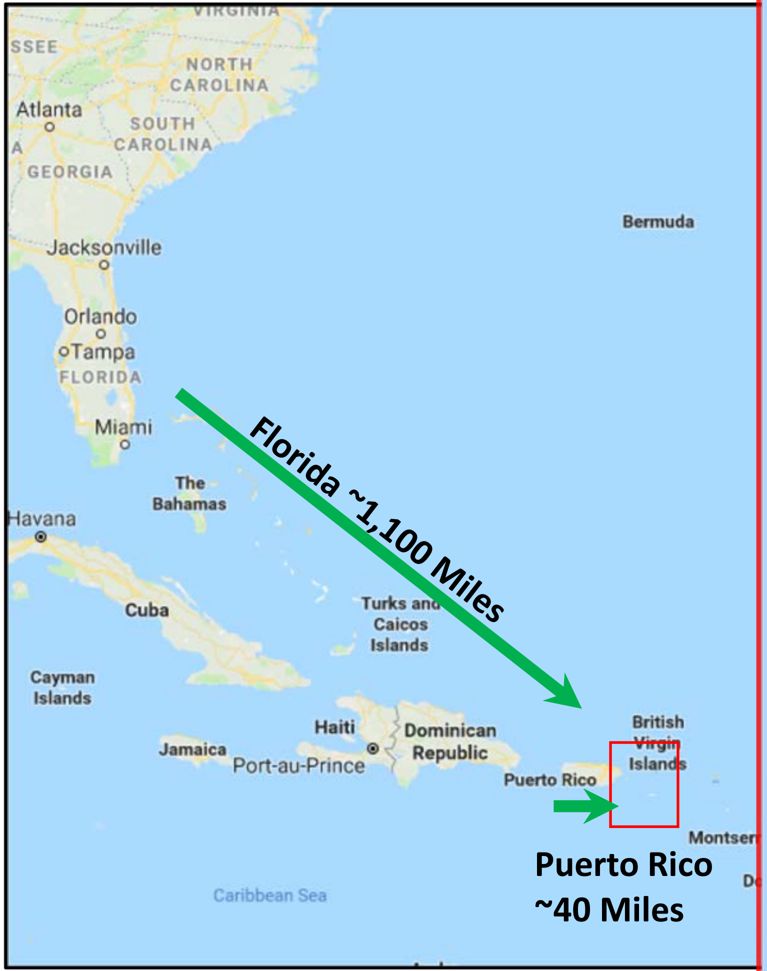

St. Thomas

Territory Characteristics

FL→PR→STT ↗STJ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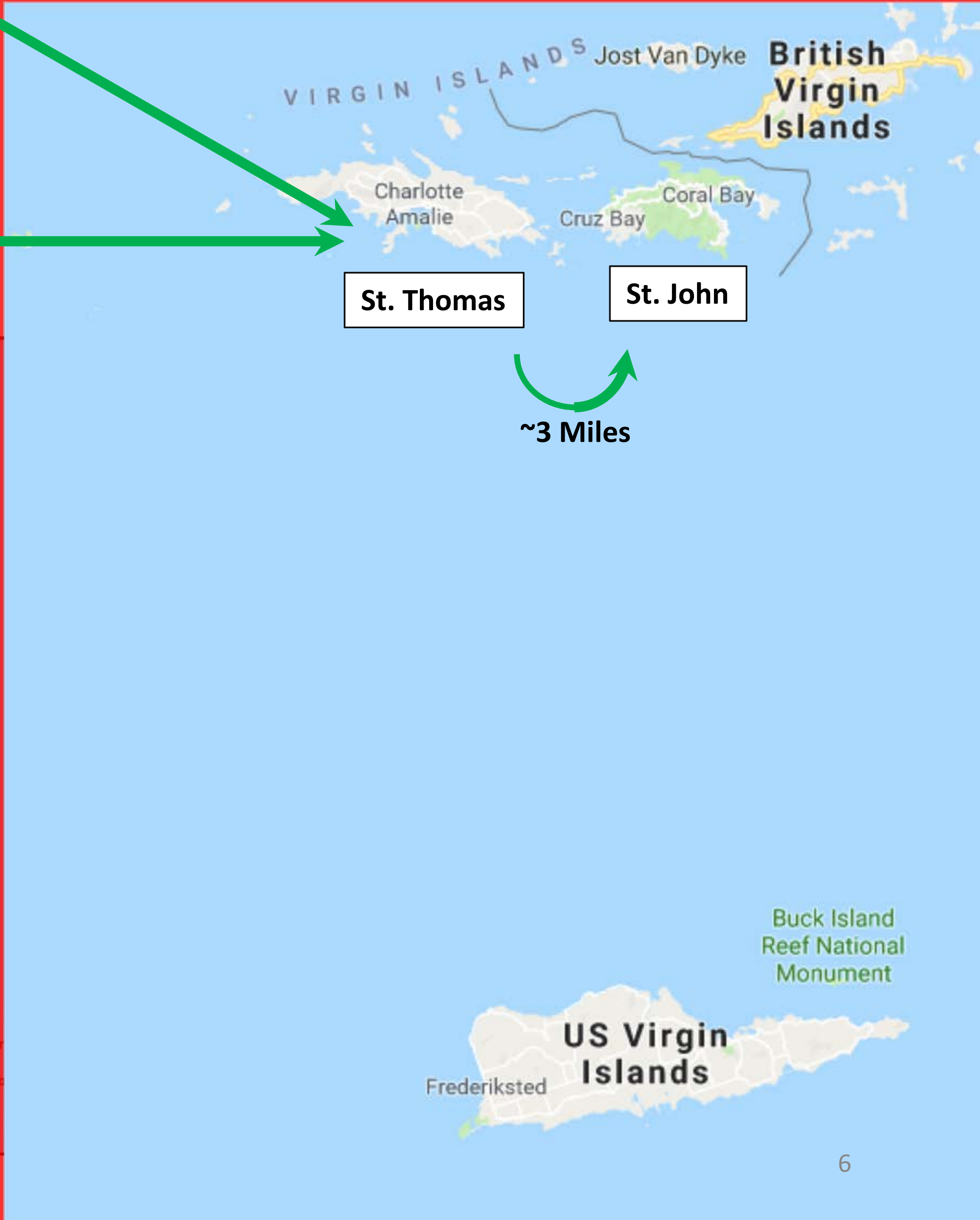
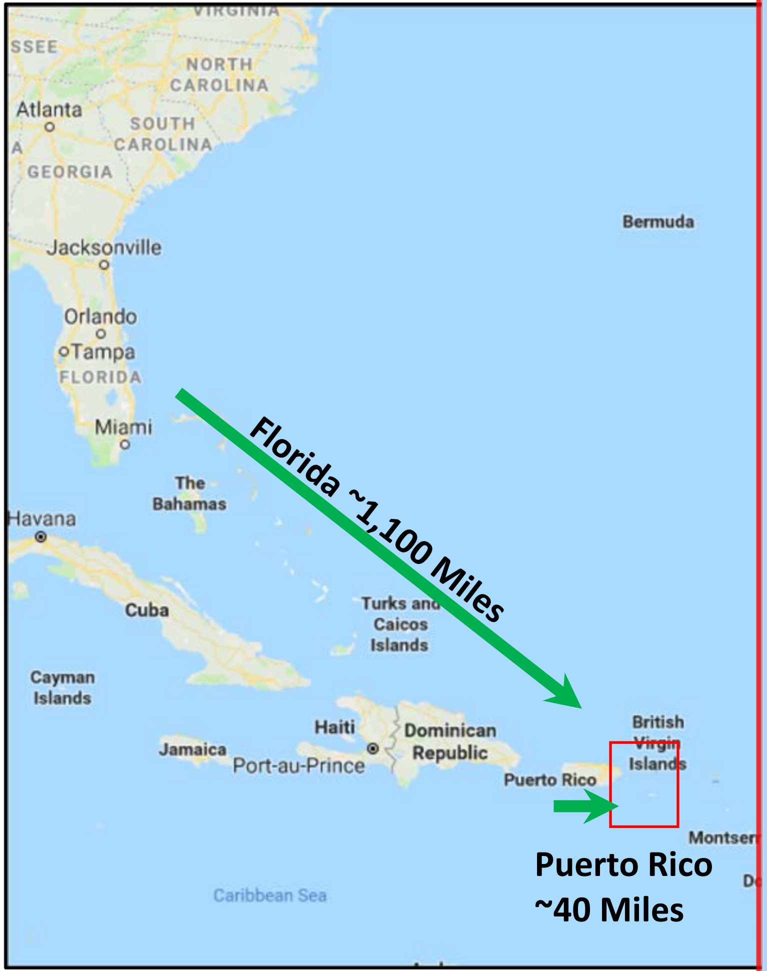

St. Thomas

St. John

~3 Miles

Territory Characteristics

FL → PR → STT → STJ
STT → STX



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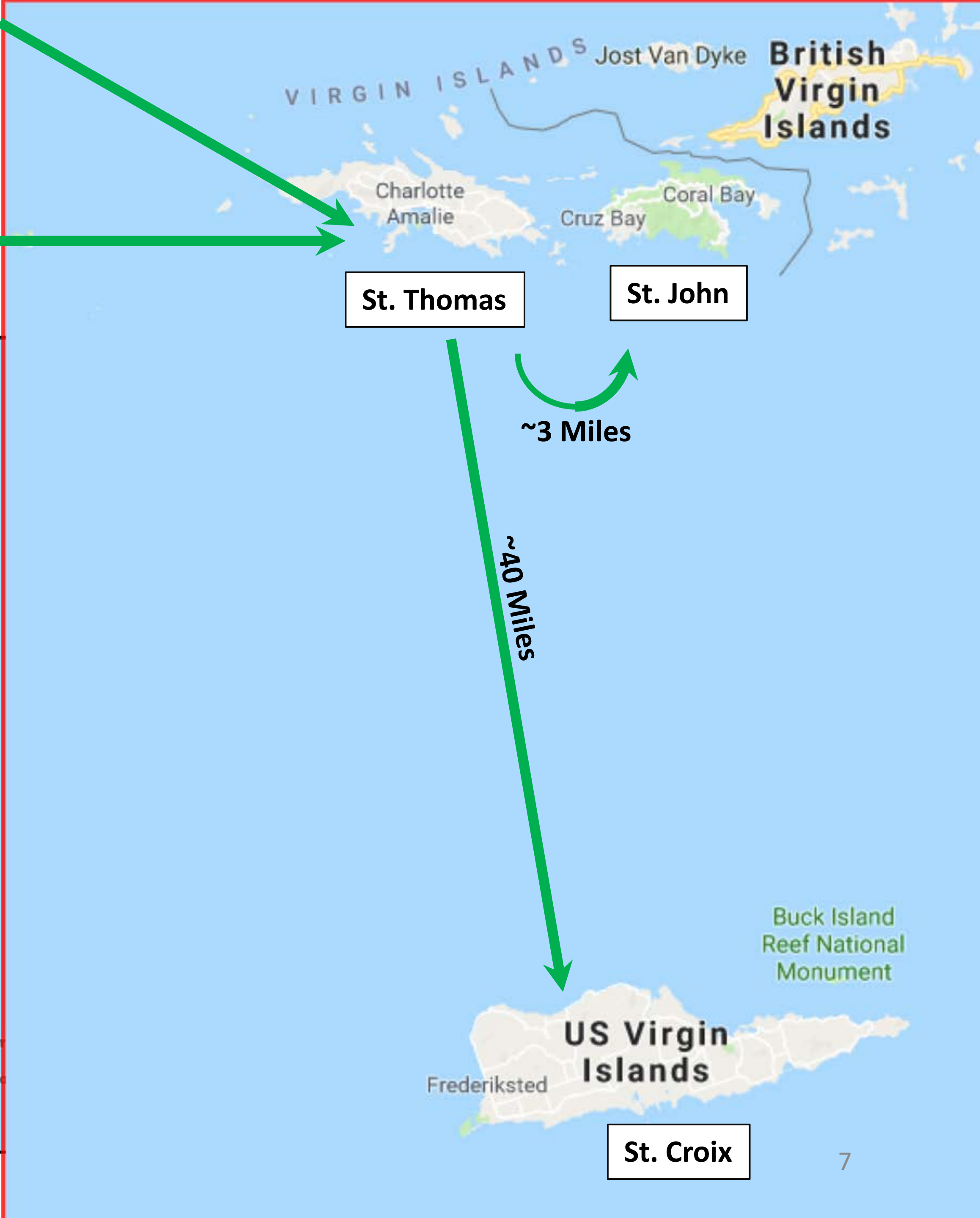


St. Thomas

St. John

~3 Miles

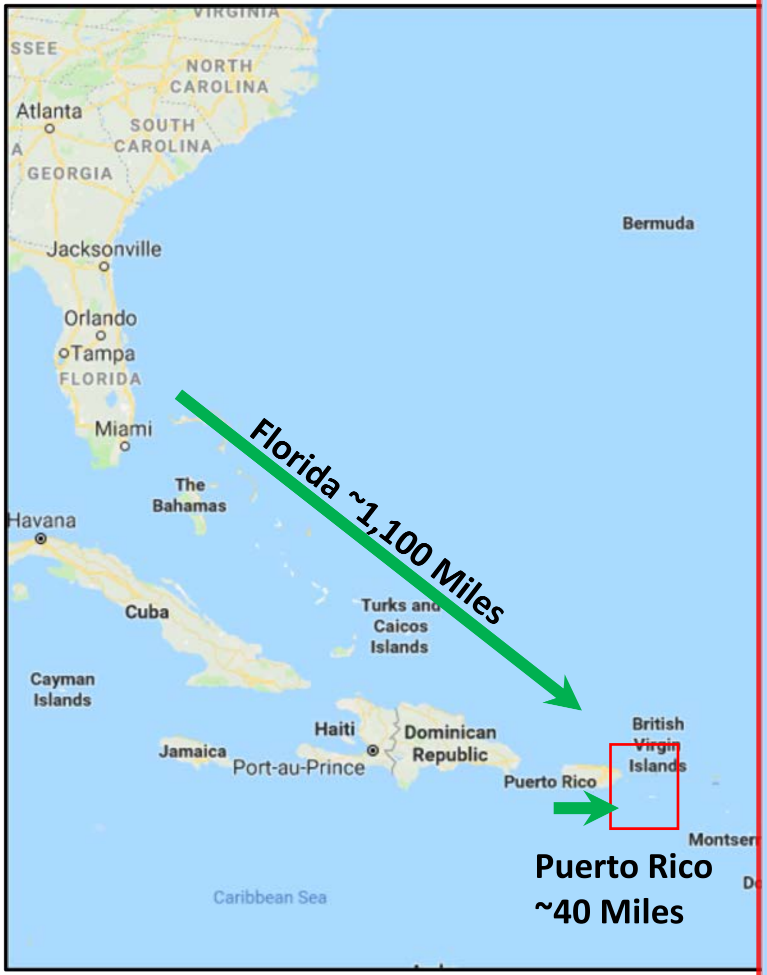
~40 Miles

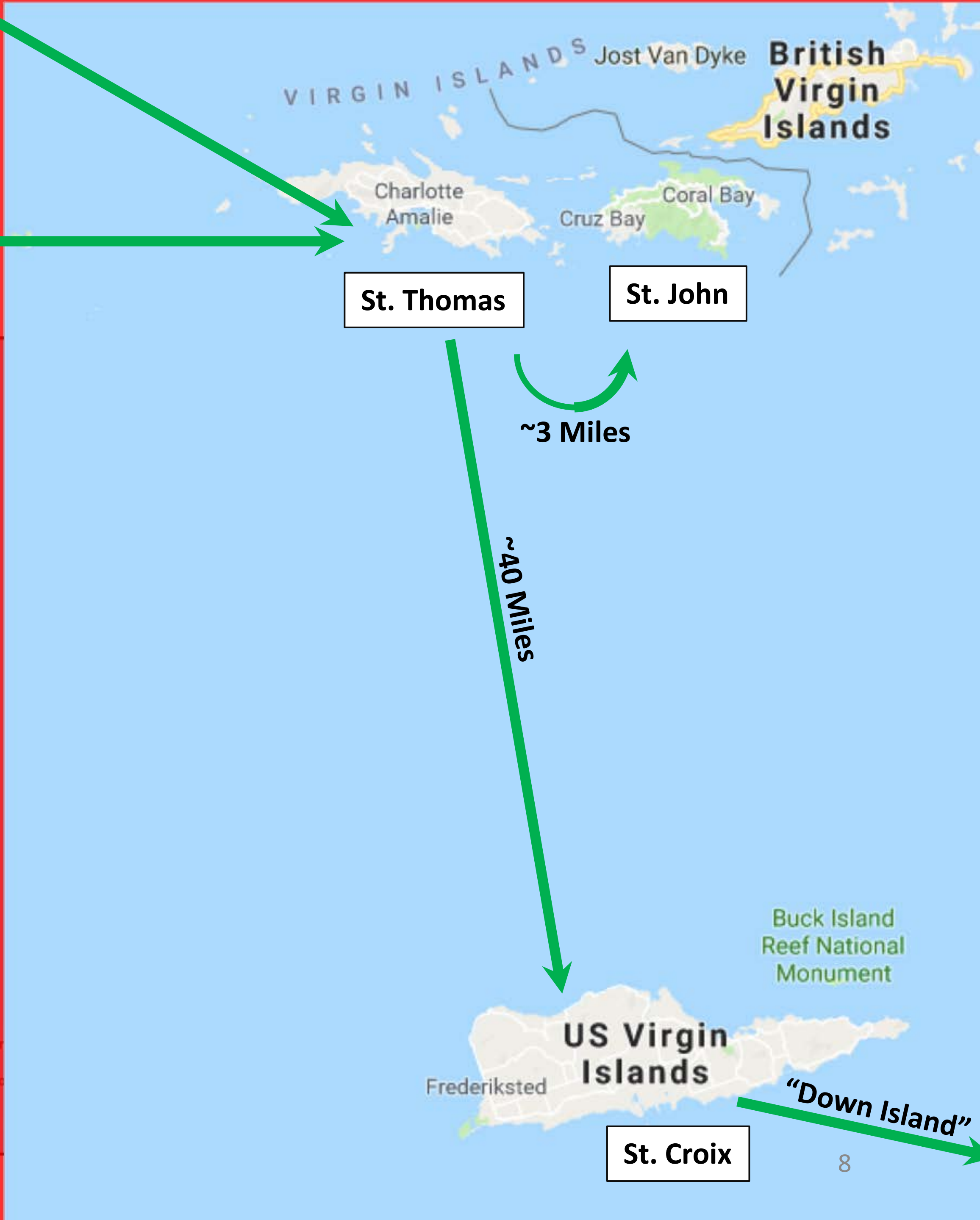
St. Croix

Territory Characteristics

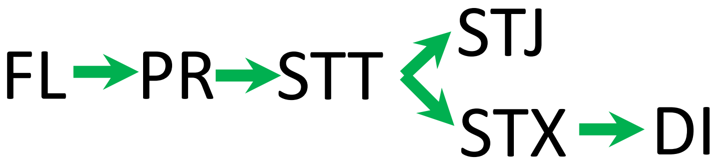
FL → PR → STT → STJ

STT → STX → DI





Storm Characteristics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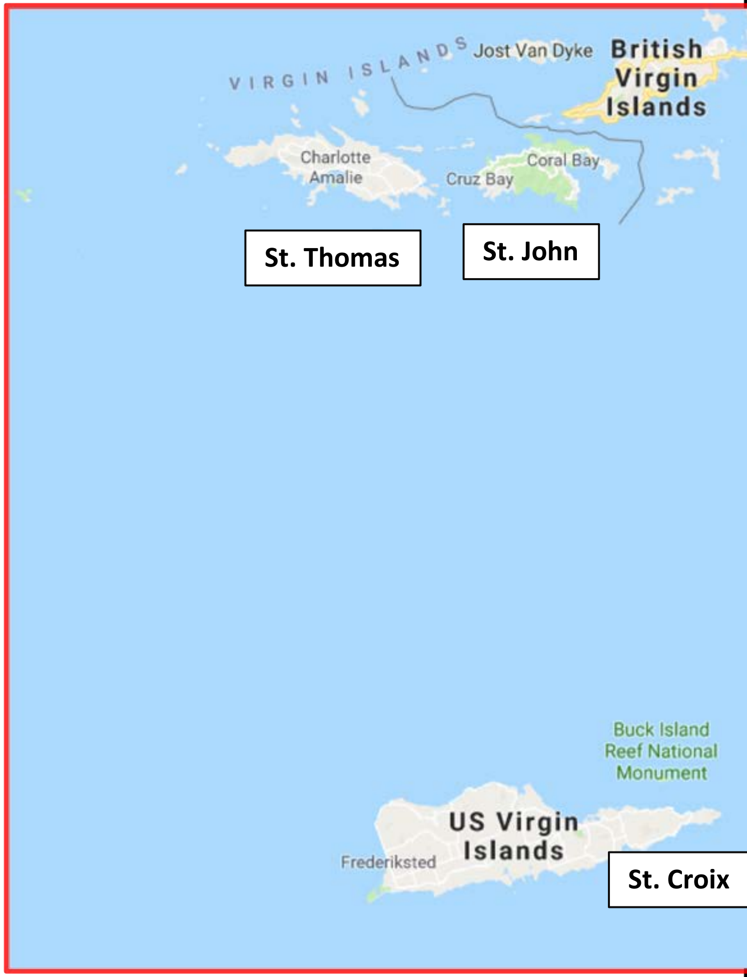
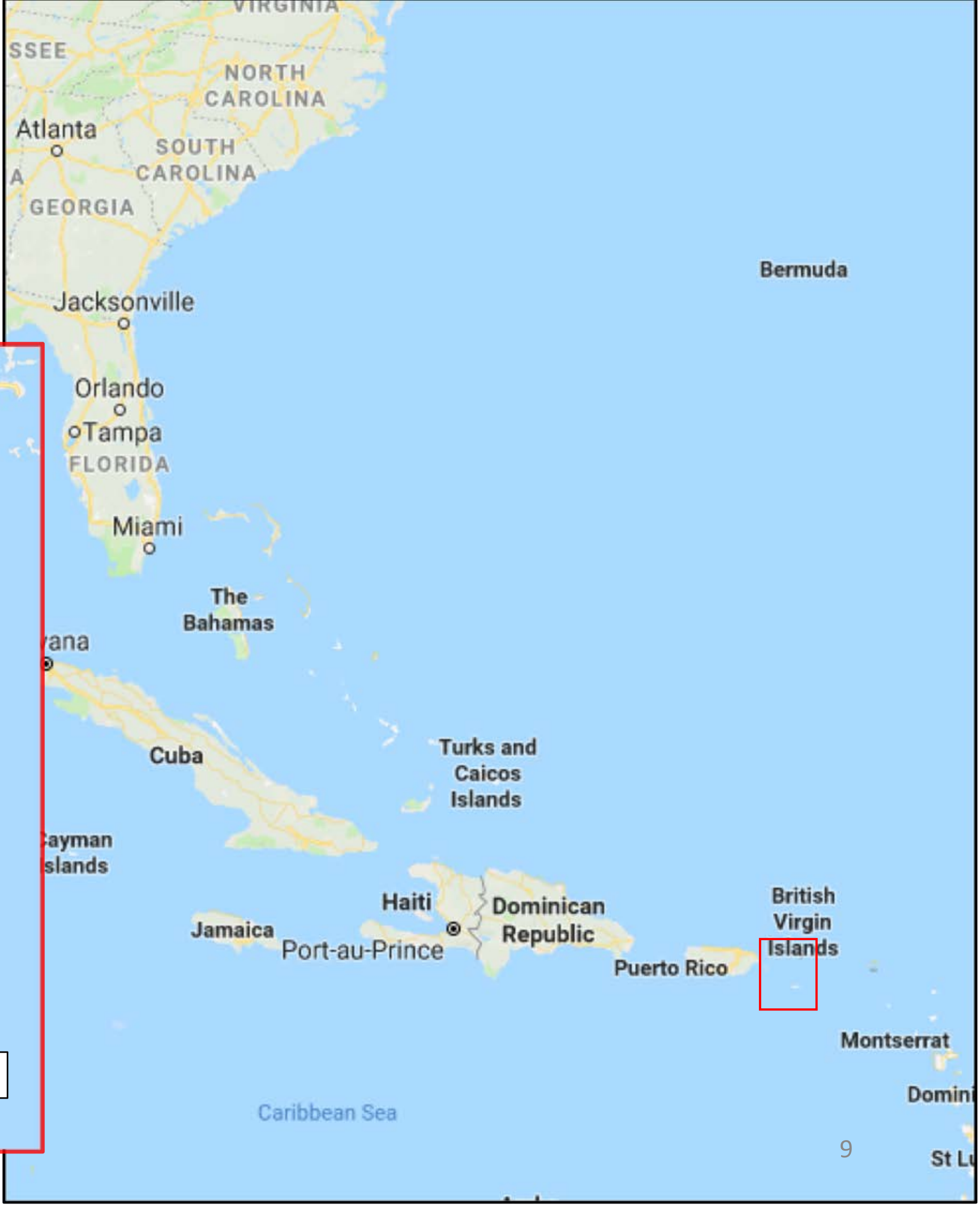
STT → STX → DI





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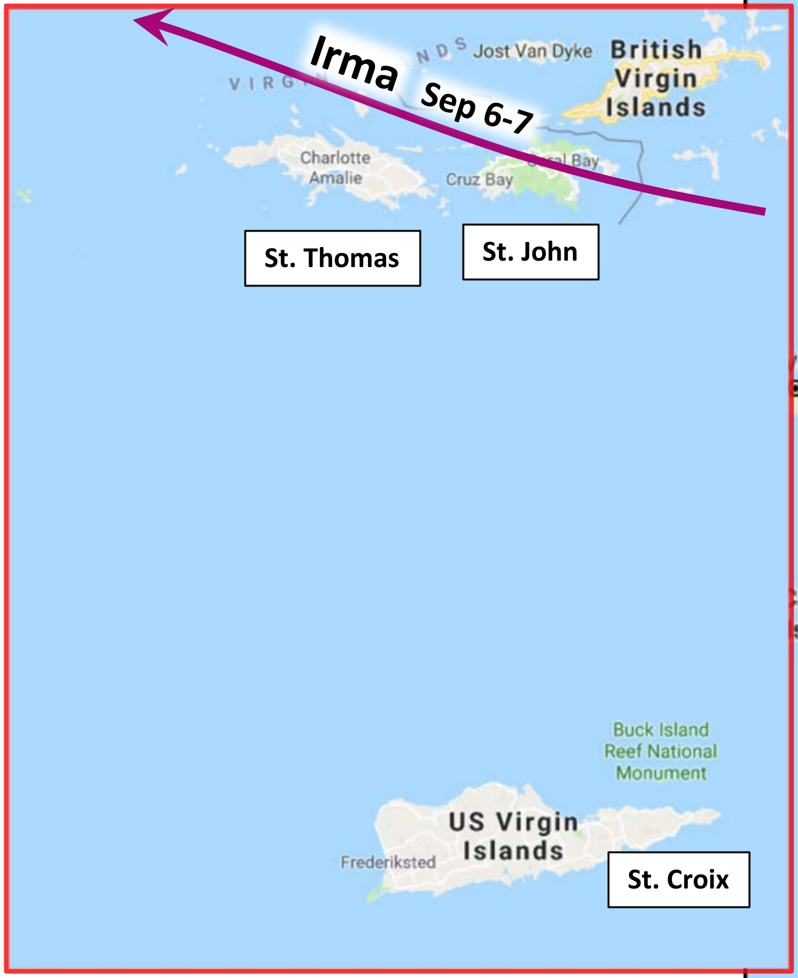

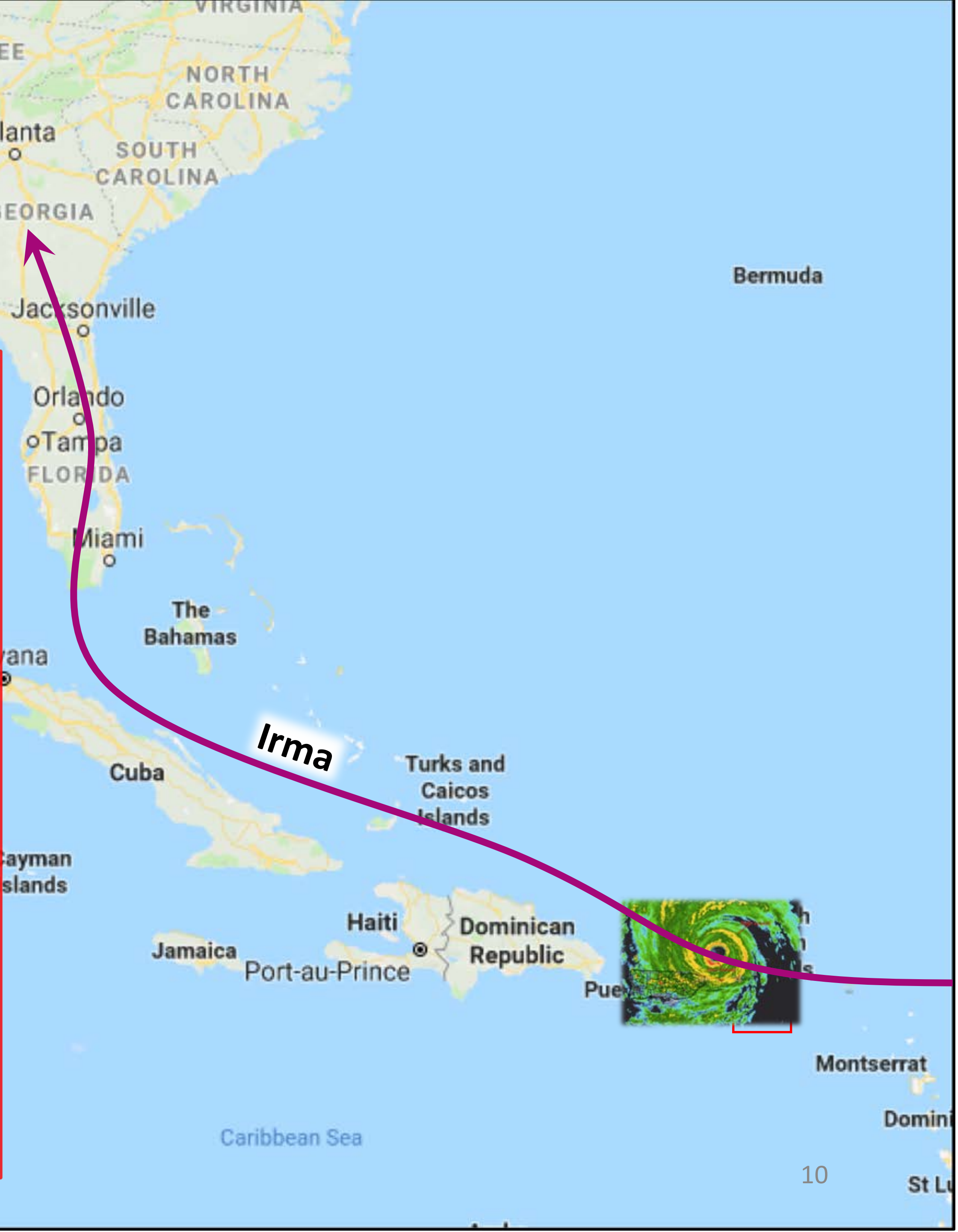

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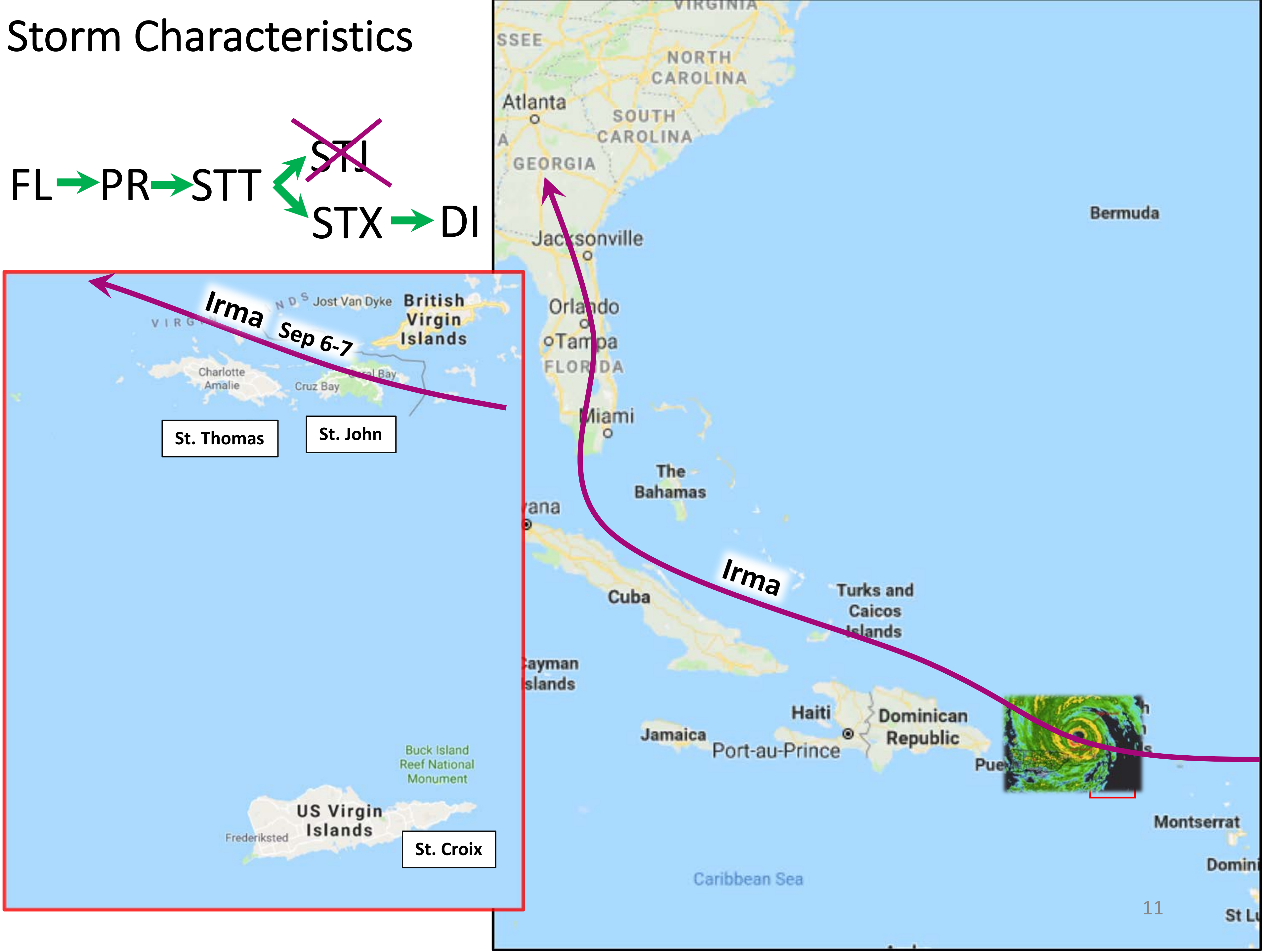

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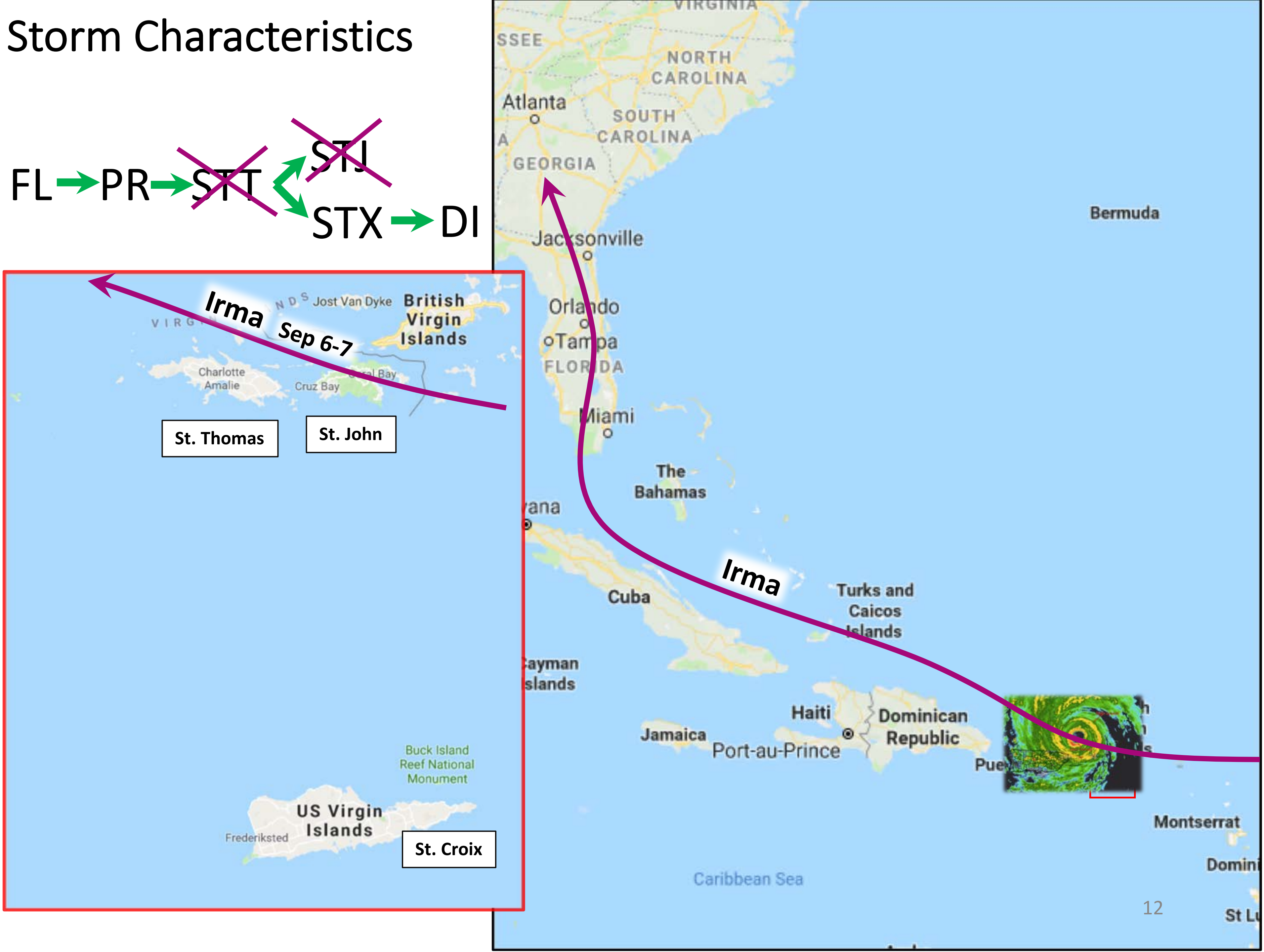

Storm Characteristics

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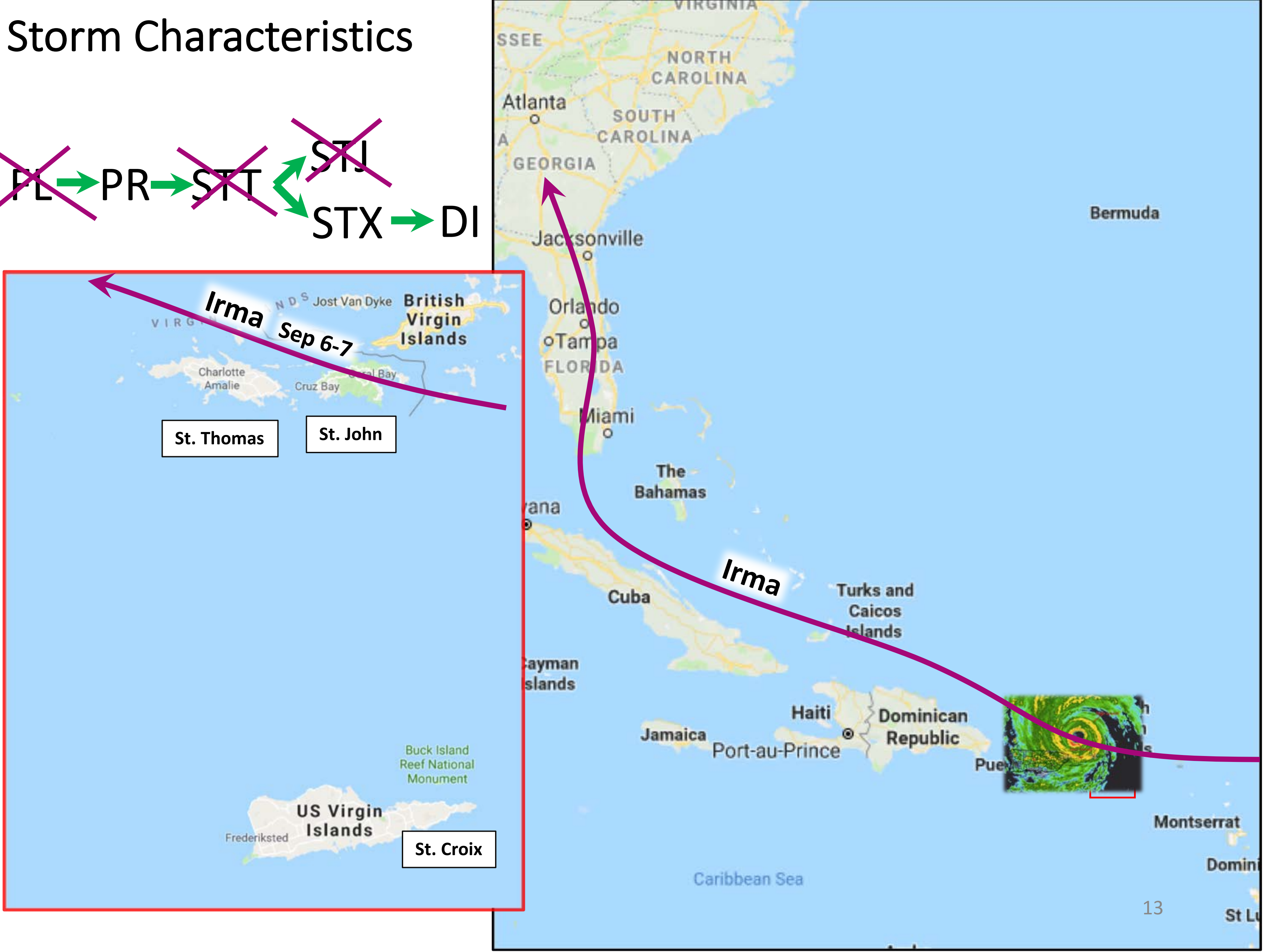

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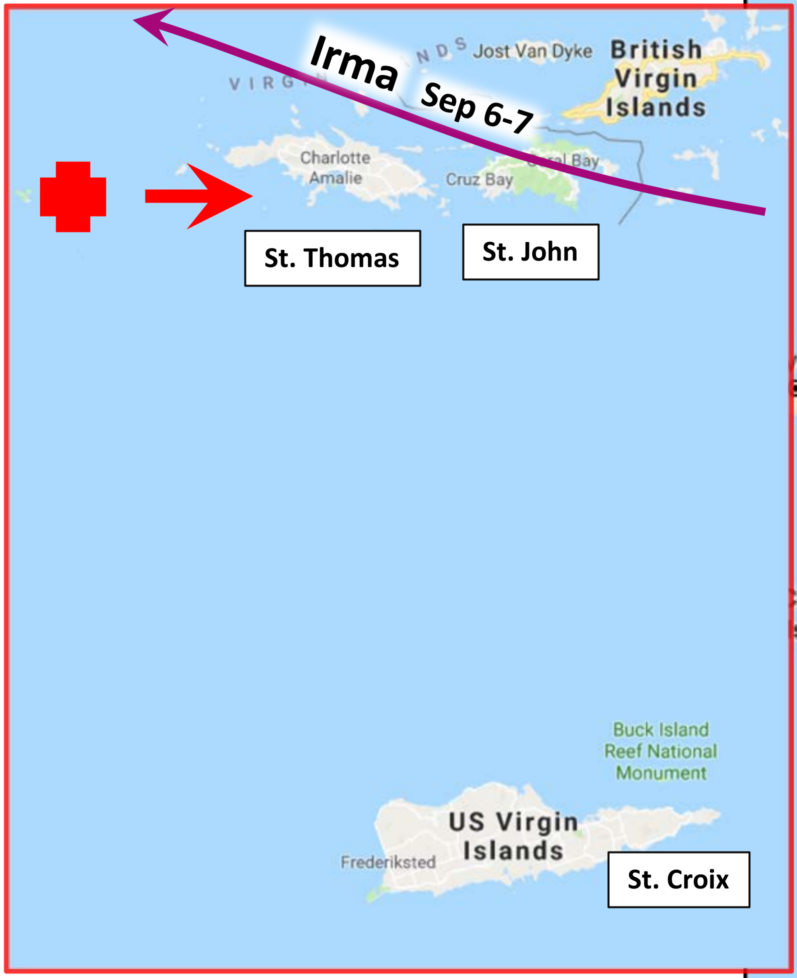

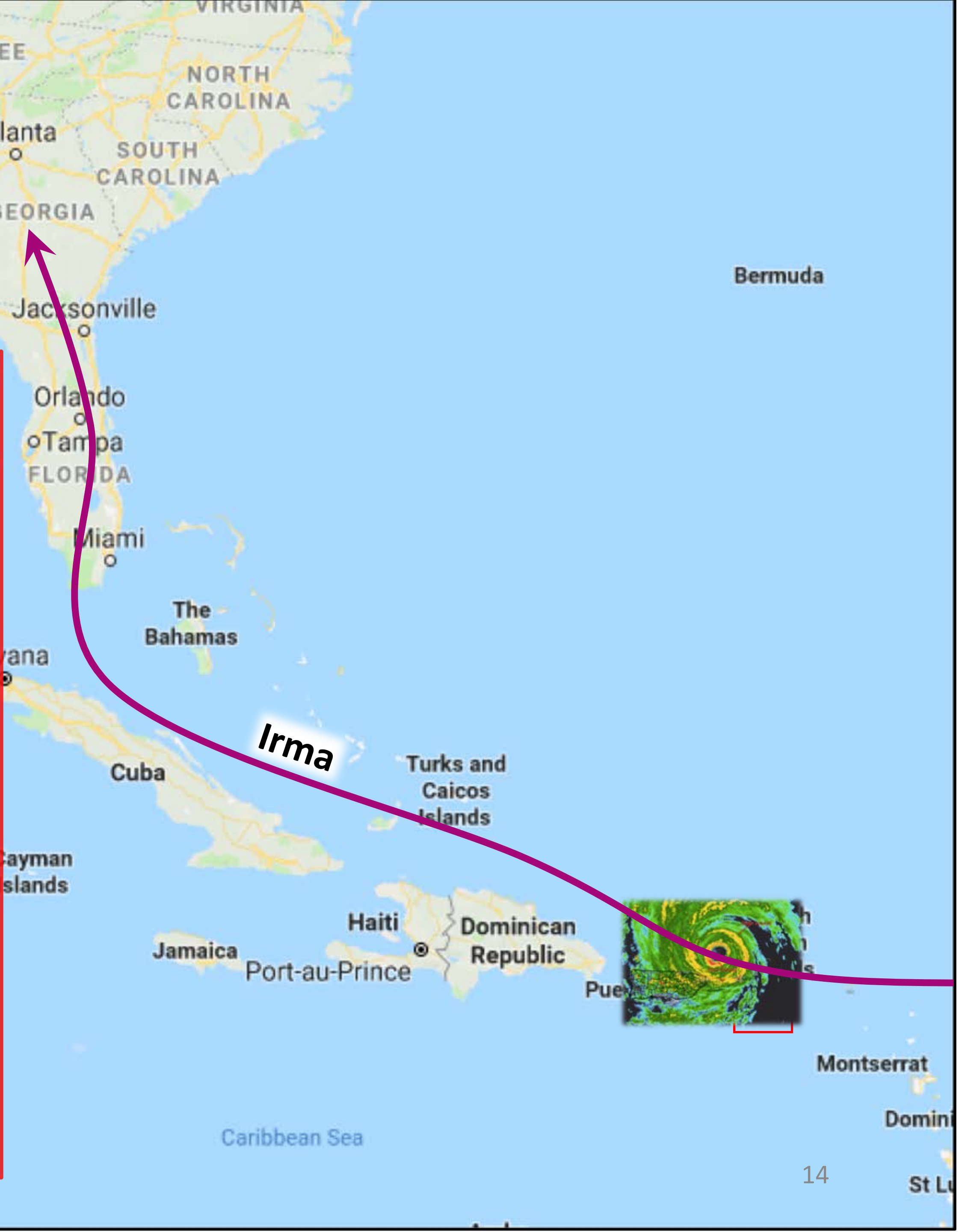

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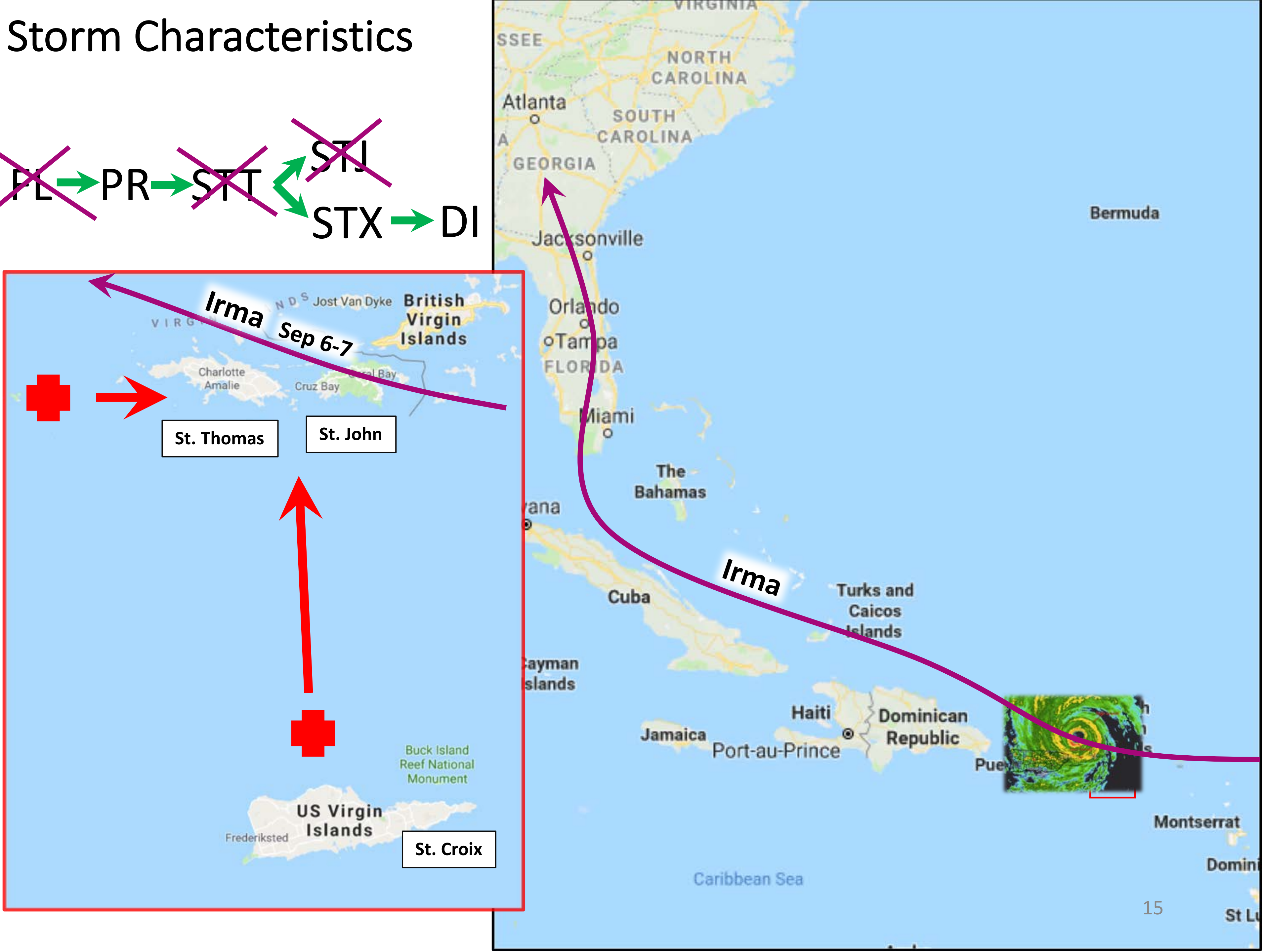

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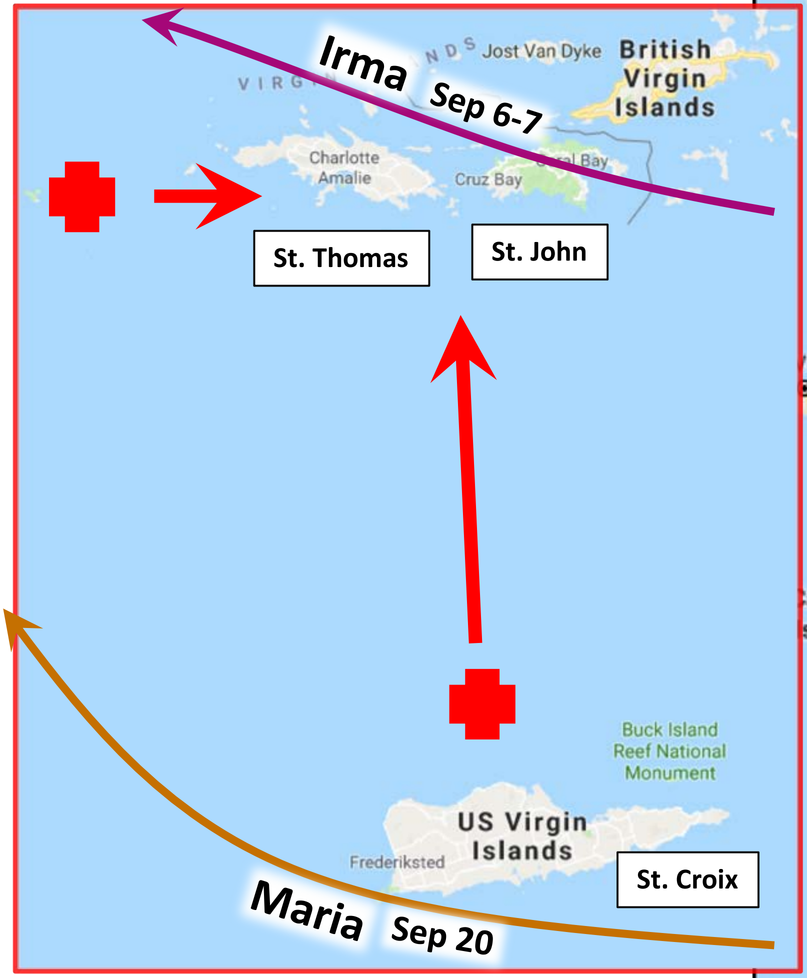

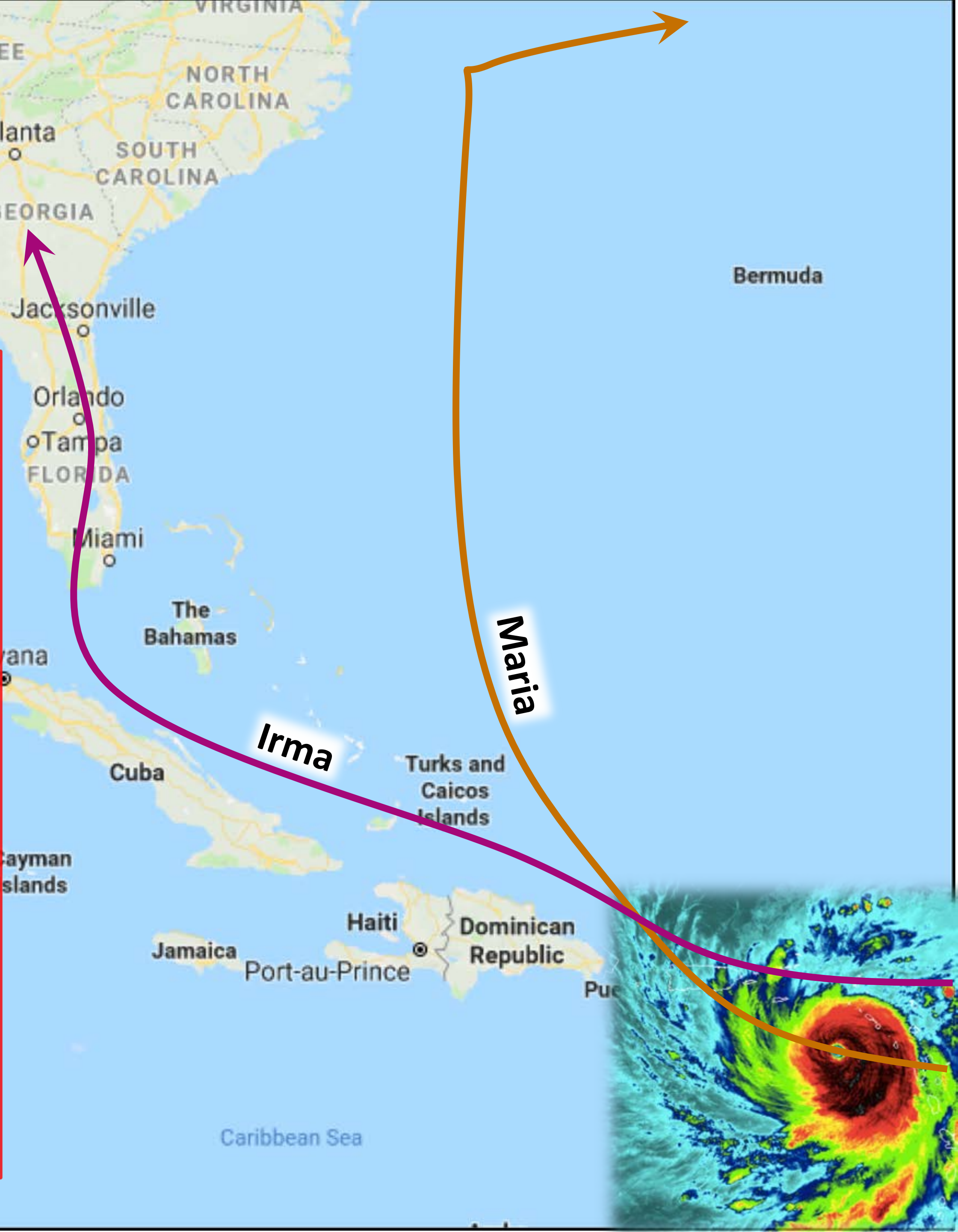

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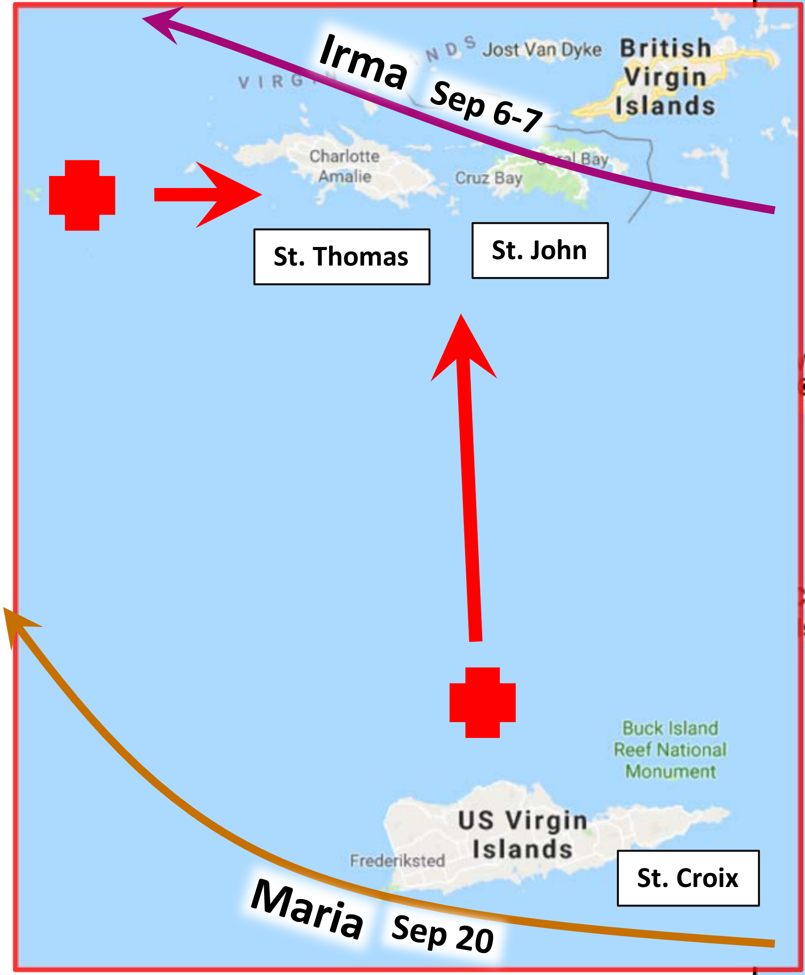

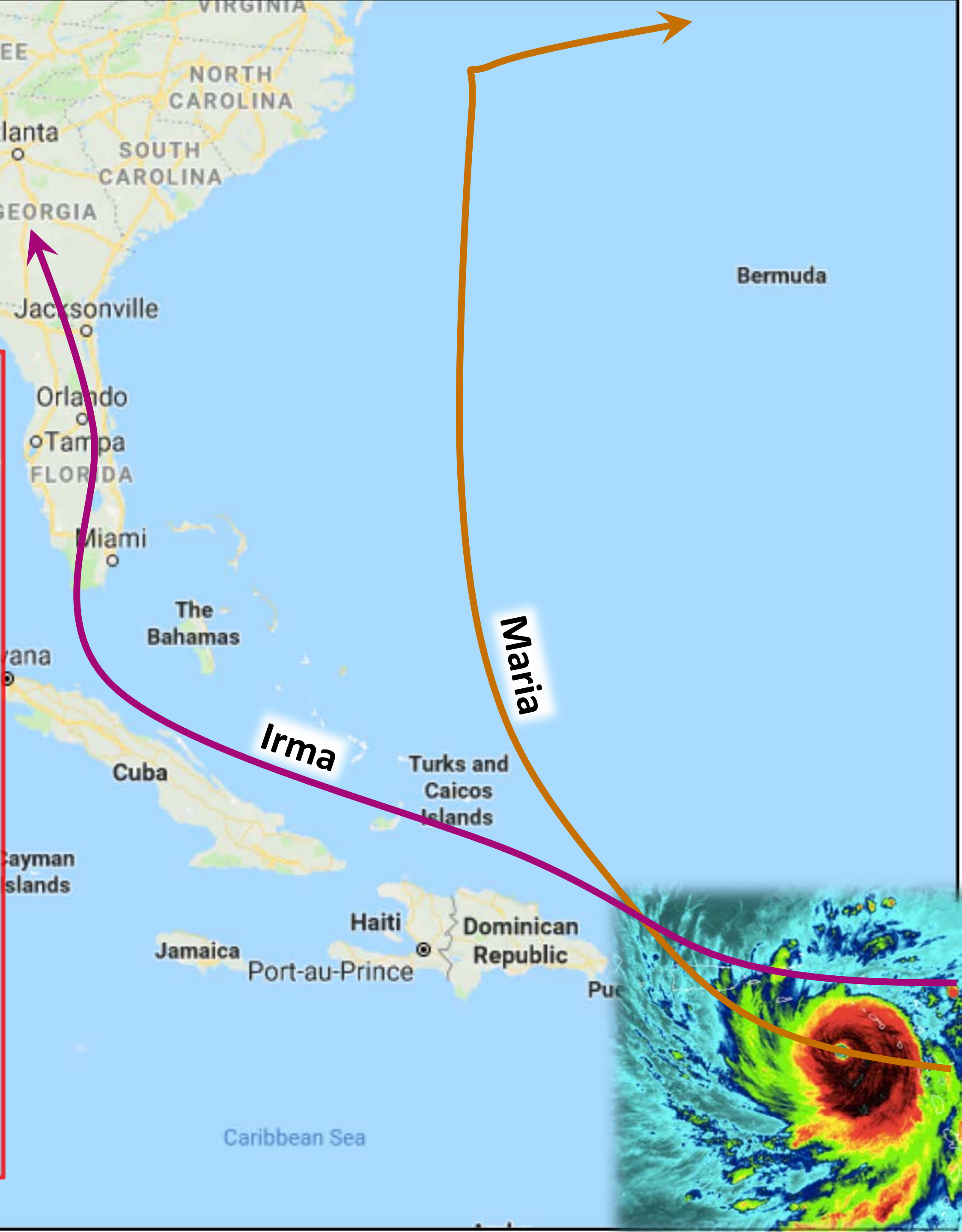

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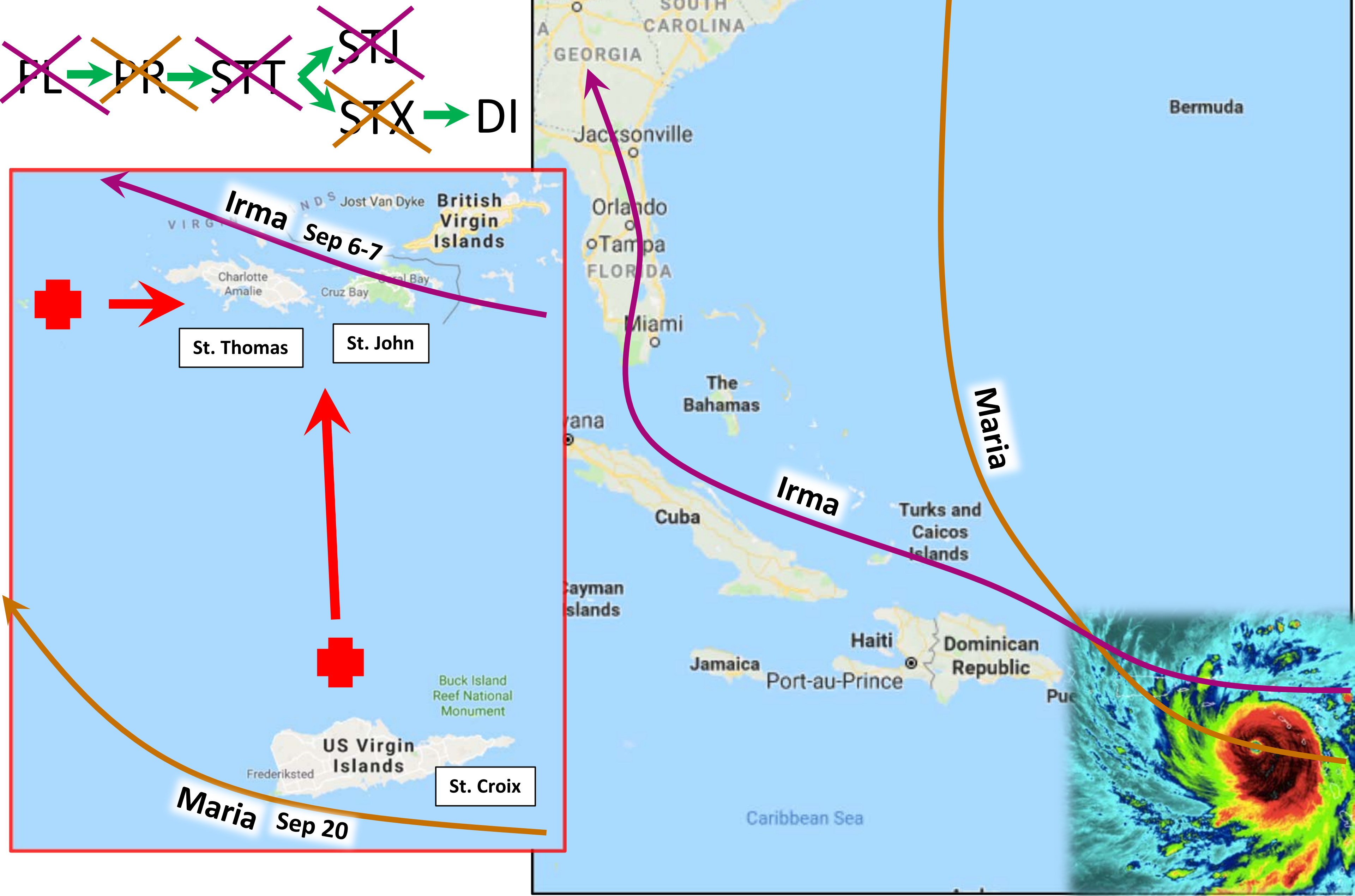


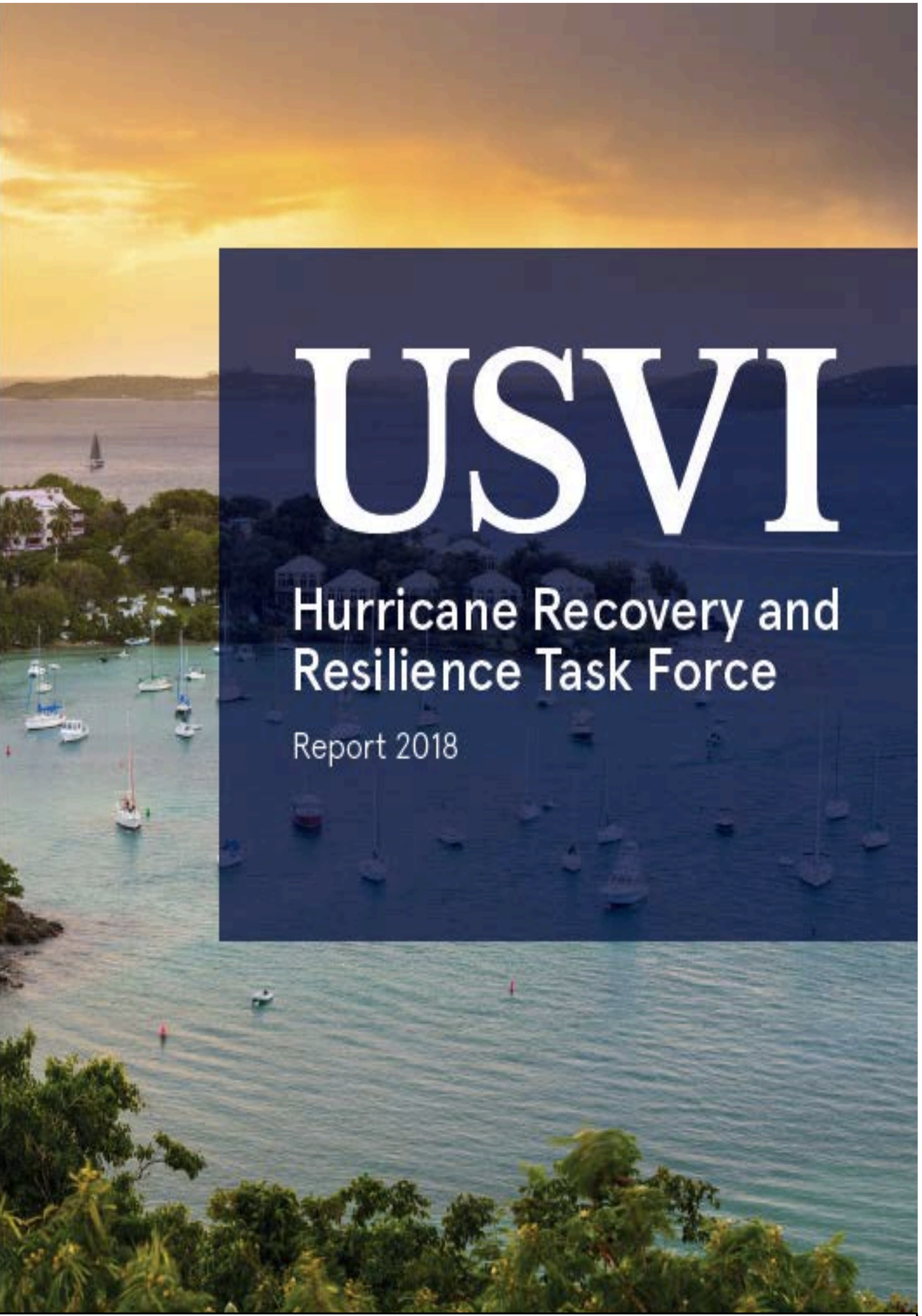
~~FL~~ → ~~PR~~ → ~~STT~~ → ~~STJ~~ / ~~STX~~ → DI

Situation

September, 2017

Hurricanes Irma and Maria cause:

- Massive devastation to homes, businesses, and infrastructure
- Major loss of roadways, traffic lights, bridges, ports, and other transportation infrastructure



USVI

Hurricane Recovery and Resilience Task Force

Report 2018

Source: https://www.usvihurricanetaskforce.org/

How Bad Was It?

- Estimated $10B in damages
  - $6.9B to infrastructure
- Roads
  - Curfew restrictions
  - Traffic lights out
  - Sevenfold increase in crashes
- Electricity
  - 90% of above ground lines damaged
  - Over 50% of poles knocked down
- Water
  - Reserves dropped to 3-day volume
  - Service restored after a month
- Telecommunications
  - 80% of towers down
  - Public radio/tv out for months

How we are taught Network Modeling…

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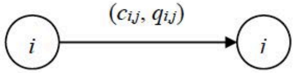
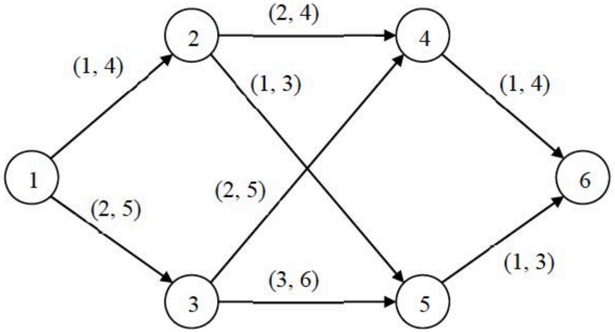


1. Download the data



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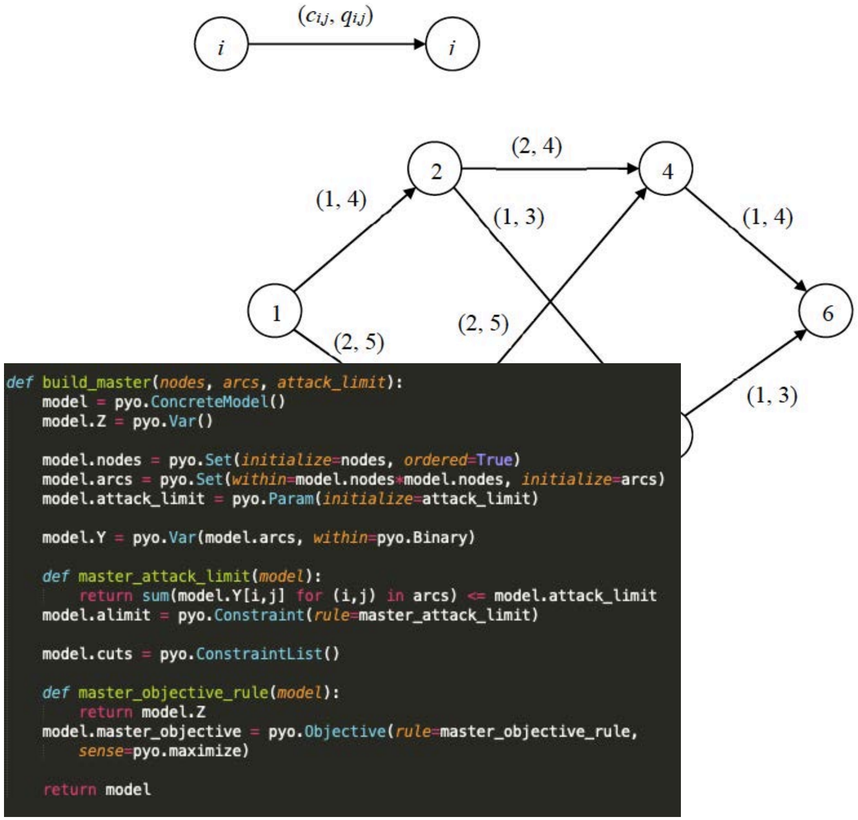
2. Build model



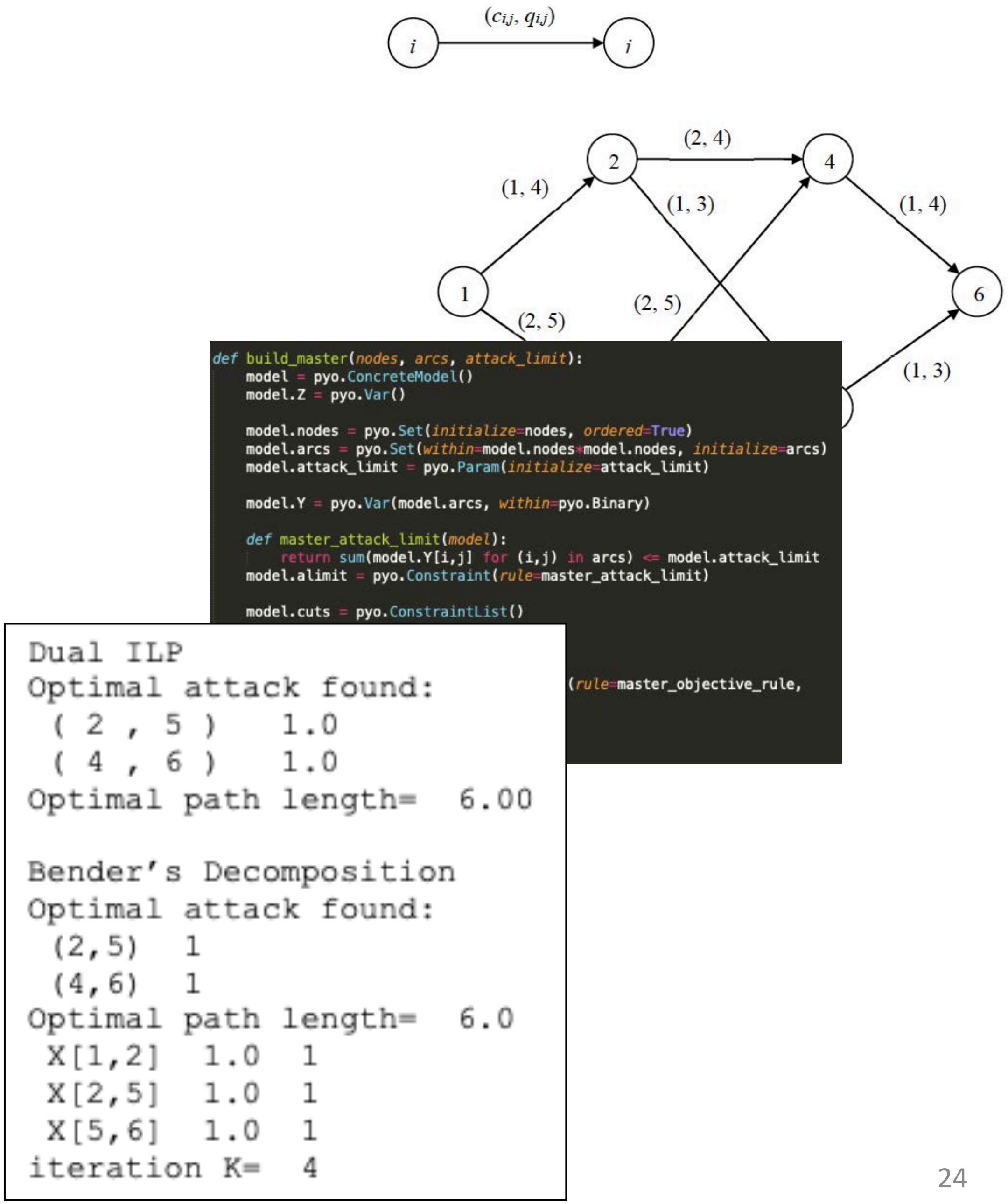
```python
def build_master(nodes, arcs, attack_limit):
    model = pyo.ConcreteModel()
    model.Z = pyo.Var()

    model.nodes = pyo.Set(initialize=nodes, ordered=True)
    model.arcs = pyo.Set(within=model.nodes*model.nodes, initialize=arcs)
    model.attack_limit = pyo.Param(initialize=attack_limit)

    model.Y = pyo.Var(model.arcs, within=pyo.Binary)

    def master_attack_limit(model):
        return sum(model.Y[i,j] for (i,j) in arcs) <= model.attack_limit
    model.alimit = pyo.Constraint(rule=master_attack_limit)

    model.cuts = pyo.ConstraintList()

    def master_objective_rule(model):
        return model.Z
    model.master_objective = pyo.Objective(rule=master_objective_rule,
        sense=pyo.maximize)

    return model
```

How we are taught Network Modeling…

1. Download the data

2. Build model

3. Conduct analysis



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                                       (rule=master_objective_rule,
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Dual ILP
Optimal attack found:
 ( 2 , 5 )   1.0
 ( 4 , 6 )   1.0
Optimal path length=  6.00

Bender's Decomposition
Optimal attack found:
 (2,5)  1
 (4,6)  1
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 X[1,2]  1.0  1
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iteration K=  4
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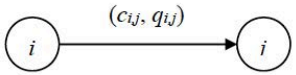
My Naïve Understanding…



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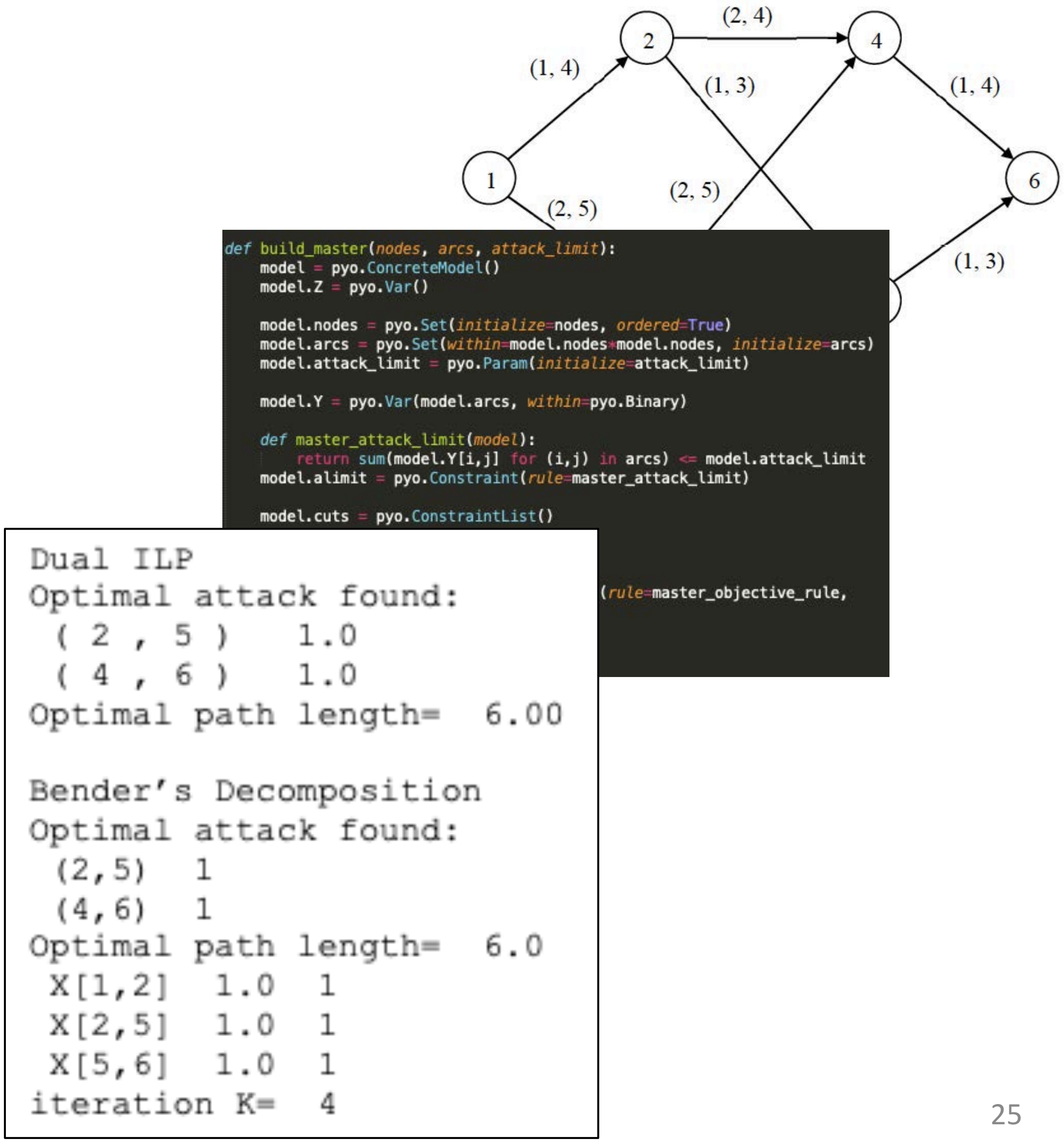

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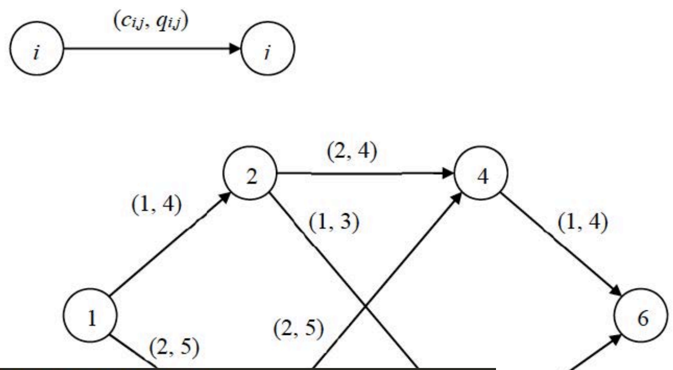

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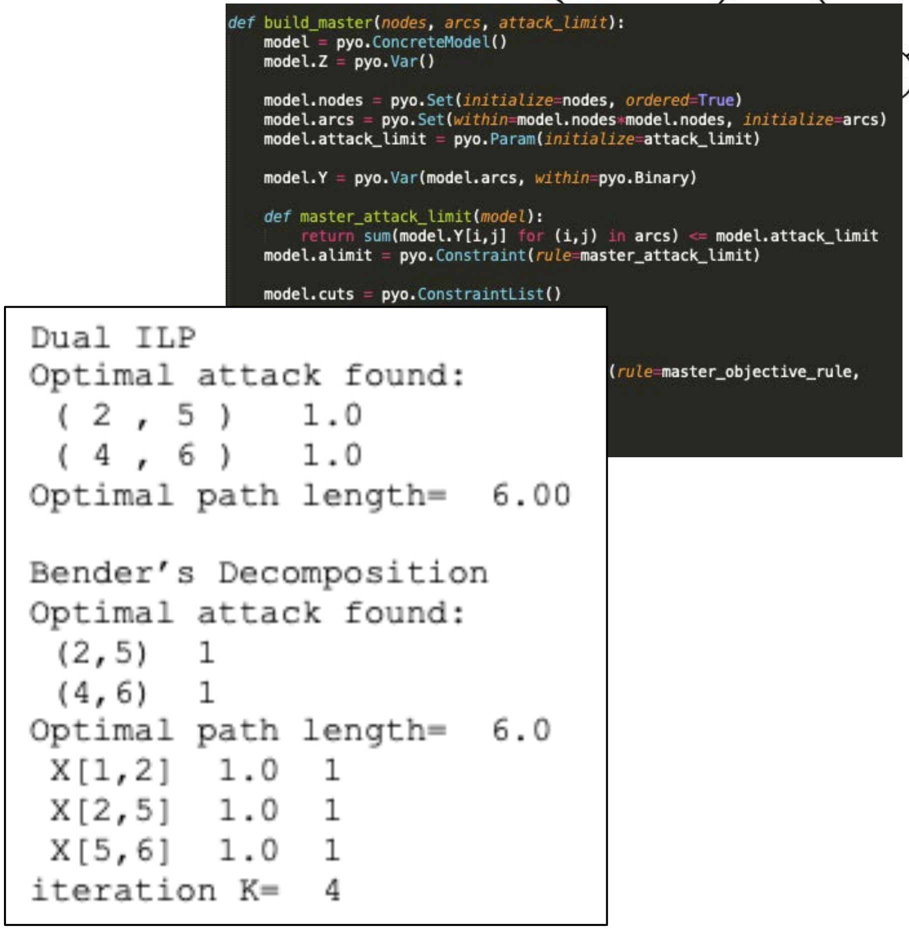

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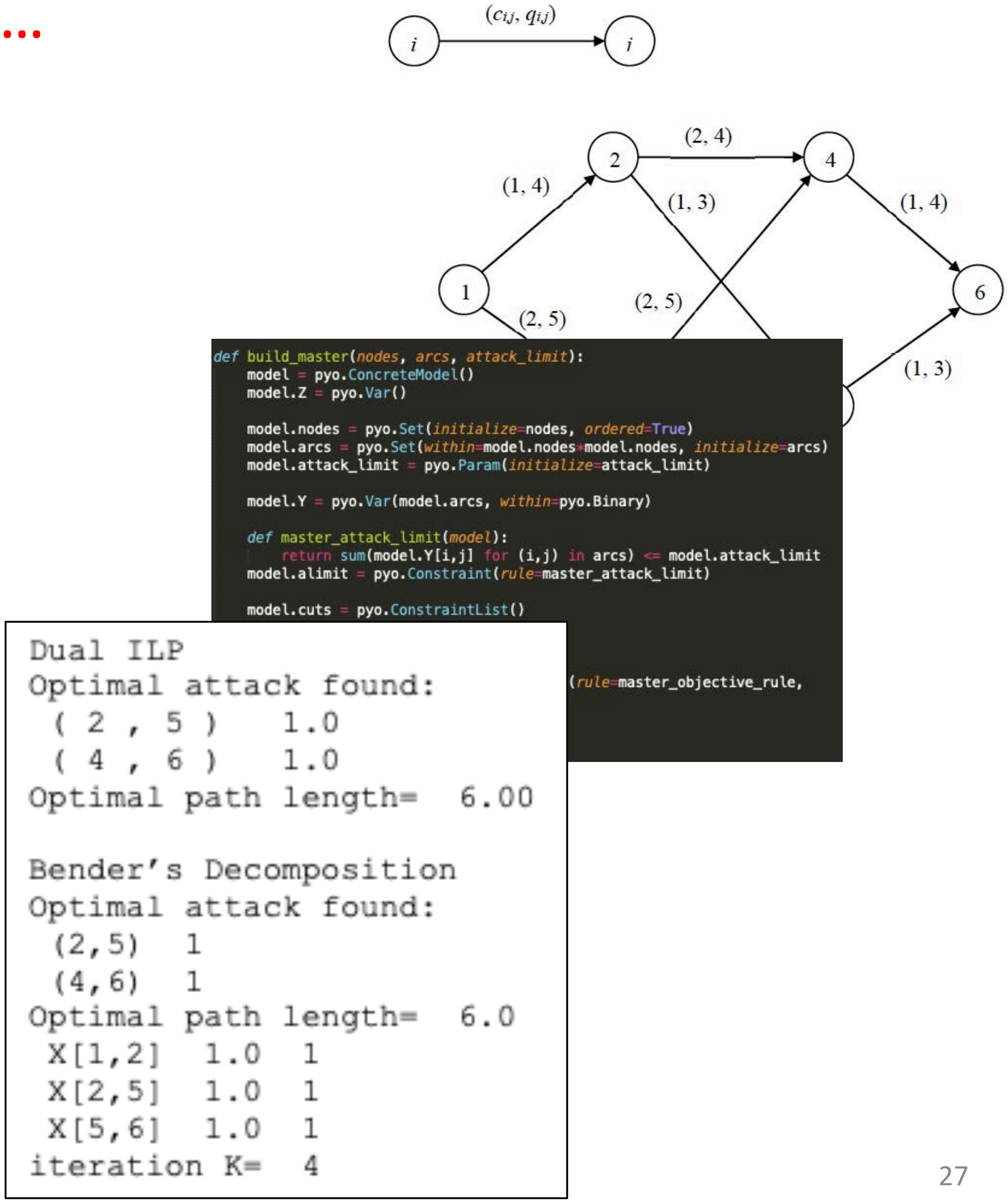

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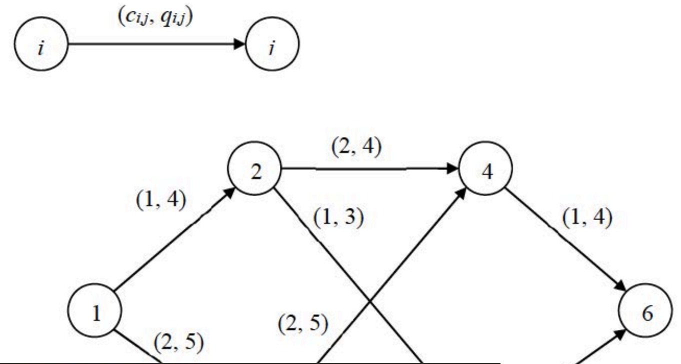

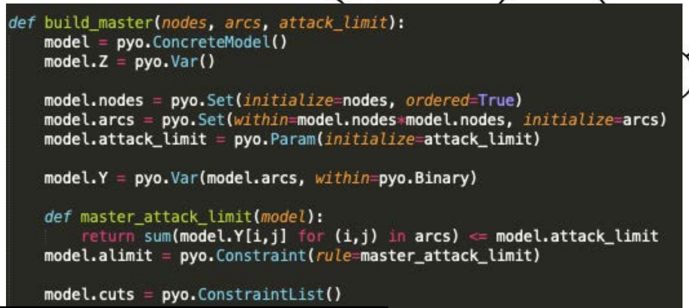

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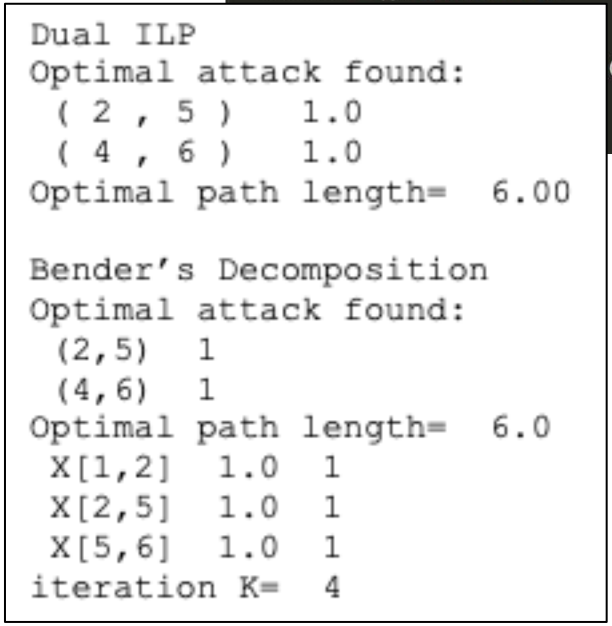

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Thesis Motivation

Understand transportation infrastructure to support:

- Movement of goods into ports and onto stores via surface roads
- Movement of people from their homes to stores via surface roads

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Quantify impacts of:

- Imposed curfews
- Surface road restrictions or blockages
- Alternative relief locations

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Quantify impacts of:

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- Alternative relief locations

Goals:

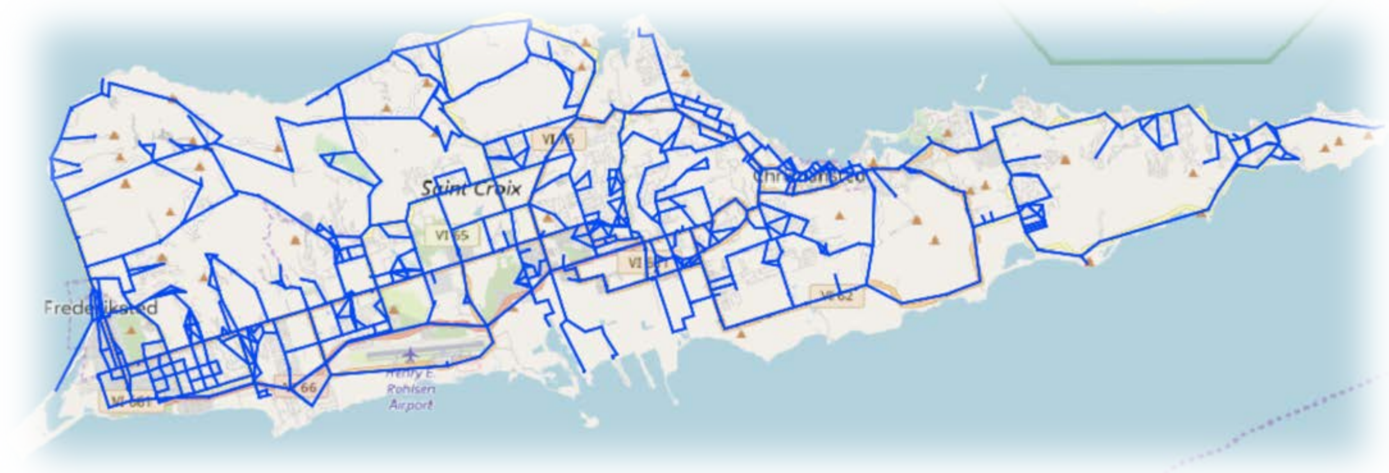
- Maximize supply chain throughput
- Minimize household travel time
- Facilitate faster recovery

Model Overview

Based on an ***operational view*** of critical infrastructure that is rooted in "how things work" before and after the 2017 hurricanes

Data Requirements

- Road and bridge inventory by type



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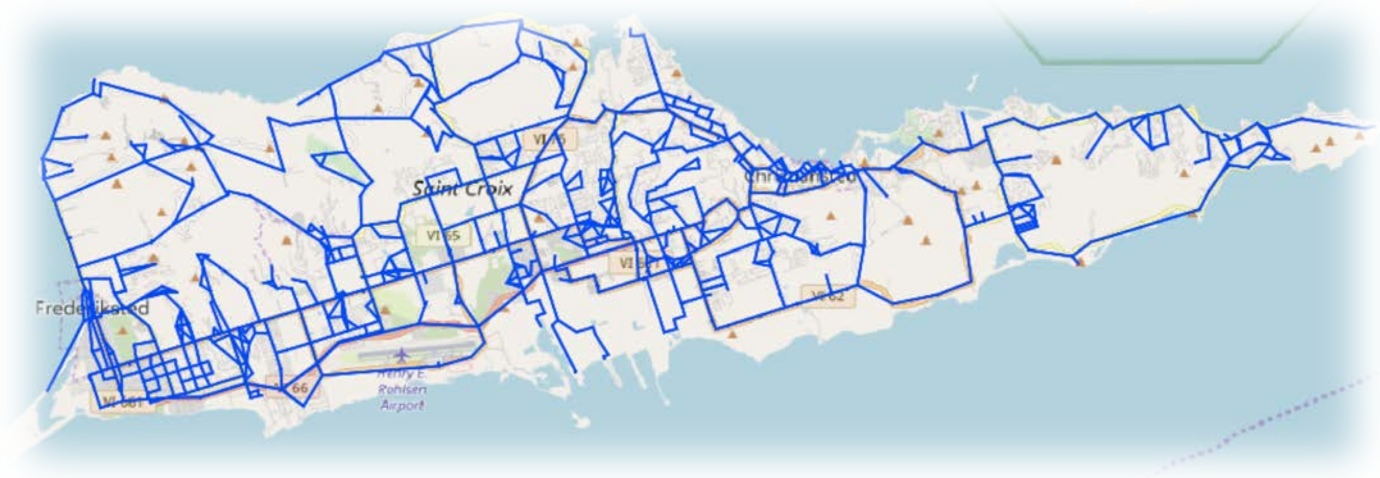

Model Overview

Based on an ***operational view*** of critical infrastructure that is rooted in "how things work" before and after the 2017 hurricanes

Data Requirements

- Road and bridge inventory by type
- Population centers and their characteristics

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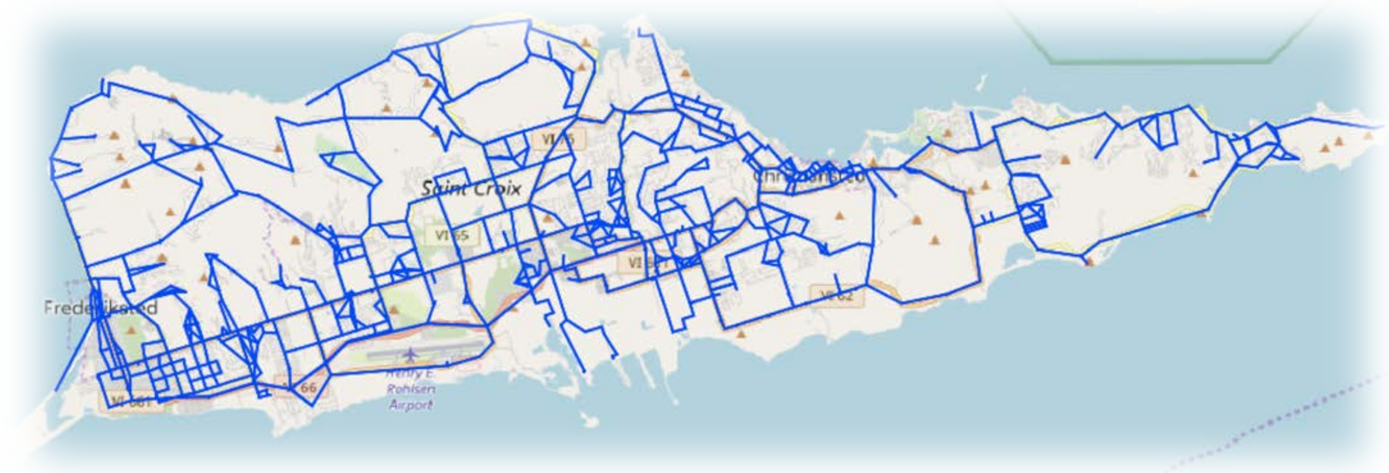

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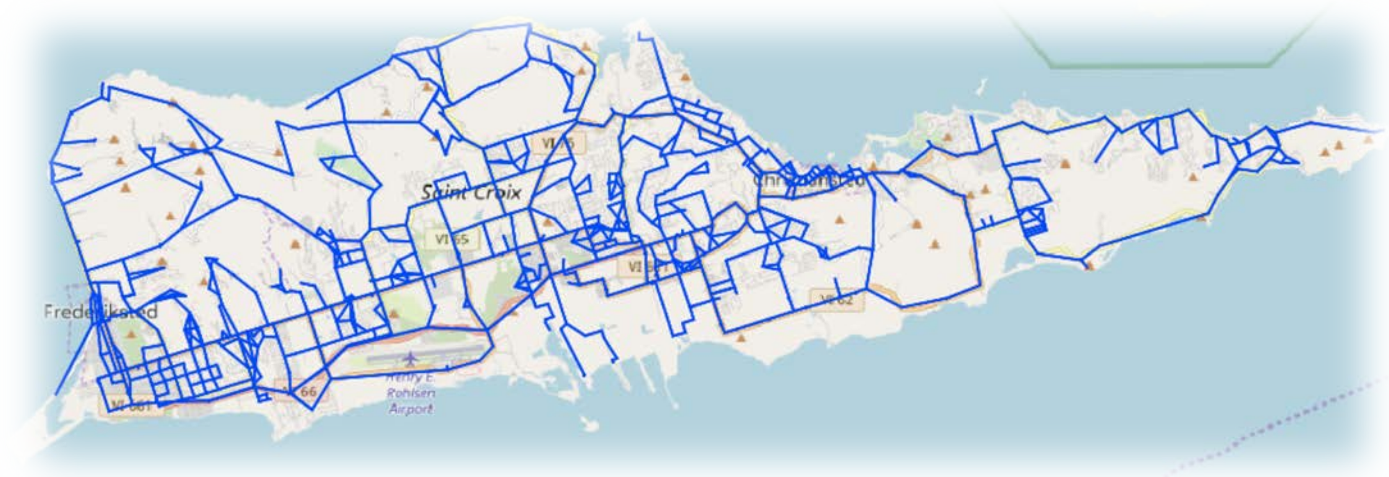
Based on an ***operational view*** of critical infrastructure that is rooted in “how things work” before and after the 2017 hurricanes

Data Requirements

• Road and bridge inventory by type	**Does Not Exist**
• Population centers and their characteristics	**Estates (2010 Census)**



Model Overview

Based on an ***operational view*** of critical infrastructure that is rooted in "how things work" before and after the 2017 hurricanes

Data Requirements

- Road and bridge inventory by type
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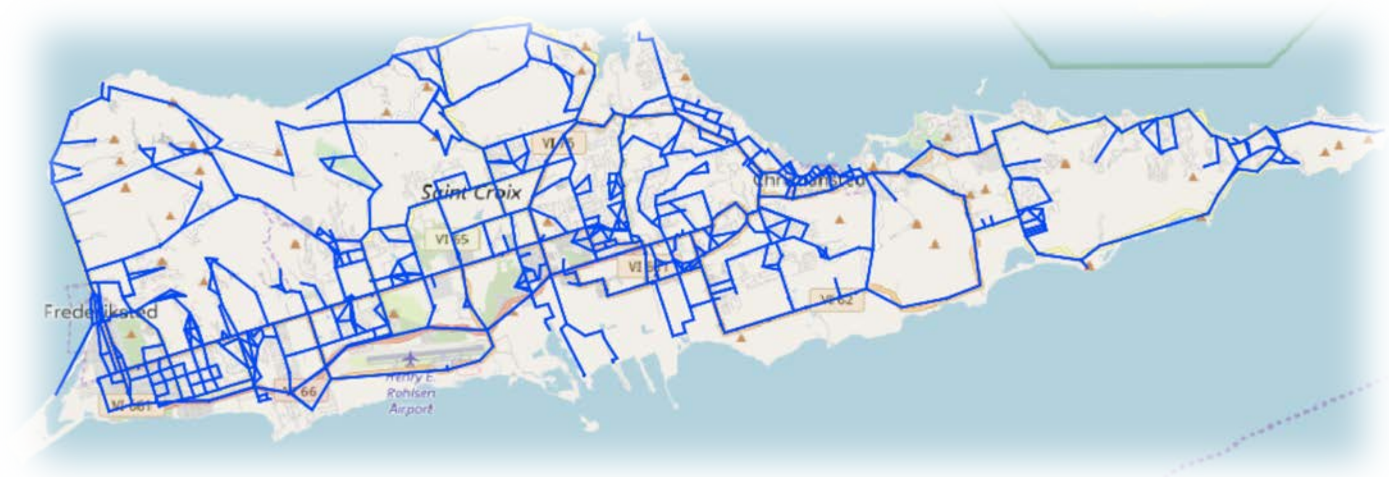
- Port schedules for containerized cargo
- Delivery schedules for major grocery stores, gas stations, or hardware stores
- Known shelter in place locations, both designated and non-designated

Does Not Exist

Estates (2010 Census)



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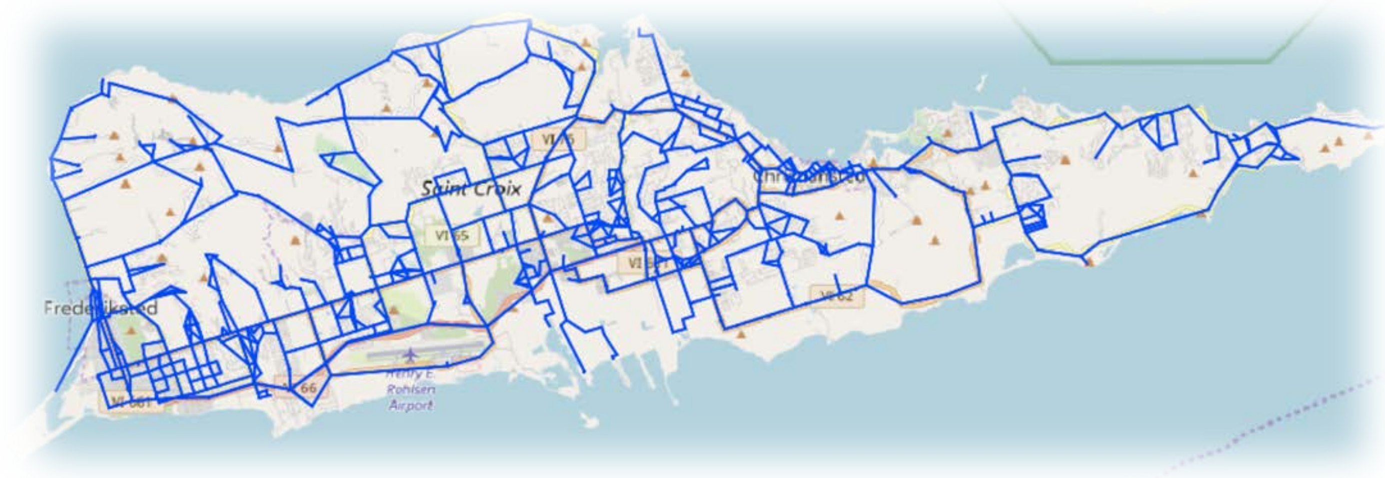

Building the Data

USVI Site Visit: 24-29 March

- US Coast Guard
- Crowley Shipping
- Dept. of Public Works
- VI Port Authority
- FEMA Joint Field Office

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Road Survey

- Tourist Map
- Noted speeds
- Road conditions
- Potential relief points
- Stores

Building the Data

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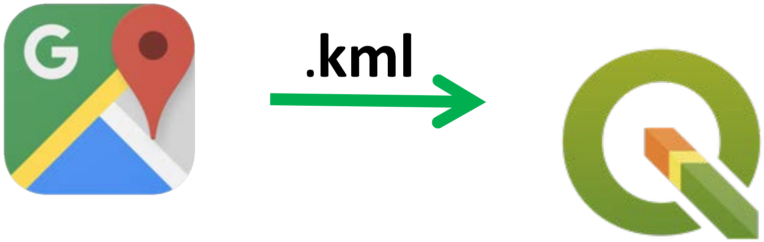

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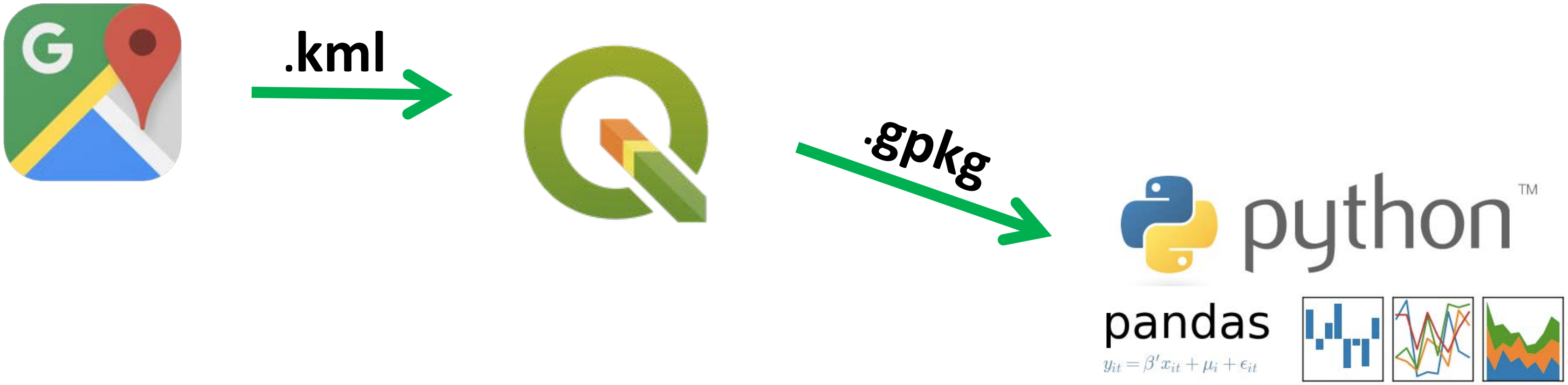
Building the Data



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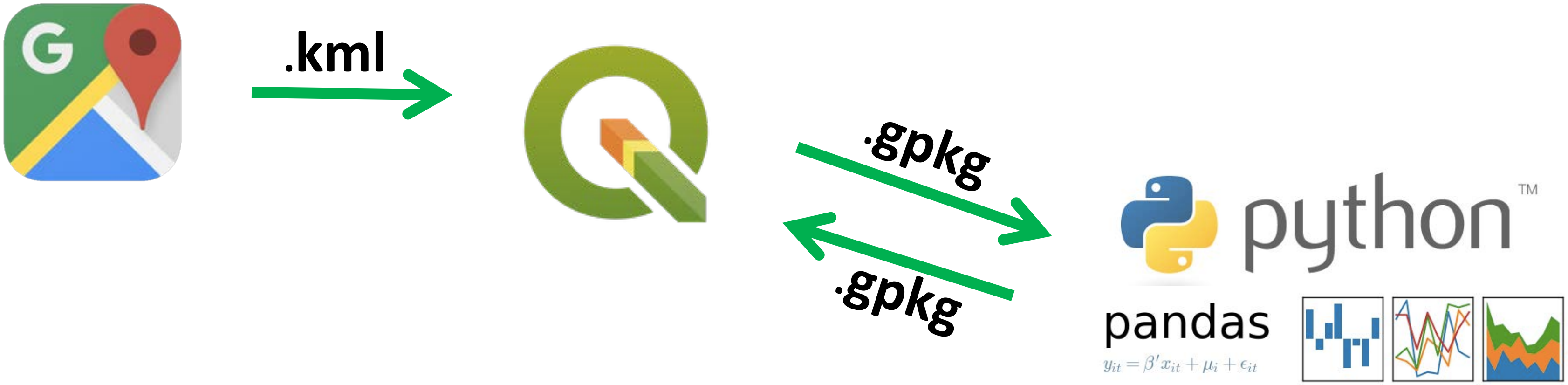

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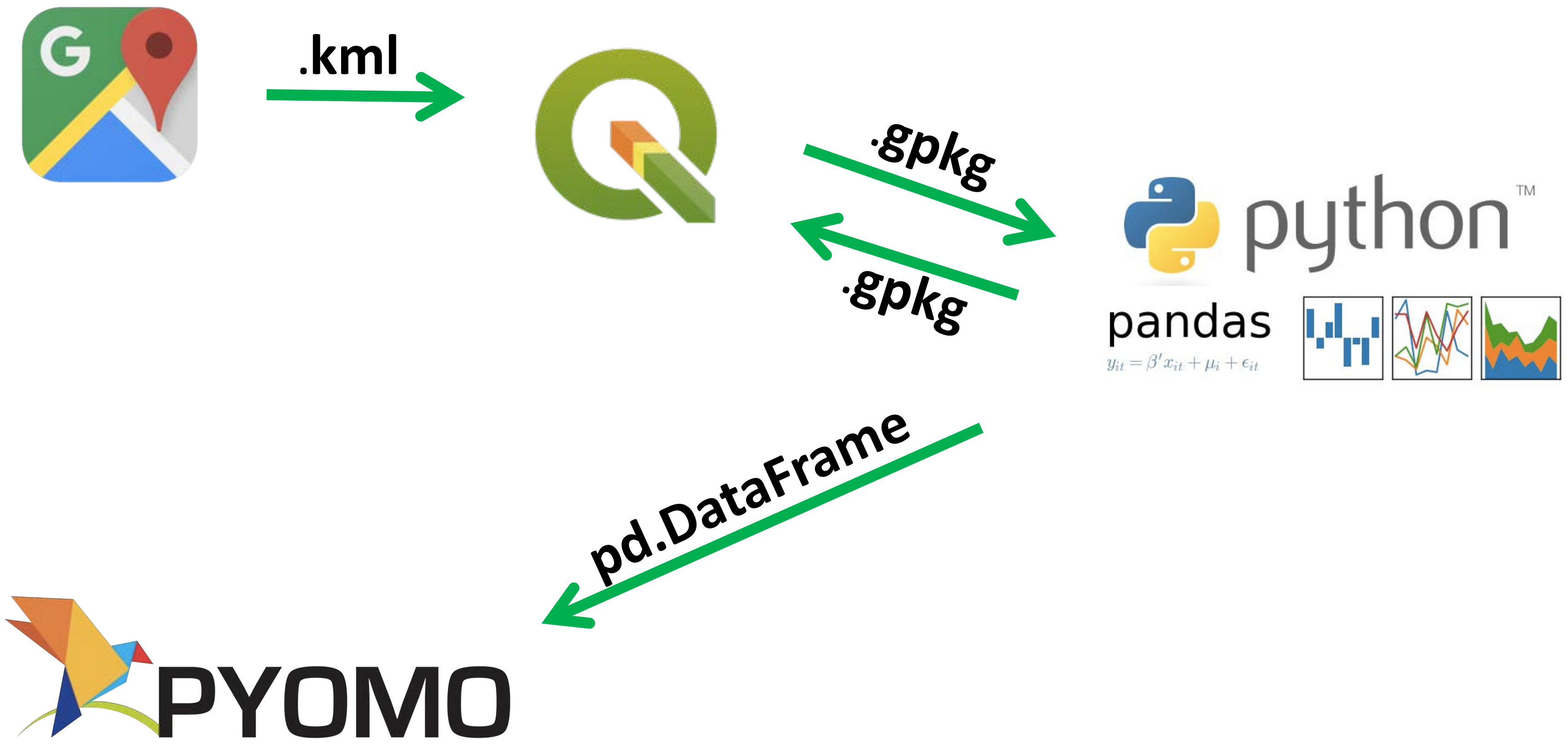

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pd.DataFrame

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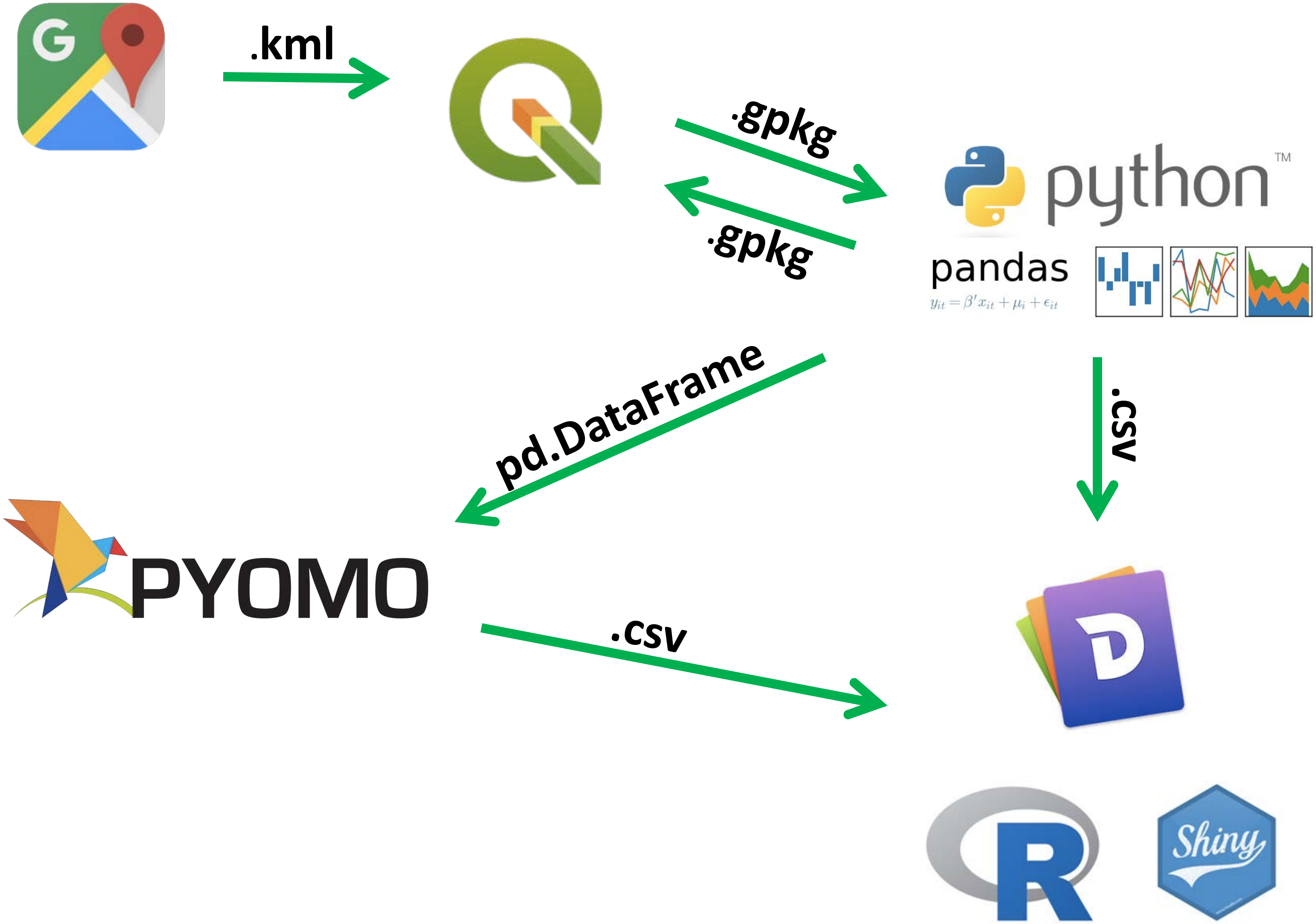

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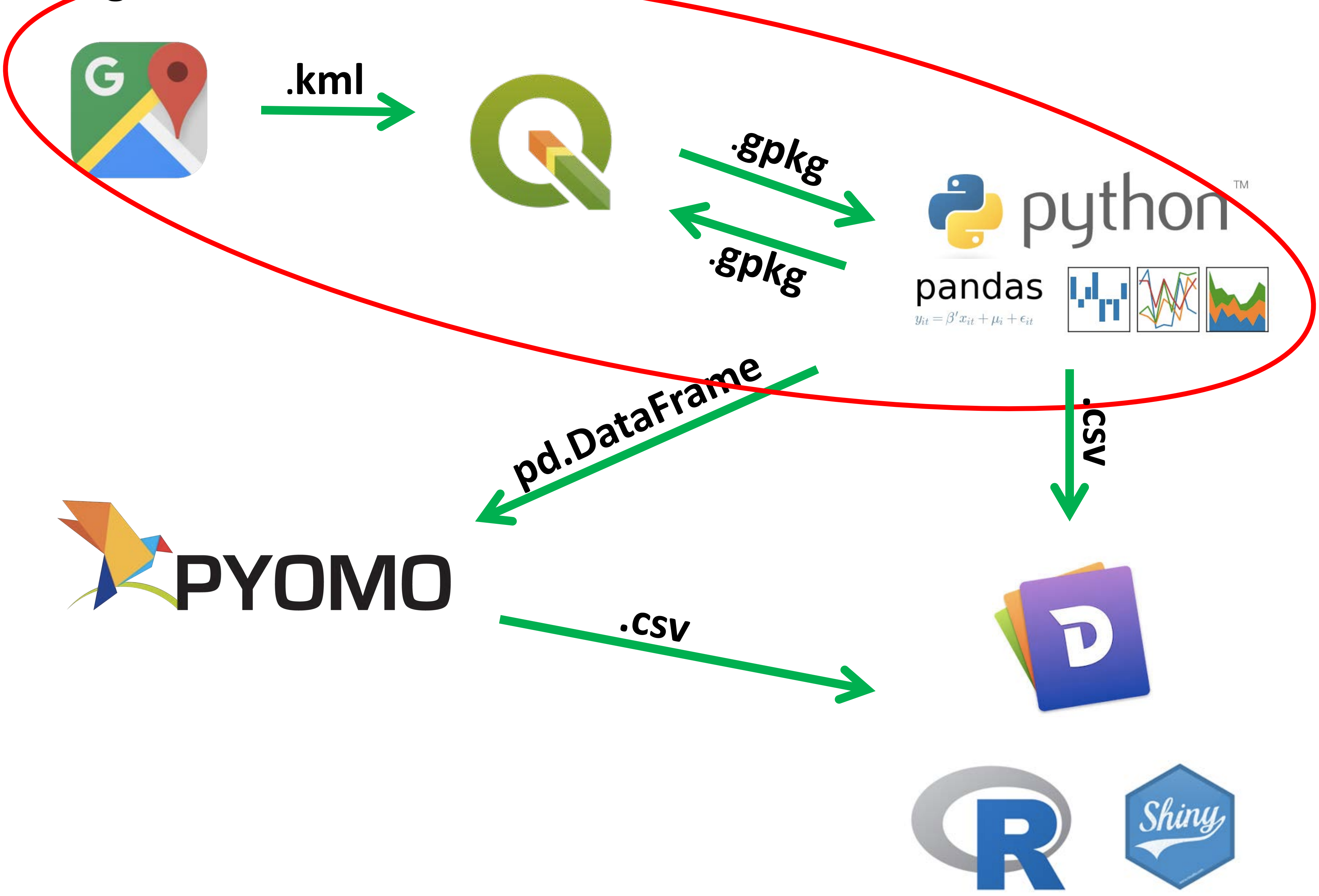
pd.DataFrame

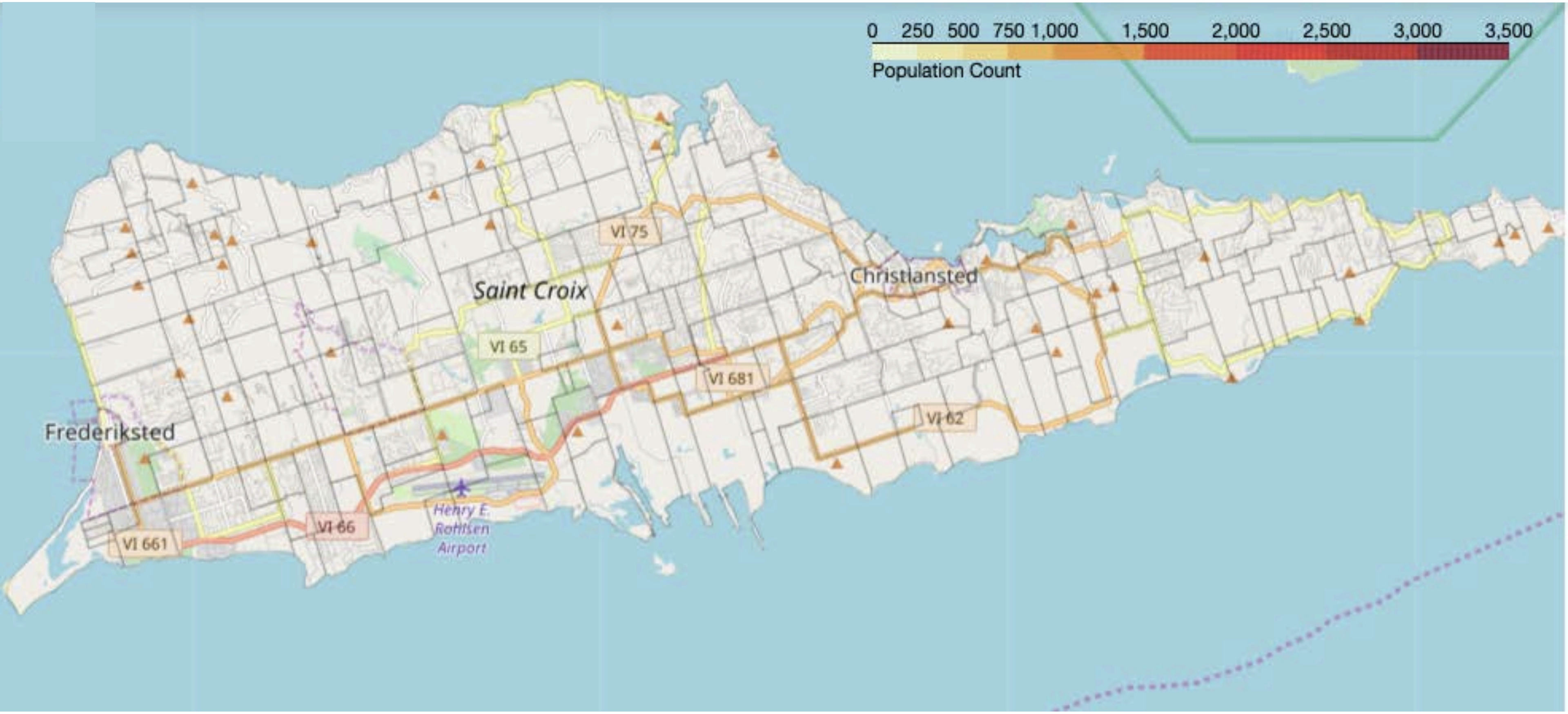
.csv

.csv

Building the Data

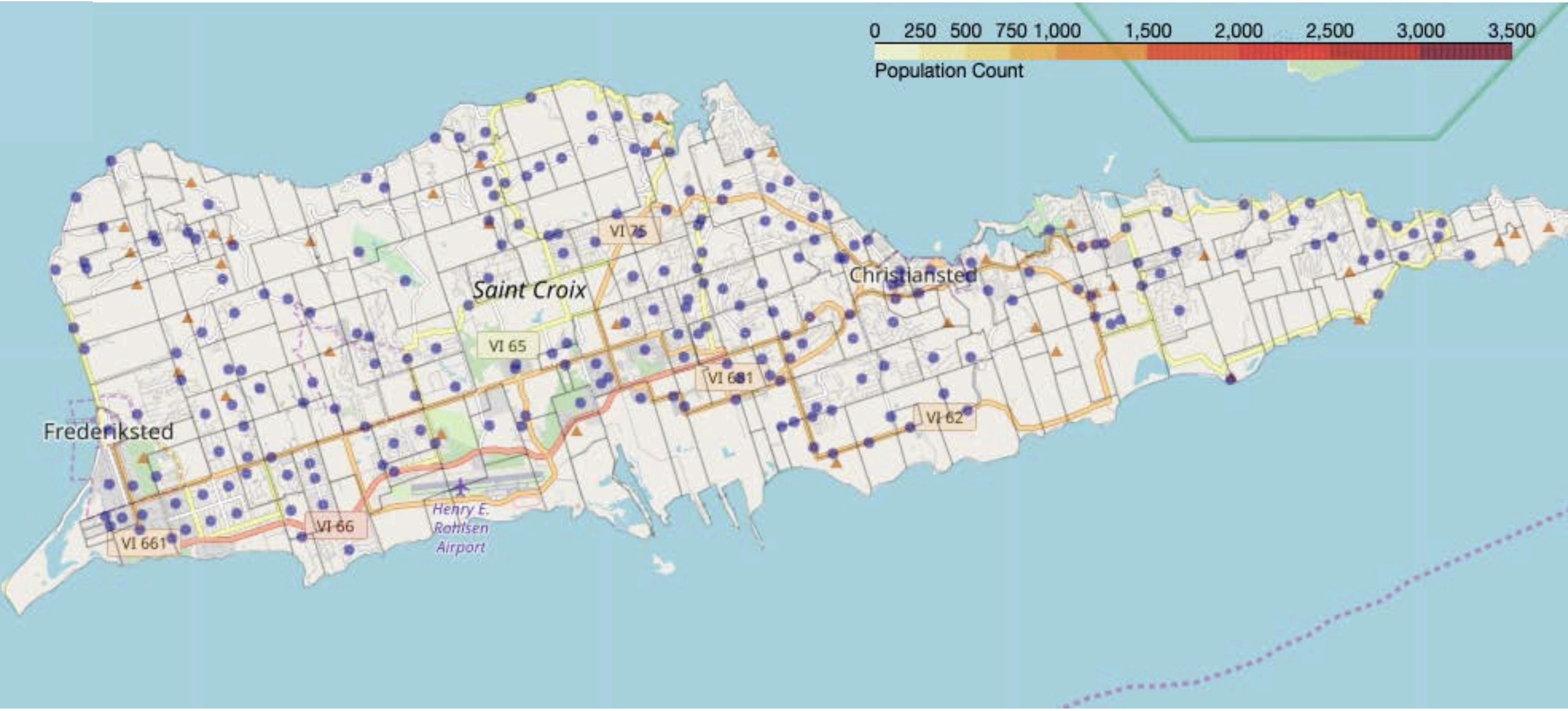


Analysis: Estates

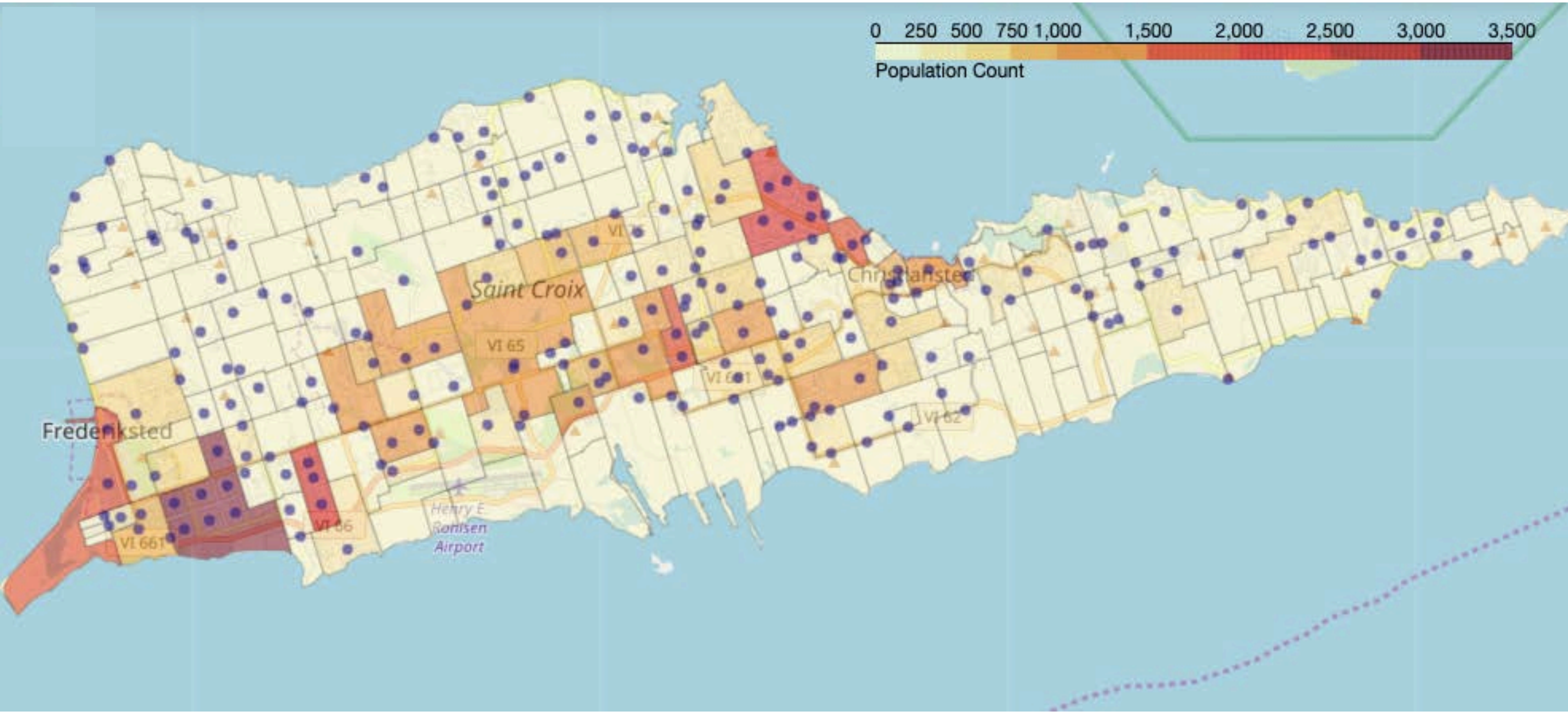


Analysis: Population “Centroids”

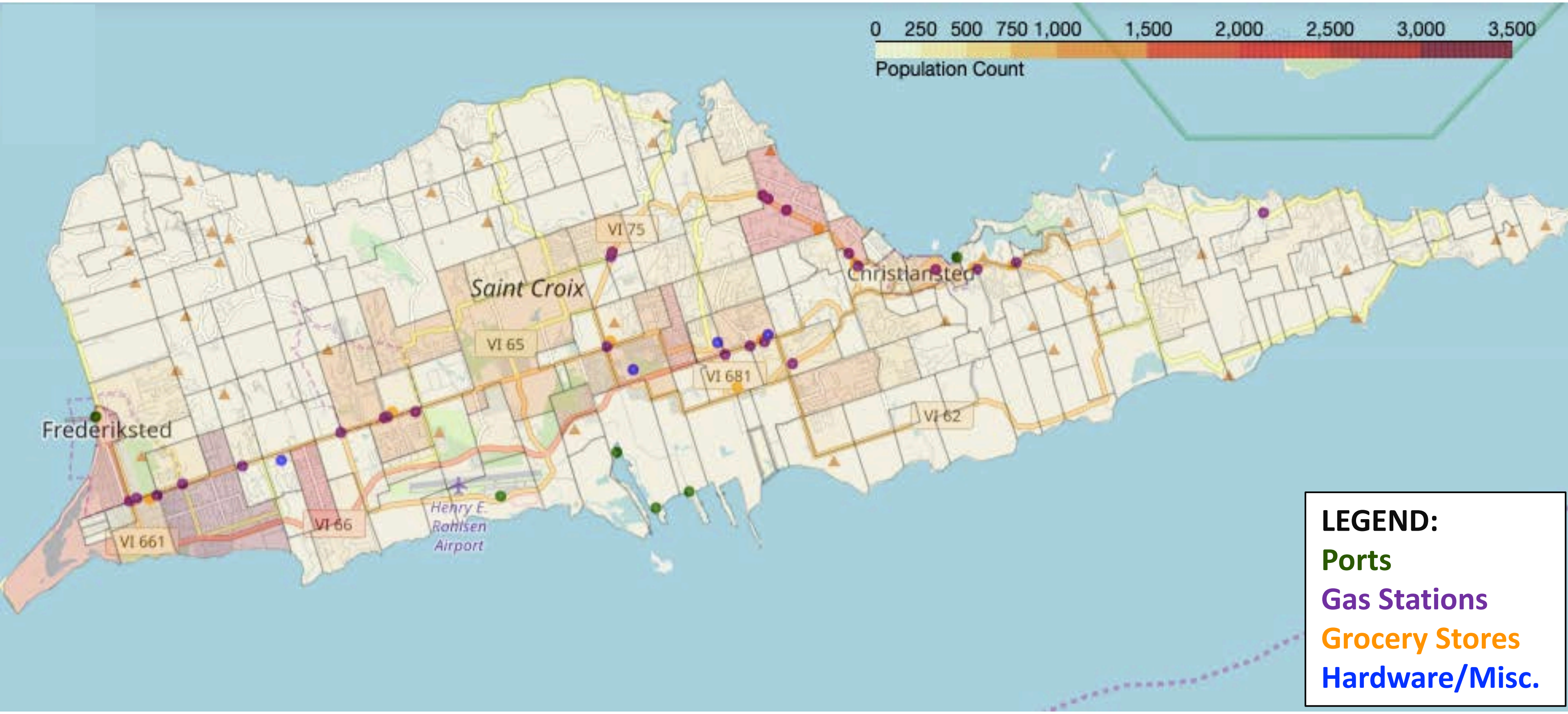
Actual location based on verification of homes and neighborhoods on Google Satellite view.



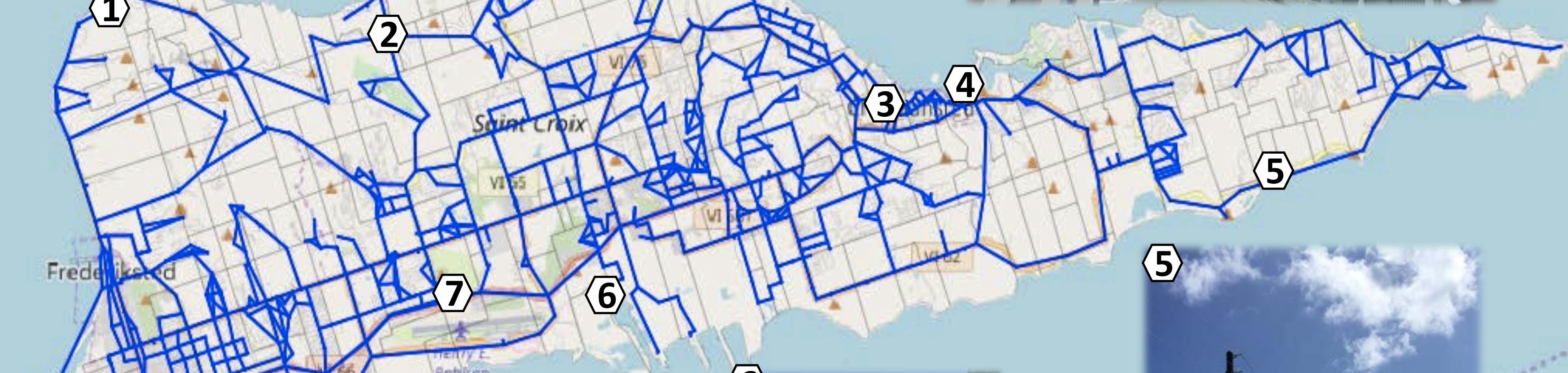
Analysis: Population Density by Estate



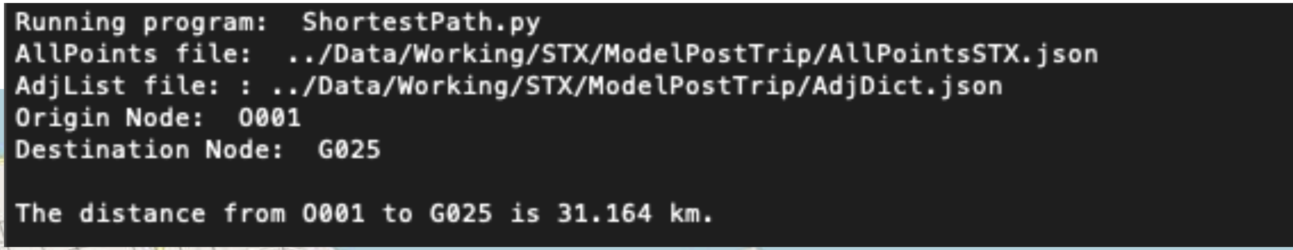
Analysis: Ports and Stores



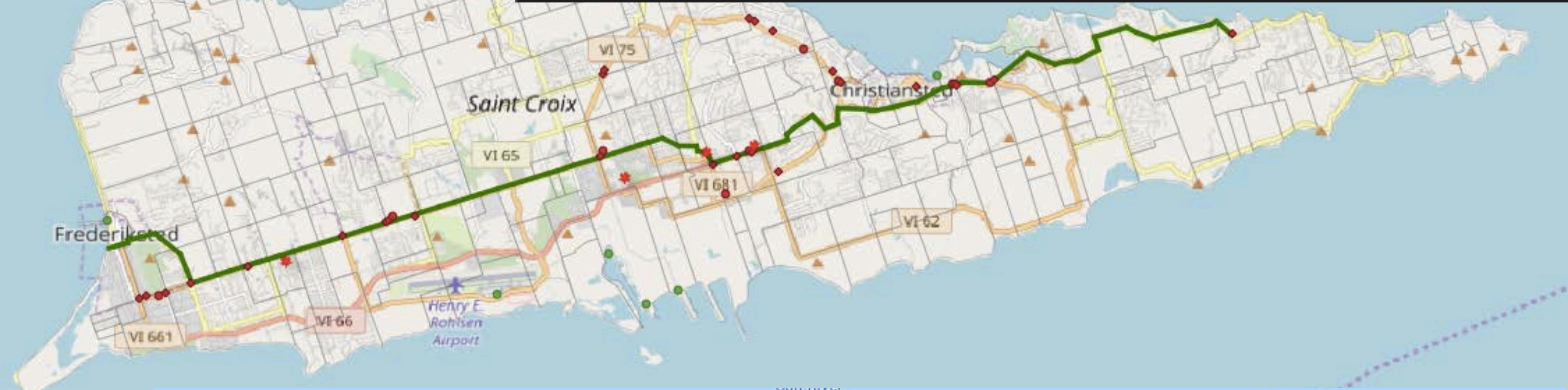
Analysis: Road Network

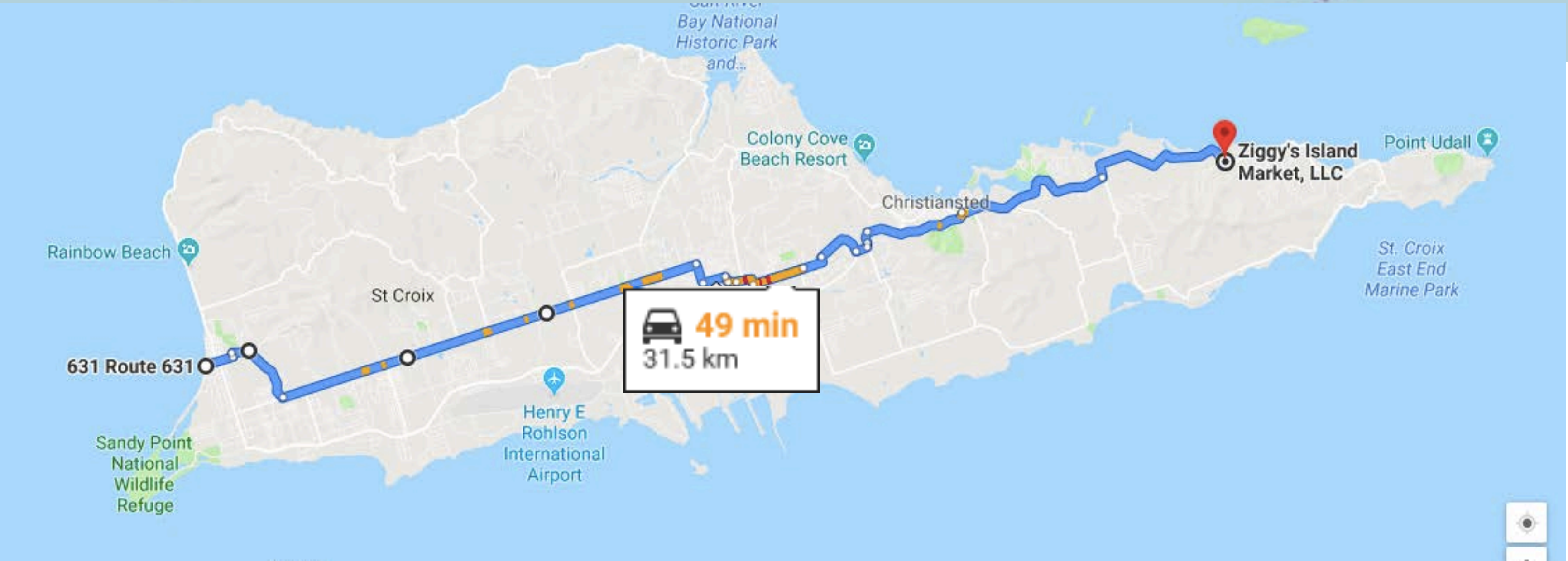


Analysis: Shortest Path Validation



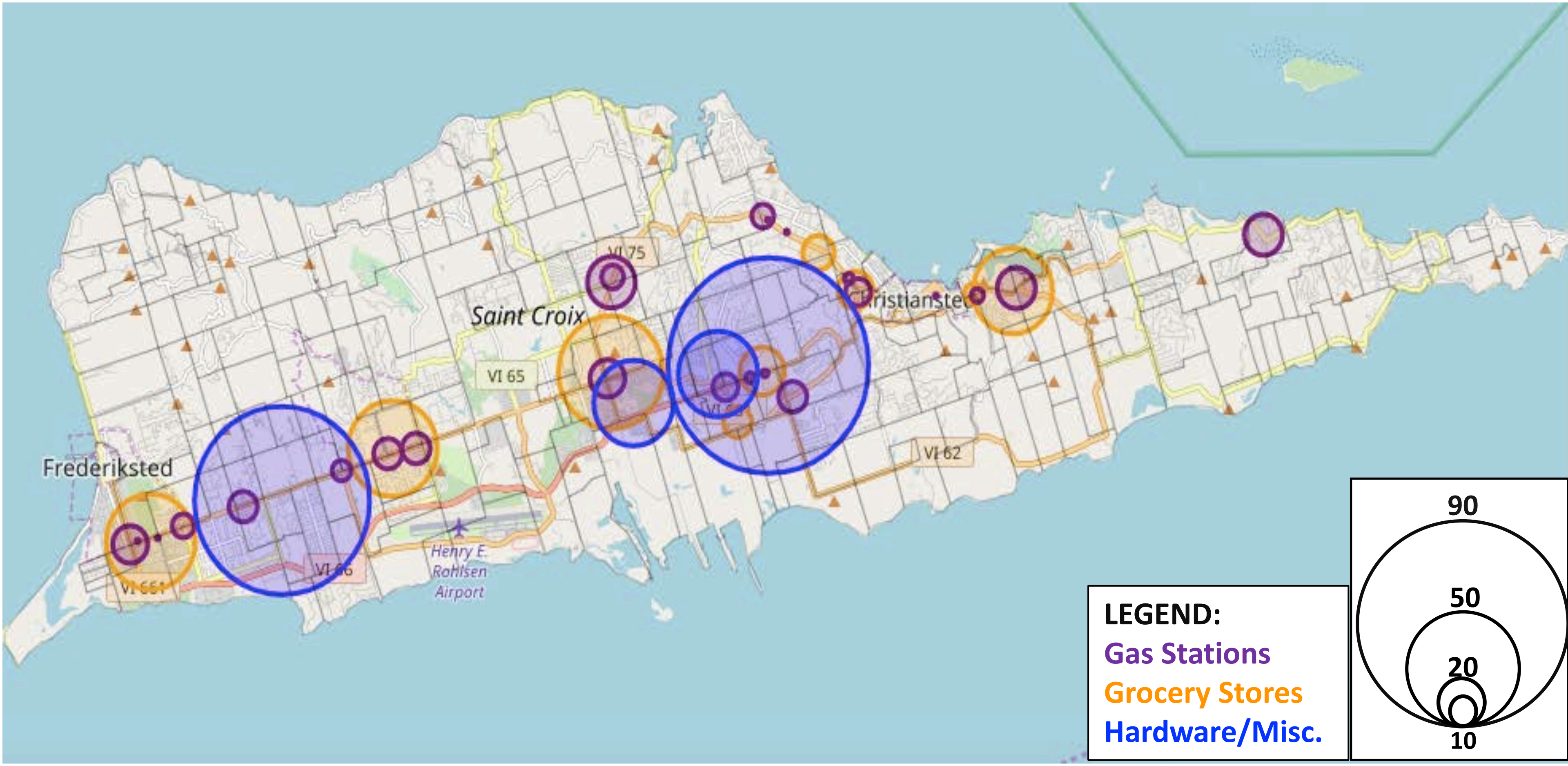
```
Running program:  ShortestPath.py
AllPoints file:  ../Data/Working/STX/ModelPostTrip/AllPointsSTX.json
AdjList file: : ../Data/Working/STX/ModelPostTrip/AdjDict.json
Origin Node:  0001
Destination Node:  G025

The distance from 0001 to G025 is 31.164 km.
```




Bay National Historic Park and...
Colony Cove Beach Resort
Christiansted
Ziggy's Island Market, LLC
Point Udall
St. Croix East End Marine Park
Rainbow Beach
St Croix
631 Route 631
49 min
31.5 km
Henry E Rohlson International Airport
Sandy Point National Wildlife Refuge

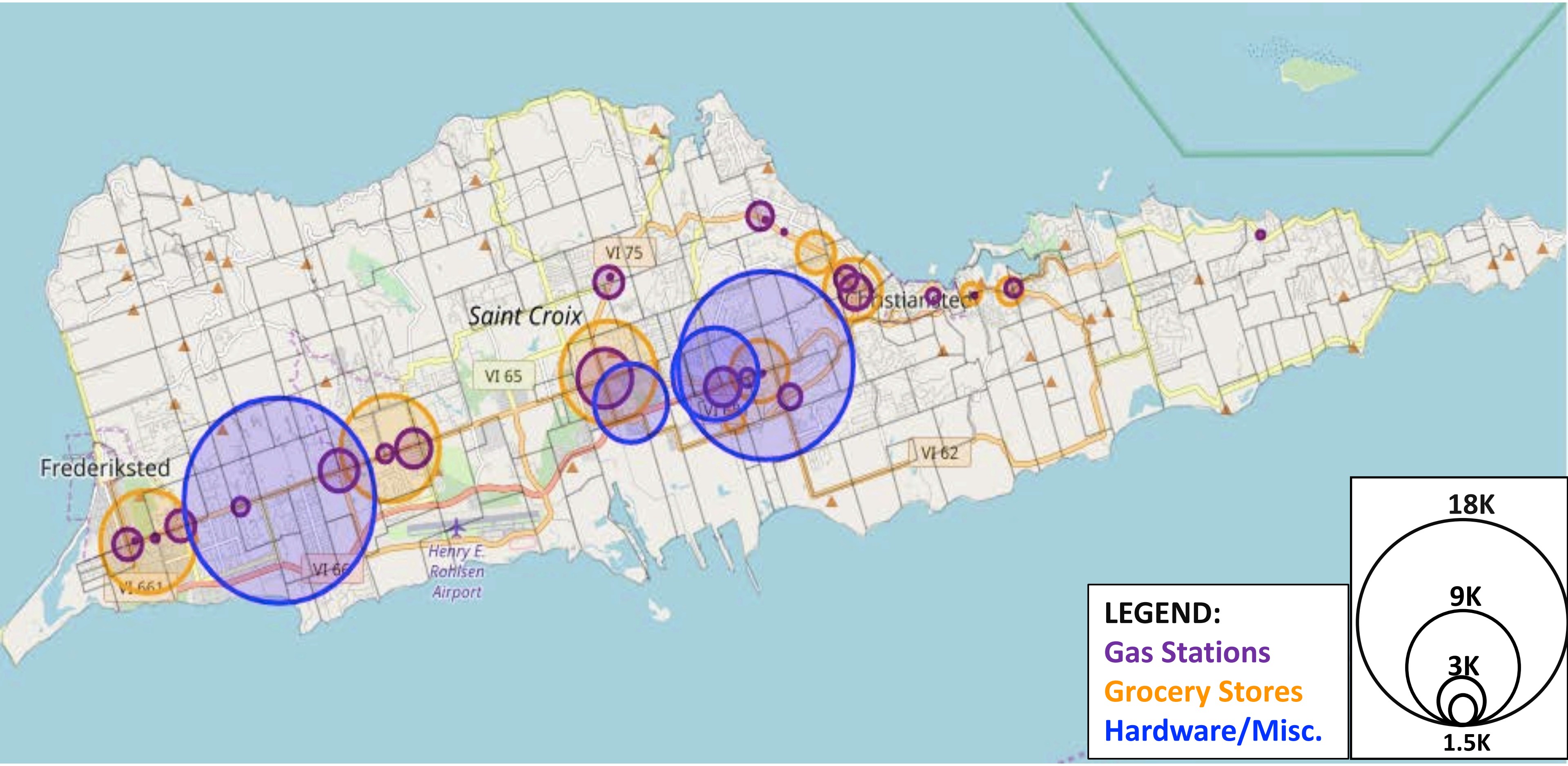
Analysis: Demand for Service by Estate (Shortest Path)

Radius of POINT OF INTEREST nodes indicates number of ORIGIN nodes serviced based on nearest neighbor.



Analysis: Demand for Service by Population (Shortest Path)

Radius of POINT OF INTEREST nodes indicates population of ORIGIN nodes serviced based on nearest neighbor.

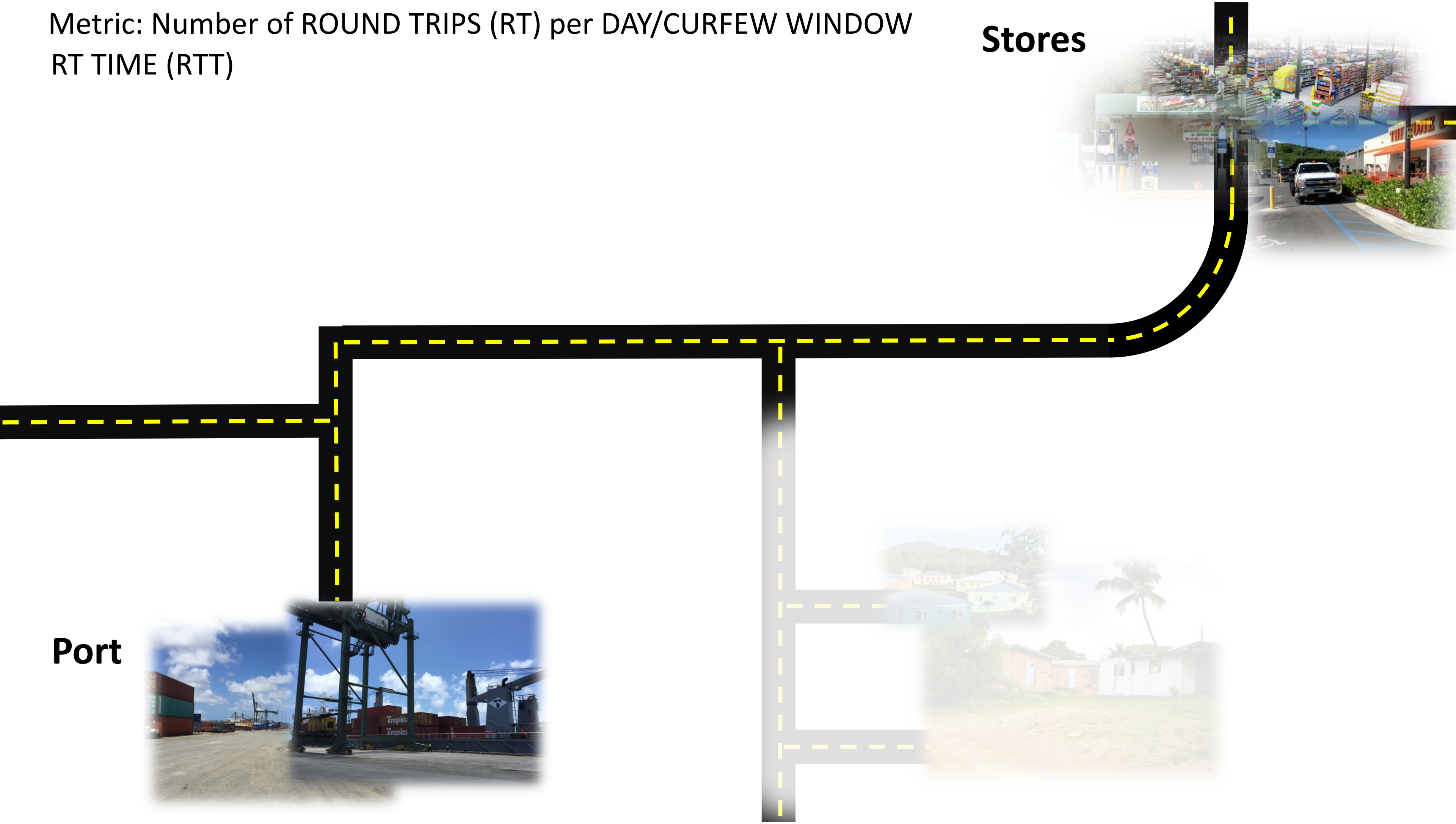


Understanding Traffic Demand (Congestion): Delivery Model

Objective: ***Maximize*** supply chain access

Metric: Number of ROUND TRIPS (RT) per DAY/CURFEW WINDOW

RT TIME (RTT)



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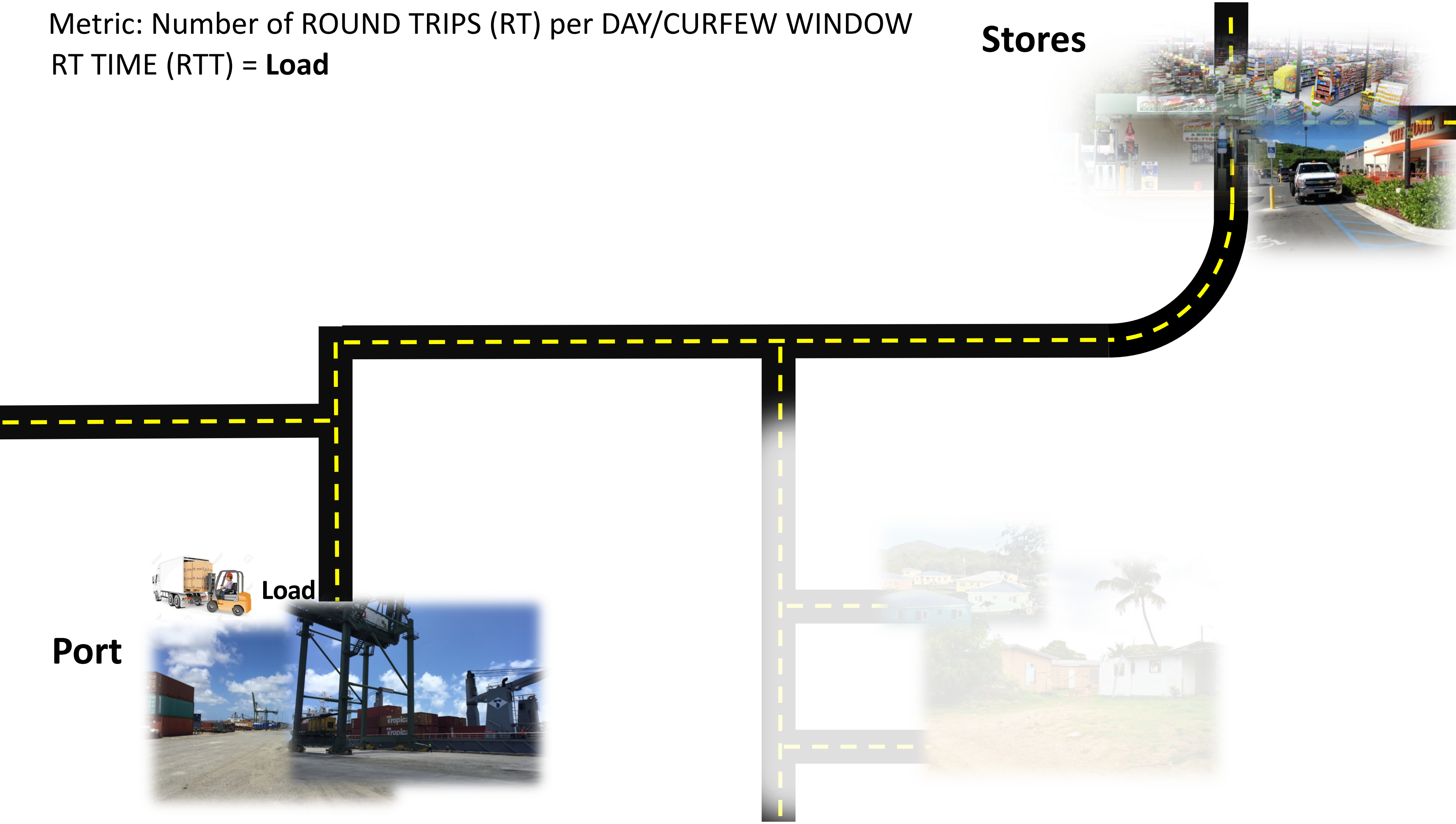
RT TIME (RTT) = **Load**



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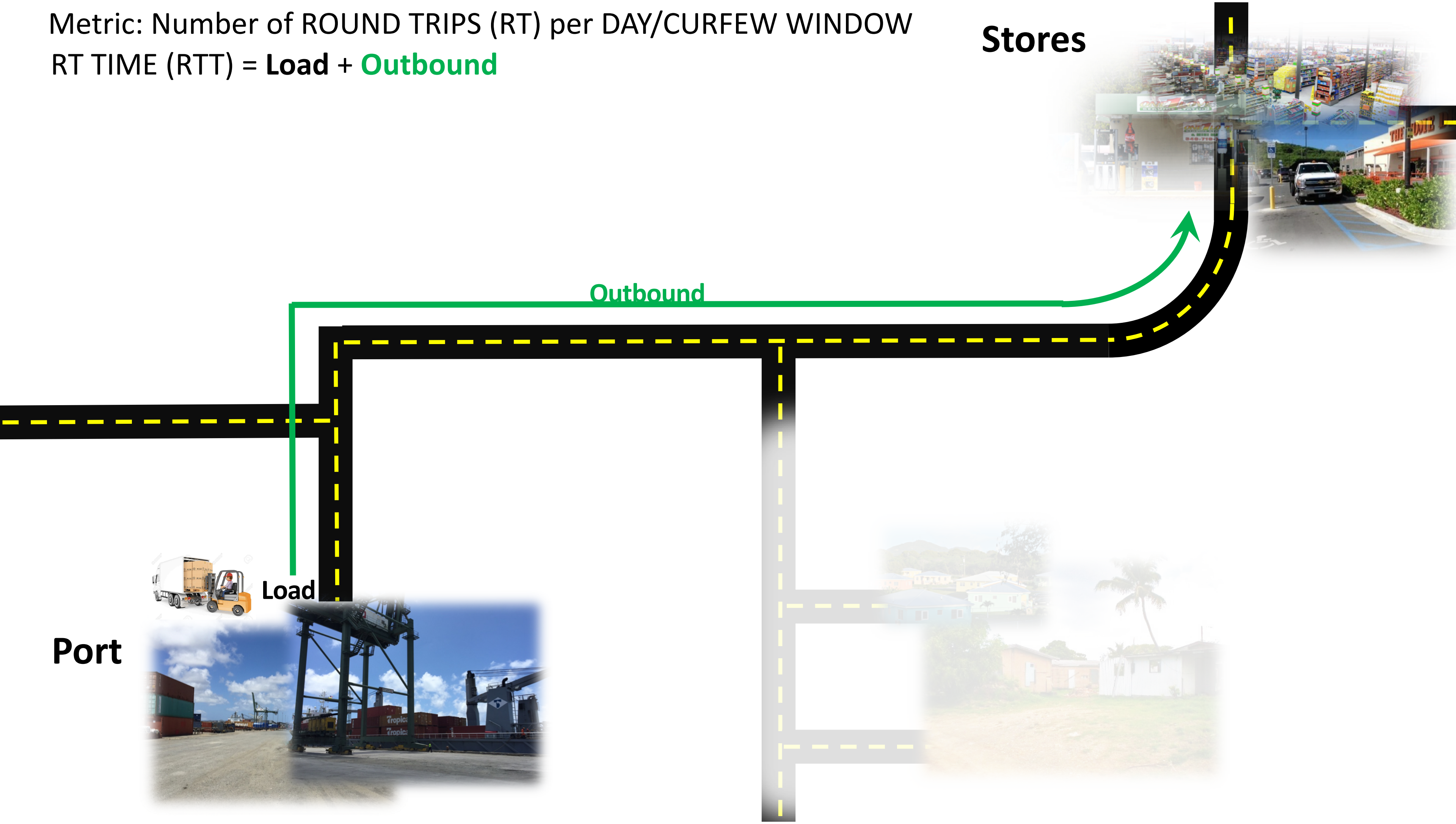
Metric: Number of ROUND TRIPS (RT) per DAY/CURFEW WINDOW

RT TIME (RTT) = **Load** + **Outbound**



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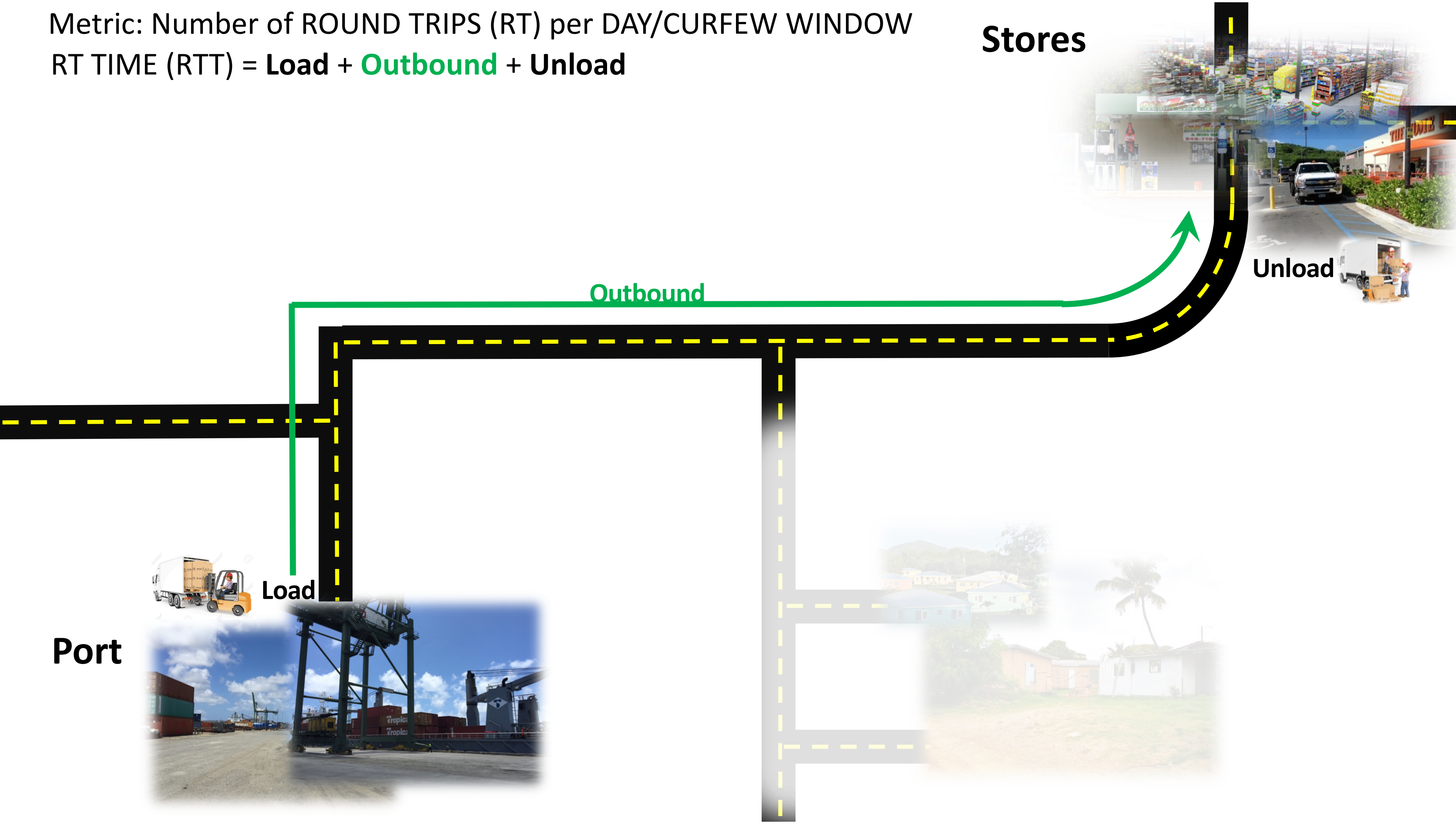

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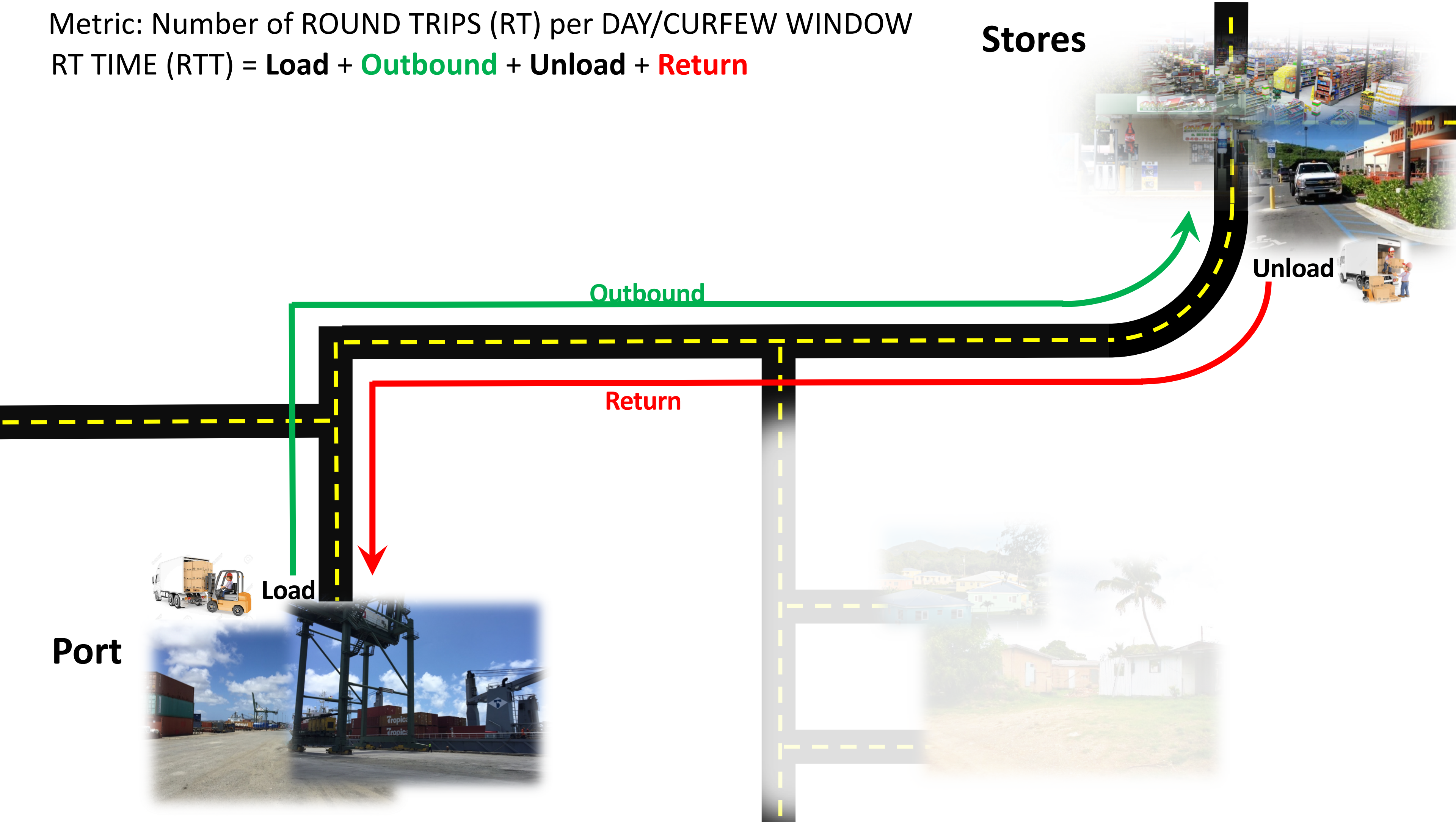
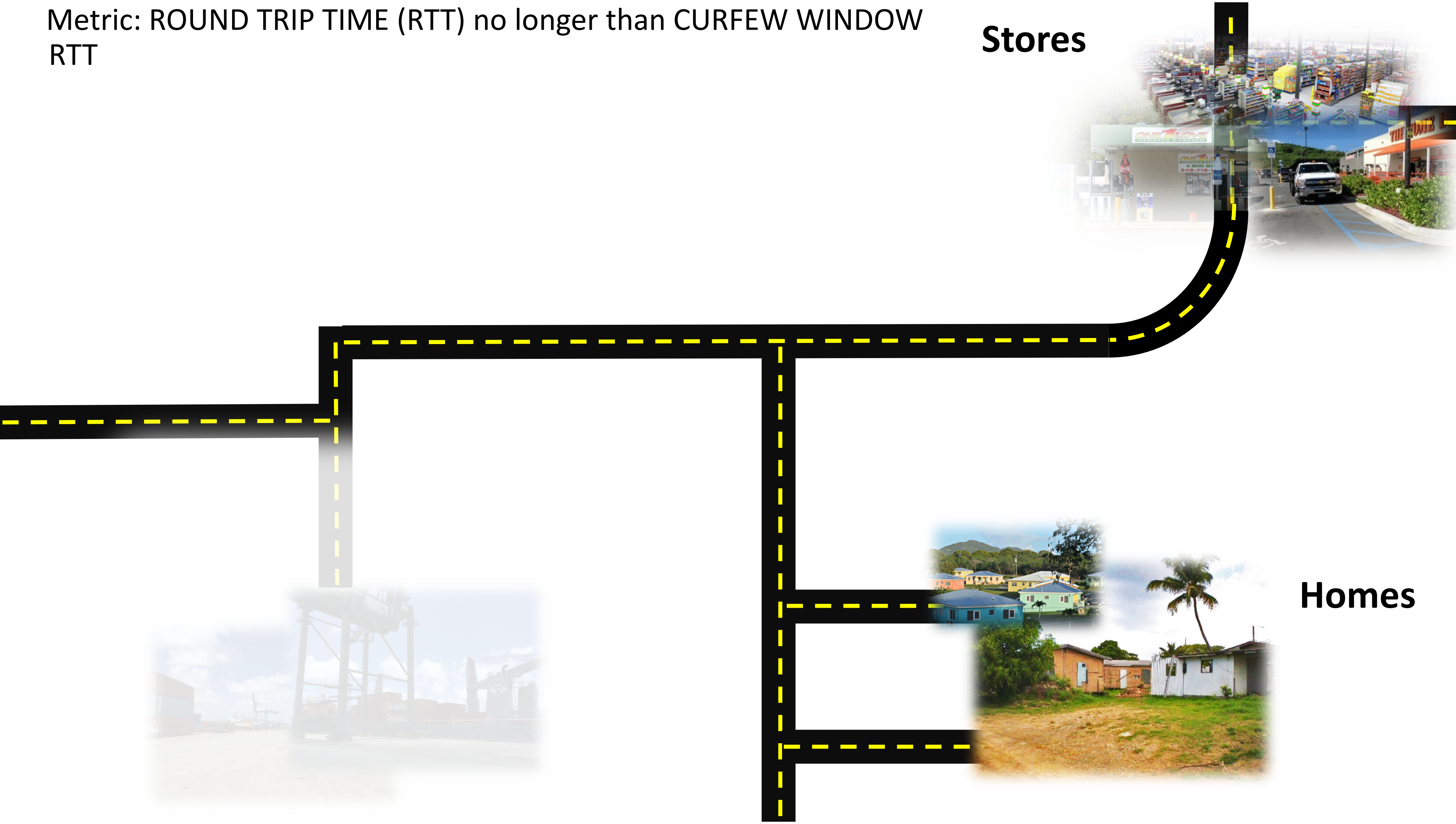


Understanding Traffic Demand (Congestion): Customer Model

Objective: ***Minimize*** household travel time
Metric: ROUND TRIP TIME (RTT) no longer than CURFEW WINDOW
RTT



Understanding Traffic Demand (Congestion): Customer Model

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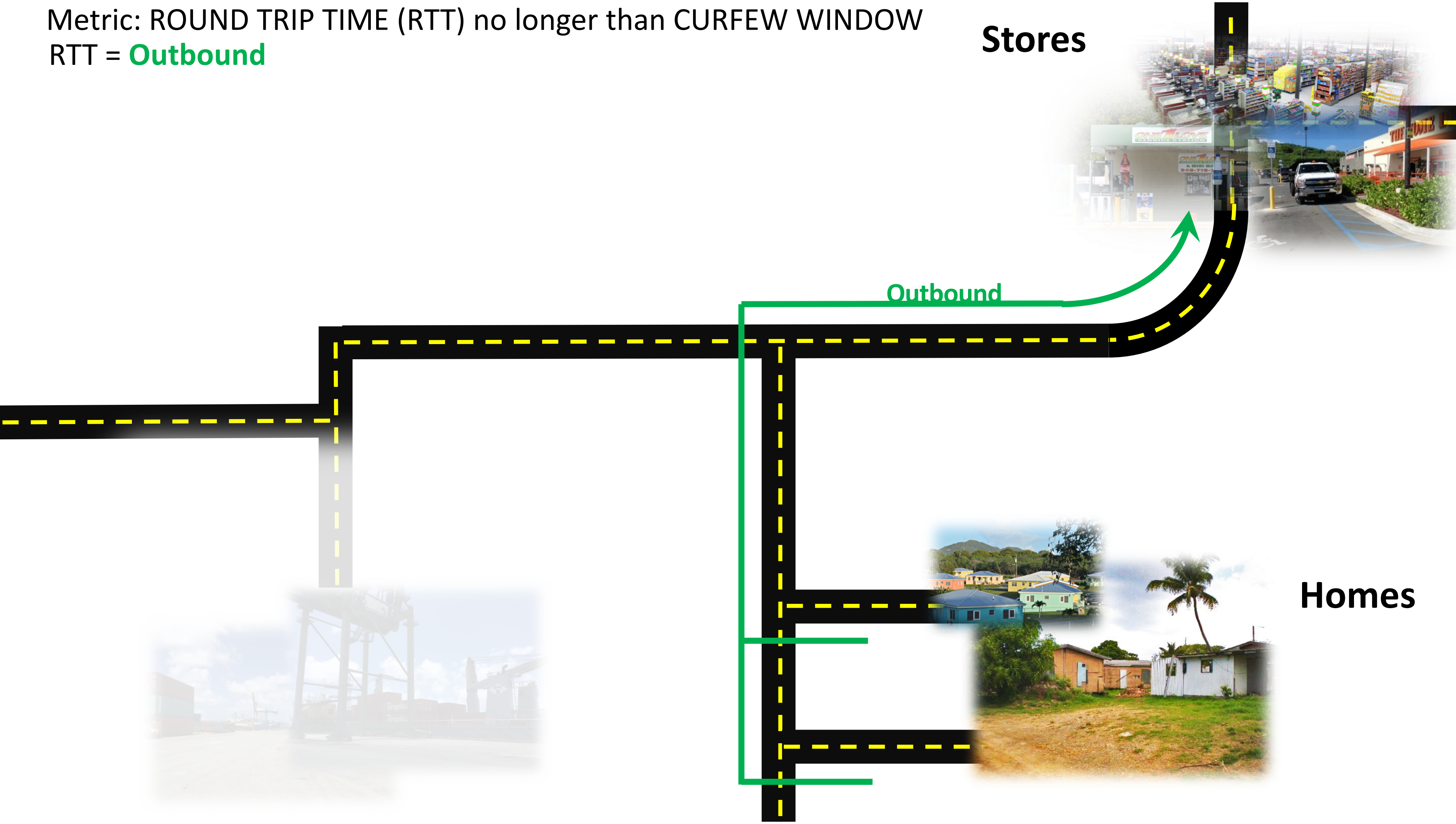
RTT = **Outbound**



Stores

Outbound

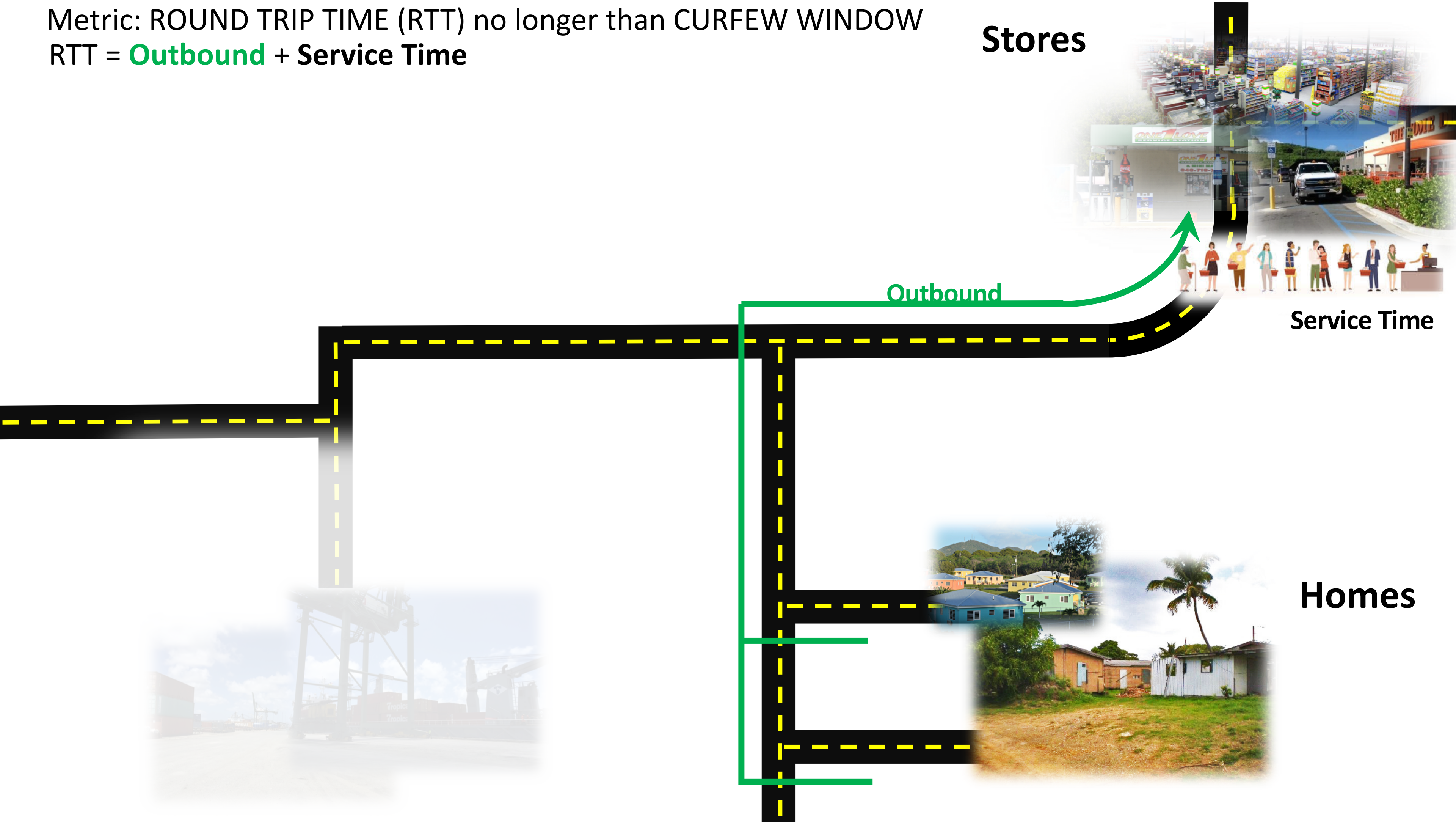
Homes

Understanding Traffic Demand (Congestion): Customer Model

Objective: ***Minimize*** household travel time

Metric: ROUND TRIP TIME (RTT) no longer than CURFEW WINDOW

RTT = **Outbound** + **Service Time**



Stores

Outbound

Service Time

Homes

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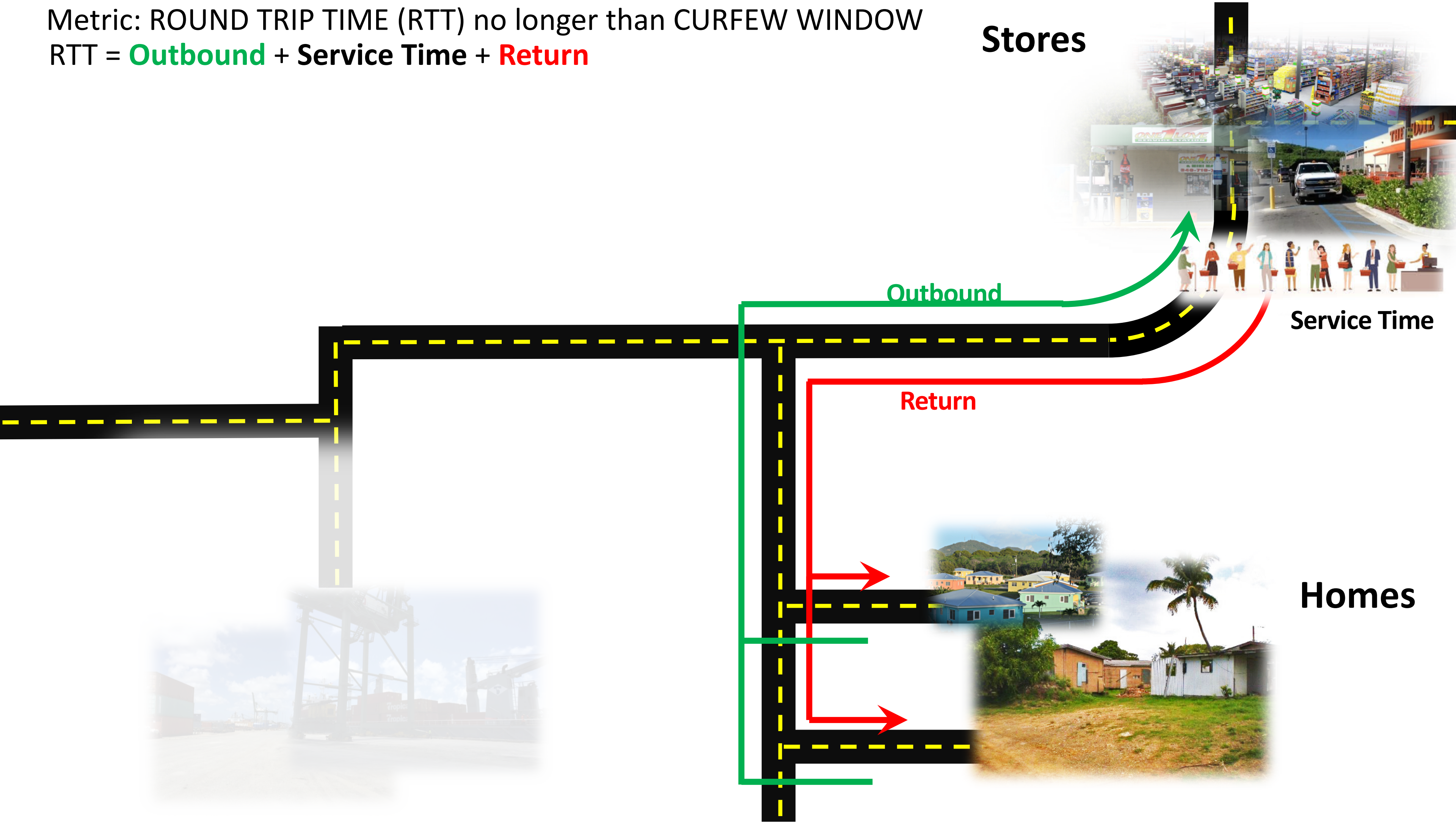
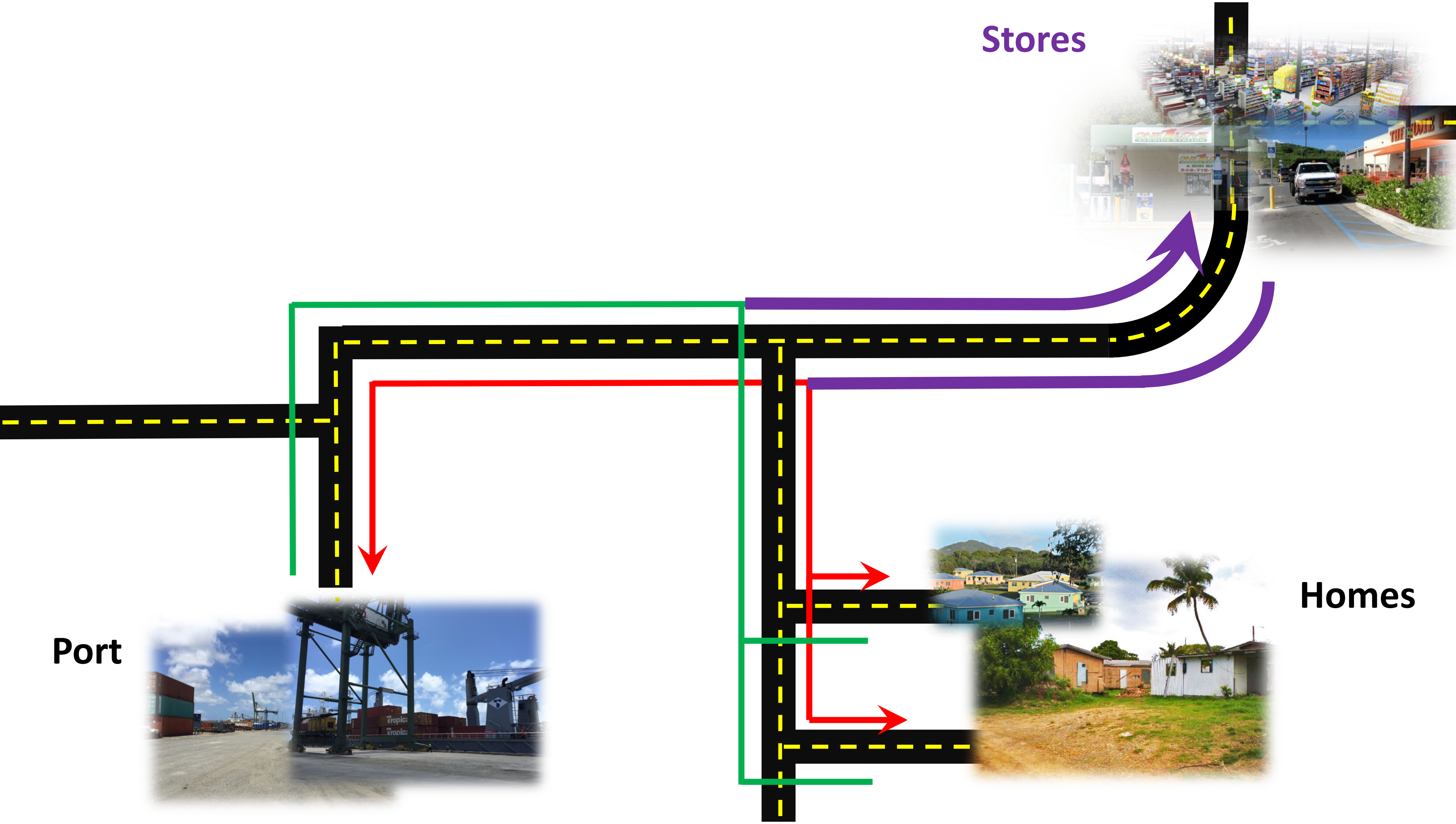
RTT = **Outbound** + **Service Time** + **Return**



Understanding Traffic Demand (Congestion): Combined Model

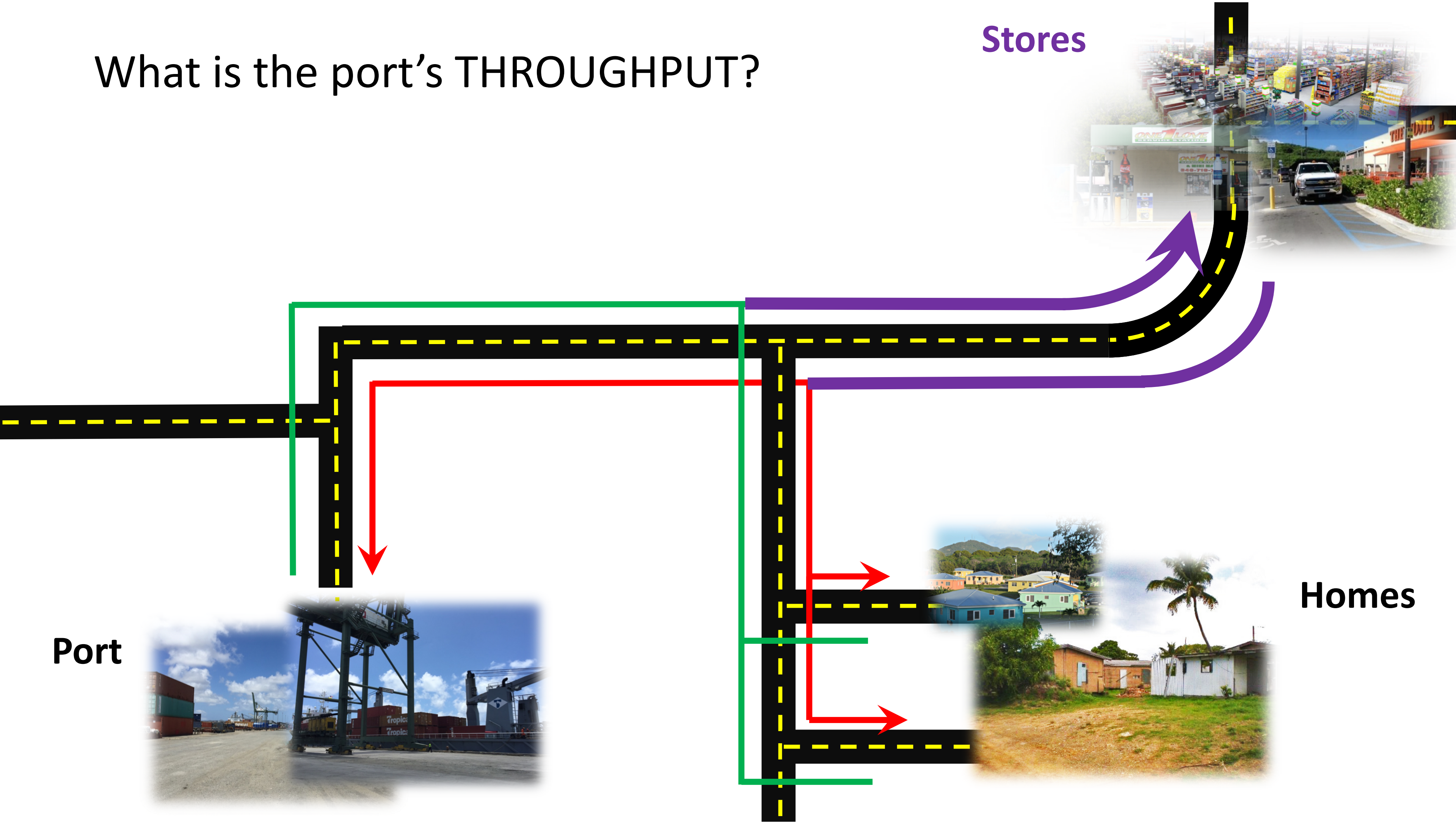
Shared: Roads and Stores



Understanding Traffic Demand (Congestion): Combined Model

Shared: Roads and Stores

What is the port’s THROUGHPUT?

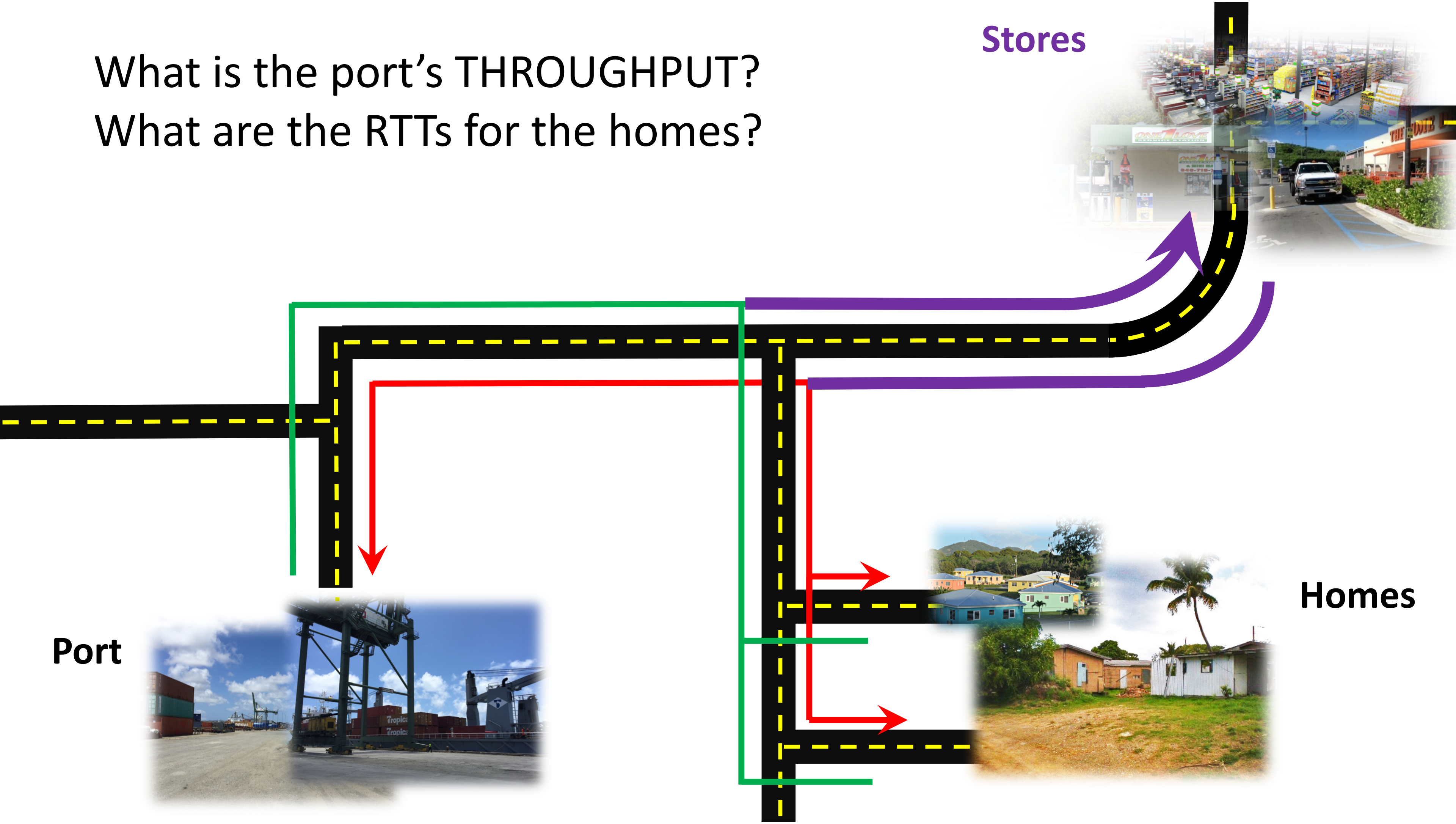


Understanding Traffic Demand (Congestion): Combined Model

Shared: Roads and Stores

What is the port's THROUGHPUT?

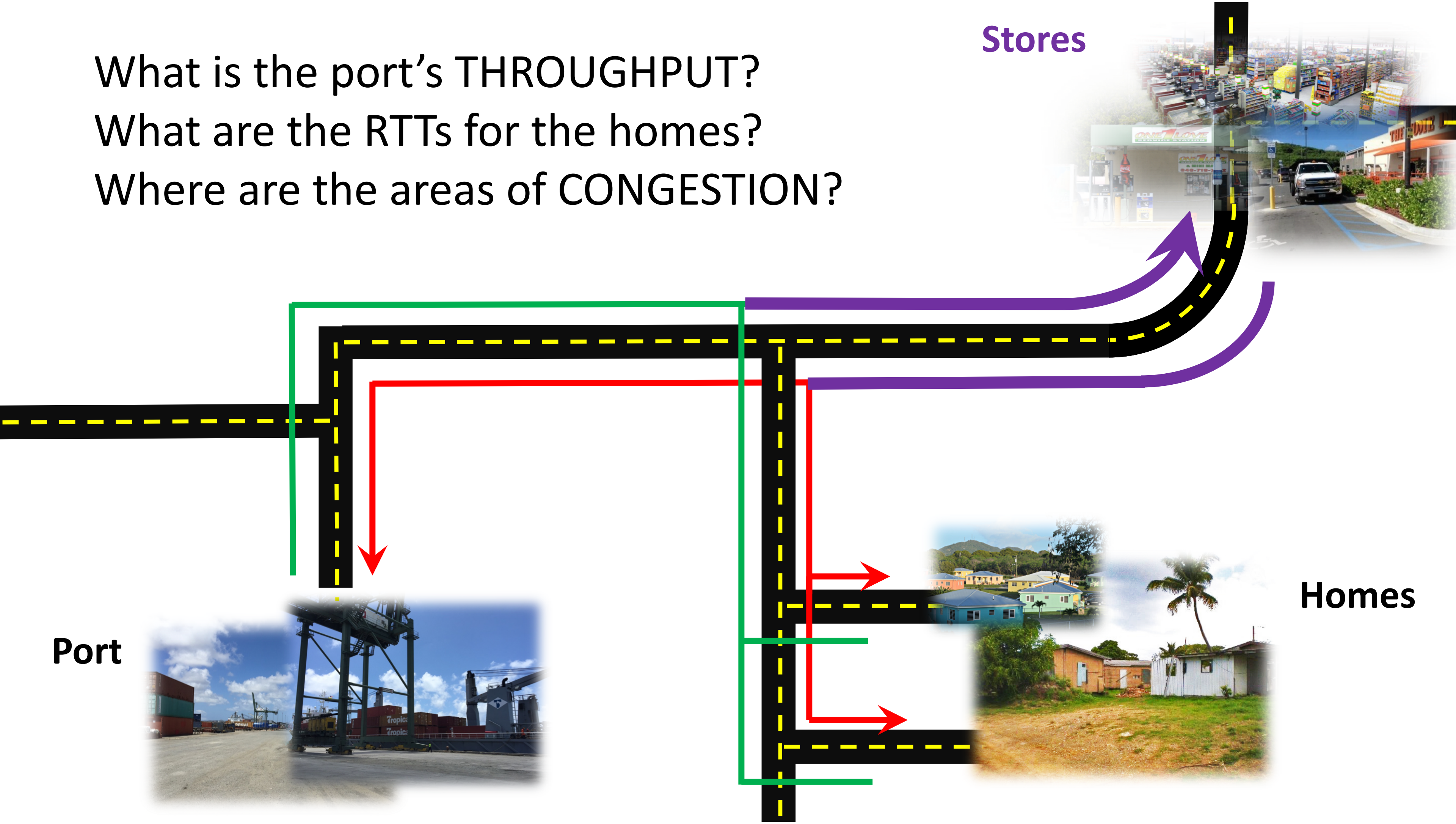
What are the RTTs for the homes?



Understanding Traffic Demand (Congestion): Combined Model

Shared: Roads and Stores

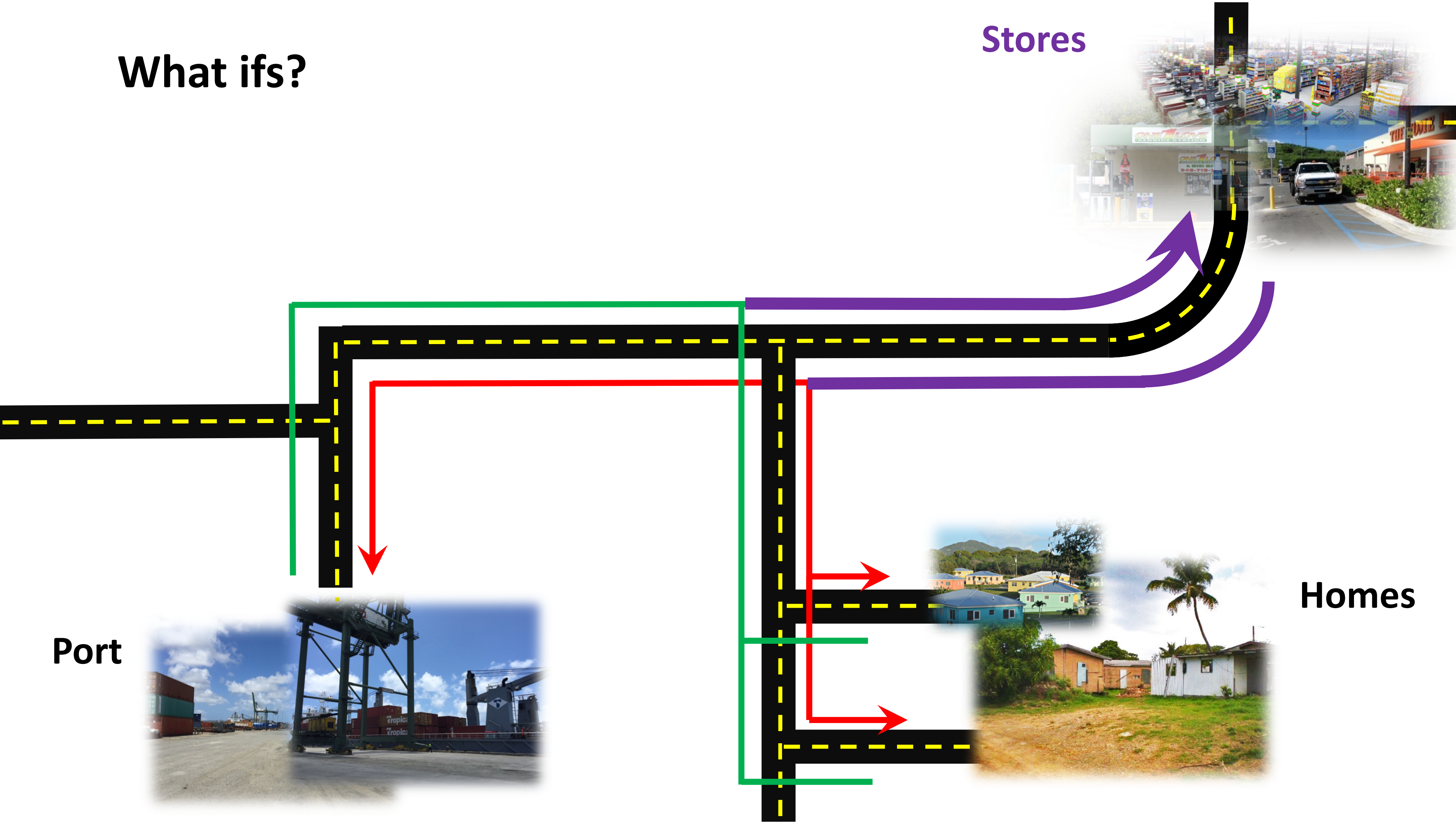
What is the port's THROUGHPUT?
What are the RTTs for the homes?
Where are the areas of CONGESTION?



Understanding Traffic Demand (Congestion): Combined Model

Shared: Roads and Stores

What ifs?



Stores

Port

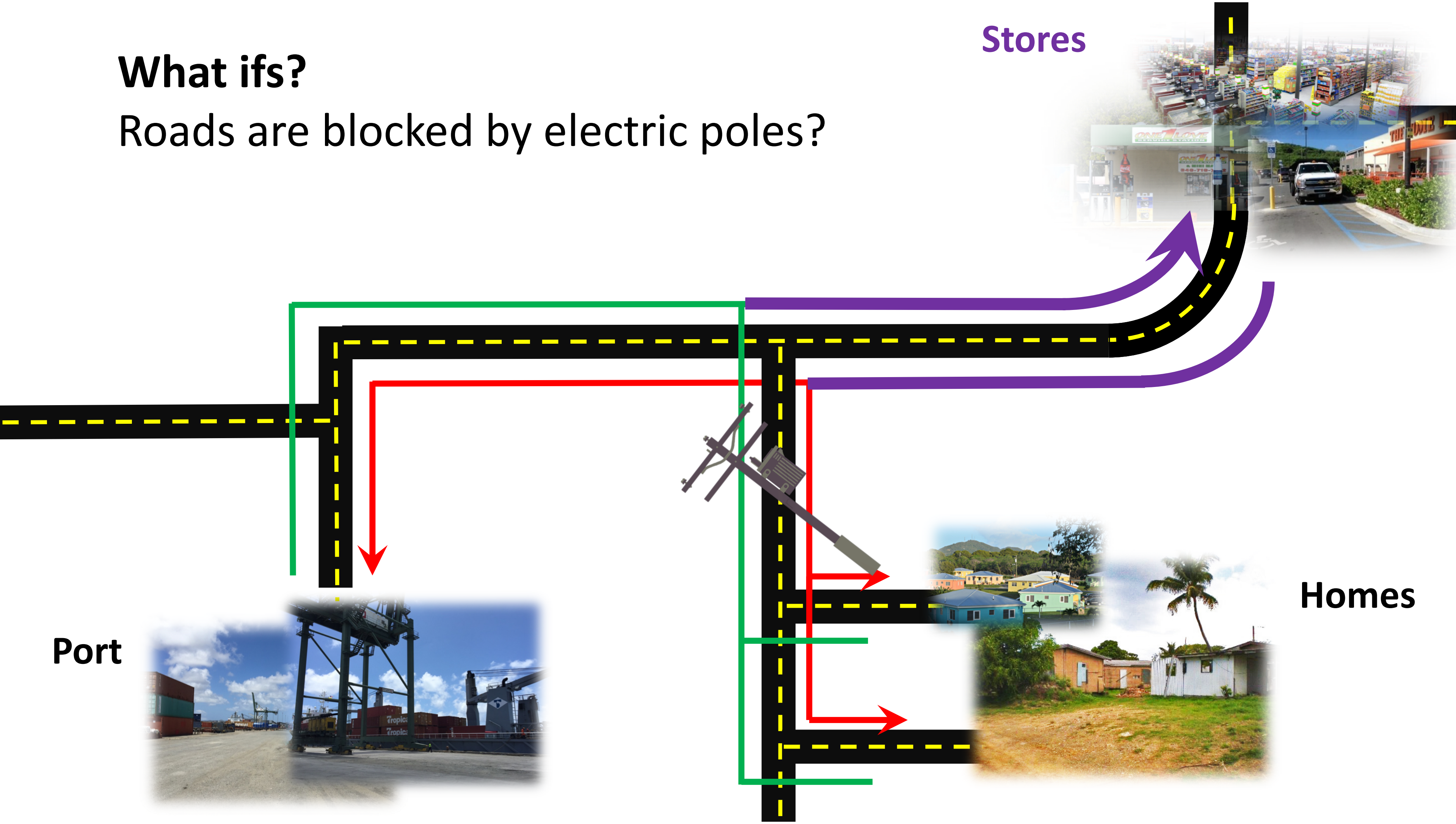
Homes

Understanding Traffic Demand (Congestion): Combined Model

Shared: Roads and Stores

What ifs?

Roads are blocked by electric poles?



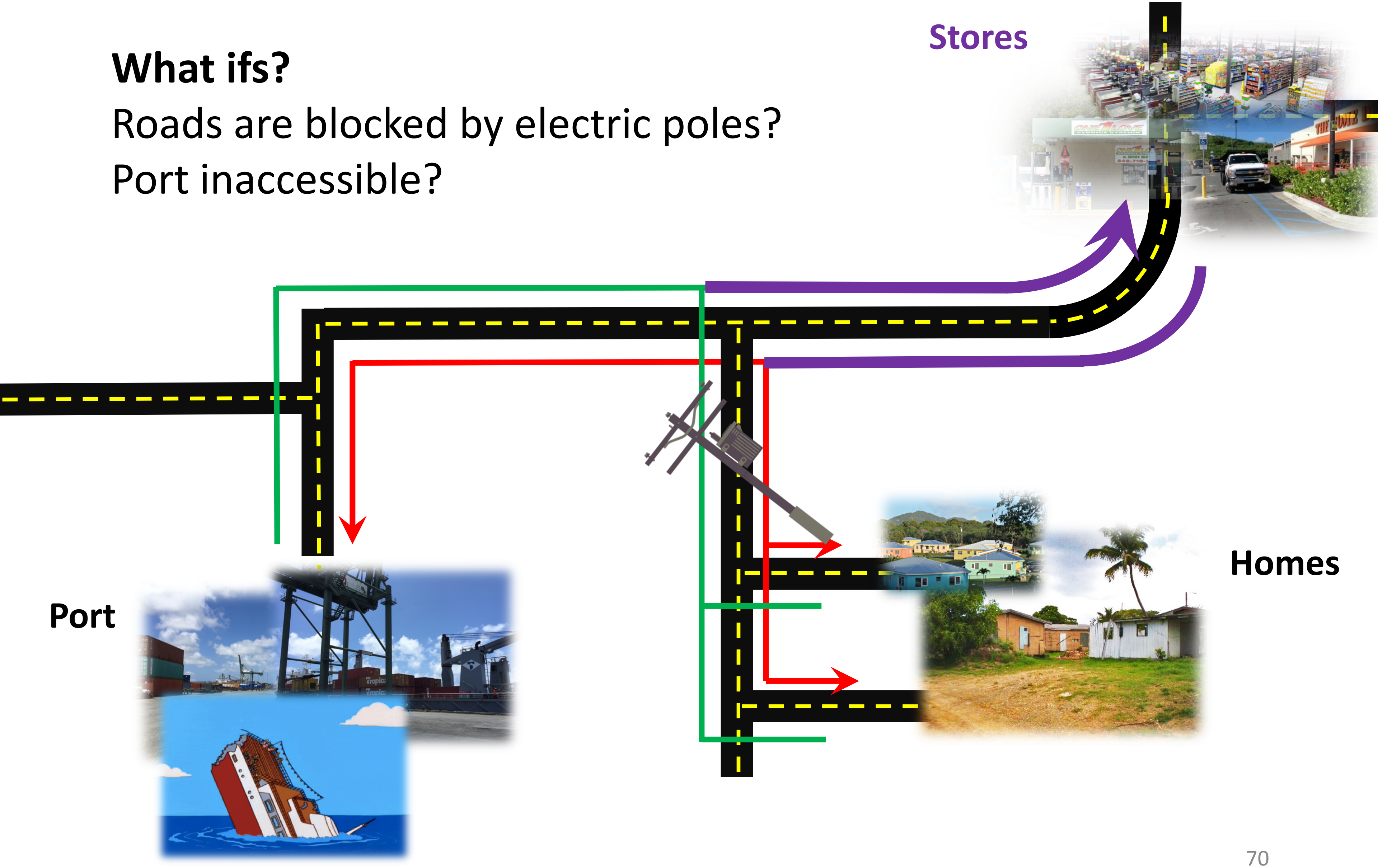
Understanding Traffic Demand (Congestion): Combined Model

Shared: Roads and Stores

What ifs?

Roads are blocked by electric poles?

Port inaccessible?



Understanding Traffic Demand (Congestion): Combined Model

Shared: Roads and Stores

What ifs?

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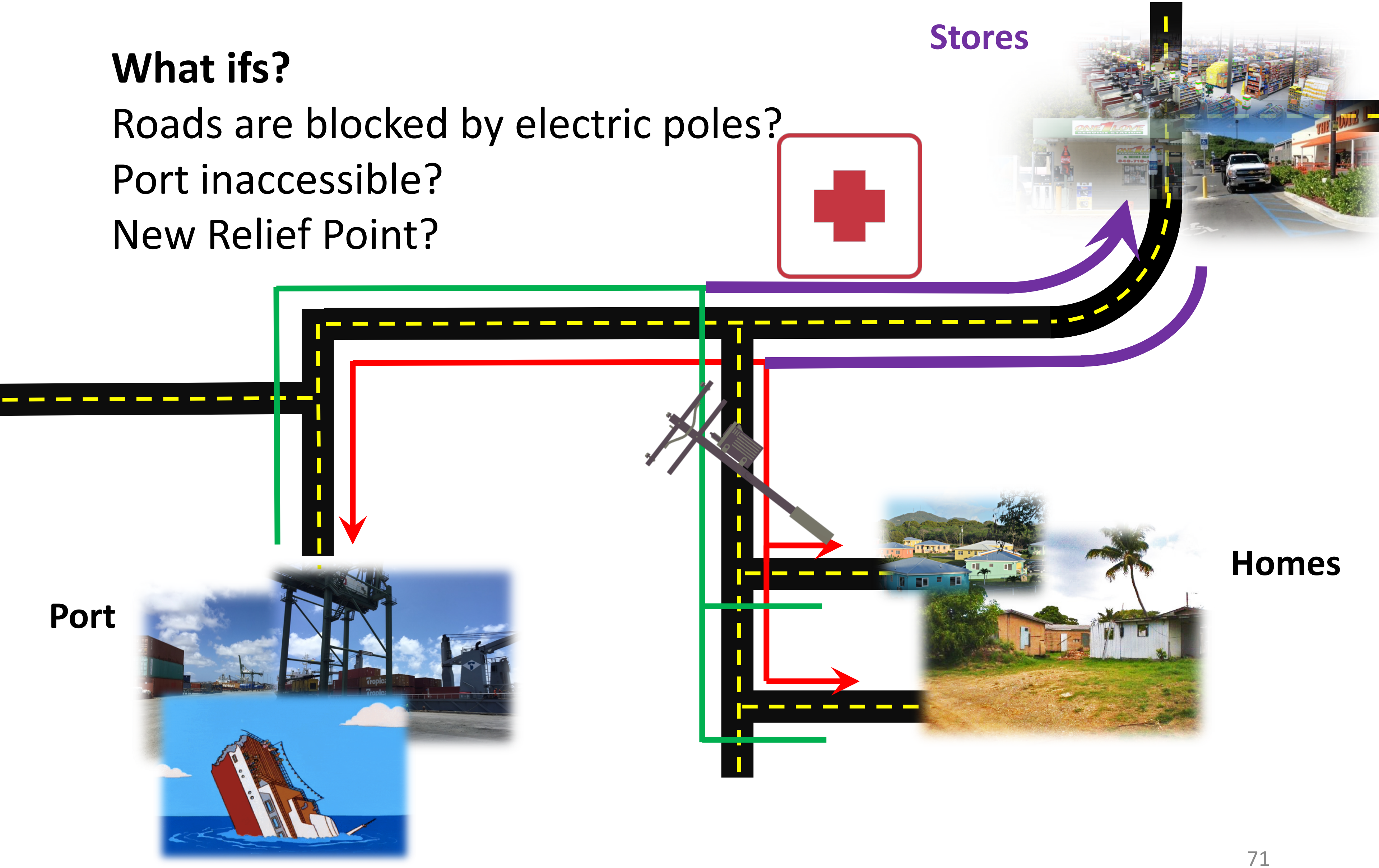
Port inaccessible?

New Relief Point?



Phases of Work

Phase 1 – Data Collection and Demand Modeling

- ☑ Curate and Validate Data
- ☑ Build network
- ☑ Validate traffic flow via shortest path

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Phase 2 – Congestion Modeling and Relief Point Analysis

- ❑ Equilibrium model of congestion based on road conditions and O-D pairs
- ❑ Calculate estate round trip times and analyze curfew impacts
- ❑ Estimate supply round trip times and calculate delivery volume per point of interest

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Phase 3 – Sponsor Outbriefs

❑ 2nd Week of September - Next trip to USVI

  ❑ Brief FEMA, Governor's Office, UVI

❑ 27 September – Graduation (Expected)