SAND2015-4488C

Simulating transient flows, storage, and recovery on disrupted petroleum infrastructure networks: algorithm and application by federal agencies

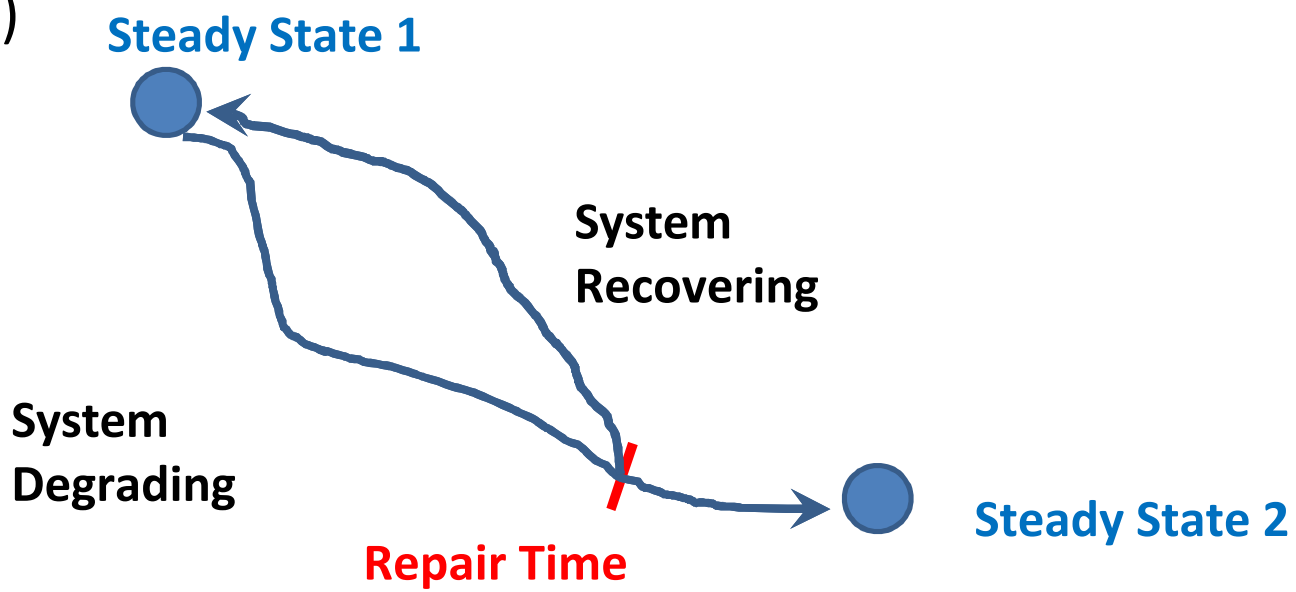
83 MORS Symposium

June 23-25, 2015

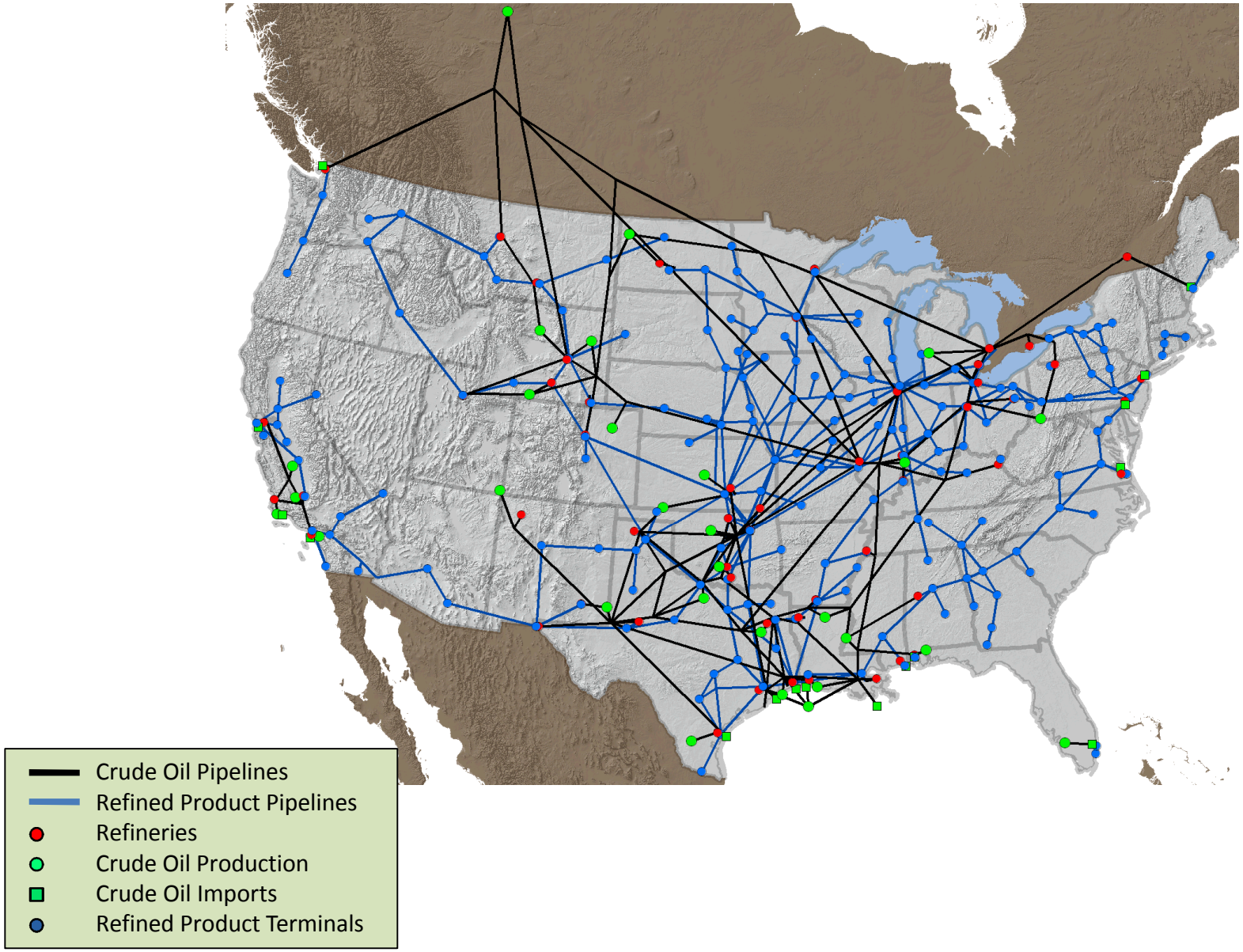
- We developed a network modeling environment (NetFlow Dynamics) consisting of algorithms, databases, and a GIS-based interface to simulate commodity flows in supply networks
- One application of this environment, the National Transportation Fuels Model (NTFM), is a network-based model of the U.S. transportation fuel infrastructure
- The Department of Homeland Security and Sandia National Laboratories developed the NTFM to inform analyses of the availability of transportation fuels during disruptions to the fuel supply network
- In this presentation we will:
  - introduce the NTFM
  - describe the governing equations for the NetFlow Dynamics algorithm
  - discuss potential uses of NetFlow Dynamics by the Department of Energy

Requirements

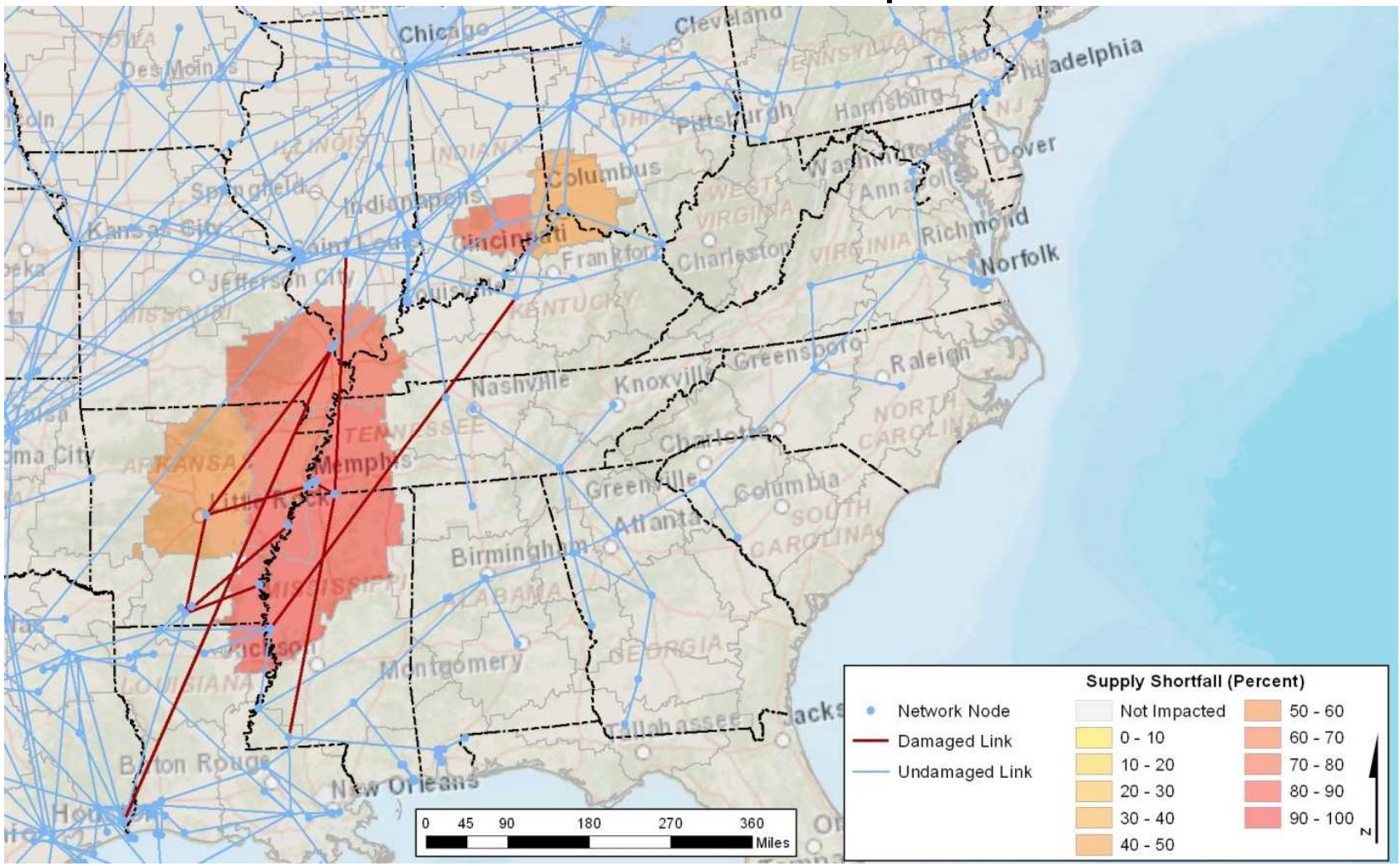
- Adapts to stress:
  - Rerouting of shipments.
  - Drawdown of inventories.
  - Use of surge capacity in transportation, refining, and imports to mitigate fuel shortage
- Constrained by connectivity and capacities
- Dynamic (transient)



NTFM Network



Calculated Consumption Shortfall of Fuel Due to a New Madrid Earthquake



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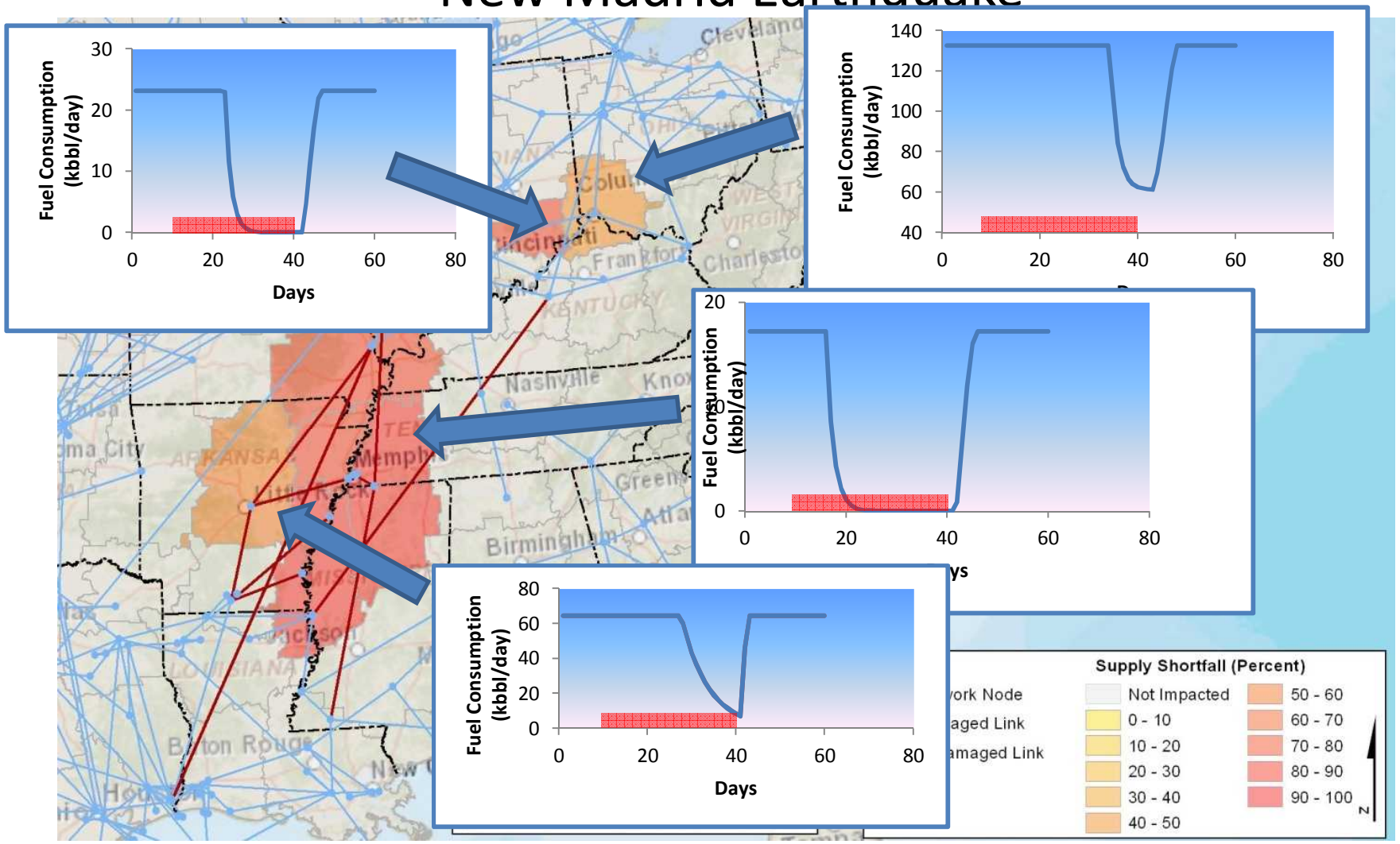
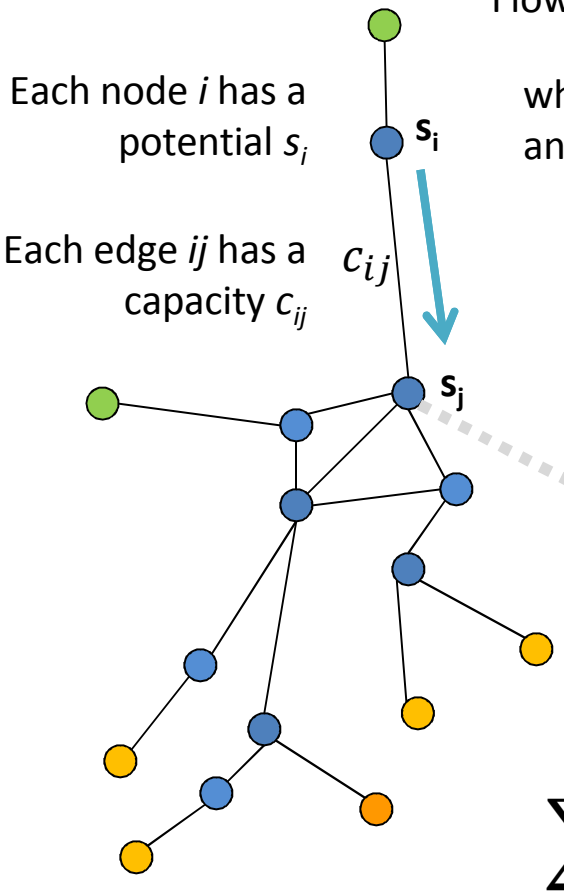


Diffusion Equation Approach

- Analogous to physical systems in which there is storage, and flows occur along gradients of a potential. Examples include:
  - heat flow in which heat flows from regions of higher temperature to regions of lower temperature
  - hydraulic systems in which fluids flow along pressure gradients.
- Captures the transient, non-equilibrium, behaviors that we require.
- We conceptualize the flow solution to represent the aggregate behaviors of markets and infrastructure operators, where the potential is a function of the amount of inventory at each node.

Balance Mass Without Exceeding Capacities



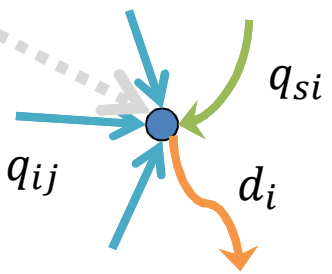
Flow rates are given by : $$q_{ij} = c_{ij}\, f\big((s_i - s_j)u_{ij}\big) \quad (1)$$

where u_{ij} is a utilization parameter and the function f(x) is: $$f(x) \equiv 1 - e^{-x} \quad (2)$$

In equilibrium, the net flow at each node *i* is 0: $$\sum_j q_{ji} + q_{si} - d_i = 0 \quad \forall i \quad (3)$$

where d_i is a source or sink

The equilibrium solution $\{\hat{s}_i\}$ is obtained by solving equations (1-3)



In the transient case, net inflow into a node results in the accumulation of stored fluid (v_i):

$$\sum_j q_{ji} + q_{si} - d_i = \frac{dv_i}{dt} = r_i \left[1 + \left(\frac{s_i - a_i}{b_i}\right)^2\right]^{-3/2} \frac{ds_i}{dt} \quad \forall i$$

where r_i , a_i and b_i are storage parameters

Beyeler, Corbet, and Hobbs, 2012

NetFlow Dynamics for DOE

A decision support tool to provide greater situational awareness for petroleum network disruptions.

Core capabilities

Simulating, displaying, and measuring impacts of disruptions in terms of barrels affected and number of days until return to normal system operations.

Support for Emergency Response (2015 Hurricane Season Test):

1. Provide a more national view of the disruption
   - Impacts beyond the affected area
   - Network flows projected over time
2. Highlight potential network flow responses

Electric vs Petroleum Disruptions

Electric Network Disruptions

Immediate and distinct

Impacts within damaged area

Bottom line measures exist (customers out, customers restored)

Petroleum Network Disruptions

Non-immediate and less certain

Impacts can be felt far away from impact area

Resilience and market response play big roles

- Storage and multi-transport modes provide resilience
- Market responses (price, demand drop, etc.)
- Human decisions and reactions

Bottom line measures are difficult

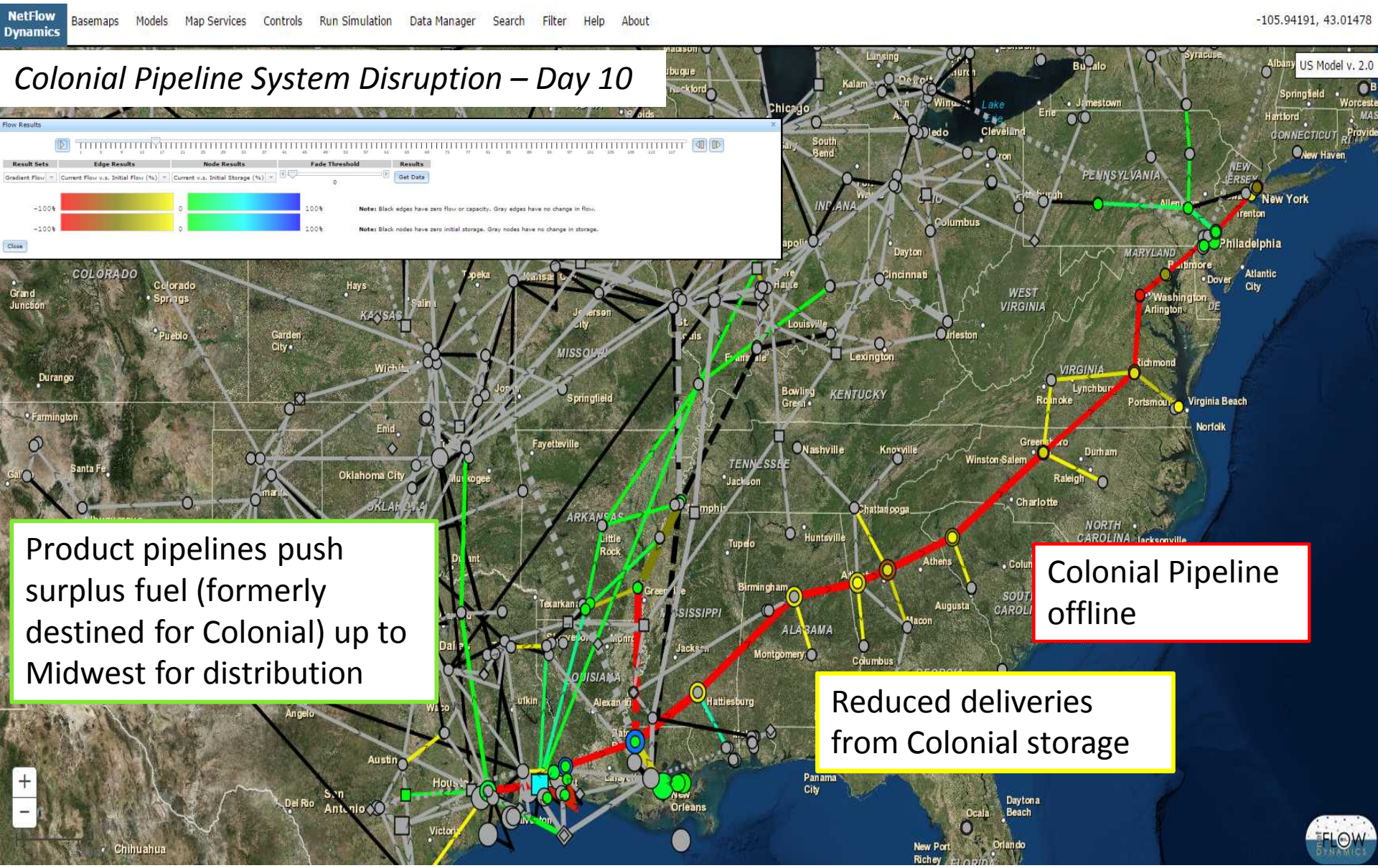
- Customers continue to be served

Scenario: Colonial Pipeline Disruption

- Colonial Pipeline crosses 13 states, delivering more than 100 million gallons/day of refined product from the Gulf Coast to the Northeast

- Simulated and analyzed the impacts of a 100% disruption of Colonial operations for 30 days

- Assumed that Colonial's many refined product storage terminals could deliver existing stored products to their customers


NetFlow Dynamics
Basemaps
Models
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Controls
Run Simulation
Data Manager
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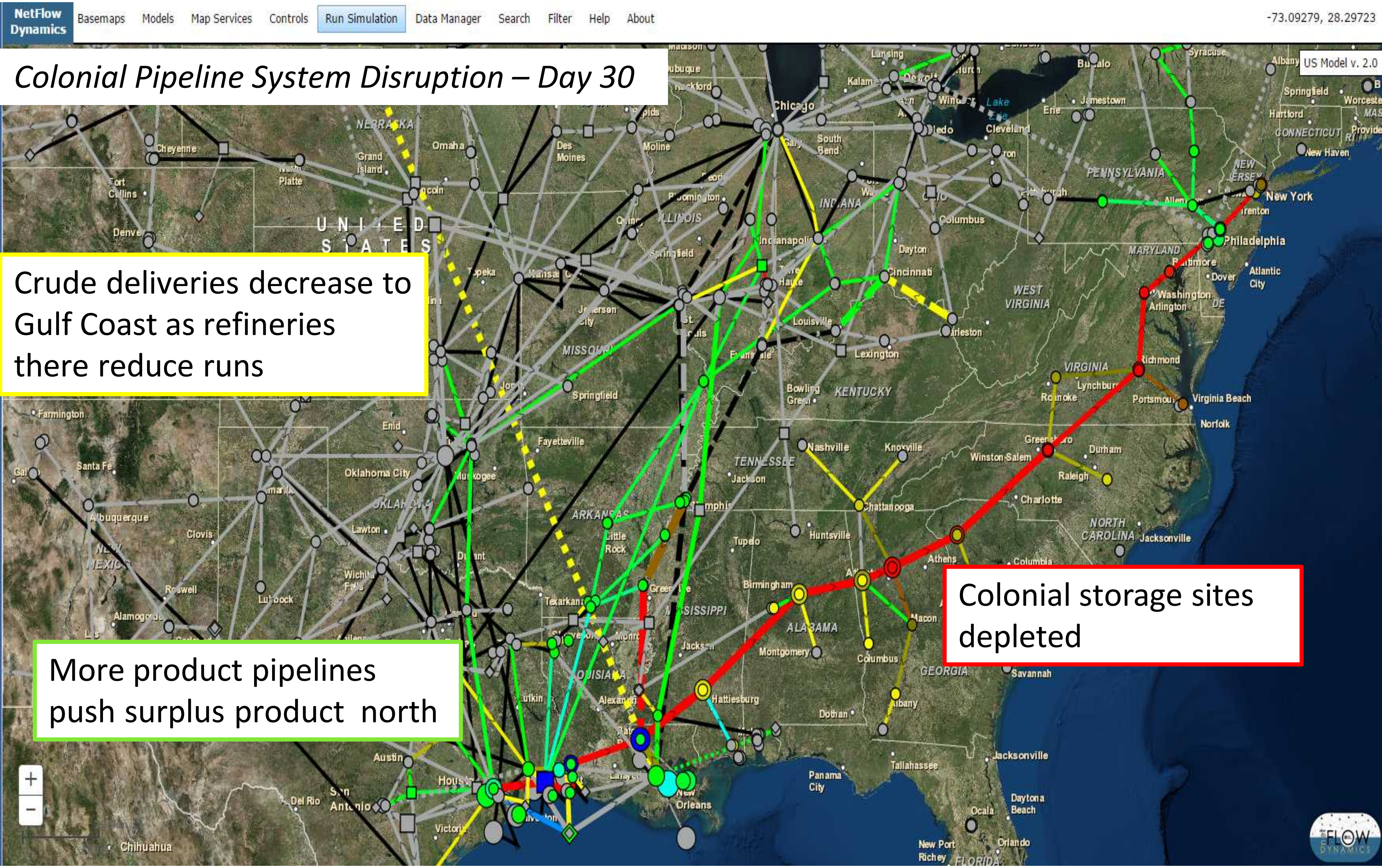
About
-105.94191, 43.01478
Colonial Pipeline System Disruption – Day 10
US Model v. 2.0
Product pipelines push surplus fuel (formerly destined for Colonial) up to Midwest for distribution
Colonial Pipeline offline
Reduced deliveries from Colonial storage

Colonial Pipeline System Disruption – Day 30



Crude deliveries decrease to Gulf Coast as refineries there reduce runs

More product pipelines push surplus product north

Colonial storage sites depleted

Real-time factors that will drive the analysis

Other likely system responses to the real world scenario must be considered in the final analysis, such as:

- Inflow of product into Midwest and shortfalls in the Mid-Atlantic and Northeast will likely result in increased movement of tanker trucks to the impacted areas
- Shipments of refined product to East Coast terminals are expected
- Smaller rail lines may augment movements of product from the Midwest and Gulf Coast to the Northeast
- Other supply- and demand-side market behaviors are likely to influence the scenario, including rationing, withdrawal from the Northeast Gasoline Supply Reserve, etc.