Price Integration in Competitive Markets with Capacitated Transportation Networks

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Are Gasoline Prices Integrated?

Prices are integrated if they respond to the same price shocks

- Typically answered using co-integration tests.
  - Does $p_1 = Ap_2 + B$?
- NA Fuel Markets “fairly” Co-integrated

Holmes et al. (2013), Paul et al. 2001

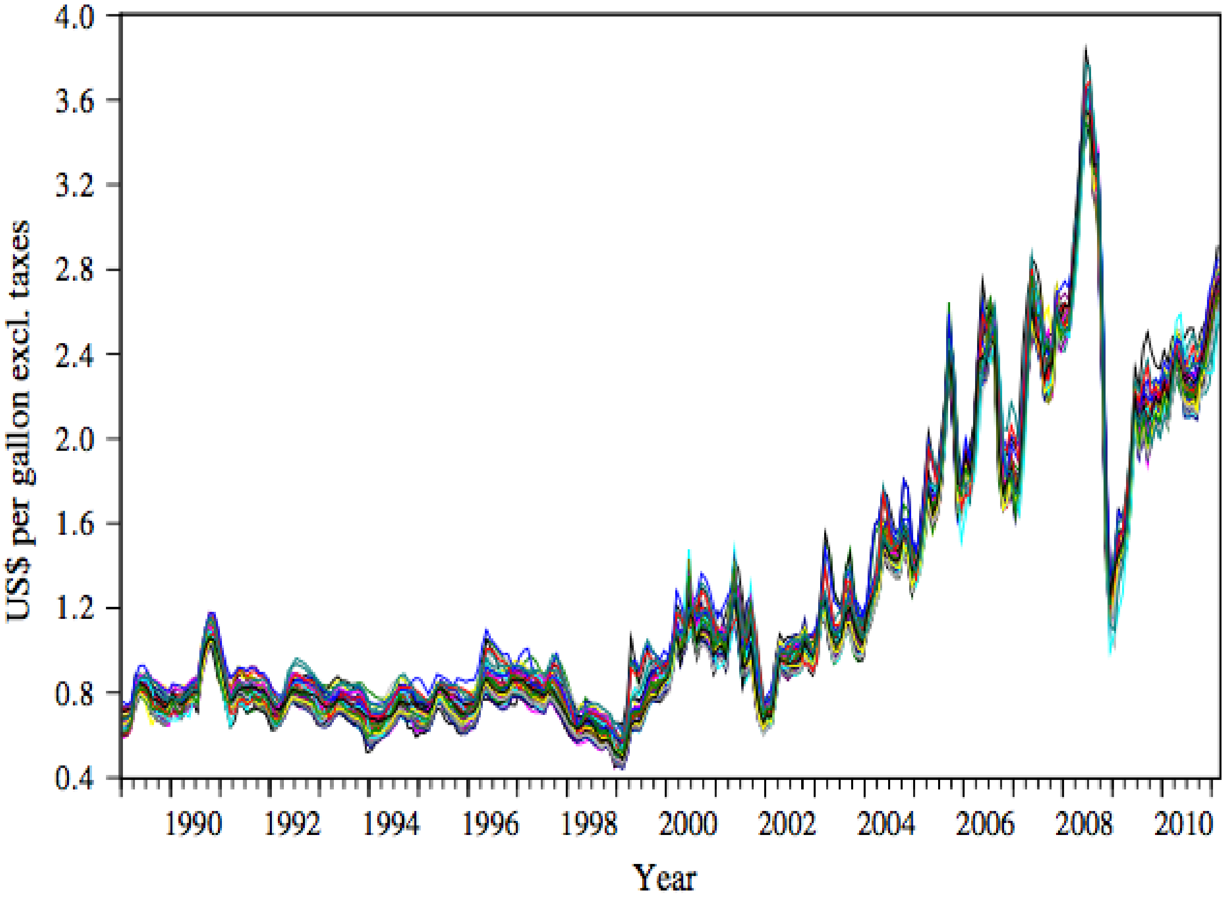
But do co-integration tests capture the whole picture?

Statistical co-integration tests

- Aggregate tests of stationarity over long periods of time
- Based on pair-wise tests

- **Not able to detect transient dis-integration**
- **Not able to detect submarkets**
  (McNew Fackler 97)

M.J. Holmes et al. / Energy Economics 36 (2013) 503–510

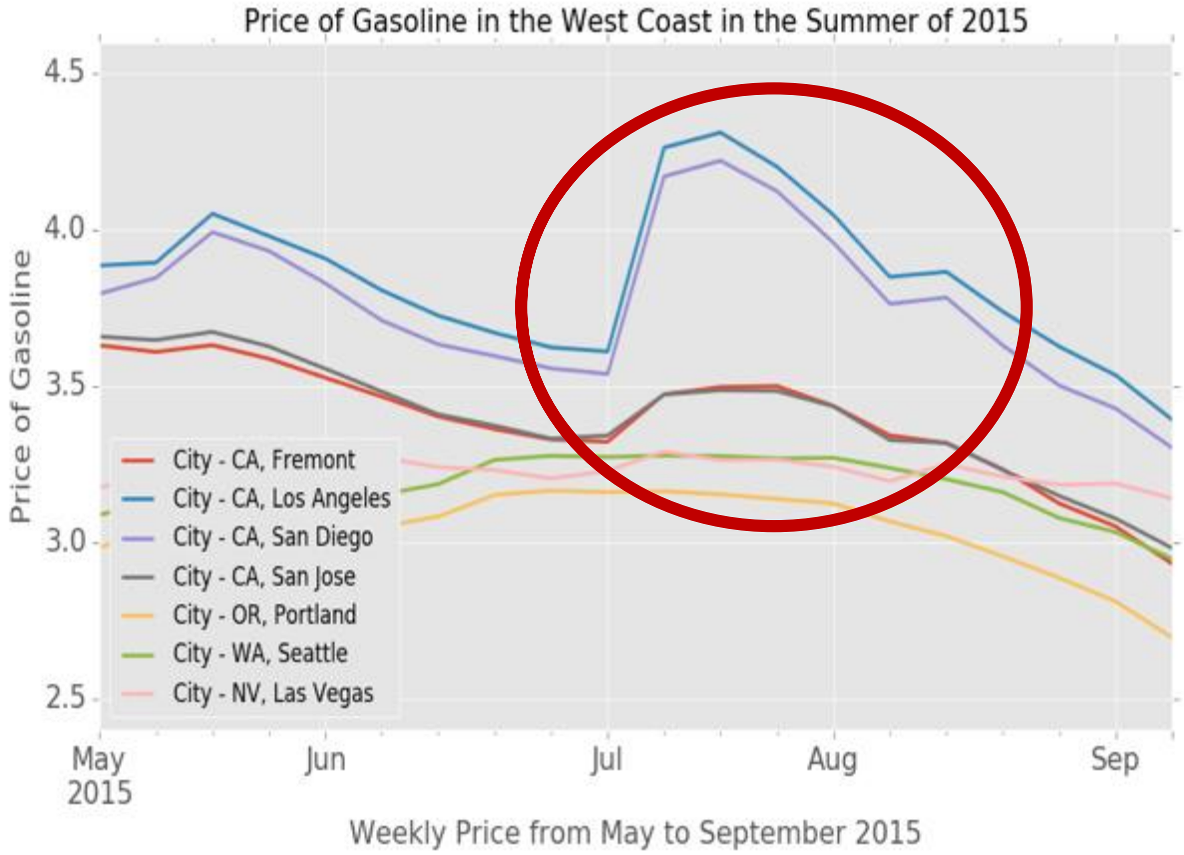


Co-integration and the Law of One Price

Zooming in: **transient failures of LOOP**

Arbitrage would fix this if:

- Same product
- Transparent pricing
- **Cheap and fast transportation**



Hypothesis:

- **Transient sub-markets can arise due to capacitated transportation**

Research questions

Theoretical:

- What are the implications of capacitated transportation to price integration?

Empirical:

- Can these results motivate algorithms to identify highly integrated sub-markets?
- Are transient submarkets identifiable in the North American gasoline market?

Aside: Overview of approach

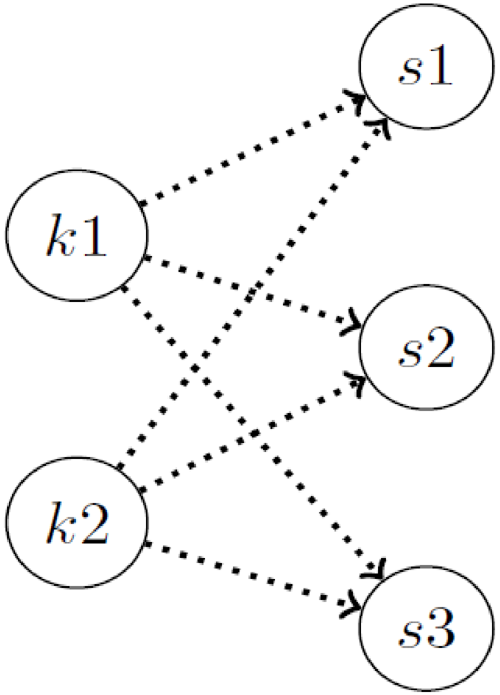
1. Concerned with markets where there is spatial variation in prices
   - Can we use pricing data to isolate the effect of capacity constraints on spatial variation?
2. Assume an optimal form to the market mechanism
   - Electricity markets: market facilitator (ISO) finds the “welfare maximizing” allocation
   - Gasoline (and other) markets
     Assumption of competitive markets: equilibrium == solution of optimal allocation problem
3. Determine data assumptions
   - Treat prices and allocation as partial dual and primal solutions
   - Allow demand and supply to vary over time
   - Fix the transportation network
4. Use optimality conditions to make inferences
   - Inverse optimization approach (Birge, Hortaçsu, Pavlin 2017)

Model: A Spatially Separated Market

Consider an idealized model of a spatially separated market for a single commodity

Uncapacitated markets: Samuelson 52, Takayama and Judge 64, McNew and Fackler 97

Capacitated energy market models Cremer et al. 03, Secomandi 2010, Gabriel et al. 05



- A market consists of a set of **production nodes** *K* and **demand nodes** *S*
  - Production node $k \in K$ produces b_k units at cost $\mathrm{W_k}(b_k)$
  - Demand node $s \in S$ consumers b_s units receiving welfare $\mathrm{W_s}(b_s)$
- Nodes are connected by a set of **capacitated transportation links** *E*
  - Flow over $(i, j) \in E$ is $f_{ij} \leq u_{ij}$ at cost $f_{ij}c_{ij}$

Market dynamics:

- **Demand/supply** functions may **change** every period
- **Network** structure remains **stable**
- At each period **prices and allocation** correspond to a **spatial price equilibrium**

Single Period: Spatial Price Equilibrium Model

SPE extends a competitive pricing equilibrium

- With diminishing marginal returns i.e. concave $W_s(b_s)$ convex $W_k(b_k)$
- **Allocation** optimizes the welfare maximization problem

$$\max_{f,b} \sum_{s} W_s(b_s) - \sum_{k} W_k(b_k) - \sum_{(i,j)} c_{ij} f_{ij}$$

$$S.T.$$

$$\sum_{(i,s)} f_{is} - b_s - \sum_{(s,j)} f_{sj} = 0 \quad \forall s \in S$$

$$\sum_{(i,k)} f_{ik} + b_k - \sum_{(k,j)} f_{k,j} = 0 \quad \forall k \in K$$

$$0 \le f_{ij} \le u_{ij}$$

$$b \ge 0$$

- Commodity **prices** λ_s, λ_k are locational and correspond to dual variables of flow balance constraints

Optimality/Equilibrium Conditions

Nodal prices

- λ_s, λ_k

ν_{ij} = shadow price of flow u.b.

Price differences

Driven by transportation costs

and a surcharge for congestion

$$
\begin{array}{ll}
\lambda_s = W_s'(b_s) + \alpha_s & \forall s \in S \\
\lambda_k = W_k'(b_k) - \alpha_k & \forall k \in K \\
\lambda_j - \lambda_i = c_{ij} - w_{ij} + \nu_{ij} & \forall (i,j) \in E \\
\alpha_n \geq 0 & \forall n \in N \\
w_{ij}, \nu_{ij} \geq 0 & \forall (i,j) \in E
\end{array}
$$

Analysis with costly transportation: The Neutral Band

A Neutral band is a range within which the **difference** between a pair of prices may deviate as a result of changes in demand and supply

- Characterized for neighbouring market locations resulting from transaction costs (e.g. Goodwin, Piggot 2001)
- Small range of neutral band ≅ higher price integration

Theorem – *network neutral band*

In the absence of active capacity constraints, the **network neutral band** between a pair of consumers *s,r* operating in a costly transportation network is defined by:

$$\min\{p^*_{ks} - p^*_{kr} | k \in \mathrm{K}\} \leq \lambda_s - \lambda_r \leq \max\{p^*_{ks} - p^*_{kr} | k \in \mathrm{K}\}$$

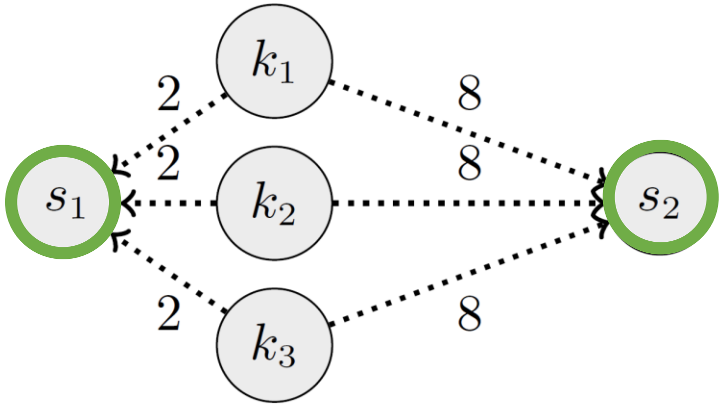
Where p^*_{ks} *is the shortest path between supplier* k *and consumer* s

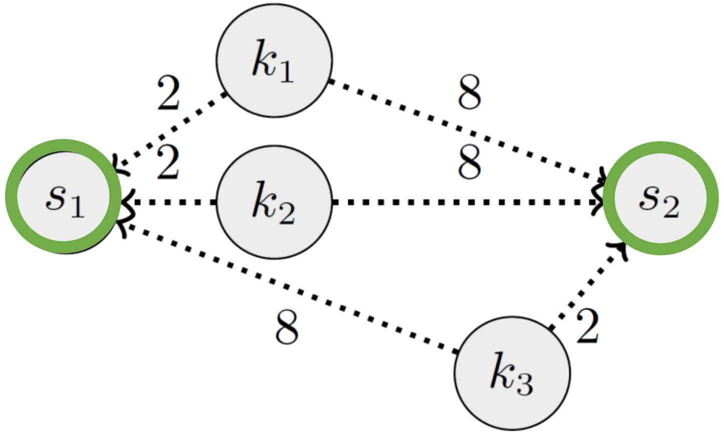
Analysis with Costly Transportation: Example of Network Neutral Bands

Network neutral band

$$\min\{p_{ks}^* - p_{kr}^* | k \in \mathrm{K}\} \leq \lambda_s - \lambda_r \leq \max\{p_{ks}^* - p_{kr}^* | k \in \mathrm{K}\}$$

Neutral band = 0





Neutral band = 6

Analysis with Costly Transportation and Capacity Constraints: The congestion surcharge

The congestion surcharge w_s is the amount by which the equilibrium cost exceeds the uncapacitated delivery cost

$$w_s = \max\{\lambda_s - \lambda_k - p_{ks}^* | k \in K\}$$

Theorem – *neutral band shifted by congestion surcharge*

The price difference between a pair of consumers r and s is bounded by:

$$\min\{p_{ks}^* - p_{kr}^* | k \in \mathrm{K}\} + w_s - w_r \leq \lambda_s - \lambda_r \leq \max\{p_{ks}^* - p_{kr}^* | k \in \mathrm{K}\} + w_s - w_r$$

Where $\mathrm{p}_{\mathrm{ks}}^*$ is the shortest path between supplier k and consumer s

Analysis with Costly Transportation and Capacity Constraints: A bottleneck link may not evenly affect all downstream consumers

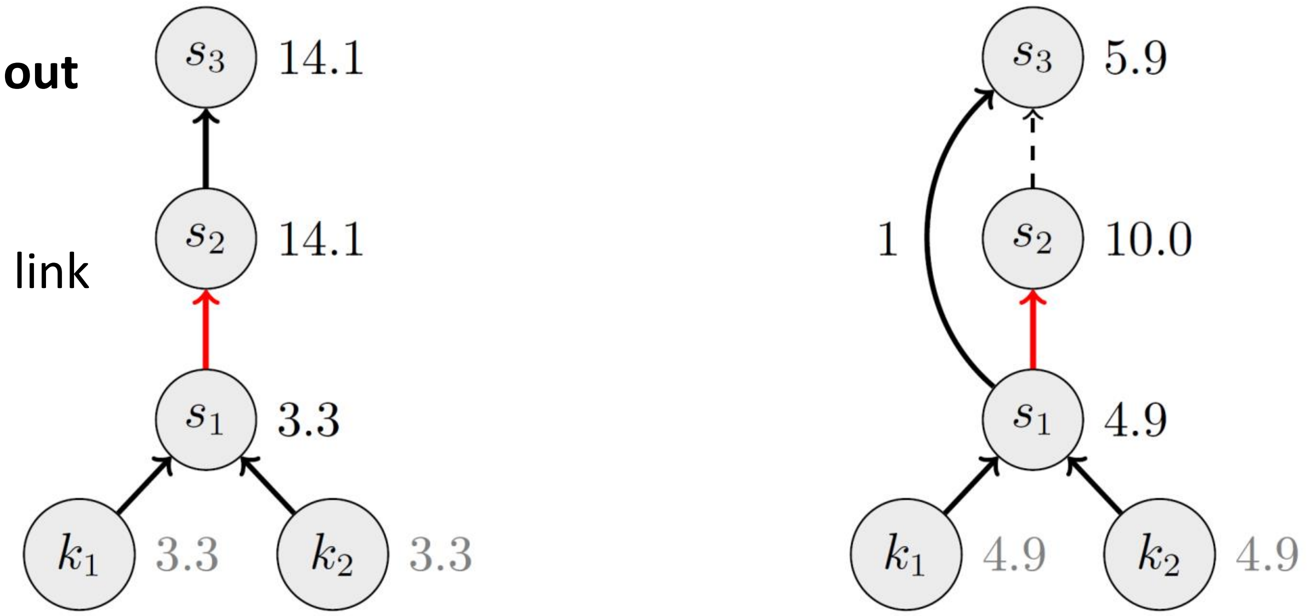
Congestion surcharge w_s from a single congested link e

- w_s is less than or equal to the shadow price ν_e
- $w_s \in [\min\{\nu_e, \min(\delta_{ks}(e))\}, \min\{\nu_e, \max(\delta_{ks}(e))\}]$
  - Rerouting cost $\delta_{ks}(e)$ is the additional cost of routing from k to s without link e

Equilibrium prices with and without an additional link

Red link is at capacity

Links are costless except the new link



Analysis with Costly Transportation and Capacity Constraints: Price Decomposition

Theorem

Assume stable market structure, set of sample market realizations T, price λ_n^t of node *n* may be decomposed as follows:

$$\lambda_n^t = \eta^t + \rho_n + \epsilon_n^t + w_n^t,$$

- Supply cost in green
  - η^t — node invariant "market price"
  - ρ_n — time invariant "transportation cost"
- Neutral band variation in blue
  - $\epsilon_n^t \in [-h, h]$ — variation within the uncongested neutral band
- Congestion surcharge in red

Analysis of Equilibrium With Capacity Constraints: Implications of Price Decomposition

Implications for Co-Integration

Without congestion:

- Prices are integrated if $h = 0$, otherwise they may vary within a neutral band

With congestion:

- Variation in congestion surcharge may decrease co-integration

Implication for Market Structure

Congestion-Induced Submarkets

- A Congestion-Induced Submarket S_e is a set of nodes with a non-zero congestion component for a particular link e

Implications for Identification of Price Components

- Difficult to disentangle ϵ_n^t and w_n^t
- Overcome by assuming $w_n^t = 0$ most of the time

Bringing it to data: Surcharge Estimation Model (SEM)

- Assume stable market structure (N, E, c, u) over samples *T*
- Demand and supply vary (W_k, W_s)

- *Utilize price decomposition*
- Search for congestion surcharge:
- Minimizing neutral band

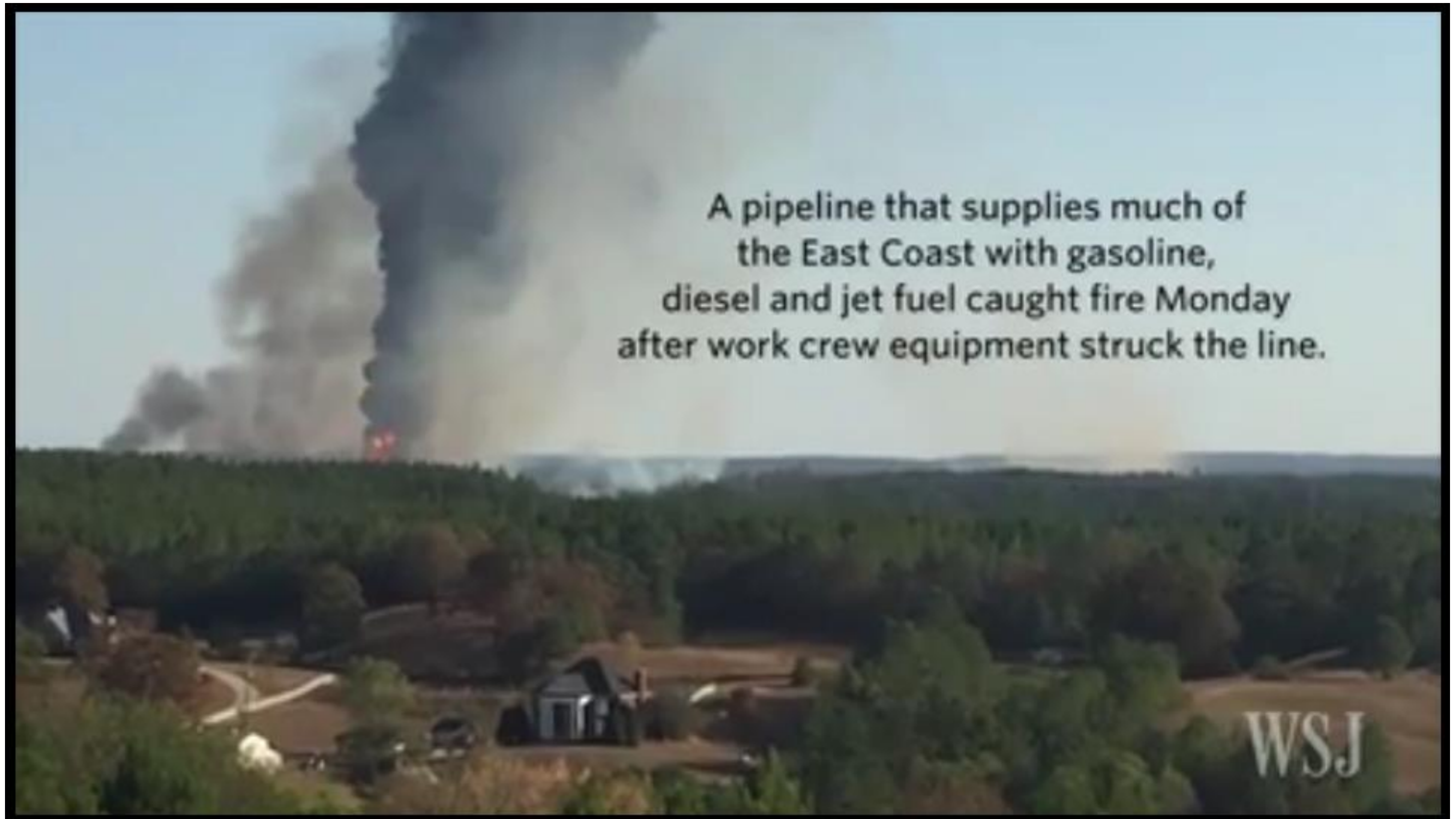
- Implemented as MIP
- Parameters:
  - Number of submarkets
  - Maximum time submarkets are active (parameter β)

$$\begin{aligned}
\underset{\eta^t, \rho_s, \epsilon_s^t, w_s^t, \alpha_s}{\text{minimize}} \quad & \sum_{s \in \mathcal{S}} \alpha_s \\
\text{subject to} \quad & \lambda_s^t = \eta^t + \rho_s + \epsilon_s^t + w_s^t, \quad \forall s \in \mathcal{S}, t \in \mathcal{T}, \\
& |\epsilon_s^t| \le \alpha_s, \quad \forall s \in \mathcal{S}, t \in \mathcal{T}, \\
& w_s^t \in \mathcal{W}(\theta)^+, \ \forall s \in \mathcal{S}, t \in \mathcal{T}.
\end{aligned}$$

Bringing it to data: Colonial Pipeline Disruption Case Study

- Colonial pipeline serves gasoline from Gulf to Eastern US
- Disruption on September 9th 2016

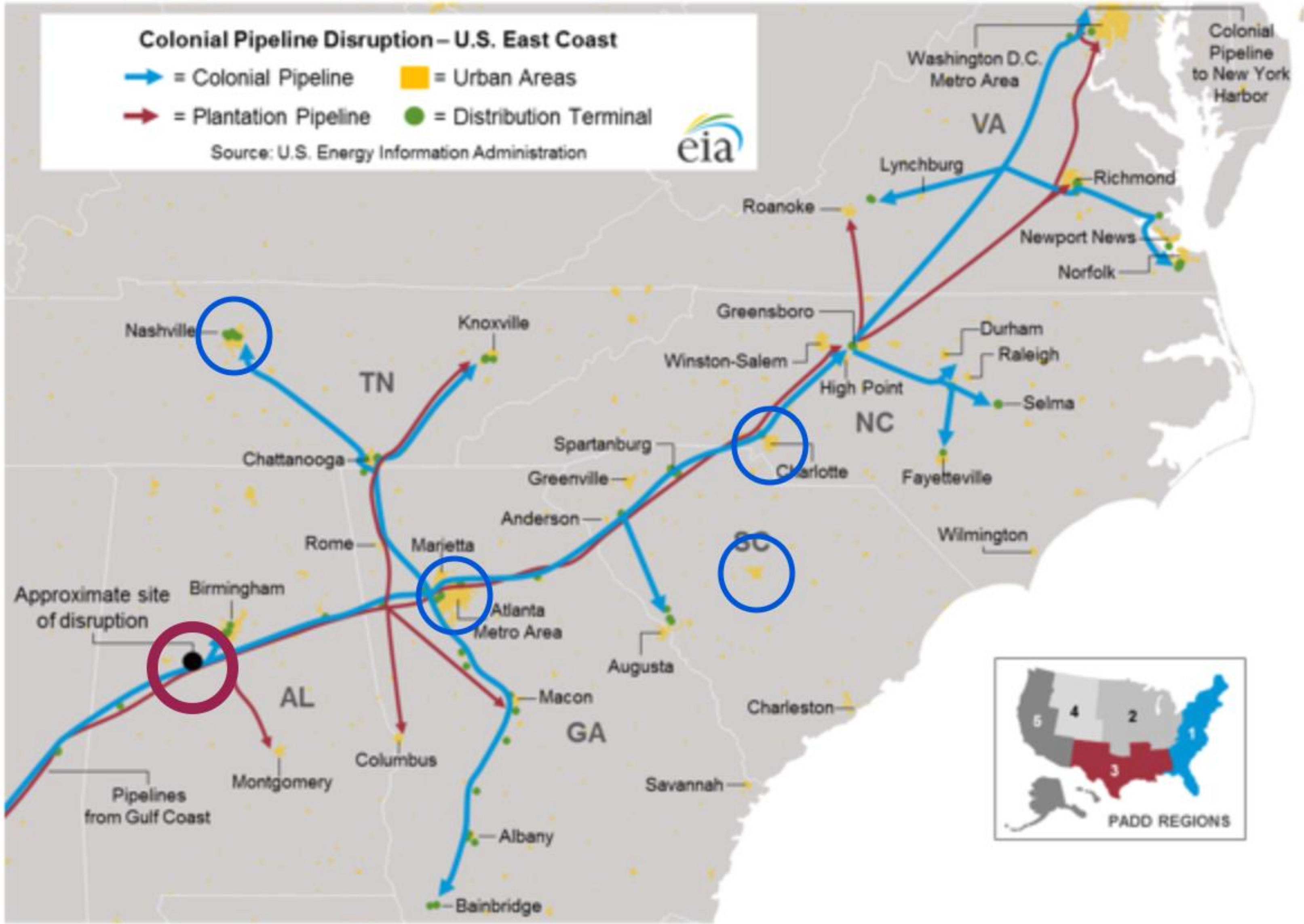
- Data
    - Jan-Dec 2016
    - Average daily prices at 18 locations



Colonial Pipeline Fire Severs Fuel Artery in Alabama

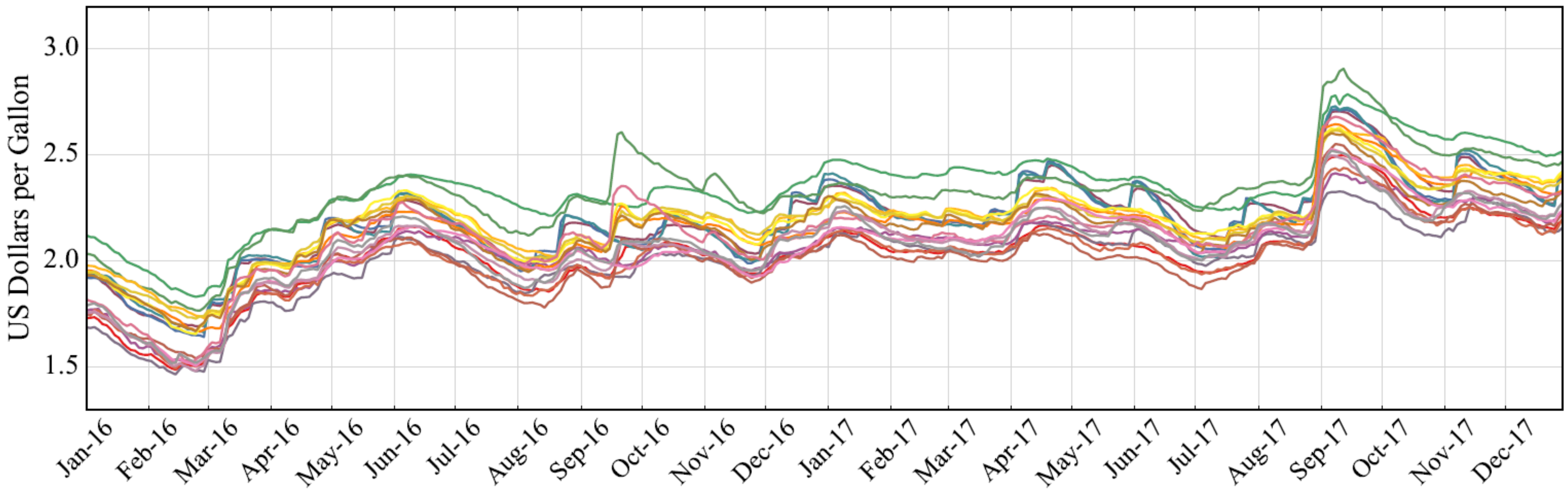
A pipeline that supplies much of the East Coast with gasoline, diesel and jet fuel caught fire Monday after work crew equipment struck the line. Photo: Facebook/April Ruth Everett

Colonial Pipeline Disruption Case Study

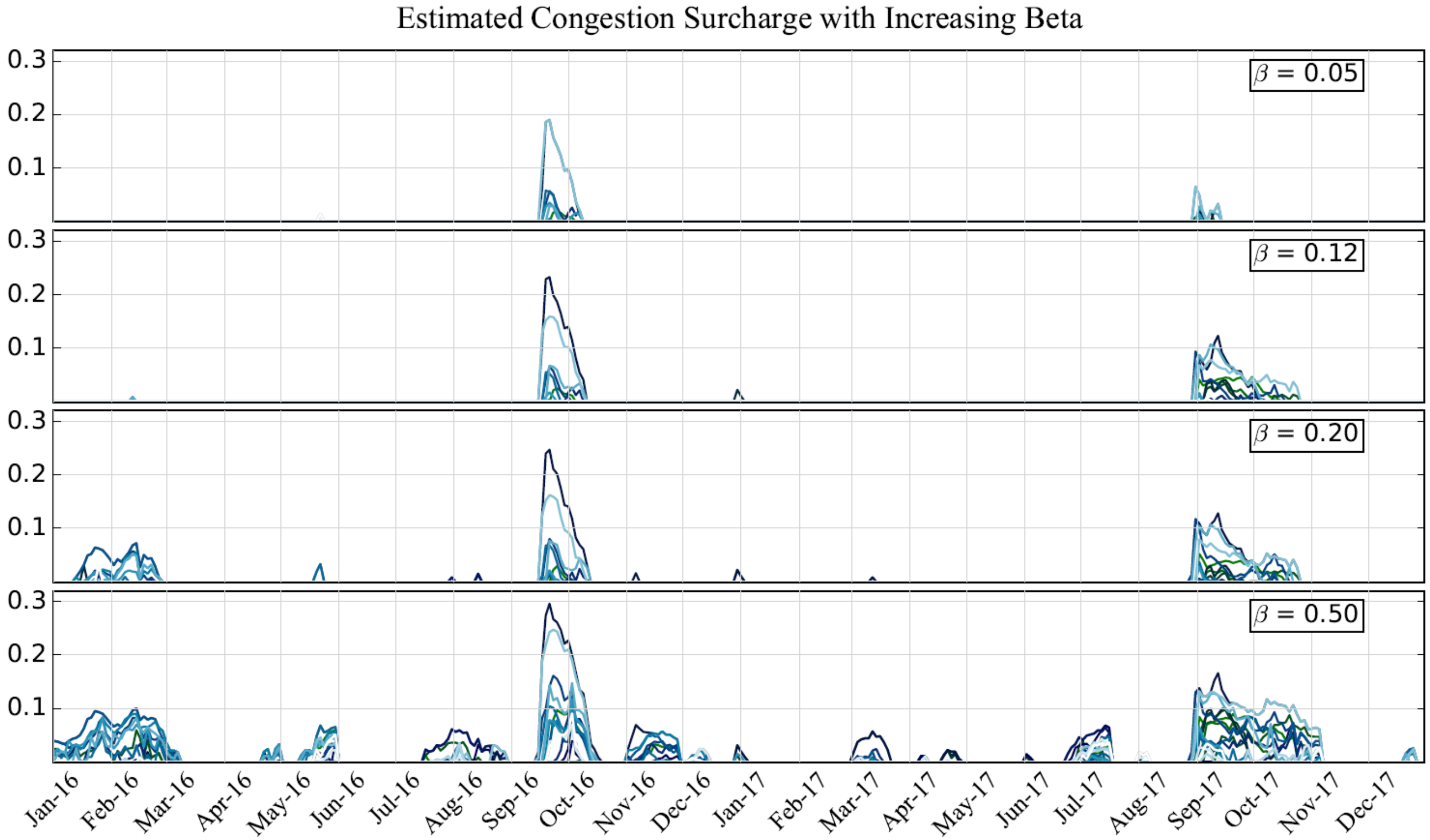


Colonial Pipeline Disruption Case Study
Prices in market footprint

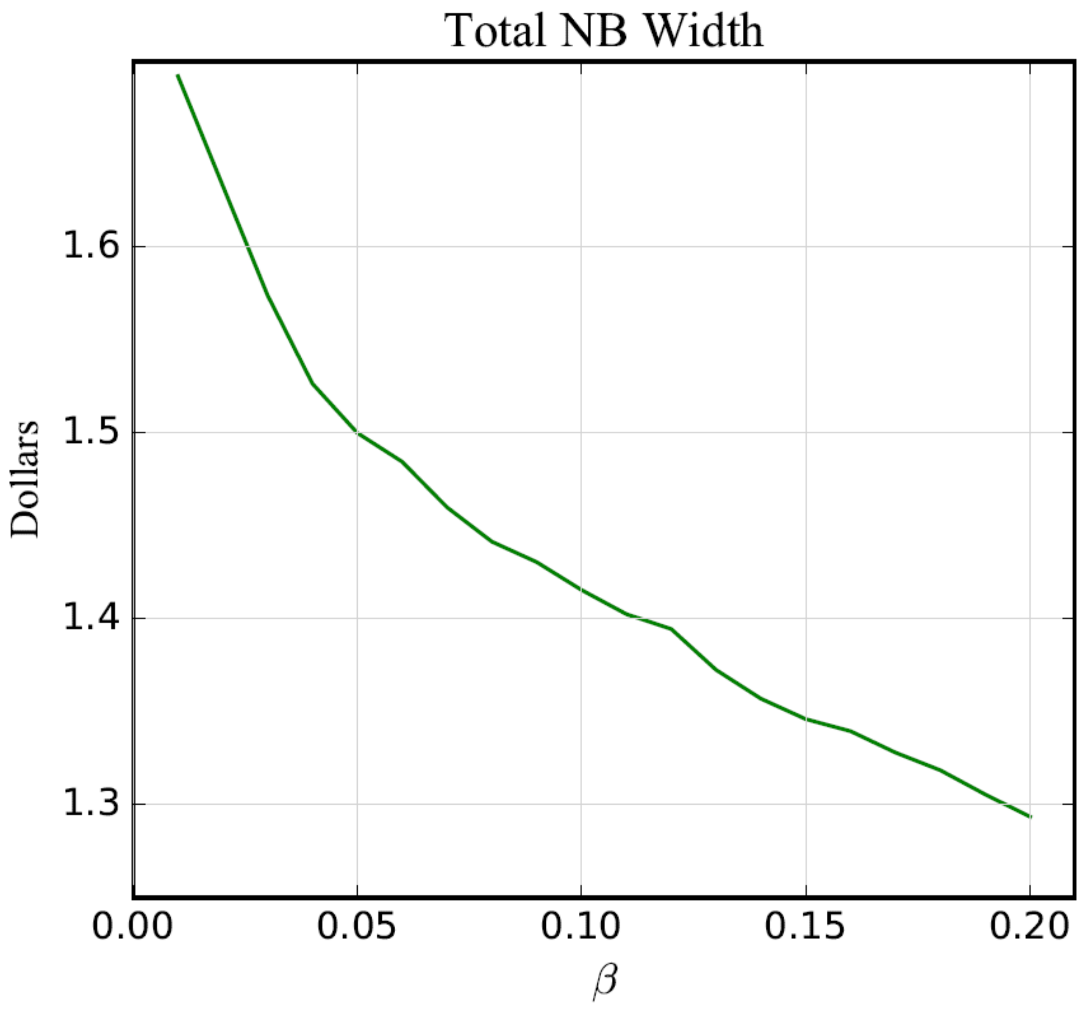
- Retail gasoline prices at 20 cities in Southeastern US

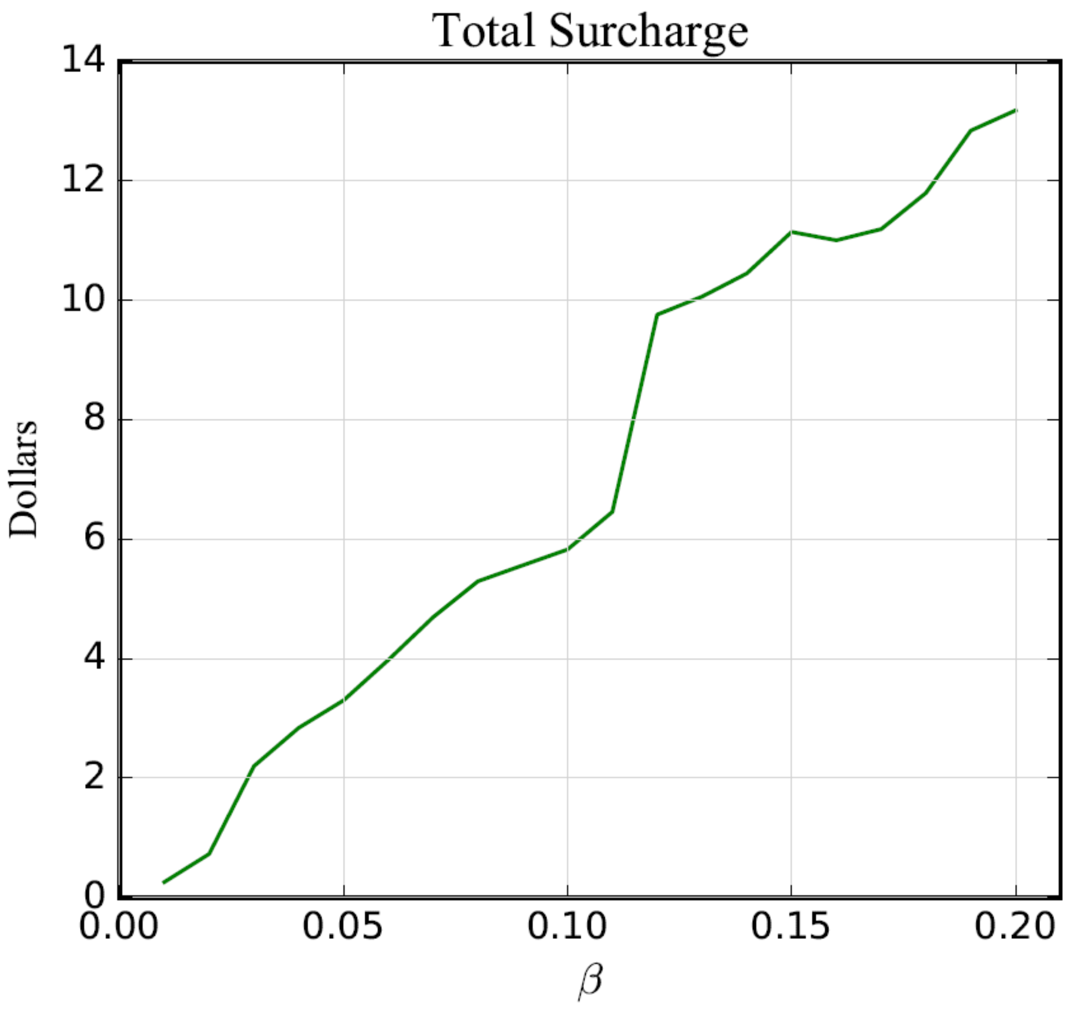


Colonial Pipeline Disruption Case Study: Consistent estimates of periods with high surcharge

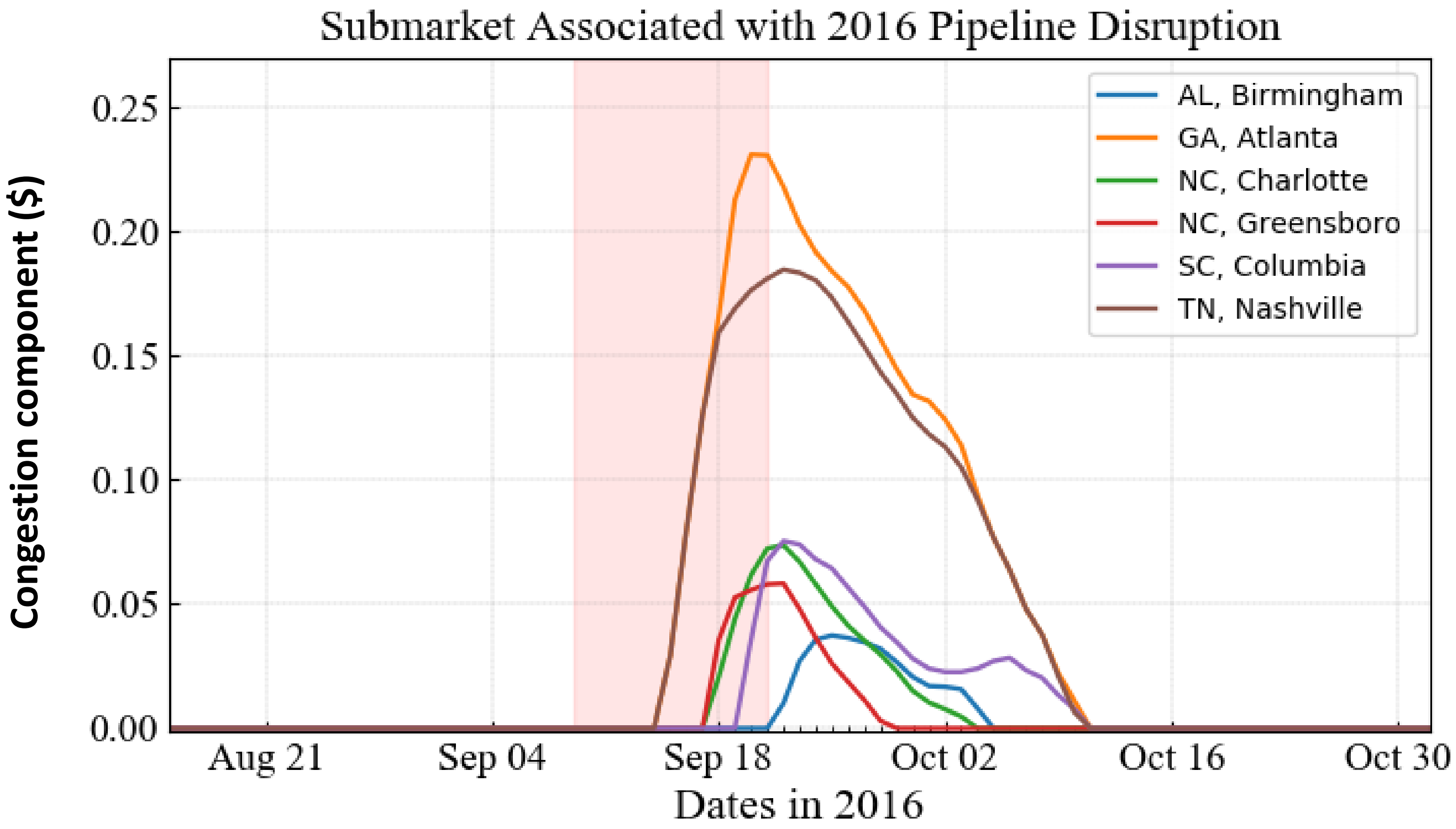


Colonial Pipeline Disruption Case Study: Difficult at present to determine "correct" β

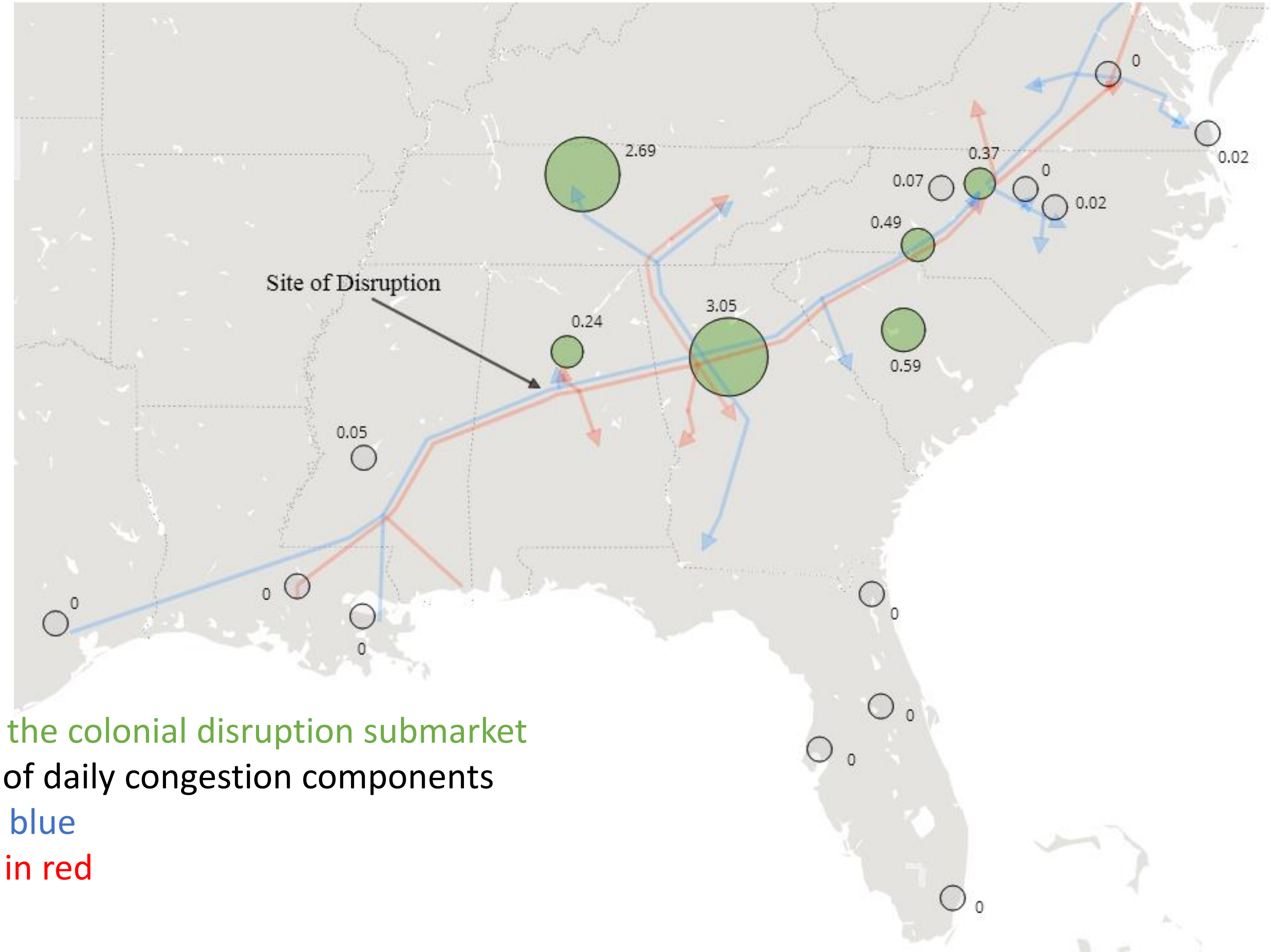




Colonial Pipeline Disruption Case Study
Congestion component of submarket



Colonial Pipeline Disruption Case Study
Pipeline map and discovered submarket



Green nodes are in the colonial disruption submarket

Size of node = sum of daily congestion components

Colonial pipeline in blue

Plantation pipeline in red

Conclusions

- Capacitated spatial price equilibrium model of energy markets
  - Characterize neutral band and congestion surcharge on network
  - Price decomposition
- Implications for market price integration
  - ϵ_n^t: Neutral band bounded by transportation network structure
  - w_s: Congestion can lead to transient separation of regional prices
- SEM Algorithm:
  - Identifying nodes consistent with pipeline disruption
  - Identifying magnitude of congestion related price changes
- Ongoing:
  - Identify appropriate parameter levels to differentiate between congestion and neutral band variation
  - perform larger scale empirical investigations