Causal Analysis of En Route Flight Inefficiency in the US

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12th US/ Europe Air Traffic Management Research and Development Seminar
Outline

• Introduction
• Data Sources and Preliminary Statistical Analysis
• Identifying Nominal Trajectories
• Mapping Causal Factors to Trajectories
• Causal Analysis of Flight Inefficiency
• Conclusions
Motivations

- FAA and Eurocontrol have published metrics to evaluate flight en route inefficiency
- Limited understanding of the causal factors behind the inefficiency
- For arrival delay we have:

Sources: http://www.transtats.bts.gov/ot_delay/ot_delaycause1.asp?type=5&pn=1
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Motivations

• FAA and Eurocontrol have published metrics to evaluate flight en route inefficiency
• Limited understanding of the causal factors behind the inefficiency
• For arrival delay we have:
• What about en route inefficiency?

Sources:
http://www.transtats.bts.gov/ot_delay/ot_delaycause1.asp?type=5&pn=1
Project Goals

• For selected metrics, identify reasons for inefficiency
  – Convective weather
  – Traffic management initiatives
  – Winds
  – NAS route structure

• Eventually allow comparison with other ANSPs such as Eurocontrol
Approach

• Inefficiency is measured by the ground distance of a flight trajectory relative to the great circle distance

• Two types of causal mechanisms
  – Cluster assignment (“Between Cluster Effect”)
    • While every flight route is unique, trajectories between an airport pair form natural clusters, which can be represented by nominal routes
    • Inefficiency is strongly affected by which cluster a flight belongs to
    • Causal factors influence cluster assignment
  – Intra-cluster inefficiency variation (“Within Cluster Effect”)
    • Flights belonging to the same cluster have varying levels of inefficiency
    • Causal factors contribute to intra-cluster inefficiency variation
Example for a Single Flight

Between cluster effect

Within cluster effect
Overview

• Apply trajectory clustering algorithm to raw trajectory data for selected OD pairs to identify clusters and construct nominal routes

• Map nominal routes with convective weather, wind and Miles-in-Trail (MIT) data

• Estimate and apply statistical models to quantify the contributions of convection, wind and MIT
  – Cluster assignment model
  – Trajectory inefficiency model
Defining En Route Inefficiency

\[
\text{Inefficiency} = \frac{A - H}{H}
\]

- \( A \): Actual flown distance from exit point to entry point;
- \( D \): Great circle distance between terminal entry and exit point;
- \( H \): Achieved distance — “projection” of \( D \) onto great circle route between departure and arrival airport

Sources:
Comments on En Route Inefficiency Metric

• Metric assumes that the ideal route is great circle
• Sources of inefficiency according to the metric include
  – Excess distance between actual exit (40 nm arc crossing) and entry (100 nm arc crossing) points compared to great circle
  – Suboptimal location of the crossing points relative to great circle
• The metric ignores winds, which may make the ideal route different from the great circle and thus can be the causes of inefficiency as we define it
• In this sense “inefficiency” is just a name for ground track distance in excess of the great circle, even when the excess distance results in a more economical route
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Data Sources

• Traffic Flow Management System (TFMS)
  – Flight Event Data
    • Flight level records, including en route inefficiency, aircraft type and etc.
  – Flight Track Data
    • 60-second update
    • Currently we focus on six pairs: IAH ↔ BOS, JFK ↔ LAX and FLL ↔ JFK

• National Traffic Management Log (NTML)
  – Miles-In-Trail (MIT) Data

• Quality Controlled Local Climatological Data (QCLCD)
  – Hourly summary of convective weather (ground-based)

• North American Mesoscale (NAM) data
  – Hourly wind forecast data
  – $0.1^\circ \times 0.1^\circ \times 25 \text{ mbar}$
En Route Inefficiency vs Great Circle Distance

En Route Inefficiency decreases with OD great circle distance

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<tr>
<td>0 - 200 NM</td>
<td>200 - 400 NM</td>
<td>400 - 600 NM</td>
<td>600 - 800 NM</td>
<td>800 - 1000 NM</td>
<td>&gt; 1000 NM</td>
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<td>5%</td>
<td>4%</td>
<td>3%</td>
<td>2%</td>
<td>1%</td>
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</tbody>
</table>
Inefficiencies for Representative Airport Pairs (2013)

ATL to ORD (6.86%)

ATL to LAX (1.28%)

Horizontal inefficiency for flights from ATL to ORD
Points with inefficiency larger than 20% are not shown.

Horizontal inefficiency for flights from ATL to LAX
Points with inefficiency larger than 20% are not shown.
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Actual Trajectories: IAH $\rightarrow$ BOS (2013)

- Trajectories from IAH to BOS in 2013.
- Trajectories (red curves) show obvious clustering in the airspace.
- Not all trajectories are following the preferred routes.
Finding Nominal Routes

• We define *Nominal Routes* as the set of representative trajectories for a given OD pair
• Nominal routes help us better understand the NAS route structure
• Finding nominal routes allows time-dependent variables such as TMIs and convective weather to be calculated in a more efficient manner
• We estimate the *hypothetical* exposure of a particular flight to convection, MIT restrictions, and wind, if it had used any one of the nominal routes, assuming its actual departure time.
Clustering Algorithms

• **Step 0: Trajectory Cleaning**
  – Exclude both spatial and temporal discontinuity trajectories;
  – Exclude trajectories starting/ending outside terminal areas.

• **Step 1: Trajectory resampling**
  – Get trajectories with equal numbers of points;
  – Linear Interpolation (with respect to distance flown);
  – Each trajectory is represented by 100 points.

• **Step 2: Principal Component Analysis (PCA)**
  – Dimension reduction & Trajectory smoothing;
  – First five components can capture more than 90% of variations.

• **Step 3: DBSCAN Clustering**
  – Trajectory classifications;
  – DBSCAN algorithm is applied to the PCA components to get representative clusters.
IAH $\rightarrow$ BOS (1679 of original 1817)

Black curves are classified as outliers
White Solid curves are Nominal Routes

DBSCAN applied to PCA mode matrix

Boxplot of Enroute Inefficiency for Different Clusters

Average En Route Inefficiencies

Weights
JFK ➔ FLL (4043 of original 4273)

**DBSCAN applied to PCA mode matrix**

**Black curves are classified as outliers**
**White Solid curves are Nominal Routes**

**Boxplot of Enroute Inefficiency for Different Clusters**

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Inefficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.85%</td>
<td>11.59%</td>
</tr>
<tr>
<td>8.05%</td>
<td>12.28%</td>
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<tr>
<td>15.09%</td>
<td>10.00%</td>
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<tr>
<td>84.14%</td>
<td>1.11%</td>
</tr>
<tr>
<td>9.57%</td>
<td>2.05%</td>
</tr>
<tr>
<td>0.64%</td>
<td>2.47%</td>
</tr>
</tbody>
</table>

**Average En Route Inefficiencies**

**Weights**
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Mapping Framework

Replace the departure time and subsequent time stamps

Flight $i$ → Departure time → Convection → Wind → MIT

Nominal Route 1 → Nominal Route 1’ → Route 1’ Features
Nominal Route 2 → Nominal Route 2’ → Route 2’ Features
... → ... → ...
Nominal Route $N$ → Nominal Route $N’$ → Route $N’$ Features
Algorithm – Convection

- Red curve: nominal route
- White dots: track points
- Yellow boxes: original time stamps for track points
- Green boxes: adjusted time stamps
- Numbers in yellow dots: average weather exposure within the ARTCC in a 2-hour time interval;
- Convective weather exposure along the route:
  - \( (5+6+3+7+2+9)/6 = 5.33\% \)
Algorithm – Wind

Wind Field Diagram (km/h) @ 200 mbar (~38,000 ft.); 01/01/2013 19:00 Zulu

39 isobaric pressure levels
For each level: 614 x 428

Trajectory at 200 mbar
Trajectory not at 200 mbar

Trajectory not at 200 mbar
Trajectory at 200 mbar
Algorithm – Wind

Wind Field Diagram (km/h) @ 200 mbar (~ 38,000 ft.)
01/01/2013 19:00 Zulu

- For each track point, find the nearest 3d reference point of the wind data file
- Assign the wind speed (vertical and horizontal) of the nearest grid to the track point
- Calculate the headwind/tailwind speed for each track point, based on heading derived from previous track point
A Miles-in-Trail (MIT) restriction specifies the minimum distance required between aircraft departing an airport, over a fix, thru a sector, or on a specific route, and is a temporary measure used to apportion traffic into a manageable flow.

In the example, ZDV is trying to protect ZLC by providing a MIT to separate aircrafts through the Navaid ONL.

Sources:
https://www.nbaa.org/ops/airspace/TFM/tools/mit.php
Algorithm – MIT

- A given nominal route, with adjusted departure time, is assumed to be affected by an MIT if:
  - It crosses the MIT facilities
  - It crosses the NAS element or follows the jet route to which the MIT applies
  - Its crossing time is within the time the MIT is in effect
  - Its crossing altitude is covered by the restriction
Metrics

• Convective weather
  – Average percentage of weather stations along the nominal route reporting weather phenomena of each of the three types – thunderstorm, rain and squalls
  – Range: 0 (no convective weather along route) – 1 (convective weather at every weather station along route)

• Wind
  – Wind distance: Difference between great circle distance and the summation of the product of airspeed and time along the nominal route, where the airspeed is calculated by summing the ground speed and the headwind/tailwind speed
  – Range (for IAH → BOS): 1021 nmi. – 1564 nmi.

• MIT
  – Summation of the MIT stringency imposed by all MIT restrictions along the nominal route, where MIT stringency is defined as the product of MIT value (in miles) and MIT duration (in hours)
  – Range (for IAH → BOS): 0 – 2800 mi. x hr.
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Impact of Causal Factors on Flight En Route Inefficiency

- **Objective:** Quantify contributions of different causal factors to flight inefficiency
- **Causal factors to be considered**
  - Weather
  - Route structure
  - MIT
  - Wind
- **Causal mechanisms**
  - Between cluster effect (Strategic route choices)
  - Within cluster effect (Tactical reroutes and maneuvers)
Framework

Flight $i$ → Departure time → Busy hour indicator

Weather exposure/wind/MIT on nominal routes → Composite weather exposure/MIT → Route inefficiency (Linear model) → Route structure and seasonal effects

Probabilistic assignment of nominal routes (Route choice model) → Predicted inefficiency under actual conditions

Weighted Average → Between cluster effect → Within cluster effect
Weather Contribution

- **Flight \( i \)**
- **Departure time**
- **Busy hour indicator**

**Weather exposure/wind/MIT on nominal routes**

**Weighted Average**

**Composite weather exposure/MIT**

**Route inefficiency (Linear model)**

**Probabilistic assignment of nominal routes** (Route choice model)

**Between cluster effect**

**Predicted inefficiency if no weather exposure**

**Within cluster effect**

**Route structure and seasonal effects**

**Predicted inefficiency under actual conditions**
- Predicted inefficiency if no weather exposure
- Weather contribution to inefficiency
Wind Contribution

Flights $i$ → Departure time → Busy hour indicator

Weather exposure/wind/MIT on nominal routes

Probabilistic assignment of nominal routes (Route choice model)

Weighted Average

Composite weather exposure/MIT

Between cluster effect

Predicted inefficiency if no wind

Route inefficiency (Linear model)

Within cluster effect

Route structure and seasonal effects

Predicted inefficiency under actual conditions

- Predicted inefficiency if no wind

Wind contribution to inefficiency
MIT Contribution

- Flight \( i \) → Departure time
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- Weather exposure/wind/MIT on nominal routes
  - Weighted Average
- Composite weather exposure/MIT
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  - Between cluster effect
- Predicted inefficiency if no MIT
  - Within cluster effect
- Predicted inefficiency under actual conditions
  - Predicted inefficiency if no MIT
  - MIT contribution to inefficiency
Framework

Flight \(i\) → Departure time → Weather exposure/wind/MIT on nominal routes → Probabilistic assignment of nominal routes (Route choice model)

- Busy hour indicator
- Composite weather exposure/MIT
- Route inefficiency (Linear model)
- Route structure and seasonal effects
- Predicted Inefficiency
Route Choice Model

- Model Specification

\[ V_0 = ASC_0 + \beta_1 \cdot TS_0 + \beta_2 \cdot R + \beta_3 \cdot SQ_0 + \beta_4 \cdot ICE_0 + \beta_5 \cdot MIT_0 + \beta_5 \cdot WD_0 + \beta_{7,0} \cdot Season + \beta_{8,0} \cdot MF \]

... 

\[ V_i = ASC_i + \beta_1 \cdot TS_i + \beta_2 \cdot R_i + \beta_3 \cdot SQ_i + \beta_4 \cdot ICE_i + \beta_5 \cdot MIT_i + \beta_5 \cdot WD_i + \beta_{7,i} \cdot Season + \beta_{8,i} \cdot MF \]

... 

\[ V_N = 0 + \beta_1 \cdot TS_N + \beta_2 \cdot R_N + \beta_3 \cdot SQ_N + \beta_4 \cdot ICE_N + \beta_5 \cdot MIT_N + \beta_5 \cdot WD_N \]

- Notation

- \( V_i \) represents the deterministic utility for the \( i^{th} \) alternative (nominal route);
- \( V_N \) represents the deterministic utility for OUTLIER cluster;
- \( Season \): Seasonal fixed effects, 3 dummy variables; Winter: Dec – Feb, Spring: Mar – Apr, Summer: May – Aug, Fall: Sep – Nov;
- \( TS \): Thunderstorm exposure;
- \( R \): Rain exposure;
- \( SQ \): Squall exposure;
- \( MIT \): MIT stringency;
- \( WD \): wind distance
Estimation Results

• Probability for flight $i$ to choose nominal route $k$, given causal factor variables $F_x$ and other control variables $X$: 
  \[ P(Y_i = k | F_x, X) = \frac{e^{V_k}}{\sum_{j=1}^{K} e^{V_j}} \]

• The estimation results indicate that thunderstorm, rain, wind distance and MIT appear to be the most significant factors that influence the strategic routing.

<table>
<thead>
<tr>
<th>Var.</th>
<th>IAH BOS</th>
<th>BOS IAH</th>
<th>FLL JFK</th>
<th>JFK FLL</th>
<th>JFK LAX</th>
<th>LAX JFK</th>
</tr>
</thead>
<tbody>
<tr>
<td>$TS$</td>
<td>-31.52*** (4.64)</td>
<td>-43.10**** (5.00)</td>
<td>-17.92*** (3.12)</td>
<td>-9.92**** (3.078)</td>
<td>-22.72**** (2.38)</td>
<td>-39.64**** (2.89)</td>
</tr>
<tr>
<td>$R$</td>
<td>-9.25*** (1.36)</td>
<td>-11.04*** (1.41)</td>
<td>-3.92*** (1.49)</td>
<td>-6.67*** (1.15)</td>
<td>-5.86*** (0.71)</td>
<td>-5.62*** (0.68)</td>
</tr>
<tr>
<td>$SQ$</td>
<td></td>
<td></td>
<td>-211.03*** (81.95)</td>
<td></td>
<td>-146.69* (79.04)</td>
<td></td>
</tr>
<tr>
<td>$WD$</td>
<td>-16.43*** (1.096)</td>
<td>-11.76*** (1.38)</td>
<td></td>
<td>-13.64*** (0.52)</td>
<td>-12.78*** (0.64)</td>
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</tr>
<tr>
<td>$MIT$</td>
<td></td>
<td></td>
<td>-1.38*** (0.47)</td>
<td>-1.39*** (0.35)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Standard errors in parentheses; * $p<.1$, ** $p<.05$, *** $p<.01$
Framework

Flight $i$ → Departure time → Weather exposure/wind/MIT on nominal routes

Busy hour indicator → Composite weather exposure/ MIT → Route inefficiency (Linear model)

Route structure and seasonal effects → Predicted Inefficiency → Probabilistic assignment of nominal routes (Route choice model)
Linear Model

• Model Specification

\[
\text{Inefficiency}(\%) = \beta_0 + \beta_1 \cdot TS + \beta_2 \cdot R + \beta_3 \cdot SQ + \beta_4 \cdot MIT + \beta_5' \cdot X_{NRoute} + \beta_6' \cdot \text{Season} + \beta_7 \cdot BH
\]

– TS: Thunderstorm exposure
– R: Rain exposure
– SQ: Squall exposure
– MIT: Average MIT stringency
– \(X_{NRoute}\): Fixed effects of nominal routes for different airport pairs
– Season: Seasonal fixed effects, winter as baseline; Winter: Dec – Feb, Spring: Mar – May, Summer: Jun – Aug, Fall: Sep – Nov
– BH: Binary variable. 1 if departure hour is between 8 am to 8 pm.
Estimation Results

- Number of observations range from 1664 (IAH → BOS) to 10637 (JFK → LAX)
- R squares range from 0.33 to 0.76
- Thunderstorm exposure is highly significant for all six pairs
- Inefficiency increases from 0 to 1 (maximum possible thunderstorm exposure) are
  - 41.4% for LAX → JFK
  - 30.7% for JFK → LAX
  - 25.8% for IAH → BOS
- Rain, squall and MIT are significant only for certain airport pairs
- The estimates of cluster membership are highly significant, indicating that the between cluster effect is important

<table>
<thead>
<tr>
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<th>BOS IAH</th>
<th>FLL JFK</th>
<th>JFK FLL</th>
<th>JFK LAX</th>
<th>LAX JFK</th>
</tr>
</thead>
<tbody>
<tr>
<td>$TS$</td>
<td>25.76** (2.87)</td>
<td>11.61** (2.68)</td>
<td>5.49** (2.39)</td>
<td>7.27** (1.27)</td>
<td>30.72*** (1.96)</td>
<td>41.35*** (2.24)</td>
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<tr>
<td>$R$</td>
<td>1.35* (0.81)</td>
<td>1.55*** (0.45)</td>
<td>3.70*** (0.52)</td>
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<tr>
<td>$SQ$</td>
<td></td>
<td>226.72*** (65.32)</td>
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</tr>
<tr>
<td>$MIT$</td>
<td>1.06*** (0.32)</td>
<td>0.86** (0.36)</td>
<td>1.29*** (0.25)</td>
<td></td>
<td>4.10*** (0.30)</td>
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Contributions of Causal Factors

- We would like to understand how much convective weather contribute to flight en route inefficiency.
- Both models are used to calculate the contributions

\[
\%\Delta = \frac{\sum_{C_L} [\mathcal{E}(\text{Inefficiency}|F, C_L)P(C_L|F) - \mathcal{E}(\text{Inefficiency}|F = 0, C_L)P(C_L|F = 0)]}{\sum_{C_L} \mathcal{E}(\text{Inefficiency}|F, C_L)P(C_L|F)}
\]

- $\mathcal{E}$: Predicted inefficiency based on route inefficiency model for a given flight
- $C_L$: Cluster $L$
- $F$: Causal factor vector (i.e., $[Wx, WD, MIT]$)
- $P(C_L|F)$: Probability that a given flight is assigned to route cluster $L$ given causal factor value $F$ based on probabilistic assignment model
Contributions of Causal Factors

- Convection accounts for 7% - 18% of en route inefficiency for the 6 pairs
- Wind accounts for 0% - 12% of en route inefficiency
- MIT accounts for 0% - 5% of en route inefficiency

<table>
<thead>
<tr>
<th>City Pair</th>
<th>Base-line</th>
<th>Weather</th>
<th>Wind</th>
<th>MIT</th>
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<tbody>
<tr>
<td></td>
<td>Without Contribution</td>
<td>Without Contribution</td>
<td>Without Contribution</td>
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<tr>
<td>IAH BOS</td>
<td>4.36%</td>
<td>3.93%</td>
<td>9.99%</td>
<td>4.13%</td>
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<tr>
<td>BOS IAH</td>
<td>2.58%</td>
<td>2.21%</td>
<td>14.28%</td>
<td>2.51%</td>
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<tr>
<td>FLL JFK</td>
<td>3.59%</td>
<td>3.30%</td>
<td>8.08%</td>
<td>3.59%</td>
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</tr>
<tr>
<td>JFK FLL</td>
<td>3.06%</td>
<td>2.83%</td>
<td>7.43%</td>
<td>3.06%</td>
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<tr>
<td>JFK LAX</td>
<td>2.05%</td>
<td>1.73%</td>
<td>15.42%</td>
<td>1.82%</td>
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<tr>
<td>LAX JFK</td>
<td>2.43%</td>
<td>2.00%</td>
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43
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Conclusions

• Contributions of weather, wind, and MITs to en route inefficiency have been estimated for US domestic flights
• Our approach considers effects related to assignment of flights to trajectory clusters and variation of inefficiency within clusters
• Assignment model shows that effects of weather, wind, and MITs are statistically significant and have the expected signs
• Results of inefficiency regression model are mixed but generally reasonable
• Estimated contributions to total inefficiency:
  – From convective weather: 5-15%
  – From wind: 0 – 12%
  – From MIT: 0 – 5%
Ongoing Research

• Additional causal factors
  – Monitor alerts (indicate sectors predicted to have excess demand)
  – Airspace flow programs (ground hold flights to meter demand through airspace with reduced capacity)
  – NAS route structure

• Model refinements
  – Convective weather metrics based on better data
  – Improved exposure metrics
  – Improved statistical modeling

• Generative flight route model
  – Use deep learning methods to predict routes of specific flights based on causal factors information
  – Use counterfactuals to find impacts of particular factors
Thanks!
Q&A

liuyulin101@berkeley.edu
## Estimation Results

<table>
<thead>
<tr>
<th>Var.</th>
<th>IAH (Est.)</th>
<th>BOS (Est.)</th>
<th>FLL (Est.)</th>
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<th>LAX (Est.)</th>
</tr>
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<tr>
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<tr>
<td></td>
<td>(2.87)</td>
<td>(2.68)</td>
<td>(2.30)</td>
<td>(1.66)</td>
<td>(2.24)</td>
</tr>
<tr>
<td>R</td>
<td>1.35*</td>
<td>1.55***</td>
<td>3.70***</td>
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<tr>
<td></td>
<td>(0.81)</td>
<td>(0.45)</td>
<td>(0.52)</td>
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<tr>
<td>SQ</td>
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*Standard errors in parentheses; * p<.1, ** p<.05, *** p<.01