Taxation of Multi-Product Firms with Cost Complementarities

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November 11, 2019

Abstract

I analyze how taxes impact prices, quantities, and welfare when products are connected via demand or cost relationships. Exploiting spatial and temporal variation in taxes from 1993 to 2015, I estimate a discrete-choice, oligopoly model of the U.S. aviation industry—a network setting where demand-side substitutes are straightforward to observe and cost complementarities arise naturally. I show that cost complementarities increase incidence on taxed products and cause incidence to spill over across products. Taxation of hub airports generates larger spill-over effects and greater negative effects on consumer welfare. Simulations of revenue-neutral tax policies such as standardization of taxes across routes and subsidization of hub airports find improvement in consumer welfare on average, but effects are limited by competing effects on prices in untaxed routes.

Keywords: Taxation, Networks, Airlines

JEL Codes: H22, H73, L93, L98, R48.

*University of North Carolina at Chapel Hill, arlynnq@live.unc.edu. I am thankful for the guidance and advice of my advisor Jon Williams, and committee members David Agrawal, Gary Biglaiser, Brian McManus, and Juan Carlos Suárez Serrato. I would also like to thank Simon Alder, Jane Cooley Fruehwirth, Luca Flabbi, Qing Gong, Peter Hansen, Fei Li, Luca Maini, Peter Norman, Can Tian, Valentin Verdier, Kyle Woodward and Andy Yates for comments as well as audiences at the UNC Microeconomics workshop, the UNC IO/Theory Dissertation workshop, the UNC Econometrics workshop, Uppsala University, the University of Kentucky, and participants at the 17th International Industrial Organization Conference and 89th Southern Economic Conference. All mistakes are my own.
1 Introduction

Understanding the determinants of tax incidence is critical for setting policy to efficiently raise revenue and to minimize distortions from taxation. As Coase (1946) notes, in most market settings, products connected via demand or cost relationships can extend the burden of taxation beyond the taxed product. Despite the theoretical ambiguity surrounding changes in price, cost, and ultimately welfare when a tax is assessed on one product, there is little empirical evidence that quantifies the permeation of tax incidence across related products. Quantifying the intensity of these secondary effects can provide guidance for optimal taxation in these settings, and insight into related issues like antitrust and trade policy. In this paper, I estimate a model of competition in the U.S. aviation industry to measure tax incidence and calculate the impact of counterfactual tax policies in a network setting where cost complementarities\(^1\) between routes and oligopolistic competition can lead to widespread incidence from localized taxes.

The U.S. aviation industry is well-suited to the study of tax incidence and the impact of cross-product relationships on incidence for many reasons. First, taxes are substantial, reaching 15% of the fare under current policy. Second, taxes change frequently during the sample period, 1993 to 2015. They vary spatially, by type (percentage or unit), and the extent to which they favor certain types of products, such as nonstop vs. connecting. This variation is valuable for identifying parameters and assessing the welfare implications of different policy characteristics. Third, cost complementarities between products (i.e., flight itineraries) within a carrier’s network are well documented.\(^2\) Finally, the classification of cross-product demand and cost relationships is relatively straightforward. Demand relationships are defined by a route’s origin and final destination. Cost relationships are defined by a shared flight segment common to each route. For example, consider two itineraries. The first originates in Boston, flies to Philadelphia, and has a final destination of Atlanta. The second originates in Boston, flies to Philadelphia,

\(^1\)Cost complementarities, or declines in marginal cost from the production of another product, arise due to the hub and spoke nature of airline’s networks in which passengers share flight segments in route to their final destination.

and has a final destination of Detroit. The Boston to Philadelphia segment serves as an input to both itineraries. Cost complementarities arise as the cost of operating a segment such as Boston to Philadelphia declines with more passengers due to the use of more fuel-efficient planes, more intense use of airport resources, and lower per-passenger labor costs.

Empirical research on taxation in complex settings is often difficult due to a lack of data. Specifically, to measure tax incidence requires detailed information on prices, quantities, and taxes at a disaggregated level for all products impacted by the tax. Also, adequate exogenous variation in tax rates is necessary to identify its relationship to equilibrium outcomes such as prices and quantities. As in many industries, information on tax rates is not readily available for the airline industry. One contribution of this research project more broadly is to collect information on taxes for the airline industry. I collect information from administrative records (e.g., FAA, Homeland Security, TSA), federal legislation and statutes (e.g., Airport and Airway Revenue Act of 1970, Taxpayer Relief Act of 1997, American Infrastructure Investment and Improvement Act of 2007), and industry guidelines and documentation (e.g., Airlines for America and Aviation Services LLC) for the period of 1993-2015. I use this information to code a tax calculator that decomposes observed fares into a base fare, set by the carrier, and each of the taxes levied on every itinerary (Agrawal, White and Williams, 2018). White, Agrawal and Williams (2018) use the tax calculator to provide evidence aviation taxes may be over-shifted (i.e., a $1 tax results in more than a $1 increase in price). Despite taxes composing a substantial share of fares, prior researchers have not comprehensively studied the effect of taxes due to data availability. I contribute to an extensive literature on the determinants of fares. I also demonstrate the utility of taxes as instruments for fares in the aviation industry, a strategy which can be replicated to address a wide range of research questions.

To measure tax incidence across products and simulate counterfactual policies, I

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develop and estimate a discrete-choice, oligopoly model in which carriers compete by setting fares. Specifically, I consider a theoretical model similar to that of Berry, Carnall and Spiller (2006) in which carriers account for their ownership of multiple products within a market and cost complementarities across products generated by their observed network structure. Passengers choose the route which offers them the greatest utility conditional on the price and other characteristics of the route. I use parameter estimates from the model to describe how taxes permeate a network and to conduct a series of counterfactual exercises. Consistent with prior theoretical and empirical work on taxation in networks, cost complementarities increase incidence on taxed products and cause incidence to spill over across a firm’s products. Taxes on more centrally located airports (i.e., hubs) have larger spillover effects and greater negative effects on consumer welfare.

Changes to tax policy can significantly impact consumer welfare. In counterfactual policy simulations, eliminating taxes in a quarter provides a transfer of $1.1 B, or 5.24% of consumer welfare, to consumers. A more relevant exercise is to hold tax revenue constant and estimate the impact on consumers from policy changes. Similar to Fajgelbaum et al. (2018), one possibility would be to eliminate spatial distortions in the tax either by setting the same tax on each route, or alternatively the same tax on each segment, while holding total tax revenue constant. Standardizing taxes across routes increases consumer welfare by .2%, while standardizing taxes per segment leaves consumer welfare essentially unchanged. Finally, I estimate the potential welfare benefits from setting taxes which exploit the presence of cost complementarities. Relative to a world with standardized segment taxes, I find consumer welfare improves by .08% when the ten most central airports are subsidized. The relatively small change in welfare for revenue-neutral tax policies masks heterogeneity in effects across routes and types of products. The multi-product nature of markets and the cost structure of firms help to limit the welfare cost of taxation. Multiple products or routes allow passengers to find close substitutes, while cost complementarities potentially generate savings as passenger substitution lowers costs on alternative routes.
This paper contributes to several strands of research which span public finance and industrial organization. Within public finance, the results are important for theoretical models of tax incidence (Delipalla and Keen, 1992; Fullerton and Metcalf, 2002). Whereas much of the prior theoretical literature often focuses on factors such as the relative magnitude of supply and demand elasticities, the curvature of demand, and the nature of competition (Weyl and Fabinger, 2013), my model highlights how cost complementarities potentially influence pass-through and incidence. Hamilton (2008) introduces a model of tax incidence where consumers purchase multiple products from oligopolistic firms in a transaction. I contribute to the literature on empirical estimates of factors of incidence (Poterba, 1996; Besley and Rosen, 1999; Kenkel, 2005; Harding, Leibtag and Lovenheim, 2012; Kleven et al., 2014). More generally, I contribute to the literature on the effects of consumption taxes (Kanbur and Keen, 1993; Chetty, Looney and Kroft, 2009; Crawford, Keen and Smith, 2011).

Within industrial organization, my work contributes to the study of strategic decisions by economic agents in network settings with cost or demand complementarities. Some, such as Brueckner and Spiller (1991), Brueckner, Dyer and Spiller (1992), Brueckner and Spiller (1994), Hendricks, Piccione and Tan (1995), Berry, Carnall and Spiller (2006), and Berry and Jia (2010), focus on the airline industry, while others focus on industries such as telecommunications, payment instruments, railroad, and retail outlets (e.g., Jia (2008), Ryan and Tucker (2012), Koulayev et al. (2016), Houde, Newberry and Seim (2017), Malone, Nevo and Williams (2018), and Pus (2019)). Relatedly, economists have produced a wide range of theoretical results for tax incidence in oligopolistic settings, including taxes being over-shifted to consumers. Researchers have used empirical estimates of over-shifting as evidence of market power or collusion (Marion and Muehlegger, 2011). I also contribute to a growing literature which aims to utilize tools traditionally associated with industrial organization to study a wide range of public finance topics (Bayer, Ferreira and McMillan, 2007; Conlon and Rao, 2015; Griffith, O’Connell and Smith, 2017; Griffith, Nesheim and O’Connell, 2018).

Finally, my paper is most closely related to recent empirical work by Houde, New-
berry and Seim (2017); Flaaen, Hortaçu and Tintelnot (2019); and Agrawal, White and Williams (2018) which highlight the interaction between taxes and the multi-product nature of firms and markets. Houde, Newberry and Seim (2017) examine the importance of a firm’s internal cost structure, Amazon’s distribution network, on the incidence of taxes. They utilize growth in the distribution network to infer the relevant trade-offs between increased tax liabilities and reduced shipping costs. Flaaen, Hortaçu and Tintelnot (2019) examine a set of differentially taxed complementary products, washers and dryers, and the resulting change in prices. Lastly, Agrawal, White and Williams (2018) examine how demand or cost complementarities in a network setting, the U.S. domestic aviation industry, influence fares. They use a reduced-form, elastic-net methodology to infer which fares changes as a result of connections across products. While taking lessons from each, I differ from these papers in at least two ways. First, I model a setting in which both demand and cost relationships across products are relevant. Second, my paper attempts to explain the distribution of welfare across a network of products, while Flaaen, Hortaçu and Tintelnot (2019) and Agrawal, White and Williams (2018) focus on price changes, and Houde, Newberry and Seim (2017) focus on network growth.

2 Data

I use data from three sources. First, the primary data source for airline fares is the Data Bank 1B (DB1B) of the U.S Department of Transportation’s Origin and Destination Survey for the years 1993 through 2015. The DB1B is a quarterly 10% random sample of domestic itineraries in the United States. The data contains the ticketing carrier, details on the connections made along a route, and the total fare for a ticket. The DB1B includes only the total fare, inclusive of taxes, and does not provide a breakdown of the base fare and taxes. For this reason, I utilize the tax calculator from Agrawal, White and Williams (2018b), which returns tax rates and specific taxes for each itinerary. In section 2.3, I provide a brief discussion of the different taxes which apply to the U.S. aviation industry, all of which the tax calculator recovers. Agrawal, White and Williams (2018b) discuss the tax calculator and the evolution of U.S. aviation taxes in greater
detail. I supplement the DB1B with characteristics on the origin and destination cities. Per-capita income and population for each city-year are from the Bureau of Economic Analysis.

2.1 Sample Selection

I define a market \( m = 1, \ldots, M \) as unidirectional travel between two airports, regardless of the number of stops the passenger incurs during travel.\(^4\) Within a market \( m \), a route \( r = 1, \ldots, R \) is defined by the ordered set of airports a passenger utilizes with a particular carrier \( c \) in traveling from their origin to their destination.\(^5\) Time \( t = 1, \ldots, T \) is at the year-quarter level. I include the outbound and inbound legs of round-trip tickets as separate observations.

I restrict the sample along four dimensions. At the individual passenger itinerary level, I drop both interline and open-jaw tickets. I exclude itineraries with fares the DOT deems unreliable and itineraries with fares less than $25 or greater than $2000 in either direction, as they are likely to be the redemption of frequent-flier miles or key-stroke errors. I drop itineraries with more than one stop in either direction and those utilizing multiple carriers. At the airport level, I rank airports by the number of originating passengers during the sample period and keep routes involving those in the top 150 for which the BEA has population data.\(^6\) At the carrier level, I include all major carriers which operate during the sample as well as smaller carriers who transport a substantial number of passengers. The full list is American (AA), Alaska (AS), JetBlue (B6), Continental (CO), Delta (DL), Frontier (F9), ATA (TZ), Allegiant (G4), Spirit (NK), Northwest (NW), AirTran (FL), United (UA), USAir (US), Southwest (WN), Hawaiian Pacific (HP), Hawaiian Air (HA), Trans World Airlines (TW), Aloha Airlines (AQ), and Virgin Atlantic (VX). Finally, I include only segments which have at least 1200

\(^4\)This market definition is common in the airline literature. For example, it is also used in Evans and Kessides (1994) and Ciliberto and Williams (2014).

\(^5\)For example, nonstop travel from Raleigh-Durham (RDU) to Los Angeles (LAX) with United Airlines and travel from RDU to LAX via Atlanta with Delta Airlines are two routes within the RDU-LAX market.

\(^6\)The smallest airport included is Key West, FL. The first airport excluded is Charleston, WV.
passengers (approximately 100 per week) in at least one quarter. The data are aggregated to the route-carrier-quarter level, resulting in 10,043,026 observations in 19,818 airport-pair markets.

Figure 1 describes the number of routes and markets observed in the data throughout the sample period, which vary as carriers enter and exit markets or merge with one another. The number of routes in a given period \( t \) ranges from 79,257 to 131,671 while the number of markets ranges between 15,925 and 18,441.\(^7\) The number of routes and extent of market coverage have expanded considerably.

![Figure 1: Routes and Markets](image)

(a) Routes (b) Markets

Note: The figures above depict the total number of routes and markets for the years 1993 to 2015. Panel (a) plots the total number of routes. A route is the ordered set of airports a passenger utilizes with a particular carrier from their origin to their destination. Total routes are equivalent to the number of observations in a given year and quarter. Panel (b) depicts the total number of markets. A market is unidirectional travel between two airports, regardless of the number of stops the passenger incurs during travel. Many potential routes exist within a given market. The plots are conditional on the sample restrictions outlined in Section 2.1.

### 2.2 Variables

Table 1 provides a brief description and source of the main variables used in the analysis. Table 2 provides the summary statistics for these variables, including the mean and standard deviation when each route is weighted equally as well as the mean.

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\(^7\)Note this is relatively close to the full set of permutations for the included set of airports, approximately 21,000, and thus close to complete network coverage.
and standard deviation when weighted by passenger volume.

Table 1: Variable Description and Sources

<table>
<thead>
<tr>
<th>Variable Descriptions Source</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean passenger price on a route</td>
<td>DB1B</td>
</tr>
<tr>
<td>Indicator if nonstop service from origin to destination</td>
<td>DB1B</td>
</tr>
<tr>
<td>Distance of route flown</td>
<td>DB1B</td>
</tr>
<tr>
<td>Share of nonstop destinations from origin by a carrier</td>
<td>DB1B</td>
</tr>
<tr>
<td>Ad Valorem tax rate (%)</td>
<td>Tax Calculator</td>
</tr>
<tr>
<td>Airport specific tax ($)</td>
<td>Tax Calculator</td>
</tr>
<tr>
<td>Segment specific tax ($)</td>
<td>Tax Calculator</td>
</tr>
<tr>
<td>Per-segment or per-leg specific tax ($)</td>
<td>Tax Calculator</td>
</tr>
<tr>
<td>Tax on flights to/from AK/HI ($)</td>
<td>Tax Calculator</td>
</tr>
<tr>
<td>Count of rivals offering direct service</td>
<td>DB1B</td>
</tr>
<tr>
<td>Indicator if any rival offers nonstop service</td>
<td>DB1B</td>
</tr>
<tr>
<td>Count of rival routes in the market</td>
<td>DB1B</td>
</tr>
<tr>
<td>Carriers in the market</td>
<td>DB1B</td>
</tr>
</tbody>
</table>

Note: Outside of Fare and Distance, DB1B variables were constructed from the raw data in the DB1B

Table 2: Summary Statistics

<table>
<thead>
<tr>
<th>Variable</th>
<th>Route-level mean</th>
<th>Route-level sd</th>
<th>Passenger-level mean</th>
<th>Passenger-level sd</th>
<th>min</th>
<th>max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fare</td>
<td>292.19</td>
<td>155.33</td>
<td>219.46</td>
<td>99.59</td>
<td>24.80</td>
<td>3255.80</td>
</tr>
<tr>
<td>Nonstop</td>
<td>.09</td>
<td>.72</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Distance (in 1000s)</td>
<td>1.53</td>
<td>.84</td>
<td>1.07</td>
<td>.72</td>
<td>.02</td>
<td>7.54</td>
</tr>
<tr>
<td>Origin centrality</td>
<td>.37</td>
<td>.24</td>
<td>.48</td>
<td>.28</td>
<td>.01</td>
<td>1</td>
</tr>
<tr>
<td>U.S. Ticket Tax</td>
<td>.075</td>
<td>.02</td>
<td>.075</td>
<td>.02</td>
<td>0</td>
<td>.1</td>
</tr>
<tr>
<td>PFC</td>
<td>7.75</td>
<td>2.74</td>
<td>5.27</td>
<td>2.54</td>
<td>0</td>
<td>11.99</td>
</tr>
<tr>
<td>Segment tax</td>
<td>5.94</td>
<td>2.96</td>
<td>3.97</td>
<td>2.38</td>
<td>0</td>
<td>8.05</td>
</tr>
<tr>
<td>Sept. 11 fee</td>
<td>3.50</td>
<td>2.67</td>
<td>2.45</td>
<td>2.12</td>
<td>0</td>
<td>6.57</td>
</tr>
<tr>
<td>AK/HI tax</td>
<td>.30</td>
<td>1.58</td>
<td>.18</td>
<td>1.24</td>
<td>0</td>
<td>9.90</td>
</tr>
<tr>
<td>Nonstop rivals</td>
<td>.97</td>
<td>1.36</td>
<td>1.62</td>
<td>1.54</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>1 (Rivals nonstop)</td>
<td>.46</td>
<td>.71</td>
<td>0</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rival routes</td>
<td>9.56</td>
<td>8.46</td>
<td>11.34</td>
<td>9.36</td>
<td>0</td>
<td>77</td>
</tr>
<tr>
<td>Market carriers</td>
<td>5.01</td>
<td>2.13</td>
<td>5.35</td>
<td>2.18</td>
<td>1</td>
<td>14</td>
</tr>
</tbody>
</table>

N 10,043,026 6,966,031,550

Fare is the average fare of itineraries for ticketing carrier $c$ on route $r$ in market $m$ during period $t$. Nonstop equals one if route $r$ is direct service from the origin to destination in its market $m$. Distance is defined by the route flown and thus varies.
across routes within a market. *Origin centrality* is defined by the origin and carrier on a route. It is the number of nonstop destinations from the origin by the carrier at time \( t \) divided by the total number of airports. The individual taxes are discussed in greater detail below but briefly, *U.S. Ticket Tax* is the percentage or ad valorem tax applied to the base fare set by the carrier, while *PFC*, *Segment tax*, *Sept. 11 fee*, and *AK/HI tax* are all specific or dollar-value taxes added to the base fare. All of the tax variables are products of the tax calculator. *Nonstop rivals* is the number of rival carriers observed offering nonstop service in market \( m \) at time \( t \). The variable \( 1(Rivals\ nonstop) \) is an indicator if any rival offers nonstop service in market \( m \) at time \( t \). *Rival routes* is the number of rival routes in market \( m \) at time \( t \). Finally, *Market carriers* is the number of carriers providing service in market \( m \) at time \( t \).

### 2.3 Aviation Taxation

![Figure 2: Tax Share of Fares](image)

Note: This figure graphs the distribution of the share of consumer’s fare attributable to taxes for the years 1993 to 2015. For each quarter it depicts mean, median, 10th, 25th, 75th, and 90th percentiles across passengers. I calculate each statistic at the passenger-level. The plot is conditional on the sample restrictions outlined in Section 2.1.
Table 3: Summary of Aviation Taxation: 1993 to 2015

<table>
<thead>
<tr>
<th>Tax Type</th>
<th>Change</th>
<th>Year</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.S. Ticket Tax</td>
<td>Lapse</td>
<td>1996</td>
<td>Lack of reauthorization: 0%</td>
</tr>
<tr>
<td></td>
<td>Valorem</td>
<td>Lapse</td>
<td>1997</td>
</tr>
<tr>
<td></td>
<td>Statutory</td>
<td>1997-1999</td>
<td>Periodic decline: 10% to 7.5%</td>
</tr>
<tr>
<td></td>
<td>Lapse</td>
<td>2011</td>
<td>Lack of reauthorization: 0%</td>
</tr>
<tr>
<td>PFC</td>
<td>Specific</td>
<td>Statutory</td>
<td>2001</td>
</tr>
<tr>
<td>Segment</td>
<td>Specific</td>
<td>Statutory</td>
<td>1997-2015</td>
</tr>
<tr>
<td>September 11th Fee</td>
<td>Specific</td>
<td>Statutory</td>
<td>2002</td>
</tr>
<tr>
<td></td>
<td>Lapse</td>
<td>2003</td>
<td>Lack of reauthorization: $0</td>
</tr>
<tr>
<td></td>
<td>Statutory</td>
<td>2014</td>
<td>Changed to $5.60 per direction</td>
</tr>
<tr>
<td>AK/HI Travel Facilities Tax</td>
<td>Specific</td>
<td>Statutory</td>
<td>1993-2015</td>
</tr>
</tbody>
</table>

Between 1993 and 2015, taxation in the aviation industry changed dramatically in terms of the amount of taxation on any individual route as well as the type of tax or tax instrument used to raise revenues. Table 3 summarizes aviation taxes and how they have changed during the sample period. After a carrier sets a base fare, two types of taxes are directly assessed on domestic flight itineraries: specific or unit taxes, which add a set dollar amount to the base fare, and ad valorem taxes, which add a percentage to the base fare. Figure 2 displays the mean percentage of a passenger’s fare, inclusive of both specific and ad valorem taxes, remitted to the government. Since the 2nd quarter of 2002, and the introduction of fees related to the 9/11 attacks, taxes or fees compose an average of approximately 15% of a passenger’s fare. As evident from Figure 2, this is an approximately 50% increase from the beginning of the sample, when taxes composed less than 10% of a fare.

Four types of specific taxes are potentially applied to domestic itineraries: the U.S. Federal Segment Fee, the Alaska-Hawaii Ticket Tax, the September 11th Security Fee, and Passenger Facility Charges (PFC), many of which were introduced during the sample period. The U.S. Federal Segment Fee was first introduced at $1.00 per non-rural segment in the 4th quarter of 1997 and has steadily increased to $4.00 per non-rural seg-

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8Other taxes, such as corporate income taxes on airline profits or fuel taxes on jet fuel, are not captured by the tax calculator or directly assessed on itineraries.
ment in 2015. Flights to and from the continental US and Alaska or Hawaii (or between Alaska and Hawaii) are subject to the Alaska-Hawaii Ticket Tax, which has ranged from $6.00 in 1993 to $8.90 in 2015. The September 11th Security Fee, depending on the year and quarter, is either $2.50 per-segment with a $5.00 maximum, or $5.60 each direction of an itinerary. Finally, PFCs are airport-specific fees assessed when a passenger enplanes at the designated airport. For an airport to assess the charge, the PFC must be authorized by the FAA. The revenue is treated as local funds and restricted to use on specific long-term capital projects. First authorized in 1992, PFCs initially had a maximum allowable charge of $3.00 per airport. In 2001, the Wendell H. Ford Aviation Investment and Reform Act for the 21st Century increased the maximum charge to $4.50. Figure 3 displays the total average specific tax by year and quarter.

Figure 3: Specific Taxes

Note: This figure illustrates the distribution of the specific taxes applicable to each fare for the years 1993 to 2015. Specific taxes are measured in dollars. It depicts mean, median, 10th, 25th, 75th, and 90th percentiles. I calculate each statistic at the passenger-level. The plot is conditional on the sample restrictions outlined in Section 2.1.

Itineraries in the US are subject to a single ad valorem tax, the U.S. Ticket Tax (also known as the U.S. Domestic Transportation Tax or U.S. Excise Tax). The ad
Figure 4: Effective U.S. Ticket Tax

Note: This figure plots the statutory ad valorem tax rate on U.S. tickets for the years 1993 to 2015. In quarters where the tax rate changes during the quarter, the tax rate is weighted by the number of days for which each tax rate is in effect. The solid line depicts the tax rate which applies to non-rural segments and thus the vast majority (>99%) of passengers. A rural segment involves an airport which serves fewer than 100,000 passengers and is not located within 75 miles of an airport serving more than 100,000 passengers. The tax calculator accounts for and allows me to control for these airports, but they are not a focus of the analysis.
valorem rate, which in some years varies by an airport’s rural status, is set by the federal government. The tax applies only to portions of the route over the United States. It thus does not apply if the flight goes over international waters or Canada (i.e., involves Hawaii or Alaska). Figure 4 shows the effective U.S. Ticket Tax rate from 1993 to 2015. The tax ranges from 0% to 10%. The high volatility in the tax rate where it drops to 0% is due to congressional budget lapses.

3 Empirical Model of Demand and Oligopoly Firms

Directly modeling demand and a firm’s decision-making provides benefits for addressing the complex role of taxes for multi-product firms in a network setting and simulating counterfactual tax policy. I model the U.S. domestic aviation industry using a discrete-choice framework similar to that of Berry (1994) and Berry, Levinsohn and Pakes (1995). The model is most similar to that of Berry, Carnall and Spiller (2006), Berry and Jia (2010), and Ciliberto and Williams (2014), who utilize these models to analyze the domestic U.S. aviation industry.\(^9\) These models view carriers as offering a set of differentiated products, i.e. routes, for markets defined by their origin and destination.

I model demand using a nested logit model. Nested logit models have been used to study a wide range of topics and industries including automobiles (Goldberg, 1995; Fershtman, Gandal and Markovich, 1999), alcohol (Slade, 2004), and pharmaceutical drugs (Duso, Herr and Suppliet, 2014). Due to their flexibility and closed-form analytical properties, they are also frequently used to inform policy debates (Werden and Froeb, 1994). Unlike the multinomial logit model, which does not allow for consumer responses to be correlated according to a product’s characteristics, the nested logit model allows for correlation across products in a restricted fashion predetermined by the researcher.

On the supply side, the cost for a route is the cost of segments which compose the route, whether the route is nonstop, the characteristics of the endpoints, and an error

\(^9\)Discrete-choice models have also been used to study a variety of topics in public finance. Bayer, Ferreira and McMillan (2007) estimate a household’s willingness-to-pay for school and neighborhood attributes. Fershtman, Gandal and Markovich (1999) examine counterfactual tax regimes for the Israeli car market.
term meant to capture unexpected random shocks to a route’s cost. The marginal cost of a segment is a function of the total quantity of passengers on the segment. In the airline literature, economies of scale at the segment-level are often described as economies of density.\(^{10}\) Because a segment is an input to many routes, the total quantity of passengers on a route is derived from the costs and demand of many routes.

Carriers compete by choosing prices for their routes. A carrier’s pricing decision balances the potential benefits of economies of scale at the segment level, the marginal cost on a route, and the marginal revenue provided by an additional passenger.

### 3.1 Demand

A nested logit model requires the specification of mutually exclusive sets of products. I nest products (i.e., route-carrier combinations) according to their markets as defined by the origin, final destination, year, and quarter. The utility \( u \) of consumer \( i \) purchasing product \( r \) (i.e., a route-carrier combination) in period \( t \) is

\[
    u_{irt} = x_{rt} \beta - \alpha p_{irt} + \xi_{rt}(\sigma) + (1 - \sigma) \epsilon_{irt},
\]

where \( x_{rt} \) is a vector of product characteristics, \( p_{rt} \) is the price for route \( r \) in period \( t \), \( \beta \) captures the taste for consumers of different characteristics, \( \alpha \) captures consumers’ disutility from a price increase, and \( \xi_{rt} \) represents a product characteristic unobserved to the econometrician. The term \( \nu_{it} \) is the “nested logit” random taste, which is constant across airline products and differentiates air travel from the outside option. The outside option includes not traveling as well as driving, taking a train, or any other non-aviation method of transit.\(^{11}\) The nested logit parameter \( \sigma \) varies between 0 and 1, where \( \sigma = 0 \) reduces the model to the multinomial logit model. The \( \sigma \) parameter captures substitution between flying and the outside option. The term \( \epsilon_{irt} \) is an i.i.d. error intended to capture

---

\(^{10}\)Segment-level economies of scale have been well documented in the airline literature. See Brueckner and Spiller (1994) and Berry, Carnall and Spiller (2006) as well as citations therein for prominent examples.

\(^{11}\)As with most discrete-choice studies, I do not observe the outside option but infer it based on the chosen market size and observed transactions.
idiosyncratic taste for a product. The term $\nu_{it}$ is distributed such that $\nu_{it}(\sigma) + (1-\sigma)e_{irt}$ has an extreme value distribution. The mean utility of the outside option is normalized to zero as only differences in utility, not levels, are identified.

Markets are defined to be one-way travel between an origin and destination.\textsuperscript{12} Thus, a round-trip itinerary will involve products in two markets; the outbound and return legs of the trip. As in Berry, Carnall and Spiller (2006), Berry and Jia (2010), and Ciliberto and Williams (2014), I define market size as the geometric mean of the origin and destination populations.

Given the assumed structure on the error-term (Cardell, 1997), for market $m$ during period $t$, the proportion of consumers who purchase air travel is

$$\frac{D_{mt}^{(1-\sigma)}}{1 + D_{mt}^{(1-\sigma)}},$$

(2)

where

$$D_{mt} = \sum_{k=1}^{R_{mt}} e^{(x_{kt}\beta - \alpha p_{kt} + \xi_{kt})/(1-\sigma)}$$

and $R_{mt}$ is the set of routes operated in market $m$ at time $t$. Conditional on purchasing a product from the air travel nest, the probability a consumer purchases product $r$ is given by

$$\frac{e^{(x_{rt}\beta - \alpha p_{rt} + \xi_{rt})/(1-\sigma)}}{D_{mt}}.$$  

(3)

Thus, the model predicts $q_{rt}$, product $r$’s market share at time $t$, as the probability of choosing air travel multiplied by the probability of choosing that particular route:

$$q_{rt}(x_{mt}, p_{mt}, \xi_{mt}; \beta, \alpha, \sigma) = \frac{e^{(x_{rt}\beta - \alpha p_{rt} + \xi_{rt})/(1-\sigma)}}{D_{mt}} \frac{D_{mt}^{(1-\sigma)}}{1 + D_{mt}^{(1-\sigma)}}.$$

(4)

\textsuperscript{12} An alternative specification would be to expand either the set of markets or products to differentiate round-trip from one-way travel. There are two problems with this approach. First, some carriers, such as Southwest, show up in the data as providing only one-way tickets despite providing round-trip travel. Second, computational burden is directly tied to the number of markets and products.
Product characteristics, $x_{rt}$, include the route’s distance, distance squared, an indicator if the route is nonstop, and the number of destinations with nonstop service divided by the total numbers of airports in the network from the origin by the carrier (i.e., the network centrality of the origin airport). I include the origin centrality measure to capture the additional benefit from utilizing a more dominant carrier out of an origin. Relative to prior models in the literature, this provides a continuous and time-varying measure of whether an airport serves as a hub for a carrier. Routes with greater origin centrality should have a marginal increase on utility for at least two reasons. First, carriers with more destinations have more valuable frequent-flier programs due to higher option value. Second, carriers with a large presence out of an origin may be able to provide higher-quality service along a number of dimensions including more reliable delivery of baggage, minimizing delays, and accommodating cancellations. Conditional on the same origin and final destination, passengers are expected to prefer a shorter route. Similarly, passengers are expected to derive greater utility from nonstop routes as opposed to routes with a connection.

3.2 Marginal Cost

I model the marginal cost of product $r$ as the sum over $S_r$, the set of segments which comprise $r$:

$$mc_{rt} = \left[ \sum_{s \in S_r} c(Q_{st}, w_{st}) \right] + \omega_{rt},$$

where $Q_{st}$ captures the total volume of passengers of segment $s$ at time $t$ from any route and $w_{st}$ is a vector of exogenous variables such as distance which shift costs. The term $w_{st}$ could include measures of the direct cost component, such as the additional fuel cost necessary for an added passenger. The term $\omega_{rt}$ is a product-specific random error term and captures unexpected shocks to marginal cost such as a shock to fuel cost which disproportionately impacts product $r$. I do not impose economies of scale in the model or during estimation but specify a segment’s marginal cost, $c(Q_{st}, w_{st})$, to be a function
of the total quantity of passengers who utilize that segment across all routes.

Segment marginal cost must be specified flexibly enough that counterfactual analysis is feasible. I utilize a spline function to capture the $Q_{st}$ portion of $c(Q_{st}; w_{st})$ to recover the relationship between segment marginal cost and quantity over the support of $Q$. An increase in segment density, $Q_{st}$, resulting in lower marginal cost provides evidence of economics of density. The complete specification of marginal cost is

$$mc_{rt} = \sum_{s \in S_r} c(Q_{st}; \gamma_s) + \sum_{s \in S_r} \gamma_w w_{st} + \gamma_N N_r + \omega_{rt},$$

(5)

where $c(Q_{st})$ captures economics of density at the segment-level and takes the form

$$c(Q_{st}; \gamma_s) = \gamma_0 + \gamma_1 Q_{st} + \gamma_2 (Q_{st} - \tilde{Q}_{25}) 1[Q_{st} > \tilde{Q}_{25}] + \gamma_3 (Q_{st} - \tilde{Q}_{50}) 1[Q_{st} > \tilde{Q}_{50}] + \gamma_4 (Q_{st} - \tilde{Q}_{75}) 1[Q_{st} > \tilde{Q}_{75}],$$

(6)

where $Q_{st}$ refers to the quantity of passengers on segment $s$ and $\tilde{Q}_{25}$, $\tilde{Q}_{50}$ and $\tilde{Q}_{75}$ refer to quantity at the 25, 50, and 75 percentiles of the quantity CDF. The range of potential estimates for a segment’s marginal cost is unrestricted. If the parameters $\gamma_1, \gamma_2, \gamma_3$, and $\gamma_4 = 0$, then marginal cost is constant. In equation (5), $w_{st}$ includes segment-level characteristics which impact costs such as distance, distance squared, and centrality of the endpoints. $N_r$ is an indicator if route $r$ is nonstop.

Similar to the theoretical model outlined in Brueckner, Dyer and Spiller (1992) and Agrawal, White and Williams (2018a), this specification follows Berry, Carnall and Spiller (2006) by modeling a route’s marginal cost as the sum of the marginal costs for its segments. This provides an intuitive structure in which cross-product linkages are explicitly captured. For cost complementarities to be a relevant feature of a firm’s profit function, products must be linked by a demand or production relationship.\footnote{Otherwise, then a multi-product firm’s profit function is a linear sum of the profits from individual products.} Airline products (routes) are linked because the same flight segment (i.e., a flight from airport A to airport B) serves as an input for multiple products or routes (A – B, A – B – C, Z – A}
Cost complementarities arise as the cost of operating a segment declines with more passengers due to the use of more fuel-efficient planes, more intense use of airport resources, and lower per-passenger labor costs. Thus, cost complementarities arise due to economies of scale at the segment level. These economies of scale incentivize carriers to form hub-and-spoke networks which group passengers with different origins and final destinations onto the same segment, thus driving down the cost for that segment, while also linking products.

3.3 Pricing Equilibrium

Conditional on their network, carriers compete by playing a Bertrand-Nash pricing game. In each period $t$ they choose a price for each route $r$ to maximize profit:

$$\pi_{ct} = \sum_{r \in R_{ct}} p_{rt} q_{rt} - \sum_{s \in S_{ct}} C(Q_{st}) - \sum_{r \in R_{ct}} T_{rt} q_{rt},$$

where $R_{ct}$ is the set of routes operated by carrier $c$ at time $t$, $q_{rt}$ is the quantity of passengers on route $r$ at time $t$, $S_{ct}$ is the set of segments operated by carrier $c$ at time $t$, and $Q_{st}$ is the total quantity of passengers on segment $s$. Thus, $Q_{st}$ is the sum of $q_{st}$'s where $s$ is a segment on $r$. Taxes, which are assessed both at the segment and product level, are captured by $T_{rt}$. $T_{rt}$ is the sum of specific taxes applied to route $r$ at time $t$.

The carrier’s choices yield $r$ first-order conditions:

$$\frac{\partial \pi_{ct}}{\partial p_{rt}} = q_{rt} + \sum_{k \in R_{cm}} p_k \frac{\partial q_{kt}}{\partial p_{rt}} - \sum_{k \in R_{fmt}} \sum_{j \in S_r} m_{cj} \frac{\partial q_{kt}}{\partial p_{rt}} - \sum_{k \in R_{fmt}} T_{kt} \frac{\partial q_{kt}}{\partial p_{rt}} = 0,$$

where $R_{fmt}$ is the set of routes offered by the carrier in market $m$ and $S_r$ is the set of segments on route $r$. This first-order condition captures two key aspects the carrier is considering when setting prices; multiple routes within a market and cost complementarities which arise because the same segment appears on multiple routes. First, because routes within a market are substitutes, a change in the price of $r$ is assumed to directly affect demand for other routes in the market, some of which the carrier may
operate. As with any multi-product firm, the carrier accounts for the change in profits to its other routes based on the derived substitution patterns specified by the underlying demand system. This could potentially mitigate or amplify price changes relative to a single-product firm. Second, the marginal cost of a route is in part the sum of the marginal cost for each segment on the route. As specified in section 3.2, I allow the marginal cost of a segment to be a function of passenger quantity. As a carrier adjusts a route’s fare this will affect the quantity of passengers on that route’s segments and thus the segment’s marginal cost. All segments appear in multiple routes. As their marginal costs change, this affects the underlying pricing decision for other routes. The carrier accounts for these cost spillovers as well.

4 Estimation

I jointly estimate demand and supply via GMM. Modeling utility and marginal costs provides two sets of moment conditions, one for each of the structural error terms on a route. Letting \( Z_d \) be the set of demand instruments, demand moments take the form

\[
E[\Delta \xi_{rt}(\theta_d)Z_d] = 0,
\]

where \( \theta_d \) is the vector of demand parameters to be estimated. Similarly, supply moments take the form

\[
E[\Delta \omega_{rt}(\theta_s)Z_s] = 0,
\]

where \( \theta_s \) is the vector of supply parameters to be estimated and \( Z_s \) the set of supply instruments.

For demand moments, I model the error term from equation (1) as \( \xi_{rt} = \xi_m + \xi_c + \xi_t + \Delta \xi_{rt} \) where fixed effects are captured by \( \xi_m \) for market, \( \xi_c \) for carrier, and \( \xi_t \) for
time fixed effects. Given my model, the demand error term is

$$\Delta \xi_{rt} = \delta_{rt} - \alpha p_{rt} - x_{rt} \beta - \xi_m - \xi_c - \xi_t,$$  \hspace{1cm} (7)

with $\delta_{rt}$ the predicted mean utility for the nested logit derived in Berry (1994).

For supply moments, I model the error term from equation (5) as $\omega_{rt} = \omega_c + \omega_o + \omega_d + \omega_t + \Delta \omega_{rt}$ where supply-side fixed effects are $\omega_c$ for carrier, $\omega_o$ for origin, $\omega_d$ for destination, and $\omega_t$ for time period. The supply error term is

$$\Delta \omega_{rt} = m c_{rt} - \sum_{s \in S_r} c(Q_{st}; \gamma) - \sum_{s \in S_r} \gamma w_{st} - \gamma N r - \omega_c - \omega_o - \omega_d - \omega_t.$$  \hspace{1cm} (8)

Let $g_d$ and $g_s$ be the demand-side and supply-side moments respectively:

$$g_d = E[\Delta \xi Z_d] = 0,$$

$$g_s = E[\Delta \omega Z_s] = 0,$$

where $\Delta \xi$ and $\Delta \omega$ are defined by equations 7 and 8, respectively.

Let $G(\theta_d, \theta_s)$ be the stacked set of moments $(g_d, g_s)$ where $\theta_d = [\alpha, \beta, \xi_m, \xi_c, \xi_t]$ includes demand-side parameters and fixed effects and $\theta_s = [\gamma, \omega_c, \omega_o, \omega_d, \omega_t]$ includes supply-side parameters and fixed effects. Thus, I estimate $\theta = (\theta_d, \theta_s)$ by minimizing

$$Q(\theta) = G(\theta)' W^{-1} G(\theta),$$

where $W$ is an efficient weighting matrix defined as $W = E[Z'GG'Z]$. See Appendix A.1 for greater details for a simple network.

4.1 Instruments

As in Berry (1994) and Berry, Levinsohn and Pakes (1995), estimation of the model exploits the fact that at the true parameter values the structural errors of the model,
\( \xi \) and \( \omega \), are orthogonal to the vector of instruments.\(^{14}\) I require instruments for all endogenous variables which enter the model: fares, within-market shares, and segment quantities. Endogeneity is caused by an omitted variable, product quality. The panel structure of my data allows me to use a rich set of fixed effects to control for unobserved heterogeneity and ease endogeneity concerns. Carrier fixed effects capture time-invariant aspects of quality as well as network structure which could impact costs. Market fixed effects reflect heterogeneity in the degree of business travel between cities as well as the necessity of air travel as they absorb the distance between the two airports. Origin and destination fixed effects capture factors such as landing fees, likelihood of runway congestion, and physical infrastructure which often do not vary even over long panels. Time fixed effects flexibly control for changes in the macroeconomic environment such as recessions which impact both prices and passenger volume. On the supply side, they capture industry-wide cost factors such as fuel prices which are largely set at the national level.

Even given the specified fixed effects, fares could be correlated with unobserved aspects of product quality which are assumed to be known to passengers, such as the time of day for a flight or aircraft amenities. I also require an instrument for the parameter \( \sigma \) which is estimated using a route’s share of air travel in a market at time \( t \) and endogenous due to the relationship between price and quantity. Instruments must be correlated with the share of air travel the route receives but uncorrelated with the utility of the product. On the supply side, the segment quantities in equation (6) are endogenous and require instruments as well.

My instruments fall into two broad categories; taxes and rival characteristics of other products within the market. Taxes can be considered classic cost-shifters, shifting a route’s marginal cost curve without affecting the underlying non-pecuniary elements of utility. Conceptually, I can trace out a demand curve by observing fares and quantities both initially and following a change in taxes. As with any exogenous variation,

\(^{14}\) This orthogonality condition, \( E(\xi Z) = E(\omega Z) = 0 \), is conceptually equivalent to the exogeneity requirement for estimation of any linear instrumental variable models. For example, see equation (5.8) in Wooldridge (2010) for the single equation case.
identification is strongest for the range of prices where tax changes are observed. Assumptions on functional form (i.e., the nested logit) play a larger role for portions of the demand curve outside the range of observed price changes. Tax instruments include the U.S. Ticket Tax rate, the total PFC, total segment tax, Sept. 11th Security Fees, and the Alaska-Hawaii ticket tax. Taxes can be used to identify both supply and demand elasticities in some contexts (Zoutman, Gavrilova and Hopland, 2018); I utilize taxes as an instrument for the after-tax fare and thus implicitly to recover demand elasticities as well as on the supply side to recover supply elasticities.

Rival product characteristics and functions of rival product characteristics, such as the number of other carriers offering nonstop service or an indicator if a rival offers nonstop service, are common instruments in the IO literature. The intuition for these instruments is characteristics of rival products impact the price a firm can charge, and hence market share, but do not affect the underlying utility or marginal cost for a product. Instead, they shift the markup a firm can charge over marginal cost. These instruments may be rich as the closeness of products in characteristic space directly impacts the ability of a firm to charge higher prices. If a rival is offering a highly similar product, for example a nonstop flight with a similar departure time, then the firm is forced to price closer to marginal cost, while the utility derived from the flight for a passenger is not affected by the other flight. The set of potential instruments is large. For example, it includes the presence of rival products in the market, the quality of rival products, indicators for particular characteristics, and measures of the scope and scale of competition.\(^\text{15}\) My set of rival characteristic instruments includes the number of rival carriers offering nonstop service, an indicator if any rival offers nonstop service, the number of rival products, an indicator for monopoly markets and the total number of carriers operating in the market. Finally, I include instruments derived from the interaction of instruments in both categories; the passenger-weighted mean tax faced by rival carriers within the market and an interaction between the monopoly indicator and

\(^{15}\) As with any instrument or set of instruments, an essentially infinite number of instruments can be created via functional form transformations and interactions. To avoid a weak instruments problem, I limit myself to a select set of linear instruments.
specific taxes on a route. The monopoly indicator varies across time, while the remaining
tax and rival characteristic instruments vary across products within a market and across
time.\footnote{Cost-shifters and rival characteristics are common instruments in the airline literature for prices,
quantities, and within-market share. Berry, Carnall and Spiller (2006) use characteristics of route end-
points as instruments. Berry and Jia (2010) instrument using the percentage of rival routes with nonstop
flights, the average distance of rival routes, the number of rival routes within a market, the number of
carriers in a market, indicators if a destination or connecting airport is a hub, and the 25th and 75th
quantiles of route characteristics. Ciliberto and Williams (2014) use unique data on gate access at air-
ports. Gayle (2007) uses the number of own-products within a market, number of rival products, number
of products with an equivalent number of stops, and average price in other markets. Other than average
price, these instruments are either cost-shifters or shift a firm’s markup over marginal cost. The tax data
allow me to use a more parsimonious and thus efficient set of instruments. Beyond this paper, taxes are
likely to be useful for any study of the aviation industry in which endogeneity of fares is a concern.}

Valid instruments must satisfy the standard econometric conditions. First, instru-
ments must be correlated with the endogenous variables: prices, within-market shares,
and segment quantities. Second, instruments need to be uncorrelated with the struc-
tural error terms $\Delta \xi_{rt}$ and $\Delta \omega_{rt}$, or more generally the unobserved portion of utility
and marginal cost. Alternatively stated, instruments need to be uncorrelated with any
omitted variable which explains utility or marginal cost. Although many studies without
data on product-level taxes, such as Dubois, Griffith and O’Connell (2017) and Griffith,
Nesheim and O’Connell (2018), can pursue similar empirical approaches to address tax
policy questions by exploiting consumer responses to price changes, the exogeneity of
taxes and their variation at the product level make them especially valuable as instru-
m ents in this setting.

With respect to relevance, utilizing the estimating equation derived for nested logit
demand in Berry (1994), I test the set of instruments predict the endogenous variables
and reject the null hypothesis of weak instruments.\footnote{Following Stock and Yogo (2005), I use the Kleibergen-Paap Wald statistic, the analog of the Cragg-
Donald statistic for equations with robust standard errors, to test and reject the null. Less formally, the
F-statistic for the first-stage regression is substantially larger than 10, the rule of thumb suggested by
Staiger and Stock (1997).} Beyond the formal test, where
rejection should be interpreted cautiously, economic theory and intuition suggest lit-
tle reason to suspect weak instruments. Standard theories of incidence predict that
taxes impact prices except under a narrow set of circumstances such as perfectly elastic
demand. Further, empirical studies of incidence have frequently found substantial pass-through, if not over-shifting in many instances (Poterba, 1996; Besley and Rosen, 1999; Kenkel, 2005). Agrawal, White and Williams (2018) provide evidence aviation taxes influence a route’s price as well as the prices of routes linked within a carrier’s network.

The exclusion restriction is inherently more difficult to justify, but there are a number of reasons to be optimistic about why taxes and rival characteristics qualify. First, rival characteristics are unlikely to directly enter the utility or marginal cost for a route. For example, other than observed changes in price, the utility a passenger receives by flying nonstop is unaffected by the presence of another nonstop flight by a different carrier. More generally, flights with closer substitutes are likely to have lower prices without changing a passenger’s willingness to pay. Similarly, taxes are also unlikely to be correlated with unobserved determinants of demand or cost for at least two reasons. First, they are assessed at either the airport or the national level while demand and cost are driven by route-level considerations. Second, they are assessed for long periods of time, require a lengthy bureaucratic process to be implemented (see Figure 5 for a flowchart from the FAA describing the timing of implementation), and as noted in Table 3 often expire at the national level due to unrelated difficulty by Congress in agreeing to a budget. More generally, the included controls and rich set of fixed effects absorb much of the unobserved heterogeneity in the demand and cost equations. The remaining portions of the error terms are difficult to predict, and, as Berry and Jia (2010) highlight, many of the elements which constitute $\Delta \xi_{rt}$ and $\Delta \omega_{rt}$ such as gate locations, aircraft fleets, etc. are exogenous in the short run.

5 Results

Tables 4 and 5 present parameter estimates of the model. Coefficients have the anticipated sign. On the demand side, higher prices, all else equal, are associated with lower utility. The nested logit parameter $\sigma$ is between zero and one, a necessary condition for demand curves consistent with standard utility theory. It is also statistically different from zero, indicating a multinomial logit model would be inappropriate. The
parameter governs substitution to the outside option, with greater values correlated with greater substitution to within-nest options. In my model, the relatively high value of .73 indicates most consumers substitute to other forms of air travel given a fare increase. Nonstop routes provide additional utility. Longer routes within a market provide less utility. They do so at a diminishing rate (which does not turn positive over any relevant range of miles). Finally, flying out of an airport with greater centrality, where a carrier has more nonstop destinations, provides greater utility. This is consistent with what other studies have found and generally attributed to improved service and increased benefits of loyalty programs. While it is generally more difficult to gauge if the magnitudes of the coefficients are appropriate, the price coefficient implies an elasticity of 1.71 for the median market. Berry and Jia (2010) report similar elasticity estimates of 1.55 in 1999 and 1.67 in 2006.

The predicted marginal cost and markups from the model are consistent with the prior literature. The average marginal cost is $164 and the average markup, defined as $\frac{p_{rt} - mc_{rt}}{mc_{rt}}$, is .52. Each of the estimates is within the range of reported estimates in
Table 4: Demand Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fare ($\alpha$)</td>
<td>0.0028</td>
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<tr>
<td>$\sigma$</td>
<td>0.7325</td>
</tr>
<tr>
<td>Nonstop</td>
<td>0.3501</td>
</tr>
<tr>
<td>Distance</td>
<td>-0.5482</td>
</tr>
<tr>
<td>Distance$^2$</td>
<td>0.0724</td>
</tr>
<tr>
<td>Origin Centrality</td>
<td>0.2424</td>
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<tr>
<td>Carrier</td>
<td>Yes</td>
</tr>
<tr>
<td>Market</td>
<td>Yes</td>
</tr>
<tr>
<td>Time</td>
<td>Yes</td>
</tr>
</tbody>
</table>

N = 10,043,026

Note: This table reports the demand parameters specified in equation (1). The fare ($\alpha$) and $\sigma$ parameters govern price sensitivity and substitution to the outside option. Nonstop is an indicator equal to one if a route does not use a connecting airport. Distance refers to the number of miles flown on the route and is per 1000 miles. Origin Centrality is defined as the share of destinations served nonstop by a carrier out of the origin. The specification includes carrier, market (i.e., origin-destination), and time (year-quarter) fixed effects. Positive values indicate greater indirect utility as the characteristic increases.

Table 5: Marginal Cost Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimate</th>
<th>$\gamma_0$</th>
<th>$\gamma_1$</th>
<th>$\gamma_2$</th>
<th>$\gamma_3$</th>
<th>$\gamma_4$</th>
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<td>Distance</td>
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<td>0.0679</td>
<td>0.0009</td>
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<tr>
<td>Distance$^2$</td>
<td>-1.685</td>
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<td></td>
<td></td>
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<tr>
<td>Nonstop</td>
<td>-69.5737</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>$c(Q_s)$</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carrier</td>
<td>Yes</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Origin</td>
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<tr>
<td>Destination</td>
<td>Yes</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time</td>
<td>Yes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

N = 10,043,026

Note: This table reports the marginal cost parameters specified in Equation (5). Distance refers to the number of miles flown on the route and is per 1000 miles. Nonstop is an indicator equal to one if a route does not use a connecting airport. The set of $\gamma$ parameters corresponds to the linear spline specification in equation (6). The specification includes carrier, origin, destination, and time (year-quarter) fixed effects. Positive values indicate increased route marginal cost.
Berry and Jia (2010). All else equal, an additional 1,000 miles adds $89 to a flight.\textsuperscript{18} The estimated spline function $c(Q_s)$ describes changes in marginal cost of a segment as more passengers are added to a segment. I find evidence for economies of scale, and thus cost complementarities. Economies of scale level off for segments with greater density. To illustrate, Figure 6 displays the marginal cost of a thousand-mile segment for the 4th quarter of 2015. The marginal cost starts at approximately $190 but declines rapidly before leveling off around $160 for routes in the largest quartile.

Figure 6: Segment Marginal Cost and Quantity

![Figure 6: Segment Marginal Cost and Quantity](image)

Note: This figure illustrates the marginal cost for a thousand-mile segment in the 4th quarter of 2015 as the quantity on the segment increases. A thousand miles is approximately the mean distance traveled by passengers on a route. It utilizes parameter estimates from Table 5 to illustrate the linear spline specification detailed in equation (6). The plot is conditional on the sample restrictions outlined in Section 2.1.

\textsuperscript{18}A thousand miles is approximately the distance of a flight from Boston to St. Louis.
6 Tax Simulation and Counterfactuals

One of the primary benefits of a structural approach is the ability to simulate alternative tax policies. Section 6.1 provides an overview of how I solve for optimal prices given a change in tax policy. In section 6.2, I begin by demonstrating that the intuition from theoretical network models and empirical results such as those in Agrawal, White and Williams (2018a) has not been compromised by the structure or assumptions made during estimation. I then review the primary predictions on how cost complementarities impact pass-through and incidence on both taxed and untaxed routes. Next, in section 6.3, I suggest alternative revenue-neutral tax policies, including those which exploit cost complementarities by subsidizing hubs.

6.1 Solving for Optimal Prices

The proposal of any alternative tax schedule requires firms to reoptimize. To find the new set of equilibrium prices, I search for the new set of equilibrium prices using the first-order conditions. Specifically, I search for a fixed point which satisfies

\[ q(p) + (\Delta \ast M)p - (\Delta \ast M)(S \ast \underbrace{mc(q(p))}_{mc_r} + T) = 0 \]  

(9)

where \( q \) is vector of route shares, \( \Delta \) is the matrix capturing how shares change in response to price changes, \( \frac{\partial q}{\partial p} \), as defined by the demand model, \( M \) is an indicator matrix (to be multiplied point-wise) if products are in the same market and operated by the same firm, \( p \) is the vector of route fares, \( S \) is the route by segment matrix of indicators for if the marginal cost of a segment is impacted, \( mc(q) \) is the vector of segment marginal costs, which are a function of \( q \), \( T \) is the vector of specific taxes on a route and \( mc_r \) equals the vector of route marginal costs. There is no guarantee that a fixed point exists or that it is unique. However, for the fixed point I find, I confirm second-order conditions hold at equilibrium prices \( p^* \). I then use \( p^* \) to calculate predicted shares, quantities, consumer surplus, and any other equilibrium values. Appendix A.1 provides more explicit details for a simple network.
6.2 Tax Simulations

Even in simple theoretical models with cost complementarities and multi-product firms, taxation has ambiguous effects on prices, quantities, and the distribution of welfare. This ambiguity arises along two dimensions: direct incidence, the change in prices and welfare on taxed products, and indirect incidence, or changes in prices and welfare on untaxed products. Also, various factors such as the centrality of an airport might mitigate or amplify changes in direct or indirect incidence.

In terms of direct incidence, a tax on a particular route causes some passengers to substitute either to not flying or to other routes. The decline in passengers increases the marginal cost of segments on the route, which leads to higher prices. To partially capture the effect on direct incidence, I use the parameters from Tables 4 and 5 to compare prices in a network without taxes to a network in which every route is taxed $1. I find taxes are on average over-shifted, as tax-inclusive prices increase by $1.04 on average. Over-shifting of taxes is consistent with cost complementarities, but can also arise due to the curvature of demand or competitive responses in imperfect markets (Weyl and Fabinger, 2013).

In addition to the direct effect, network tax models predict ambiguous changes in indirect incidence due to the multi-product nature of firms and substitution to alternative routes. First, the same segment appearing in multiple routes connects their marginal costs, even if one route is not taxed. Consider two routes, operated by the same carrier, which share a segment: the first originates in Boston, flies to Philadelphia, and has a final destination of Atlanta; the second originates in Detroit, flies to Philadelphia, and has a final destination of Atlanta. Thus, the two routes share an input, the flight segment from Philadelphia to Atlanta. A tax on enplanements in Boston will directly impact the first route but not the second. The Boston tax decreases passengers on the Boston to Atlanta route and thus decreases the number of passengers on the Philadelphia to Atlanta segment. The decline in passengers increases the marginal cost of the segment, which causes the price of the Detroit to Atlanta route to increase.

A second cause of indirect incidence arises from substitution to other routes in the
same market, including routes offered by rival carriers. Consider two connecting routes offered by rival carriers in the same Baltimore to Houston market: Baltimore to Atlanta to Houston with Delta, and Baltimore to Charlotte to Houston with American Airlines. A tax on Atlanta enplanements will increase the marginal cost of the Atlanta to Houston segment, increase the Delta route’s price, and shift marginal passengers from Delta to American. This lowers the cost of both American Airlines segments, lowers the price of that route, and lowers the price of other routes where those segments serve as an input. This example also highlights the possibility of price decreases on untaxed routes.

Empirically, the presence of indirect incidence, whether positive or negative, is clear. Figure 7 shows the mean direct and indirect effect when enplanements out of each airport are taxed individually and other segments remain untaxed. I measure indirect incidence by the mean change in price on all routes which do not have a segment originating in the taxed airport. To construct this figure, I simulate 150 tax scenarios, one for each airport in the sample, comparing before-tax and after-tax prices. For example, a $1 tax on all Atlanta enplanements leads to an average increase in price of 1.3 cents for passengers on routes without an Atlanta enplanement. While non-taxed fares often increase, fares decrease on untaxed routes for a substantial number of airports, as captured by the mass below 0 in panel (b).

The third result is that indirect incidence is greater out of more central airports, or hubs, than spoke airports. Indirect incidence occurs consistently across airports but varies in systematic ways. Notably, hubs or airports with greater centrality are predicted to exhibit greater indirect effects. A tax on enplanements at hubs impacts more passengers and segments, resulting in greater indirect incidence. Figure 9 maps the relationship between airport centrality and indirect incidence from a $1 tax on enplanements at each airport when all other airports are untaxed. Each dot represents one of the 150 airports included in the sample. The size corresponds to the airport’s centrality. A larger dot indicates a more centrally connected airport. The color corresponds to the sign and magnitude of the mean indirect incidence. Blue dots indicate negative indirect incidence. Red dots indicate positive indirect incidence. More intense colors indicate
Figure 7: Distribution of Direct and Indirect Incidence

(a) Direct

(b) Indirect

Note: Panel A and Panel B respectively depict the distribution of the mean direct and mean indirect change in prices from a $1 tax on enplanements at each airport when all other airports are untaxed. To construct this figure, I simulate 150 tax scenarios, one for each airport in the sample, comparing before-tax and after-tax prices. The figure is conditional on the sample restrictions outlined in Section 2.1 and parameters in Section 5.

greater magnitudes. In general, larger dots are a deeper shade of red. This is clearest for major hubs such as Atlanta, Dallas-Fort Worth, and Chicago O’Hare. Panel A in Figure 8 provides an alternative visualization by plotting indirect incidence as airport centrality changes from the exercise in separately taxing each airport. In panel B, I plot the change in consumer surplus and origin centrality for each airport from a $1 tax increase on enplanements.

6.3 Counterfactuals

6.3.1 Universal Tax

In many settings, consumer welfare is improved by imposing a lump-sum tax or eliminating spatial distortions in taxes. In a network setting with cost complementarities, consumers may gain little from setting universal taxes when tax reforms are constrained to be revenue neutral. Table 6 provides a comparison between current tax policy, elim-
Figure 8: Centrality and Incidence

(a) Indirect Incidence and Airport Centrality  (b) Consumer Surplus Change and Airport Centrality

Note: Panel (a) charts the mean indirect incidence and airport centrality from a $1 tax on enplanements at each airport when all other airports are untaxed. Panel (b) depicts the corresponding change in consumer surplus. Indirect incidence is defined as the change in prices from all routes which are not taxed. For a given airport, centrality is the share of airports with nonstop flights from the given airport. To construct this figure, I simulate 150 tax scenarios, one for each airport in the sample, comparing before-tax and after-tax prices. The figure is conditional on the sample restrictions outlined in Section 2.1 and parameters in Section 5.

Incorporating taxes, and collecting the same total tax revenue via either a uniform route or uniform segment tax. Under current tax policy for the final quarter in my sample, the fourth quarter of 2015, the average tax per passenger is $17.67, the average tax per route is $21.87, and the average tax per segment flown is $12.39. Holding revenue constant, standardizing taxes per route results in a tax of $17.65 per route and an increase in consumer surplus of .2%. Alternatively, standardizing taxes per segment results in a tax of $12.50 per segment and essentially no change in consumer surplus. One reason passengers do not experience greater welfare changes from eliminating tax variation is current tax policy largely treats routes equivalently, especially when they have the same number of segments. Variation in tax treatment across routes has declined as airports imposed the maximum PFC. By the end of the sample period, nearly all airports assessed the maximum allowable charge of $4.50.

While consumer welfare changes are minimal, Table 6 highlights the incentives taxes
Figure 9: Indirect Incidence and Airport Centrality

Note: This figure projects the relationship between indirect incidence and airport centrality from a $1 tax on enplanements at each airport when all other airports are untaxed. Each dot represents one of the 150 airports included in the sample. The size corresponds to the airport’s centrality. Larger indicates a more centrally connected airport. The color corresponds to the sign and magnitude of the mean indirect incidence. Blue dots indicate negative indirect incidence. Red dots indicate positive indirect incidence. More intense colors indicate greater magnitudes. The map is an alternative visualization of panel (a) in Figure 8.
Table 6: Counterfactual Policy Comparison

<table>
<thead>
<tr>
<th>Tax Policy:</th>
<th>Current</th>
<th>No Taxes</th>
<th>Universal $17.65 per route</th>
<th>Universal $12.47 per segment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tax Revenue</td>
<td>1.0</td>
<td>0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Consumer Surplus</td>
<td>1.0</td>
<td>1.053</td>
<td>1.002</td>
<td>0.999</td>
</tr>
<tr>
<td>Total Quantity</td>
<td>1.0</td>
<td>1.052</td>
<td>1.002</td>
<td>0.999</td>
</tr>
<tr>
<td>Nonstop Passengers</td>
<td>1.0</td>
<td>1.025</td>
<td>0.976</td>
<td>1.012</td>
</tr>
<tr>
<td>Connecting Passengers</td>
<td>1.0</td>
<td>1.090</td>
<td>1.036</td>
<td>0.982</td>
</tr>
<tr>
<td>Total miles flown</td>
<td>1.0</td>
<td>1.064</td>
<td>1.012</td>
<td>0.998</td>
</tr>
</tbody>
</table>

Note: This table summarizes the impact of different tax policies on total consumer surplus, the total quantity of passengers, the total number of nonstop and connecting passengers, and the total number of miles flown. For any row, 1.0 is equivalent to current policy.

have on the type of routes passengers utilize. Relative to current policy, which utilizes a mix of route and segment taxes, a universal route tax eliminates an incentive to minimize the number of segments on an itinerary. Thus, while total quantity is largely unchanged, 3.6% more passengers travel via connecting as opposed to nonstop routes. Alternatively, a universal segment tax results in a 1.2% increase in nonstop passengers relative to current policy. Also, while a universal segment tax slightly reduces total distance, a route tax will increase the total number of miles flown by 1.2%.

6.3.2 Incorporating Cost Complementarities into Tax Policy

Given the presence of cost complementarities, a universal tax is not the optimal policy. As Figure 8 indicates, greater welfare gains might be realized from subsidizing hubs, where the marginal impact on consumer welfare is largest. Figure 10 illustrates the effect of an alternative policy in which non-hub segments are taxed at the revenue-neutral rate of $12.47 per segment, while segments departing from one of the ten most central airports (i.e., hubs) are taxed at a percentage of the universal tax. From left to right, the figure depicts no subsidization, where all segments are subject to the revenue-neutral universal tax of $12.50, to 100% subsidization, where enplanements at hubs are untaxed. Subsidizing leads to consumer welfare gains but also declines in tax revenue. When the ten largest hubs are fully subsidized, consumer welfare increases by 1.6% and
tax revenue declines to 70% of current revenues.

Figure 10 depicts a tax policy which transfers tax revenue to consumers. Cost complementarities provide the possibility to subsidize hubs, and improve welfare, while raising an equivalent amount of tax revenue. Figure 11 depicts the change in consumer surplus from a revenue-neutral subsidy for the ten airports with greatest network centrality (i.e., hubs). The increase in consumer surplus is relative to consumer surplus generated by setting a universal revenue-neutral segment tax. Subsidization requires a substantial increase in the tax rate applied to enplanements on non-hub segments. Under full subsidization, every non-hub segments is assessed a tax of $18.50.

Figure 10: Consumer Surplus and Hub Subsidy: Declining Revenue

Note: This figure illustrates the increase in consumer welfare and tax revenue relative to current policy when enplanements at the ten most central airports are subject to a lower tax rate. Enplanements at non-hub segments are subject to the revenue-neutral universal tax of $12.50 per passenger. To construct this figure, for each of the subsidized tax rates, I find the new set of profit-maximizing prices and calculate total consumer surplus and total tax revenue. The figure is conditional on the sample restrictions outlined in Section 2.1 and parameters in Section 5.
Note: This figure illustrates the increase in consumer welfare when enplanements at the ten most central airports are subject to a lower tax rate. Improvement in consumer welfare is graphed on the left axis and the non-hub tax rate is graphed on the right axis. Enplanements at non-hub segments are subject to a revenue-neutral tax, which increases to offset the subsidy. To construct this figure, for each of the subsidized tax rates, I find the revenue-neutral tax to apply to non-hub segments by starting at a low tax and slowly increasing until tax-revenue is unchanged. For each iteration of subsidy and non-hub tax rate, I find the new set of profit-maximizing prices, calculate total consumer surplus, and total tax revenue. The figure is conditional on the sample restrictions outlined in Section 2.1 and parameters in Section 5.
6.3.3 Competing Effects on Prices

The small increase in consumer welfare from hub subsidies is partially due to ambiguous price effects. This is most clear when one examines a tax on enplanements at a single airport and the impact of that tax on a subset of fares. Figure 12 depicts for the 4th quarter of 2015 how a $1 tax on enplanements at Atlanta changes fares in markets where Atlanta serves as a connecting airport, even if a route is not itself taxed. Panel (a) illustrates the distribution of fare changes for directly taxed routes (i.e., RDU to ATL to LAX), while panel (b) illustrates the distribution of fare changes for untaxed routes (i.e., RDU to DFW to LAX). There are 81,796 routes in markets where Atlanta is a connecting airport. Of those routes, 11,332 connect via Atlanta and are directly taxed, while 70,464 have the same origin and final destination of a taxed route but are not directly taxed. For directly taxed routes, a $1 tax increases prices by approximately 97 cents on average. Further, 46% of routes experience over-shifting or an increase in price greater than the tax. For untaxed routes, a $1 tax increases prices by 2.7 cents per route. In terms of heterogeneity, 33.6% see fares decline while 66.4% of untaxed fares increase. In my model, declines in fare are attributable to cost complementarities, which lower cost as passengers substitute to alternative routes. Fare increases on untaxed routes are a strategic response to the price increase of a substitutable product. These competing prices effects, which are similar across airports, partially negate many of the potential welfare gains from hub subsidization.

7 Conclusion

I study how the linkages between a firm’s products impact the magnitude and distribution of incidence spatially within a network and across products. In nearly every industry, firms structure their product offerings to optimally respond to demand and cost considerations. Despite this, relatively little work has been done to better understand how connections between a firm’s products impact the welfare burden of taxes and the efficiency of raising revenue. Theoretical results (Edgeworth, 1925; Coase, 1946) have long emphasized the wide range of potential incidence outcomes from taxation of multi-
product firms. These results established the need for empirical estimates to address questions regarding how factors such as cost complementarities, which link products, influence cross-product incidence, what characteristics of products impact incidence, and how tax policy should be adjusted to account for these factors.

To explore these and other questions, I develop a discrete-choice oligopoly model where profit-maximizing firms compete by choosing prices. In choosing prices, a firm accounts for both substitution to other products it owns and how changes in price affect the cost of potentially many products. I examine a network setting, the U.S. domestic aviation industry, where connections between a firm’s products are observed and cost complementarities between products are well-established both theoretically and empirically. I estimate the model using the Data Bank 1B (DB1B) of the U.S Department of Transportation’s Origin and Destination Survey for the years 1993 through 2015 and the tax calculator from Agrawal, White and Williams (2018b), which decomposes the reported fare into taxes and the base fare set by the carrier.
The key fact for my model, as well as prior models of the industry, is that the marginal cost for operating a flight segment declines over a relevant range of equilibrium quantities. This fact, combined with the same segment appearing on multiple routes, leads to at least three notable comparative statics on the relationship between taxes and incidence across the network. First, relative to a world without cost complementarities, price will increase by a larger amount (i.e., pass-through will be greater) on the taxed route. This incidence, which I refer to as direct incidence, is greater because passengers substituting to other routes or to not flying increases the marginal costs for the segments composing the route. Second, incidence on untaxed routes, or indirect incidence, is impacted by taxes elsewhere in the network. For example, routes which share segments will see their marginal cost increase. Third, more central airports or hubs will see larger indirect effects due to their role within the network. In my empirical analysis, I find evidence for all of these comparative statics. Incorporating these findings, I propose counterfactual tax policies which mimic the current tax structure but adjust taxes according to the centrality of a route’s airports. The alternative revenue-neutral tax policy leads to an increase in consumer welfare.

While my research speaks directly to potential improvements in U.S. aviation tax policy, more broadly I provide insight on the role of firms’ strategic response to taxes and the at times conflicting incentives between local tax authorities, who fail to internalize price changes in other markets, and federal tax authorities responsible for the financial health of the industry as a whole. This situation is not dissimilar from the misalignment of incentives in models between individual agents and a social planner. As in the aviation industry, tax policy often arises in an ad-hoc fashion out of legislation to address particular concerns. A comprehensive assessment of the cumulative effects of those policies and their interaction with important institutional details offers the possibility of welfare-improving reforms.

A number of topics and issues are not addressed by my model or empirical results, and are thus left for future research. First, a more flexible demand system than nested logit, especially one which more fully captures the curvature of demand, would allow
greater decomposition of the relative weight of incidence attributed to competitive or market-level factors and factors such as cost complementarities. Second, while I assume a fixed network structure, a model of firm entry and the evolution of the network would provide valuable insight into long-term incidence factors. Finally, I exploit the exogeneity of PFC timing in the short term, but an explicit model of local tax adoption would be valuable, especially for the design of tax systems.
References


Dubois, Pierre, Rachel Griffith, and Martin O’Connell. 2017. “How well targeted are soda taxes?” 4.1


A Appendix

A.1 Simple model

For illustrative purpose and to aid in explicitly laying out the estimation procedure, I present a model of a diamond network as depicted in Figure 13 similar to that found in Brueckner, Dyer and Spiller (1992) and Agrawal, White and Williams (2018a). In this model, airports A and B are connected via two hubs $H_1$ and $H_2$. The hubs are connected via a nonstop connection. All travel is assumed to take the shortest route. I assume a monopoly carrier serves the entire network. It is straightforward to add additional carriers.

For notational simplicity, I consider only non-directional round-trip markets defined by the endpoints. Thus, passengers traveling from A to B round-trip and passengers traveling B to A round-trip are in the same market. Given the network structure, six markets exist: A to $H_1$, A to $H_2$, B to $H_1$, B to $H_2$, $H_1$ to $H_2$, and A to B. Given these markets and the assumption on travel, the full set of routes $R_c$ for carrier $c$ is
composed of routes $r_j$ where $j \in \{ah_1, ah_2, bh_1, bh_2, ah_1b, ah_2b, h_1h_2\}$. There are seven routes because market A to B includes two potential routes, capturing connection via either hub. For one-stop routes in the A to B market, the connecting hub is noted in between a and b. In this network, the set of segments $S_c$ operated by $c$ is composed of five segments $s_k$ where $k \in \{AH_1, AH_2, BH_1, BH_2, H_1H_2\}$. The carrier will choose a price $p_r$ for each route which will result in a quantity of passengers $q_r$ on each route. These quantities are inputs into the costs for each of the segments:

$$
C_{AH_1}(q_{ah_1} + q_{ah_1b})
$$

$$
C_{AH_2}(q_{ah_2} + q_{ah_2b})
$$

$$
C_{BH_1}(q_{bh_1} + q_{ah_1b})
$$

$$
C_{BH_2}(q_{bh_2} + q_{ah_2b})
$$

$$
C_{H_1H_2}(q_{h_1h_2})
$$

Prices are chosen to maximize profit for the carrier (with taxes included within the cost function for convenience):

$$
\pi = \sum_{R_c} p_r q_r - \sum_{S_c} C(Q_s)
$$

Assuming changes in prices affect only other products within a market yields a first-order condition for each of the routes:
\[
\begin{align*}
\{ah_1\} & : q_{ah_1} + p_{ah_1} \frac{\partial q_{ah_1}}{\partial p_{ah_1}} - mc_{ah_1} \frac{\partial q_{ah_1}}{\partial p_{ah_1}} = 0 \\
\{ah_2\} & : q_{ah_2} + p_{ah_2} \frac{\partial q_{ah_2}}{\partial p_{ah_2}} - mc_{ah_2} \frac{\partial q_{ah_2}}{\partial p_{ah_2}} = 0 \\
\{bh_1\} & : q_{bh_1} + p_{bh_1} \frac{\partial q_{bh_1}}{\partial p_{bh_1}} - mc_{bh_1} \frac{\partial q_{bh_1}}{\partial p_{bh_1}} = 0 \\
\{bh_2\} & : q_{bh_2} + p_{bh_2} \frac{\partial q_{bh_2}}{\partial p_{bh_2}} - mc_{bh_2} \frac{\partial q_{bh_2}}{\partial p_{bh_2}} = 0 \\
\{ah_1b\} & : q_{ah_1b} + p_{ah_1b} \frac{\partial q_{ah_1b}}{\partial p_{ah_1b}} + p_{ah_2b} \frac{\partial q_{ah_2b}}{\partial p_{ah_2b}} - mc_{ah_1b} \frac{\partial q_{ah_1b}}{\partial p_{ah_1b}} - mc_{ah_2b} \frac{\partial q_{ah_2b}}{\partial p_{ah_2b}} = 0 \\
\{ah_2b\} & : q_{ah_2b} + p_{ah_2b} \frac{\partial q_{ah_2b}}{\partial p_{ah_2b}} + p_{ah_1b} \frac{\partial q_{ah_1b}}{\partial p_{ah_1b}} - mc_{ah_2b} \frac{\partial q_{ah_2b}}{\partial p_{ah_2b}} - mc_{ah_1b} \frac{\partial q_{ah_1b}}{\partial p_{ah_1b}} = 0 \\
\{bh_1b\} & : q_{bh_1b} + p_{bh_1b} \frac{\partial q_{bh_1b}}{\partial p_{bh_1b}} - mc_{bh_1b} \frac{\partial q_{bh_1b}}{\partial p_{bh_1b}} = 0
\end{align*}
\]

For convenience in discussing the estimation procedure, I specify the first-order conditions in matrix notation:

\[
q + (\Delta \ast M)p - (\Delta \ast M) \left( S \ast mc_s + T \right) = 0
\]

(10)

where \( q \) is an \( |R_c| \times 1 \) vector of shares, \( \Delta \) is the \( |R_c| \times |R_c| \) matrix of \( \frac{\partial q_{kt}}{\partial p_{rt}} \) as defined by the demand model, \( M \) is the \( |R_c| \times |R_c| \) indicator matrix (to be multiplied point-wise) if products are in the same market and operated by the same firm, \( p \) is the \( |R_c| \times 1 \) vector of fares, \( S \) is the \( |R_c| \times |S_{ct}| \) matrix of indicators for if the marginal cost of segment is impacted, \( mc_s \) is the \( |S_{ct}| \times 1 \) vector of segment marginal costs, \( T \) is the \( |R_c| \times 1 \) vector of specific taxes on a route and \( mc_r \) is the \( |R_{ct}| \times 1 \) vector of route marginal costs.

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To be explicit, the matrices which define this network are

$$q = \begin{bmatrix} q_{ah_1} \\ q_{ah_2} \\ q_{bh_1} \\ q_{bh_2} \\ q_{ah_1b} \\ q_{ah_2b} \\ q_{bh_1b_2} \end{bmatrix}, \quad mc_s = \begin{bmatrix} mc_{ah_1} \\ mc_{ah_2} \\ mc_{bh_1} \\ mc_{bh_2} \\ mc_{bh_1b_2} \end{bmatrix}, \quad p = \begin{bmatrix} p_{ah_1} \\ p_{ah_2} \\ p_{bh_1} \\ p_{bh_2} \\ p_{ah_1b} \\ p_{ah_2b} \end{bmatrix}$$

$$\Delta = \begin{bmatrix} \frac{\partial q_{ah_1}}{\partial q_{ah_1}} & \frac{\partial q_{ah_1}}{\partial q_{ah_2}} & \frac{\partial q_{ah_1}}{\partial q_{bh_1}} & \frac{\partial q_{ah_1}}{\partial q_{bh_2}} & \frac{\partial q_{ah_1}}{\partial q_{ah_1b}} & \frac{\partial q_{ah_1}}{\partial q_{ah_2b}} & \frac{\partial q_{ah_1}}{\partial q_{bh_1b_2}} \\ \frac{\partial p_{ah_1}}{\partial q_{ah_1}} & \frac{\partial p_{ah_1}}{\partial q_{ah_2}} & \frac{\partial p_{ah_1}}{\partial q_{bh_1}} & \frac{\partial p_{ah_1}}{\partial q_{bh_2}} & \frac{\partial p_{ah_1}}{\partial q_{ah_1b}} & \frac{\partial p_{ah_1}}{\partial q_{ah_2b}} & \frac{\partial p_{ah_1}}{\partial q_{bh_1b_2}} \\ \frac{\partial q_{ah_2}}{\partial q_{ah_1}} & \frac{\partial q_{ah_2}}{\partial q_{ah_2}} & \frac{\partial q_{ah_2}}{\partial q_{bh_1}} & \frac{\partial q_{ah_2}}{\partial q_{bh_2}} & \frac{\partial q_{ah_2}}{\partial q_{ah_1b}} & \frac{\partial q_{ah_2}}{\partial q_{ah_2b}} & \frac{\partial q_{ah_2}}{\partial q_{bh_1b_2}} \\ \frac{\partial p_{ah_2}}{\partial q_{ah_1}} & \frac{\partial p_{ah_2}}{\partial q_{ah_2}} & \frac{\partial p_{ah_2}}{\partial q_{bh_1}} & \frac{\partial p_{ah_2}}{\partial q_{bh_2}} & \frac{\partial p_{ah_2}}{\partial q_{ah_1b}} & \frac{\partial p_{ah_2}}{\partial q_{ah_2b}} & \frac{\partial p_{ah_2}}{\partial q_{bh_1b_2}} \\ \frac{\partial q_{bh_1}}{\partial q_{ah_1}} & \frac{\partial q_{bh_1}}{\partial q_{ah_2}} & \frac{\partial q_{bh_1}}{\partial q_{bh_1}} & \frac{\partial q_{bh_1}}{\partial q_{bh_2}} & \frac{\partial q_{bh_1}}{\partial q_{ah_1b}} & \frac{\partial q_{bh_1}}{\partial q_{ah_2b}} & \frac{\partial q_{bh_1}}{\partial q_{bh_1b_2}} \\ \frac{\partial p_{bh_1}}{\partial q_{ah_1}} & \frac{\partial p_{bh_1}}{\partial q_{ah_2}} & \frac{\partial p_{bh_1}}{\partial q_{bh_1}} & \frac{\partial p_{bh_1}}{\partial q_{bh_2}} & \frac{\partial p_{bh_1}}{\partial q_{ah_1b}} & \frac{\partial p_{bh_1}}{\partial q_{ah_2b}} & \frac{\partial p_{bh_1}}{\partial q_{bh_1b_2}} \\ \frac{\partial q_{bh_2}}{\partial q_{ah_1}} & \frac{\partial q_{bh_2}}{\partial q_{ah_2}} & \frac{\partial q_{bh_2}}{\partial q_{bh_1}} & \frac{\partial q_{bh_2}}{\partial q_{bh_2}} & \frac{\partial q_{bh_2}}{\partial q_{ah_1b}} & \frac{\partial q_{bh_2}}{\partial q_{ah_2b}} & \frac{\partial q_{bh_2}}{\partial q_{bh_1b_2}} \\ \frac{\partial p_{bh_2}}{\partial q_{ah_1}} & \frac{\partial p_{bh_2}}{\partial q_{ah_2}} & \frac{\partial p_{bh_2}}{\partial q_{bh_1}} & \frac{\partial p_{bh_2}}{\partial q_{bh_2}} & \frac{\partial p_{bh_2}}{\partial q_{ah_1b}} & \frac{\partial p_{bh_2}}{\partial q_{ah_2b}} & \frac{\partial p_{bh_2}}{\partial q_{bh_1b_2}} \\ \frac{\partial q_{ah_1b}}{\partial q_{ah_1}} & \frac{\partial q_{ah_1b}}{\partial q_{ah_2}} & \frac{\partial q_{ah_1b}}{\partial q_{bh_1}} & \frac{\partial q_{ah_1b}}{\partial q_{bh_2}} & \frac{\partial q_{ah_1b}}{\partial q_{ah_1b}} & \frac{\partial q_{ah_1b}}{\partial q_{ah_2b}} & \frac{\partial q_{ah_1b}}{\partial q_{bh_1b_2}} \\ \frac{\partial p_{ah_1b}}{\partial q_{ah_1}} & \frac{\partial p_{ah_1b}}{\partial q_{ah_2}} & \frac{\partial p_{ah_1b}}{\partial q_{bh_1}} & \frac{\partial p_{ah_1b}}{\partial q_{bh_2}} & \frac{\partial p_{ah_1b}}{\partial q_{ah_1b}} & \frac{\partial p_{ah_1b}}{\partial q_{ah_2b}} & \frac{\partial p_{ah_1b}}{\partial q_{bh_1b_2}} \\ \frac{\partial q_{ah_2b}}{\partial q_{ah_1}} & \frac{\partial q_{ah_2b}}{\partial q_{ah_2}} & \frac{\partial q_{ah_2b}}{\partial q_{bh_1}} & \frac{\partial q_{ah_2b}}{\partial q_{bh_2}} & \frac{\partial q_{ah_2b}}{\partial q_{ah_1b}} & \frac{\partial q_{ah_2b}}{\partial q_{ah_2b}} & \frac{\partial q_{ah_2b}}{\partial q_{bh_1b_2}} \\ \frac{\partial p_{ah_2b}}{\partial q_{ah_1}} & \frac{\partial p_{ah_2b}}{\partial q_{ah_2}} & \frac{\partial p_{ah_2b}}{\partial q_{bh_1}} & \frac{\partial p_{ah_2b}}{\partial q_{bh_2}} & \frac{\partial p_{ah_2b}}{\partial q_{ah_1b}} & \frac{\partial p_{ah_2b}}{\partial q_{ah_2b}} & \frac{\partial p_{ah_2b}}{\partial q_{bh_1b_2}} \\ \frac{\partial q_{bh_1b_2}}{\partial q_{ah_1}} & \frac{\partial q_{bh_1b_2}}{\partial q_{ah_2}} & \frac{\partial q_{bh_1b_2}}{\partial q_{bh_1}} & \frac{\partial q_{bh_1b_2}}{\partial q_{bh_2}} & \frac{\partial q_{bh_1b_2}}{\partial q_{ah_1b}} & \frac{\partial q_{bh_1b_2}}{\partial q_{ah_2b}} & \frac{\partial q_{bh_1b_2}}{\partial q_{bh_1b_2}} \\ \frac{\partial p_{bh_1b_2}}{\partial q_{ah_1}} & \frac{\partial p_{bh_1b_2}}{\partial q_{ah_2}} & \frac{\partial p_{bh_1b_2}}{\partial q_{bh_1}} & \frac{\partial p_{bh_1b_2}}{\partial q_{bh_2}} & \frac{\partial p_{bh_1b_2}}{\partial q_{ah_1b}} & \frac{\partial p_{bh_1b_2}}{\partial q_{ah_2b}} & \frac{\partial p_{bh_1b_2}}{\partial q_{bh_1b_2}} \end{bmatrix}$$

$$M = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}, \quad S = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$
\[
\Delta \ast M = \begin{bmatrix}
\frac{\partial q_{ah_1}}{\partial p_{ah_1}} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{\partial q_{ah_2}}{\partial p_{ah_2}} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & \frac{\partial q_{bh_1}}{\partial p_{bh_1}} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{\partial q_{bh_2}}{\partial p_{bh_2}} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{\partial q_{ah_1b}}{\partial p_{ah_1b}} & \frac{\partial q_{ah_2b}}{\partial p_{ah_2b}} & 0 \\
0 & 0 & 0 & 0 & \frac{\partial q_{ah_1b}}{\partial p_{ah_1b}} & \frac{\partial q_{ah_2b}}{\partial p_{ah_2b}} & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{\partial q_{bh_1h_2}}{\partial p_{bh_1h_2}} & 0 \\
\end{bmatrix}
\]

In application, \( q \) and \( p \) are constructed from data. Similarly, the ownership matrix \( M \) is observed. The most complicated to construct is \( S \), but one can recover route marginal cost without it. Still, \( S \) can be observed and has an intuitive structure. Each column represents a segment. An element of 1 indicates product \( r \) has a direct impact on the marginal cost of that segment. Each row represents a product. An element of 1 indicates the segments which compose the product. Thus, the first column in \( S \) captures the segment \( AH_1 \). Given this market structure, the two products which are inputs into the marginal cost of \( AH_1 \) are \( ah_1 \) and \( ah_1b \). The first row captures the product \( ah_1 \). Segment \( AH_1 \) is the only segment for \( ah_1 \) and thus a 1 appears only for the first column. For a connecting route such as \( ah_1b \), captured by the fifth row and composed of segments \( AH_1 \) and \( BH_1 \), a one appears in the first and third columns corresponding to their respective columns.

A.2 Estimation

Estimation exploits the fact that at the true parameter values the error terms are uncorrelated with the instruments, i.e., \( E[\Delta \xi Z_d] = E[\Delta \omega Z_s] = 0 \). Modeling utility and marginal costs provides two sets of moment conditions, one for each of the error terms on a route. The terms \( \Delta \xi \) and \( \Delta \omega \) are defined by the model laid out in section 3. Explicitly,
θ, the full set of parameters, is chosen to minimize $q(\theta) \equiv g(\theta)W^{-1}g(\theta)'$ where

$$g(\theta) = \begin{bmatrix} \Delta \xi_1 & \cdots & \Delta \xi_r & \Delta \omega_1 & \cdots & \Delta \omega_r \end{bmatrix}'\begin{bmatrix} z_{11} & \cdots & z_{1z_d} & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ z_{r1} & \cdots & z_{rz_d} & 0 & \cdots & 0 \\ 0 & \cdots & 0 & z_{11} & \cdots & z_{1z_s} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & z_{r1} & \cdots & z_{rz_s} \end{bmatrix}$$

$$W = \begin{bmatrix} Z_d & 0 \\ 0 & Z_s \end{bmatrix}$$

where $Z_d$ and $Z_s$ are $r \times z_d$ and $r \times z_s$ matrices.

To be precise, the error terms defined by the model are

$$\begin{bmatrix} \Delta \xi_1 \\ \vdots \\ \Delta \xi_r \\ \Delta \omega_1 \\ \vdots \\ \Delta \omega_r \end{bmatrix} = \begin{bmatrix} \delta_1 \\ \vdots \\ \delta_r \\ mc_1 \\ \vdots \\ mc_r \end{bmatrix} - \begin{bmatrix} x_{11} & \cdots & x_{1k_d} & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ x_{r1} & \cdots & x_{rk_d} & 0 & \cdots & 0 \\ 0 & \cdots & 0 & x_{11} & \cdots & x_{1k_s} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & x_{r1} & \cdots & x_{rk_s} \end{bmatrix}$$

The nested logit framework provides an analytical solution for the mean utility $\delta$ such that for a given route $\delta = ln(q_r) - \sigma ln(\bar{q}_r/m) - ln(q_0)$ where $q_r$ is the route’s market share, $\bar{q}_r/m$ is route’s share of passengers choosing air travel, and $q_0$ is the share of the outside option. The marginal cost for a given route is defined by taking the log of the inversion of the firm’s first-order conditions, as laid out in equation (10). Explicitly, it is

$$mc = ln(p_r - (\Delta \ast M)^{-1}q_r)$$

where $\Delta$ is defined by the nested logit demand specification.
Explicitly, $\Delta$, an $r \times r$ matrix, is defined so element $(r, r')$ is

$$\frac{\partial q_{r'}}{\partial p_r} = \begin{cases} 
-\alpha q_r \frac{1}{1-\sigma} \left(1 - \sigma \bar{q}_{r/m} - (1-\sigma)q_r\right) & \text{if } r = r' \\
\alpha q_r \frac{\sigma}{1-\sigma} \bar{q}_{r'/m} + q_{r'} & \text{if } r \neq r' \text{ and } r \text{ and } r' \text{ in same nest} \\
0 & \text{if } r \neq r' \text{ and } r \text{ and } r' \text{ in different nests}
\end{cases}$$

The third row’s specification that substitution between nests equals zero is a direct consequence of the assumption passengers do not shift across markets when price changes. In other words, an increase in the price of a route between New York and Los Angeles will not cause a potential passenger to shift their travel plans to New York to Miami. They may still choose to not fly. This assumption is violated for a subset of consumers, especially tourists, but is necessary to make computation feasible.

To recover parameters, I perform a non-linear search over the terms linking supply and demand, $\alpha$ and $\sigma$, and recover the remaining linear parameters via two-staged least squares. Specifically, for the linear parameters, given a guess of $\alpha$ and $\sigma$, I estimate:

$$\hat{\theta} = \left( \begin{bmatrix} X_d & 0 \\ 0 & X_s \end{bmatrix} \begin{bmatrix} Z_d & 0 \\ 0 & Z_s \end{bmatrix} \right) W^{-1} \left( \begin{bmatrix} X_d & 0 \\ 0 & X_s \end{bmatrix} \begin{bmatrix} Z_d & 0 \\ 0 & Z_s \end{bmatrix} \right)^{-1} \begin{bmatrix} \hat{\delta} \\ \hat{mc} \end{bmatrix}$$

where $\hat{\delta}$ and $\hat{mc}$ are conditional on the guess of $\alpha$ and $\sigma$. 

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### A.3 Notation

Table 7: Notation

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r$</td>
<td>route-carrier (product)</td>
</tr>
<tr>
<td>$m$</td>
<td>airport-pair (market)</td>
</tr>
<tr>
<td>$c$</td>
<td>carrier/airline (firm)</td>
</tr>
<tr>
<td>$t$</td>
<td>year-quarter (time)</td>
</tr>
<tr>
<td>$u$</td>
<td>utility</td>
</tr>
<tr>
<td>$i$</td>
<td>individual consumer</td>
</tr>
<tr>
<td>$\mathbf{x}_{rt}$</td>
<td>vector of route characteristics for $r$ in period $t$</td>
</tr>
<tr>
<td>$p_{rt}$</td>
<td>fare (price) for route $r$ in period $t$</td>
</tr>
<tr>
<td>$\beta$</td>
<td>parameter vector of consumer preferences</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>fare coefficient</td>
</tr>
<tr>
<td>$\xi_{rt}$</td>
<td>unobserved (to econometrician) product characteristic or quality</td>
</tr>
<tr>
<td>$\nu_{it}$</td>
<td>“nested logit” taste parameter</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>nested logit parameter governing within-nest correlation</td>
</tr>
<tr>
<td>$\epsilon_{irt}$</td>
<td>multinomial logit error term</td>
</tr>
<tr>
<td>$D_{mt}$</td>
<td>total of all route shares in market $m$ during period $t$</td>
</tr>
<tr>
<td>$R_{mt}$</td>
<td>set of routes operated in market $m$ at time $t$</td>
</tr>
<tr>
<td>$q_{rt}$</td>
<td>market share for route $r$ during period $t$</td>
</tr>
<tr>
<td>$\xi_{m}$</td>
<td>time-invariant market-level unobserved product characteristic</td>
</tr>
<tr>
<td>$\xi_{c}$</td>
<td>time-invariant carrier-level unobserved product characteristic</td>
</tr>
<tr>
<td>$\xi_{t}$</td>
<td>period-level unobserved product characteristic</td>
</tr>
<tr>
<td>$m_{crt}$</td>
<td>marginal cost of route $r$ in period $t$</td>
</tr>
<tr>
<td>$s$</td>
<td>carrier-specific flight segment</td>
</tr>
<tr>
<td>$S_r$</td>
<td>set of segments which compose $r$</td>
</tr>
<tr>
<td>$Q_{st}$</td>
<td>total quantity of passengers on segment $s$ in period $t$</td>
</tr>
<tr>
<td>$w_{st}$</td>
<td>segment-level supply-side characteristics</td>
</tr>
<tr>
<td>$\omega_{rt}$</td>
<td>route specific error term</td>
</tr>
<tr>
<td>$\omega_o$</td>
<td>origin portion of route error term</td>
</tr>
<tr>
<td>$\omega_d$</td>
<td>destination portion of route error term</td>
</tr>
<tr>
<td>$\omega_t$</td>
<td>period-level portion of route error term</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>supply-side parameter vector</td>
</tr>
<tr>
<td>$N_r$</td>
<td>indicator if route $r$ is nonstop</td>
</tr>
<tr>
<td>$Q_{25}$</td>
<td>25 percentile of quantity CDF</td>
</tr>
<tr>
<td>$Q_{50}$</td>
<td>50 percentile of quantity CDF</td>
</tr>
<tr>
<td>$Q_{75}$</td>
<td>75 percentile of quantity CDF</td>
</tr>
<tr>
<td>$\pi_{ct}$</td>
<td>profit for carrier $c$ in period $t$</td>
</tr>
<tr>
<td>$R_{ct}$</td>
<td>set of routes operated by carrier $c$ in period $t$</td>
</tr>
<tr>
<td>$S_{ct}$</td>
<td>set of segments operated by carrier $c$ in period $t$</td>
</tr>
<tr>
<td>$T_{rt}$</td>
<td>sum of specific taxes applied to route $r$ in period $t$</td>
</tr>
<tr>
<td>$R_{cmt}$</td>
<td>set of routes by carrier $c$ in market $m$ in period $t$</td>
</tr>
</tbody>
</table>