A Model of Dynamic Limit Pricing with an Application to the Airline Industry

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Abstract

We develop a dynamic limit pricing model where an incumbent repeatedly signals information relevant to a potential entrant's expected profitability. The model is tractable, with a unique equilibrium under refinement, and dynamics contribute to large equilibrium price changes. We show that the model can explain why incumbent airlines cut prices dramatically on routes threatened with entry by Southwest, presenting new reduced-form evidence and a calibration which predicts a pattern of price changes across markets similar to the one observed in the data. We use our calibrated model to quantify the welfare effects of asymmetric information and subsidies designed to encourage Southwest's entry.

1 Introduction

Economists have long been interested in models where incumbents try to deter entry (Kaldor (1935) and Bain (1949) provide early examples, and chapters 8 and 9 of Tirole (1988) are devoted to models of strategic investment). However, even though survey evidence suggests that managers engage in deterrence (Smiley (1988)), little empirical evidence exists that any particular model can explain observed firm behavior. This may be partly due to the fact that it is unclear what the stylized two-period models that dominate the theoretical literature predict should happen when firms interact repeatedly as happens, for example, when a potential entrant can wait for several years before entering. In this paper, we extend one particular model of entry deterrence, the classic Milgrom and Roberts (1982) (MR) model of limit pricing with asymmetric information, to a dynamic setting and we show that it provides a plausible explanation for why, in the 1990s and 2000s, incumbent airlines often responded to the threat of entry by Southwest by lowering their prices, and then keeping them low, before entry actually occurred.[1] This empirical pattern is part of the phenomenon commonly known as the "Southwest Effect", a term coined by Bennett and Craun (1993) in a Department of Transportation study which showed that many contemporary pricing trends in the industry could be attributed to the presence of Southwest on airline routes or at their endpoint airports.

In the two-period MR model, an incumbent faces a potential entrant who is uninformed about some relevant aspect of the market, such as the incumbent's marginal cost. In equilibrium, the incumbent may deter entry by choosing a low price to credibly signal that its marginal costs are so low that the potential entrant's post-entry profits would likely not cover its entry costs. However, it is unclear whether the incumbent would keep setting low prices if entry is repeatedly threatened. In contrast to the view that dynamic games of asymmetric information are intractable when using standard equilibrium concepts (Doraszelski and

[1] The term dynamic limit pricing has sometimes been used to refer to incumbents keeping prices low to limit the growth of entrants (Gaskins (1971)). Instead we present a model where an incumbent faces a long-lived potential entrant and may lower prices for many periods to keep entry from happening.

Pakes (2007), Fershtman and Pakes (2012)), we develop a tractable model where we allow the incumbent's private information to be positively serially correlated, but not perfectly persistent, over time. The model has a unique Markov Perfect Bayesian equilibrium under a refinement when the incumbent's payoffs satisfy several conditions. When the incumbent's marginal cost evolves exogenously, the required conditions can be shown to always hold under quite weak, and easy-to-check, conditions on the primitives of the model. The unique equilibrium involves the incumbent using fully separating price strategies, which allows us to devise a computationally simple strategy for solving and calibrating the model. The introduction of dynamics can substantially increase the magnitude of the equilibrium price cuts, so that prices may fall significantly even when the incumbent's information can only have a small effect on the probability of entry.

As documented by Goolsbee and Syverson (2008) (GS), incumbent airlines lower prices by as much as 20% on airport-pair routes when Southwest serves both endpoint airports without (yet) serving the route itself, and these price cuts can have substantial welfare effects. For example, Morrison (2001) estimates that Southwest's presence as a potential competitor lowered expenditure on airfares by $3.3 billion in 1998. While this is a natural setting in which to consider limit pricing as these price reductions are the largest documented in response to a threat of entry in any industry (Bergman (2002)), we are not aware of anyone testing a model of limit pricing or any other strategic investment model in this context.

We present two forms of evidence in favor of our model. The first type of evidence comes from analyzing markets where there is a dominant incumbent carrier before Southwest enters, which matches the assumed market structure in our model. We show that in these markets there is a non-monotonic relationship between the magnitude of observed price declines and a measure of how likely Southwest is to enter these markets, where the measure is defined in a way that it should not be affected by how the incumbent changes its pricing when entry is threatened. The price declines are largest in markets with intermediate probabilities of entry. Under some fairly standard assumptions, our limit pricing model predicts exactly this type of non-monotonic relationship. We show that several explanations for the shape of this relationship that do not involve limit pricing (for example, strategic increases in capacity, declining load factors or competition with connecting service on Southwest) are not consistent with the data.

Second, we calibrate a parameterized version of our model. We estimate demand and marginal cost parameters using data from quarters where limit pricing should not be taking place, and we estimate the distribution of Southwest's entry costs using information on how the probability of entry varies across markets and over time. This is computationally feasible because entry decisions in equilibrium will be the same as under complete information. We use no information on how much prices fall when entry is threatened. However, when we introduce asymmetric information, the model predicts a magnitude of price cuts and a marked non-monotonic relationship between price cuts and the probability of entry that are similar to those observed in the data. We use the calibrated model to quantify the welfare effects of limit pricing. Even though we consider only 109 medium-sized and smaller markets we find substantial welfare effects: in present value terms, limit pricing increases consumer surplus by almost $600 million and total welfare by over $500 million (2009 dollars). We also examine the welfare effects of a policy that provides Southwest with small financial subsidies when it provides nonstop service, motivated by the fact that service subsidies are quite common in the industry (Ryerson, 2016). We predict that even small subsidies can substantially increase welfare, and at low cost to the government. A large proportion of the gains comes from the smallest markets where, under asymmetric information, subsidies can cause dominant incumbents to significantly lower prices even when entry is a low probability event.

Our focus in the text is on relatively simple models where the incumbent has full information about the potential entrant, the potential entrant is uninformed about the incumbent's exogenously evolving marginal cost and exogenous serial correlation in the incumbent's marginal cost and signaling incentives provide the only source of dynamics. Appendix F shows that we can also solve models where marginal costs depend on carriers' sticky capacity investments and the incumbent may also learn about the probability of entry over time. These extensions are interesting in their own right (for example, we are not aware of entry deterrence models with two-way learning being explored in the literature), and, as well as generating large limit price reductions in equilibrium, these models also help explain some features of the data. For example, two-way learning can help to explain why the magnitude of price cuts tends to increase over time in some markets. In the model with endogenous capacity investments we show that even though the incumbent could try to deter entry by building additional, observable, capacity, it chooses not to do so, engaging in limit pricing instead.[2] Consistent with this prediction, in our data we do not observe incumbents significantly changing capacity when entry is threatened. We set up this extended model to show how asymmetric information about connecting traffic, which makes up the majority of traffic on the routes in our empirical sample, can lead to limit pricing. This is consistent with the existing airline literature that has pointed out that connecting traffic makes it difficult to accurately measure a carrier's marginal cost on many routes (Edlin and Farrell (2004) and Elzinga and Mills (2005)).

Our work draws on, and is related to, two broad literatures aside from the ones that have studied market power in airlines and the Southwest Effect (we discuss these literatures in Section 3). Limit pricing is an old idea, but early models (e.g., Modigliani (1958), Kamien and Schwartz (1971)) assumed that low prices would lead a potential entrant to expect low post-entry prices without explaining why. MR provided an equilibrium explanation based on asymmetric information between the incumbent and potential entrant, with Matthews and Mirman (1983) and Harrington (1986) exploring different extensions of the MR framework. In characterizing what happens in a dynamic, finite horizon version of MR, we recursively apply the results of Mailath (1987), Mailath and von Thadden (2013) and Ramey (1996) in one-shot signaling models. Roddie (2012a) and Roddie (2012b) also take a recursive

[2] Spence (1977) compares price levels in a model where an incumbent limit prices (through an assumed price commitment) and a model where an incumbent can deter entry by investing in capacity.

approach to solving a dynamic game of asymmetric information, focusing on the example of a quantity-setting game between two incumbents, one of whom has a privately-known marginal cost that evolves exogenously. As in these papers, we formally assume a finite-horizon structure, where we can use backwards induction to show existence and uniqueness properties. We allow the number of periods to go to infinity to deliver a model where we can compute equilibria in an efficient manner. We differ from Roddie in considering an entry-deterrence game; in using different high-level conditions on incumbent payoffs to show the existence and uniqueness of our equilibrium; and, in the exogenous marginal cost version of our model, showing how these conditions will be satisfied under a small number of easy-to-check conditions on the static primitives of the model. Kaya (2009) and, in a limit pricing context, Toxvaerd (2017) consider repeated signaling models where the sender's type is fixed over time. This structure can lead to signaling only in the early periods of a game, whereas, with an evolving type, our model has repeated signaling in equilibrium. A model where the incumbent's type is fixed would have difficulty in explaining two aspects of our empirical application. First, incumbents not only cut prices when Southwest first appears as a potential entrant, they also keep prices low even if Southwest does not initially enter. Second, and more fundamentally, if the incumbent's type is fixed then Southwest should be able to infer the incumbent's type from how it set prices *before* Southwest became a potential entrant, leaving it unclear what cutting prices once Southwest threatens entry would achieve.

A second directly related literature has tried to provide empirical evidence of strategic investment. A common approach has looked for evidence of different investment strategies amongst firms (e.g., Lieberman (1987)) or effects of incumbent investment on subsequent entry (e.g., Chevalier (1995)) without specifying the exact mechanism involved. Masson and Shaanan (1982) and Masson and Shaanan (1986) provide empirical evidence for limit pricing using annual data on a large number of industries. While the empirical approach is very different, this conclusion is consistent with our results, although Strassmann (1990) did not find evidence of limit pricing when applying the Masson and Shaanan approach to 92 heavily-traveled airline routes. Ellison and Ellison (2011) introduced the idea of interpreting non-monotonicites between the probability of entry and an investment decision of an incumbent as evidence of entry deterrence. Our reduced-form analysis is based on a similar approach, and we complement it by providing additional evidence through our calibration.[3]

Snider (2009) and Williams (2012) provide structural evidence in favor of hub carriers predating by increasing their capacities. Our evidence suggests that incumbents did not use capacity investment as a strategy to try to deter a much stronger potential entrant, Southwest. Both of these papers use infinite horizon dynamic structural models with complete information (up to i.i.d. payoff shocks) in the tradition of Ericson and Pakes (1995). One feature of these models is that there are often multiple equilibria. We differ from this literature by considering a dynamic model with asymmetric information and explicitly establishing conditions and a refinement under which the Markov Perfect Bayesian equilibrium that we look at is unique. Fershtman and Pakes (2012) consider an alternative way of incorporating persistent asymmetric information in a dynamic game, using an alternative concept of Experience Based Equilibrium (EBE), where players have beliefs about the payoffs from different actions, not the types of other players. When the structure of equilibrium beliefs is unknown ex-ante, this EBE approach may have computational advantages. However, in our model we can show uniqueness of a Markov Perfect Bayesian equilibrium where the entrant's beliefs will always be correct on the equilibrium path.[4] This allows us to provide a natural dynamic extension of one of the classic two-period models of theoretical Industrial Organization.

[3]Seamans (2013) uses the Ellison and Ellison approach to argue that the pricing of incumbent cable TV systems is consistent with the MR model based on cross-sectional variation in how incumbent prices vary with the distance to the nearest potential telephone company entrant. In our analysis we look directly at whether price *changes* vary non-monotonically with the probability of entry once Southwest becomes a potential entrant.

[4]Fershtman and Pakes (2012) consider an infinite horizon, discrete state and discrete action model where players may have limited recall or information is sometimes publicly released. Our structure involves continuous actions and continuous states, and we use a finite horizon structure to prove the properties of our game. Borkovsky, Ellickson, Gordon, Aguirregabiria, Gardete, Grieco, Gureckis, Ho, Mathevet, and Sweeting (2014) contains a more detailed comparison of the EBE approach and the one used here.

The rest of the paper is organized as follows. Section 2 lays out our model of dynamic limit pricing when marginal costs are exogenous, characterizes the equilibrium and examines the predictions of the model. Section 3 introduces our empirical application and describes our data. Section 4 provides the reduced-form evidence in support of our limit pricing model. Section 5 presents our calibration of the model and quantifies the welfare effects of limit pricing and the welfare effects of counterfactual subsidies that would encourage Southwest to enter. Section 6 outlines several extensions to the basic model. Section 7 concludes. While the text is intended to be self-contained, the online Appendices contain proofs, computational details, robustness checks, and the details of the extensions. In each section we indicate which Appendix the reader should consult for further details.

2 Model

In this section we develop the most tractable version of our model where the incumbent's marginal cost is private information and evolves exogenously. Section 2.1 shows the existence and uniqueness of a fully separating Markov Perfect Bayesian Equilibrium (MPBE) under some simple conditions on static payoff functions for a given market. Section 2.2 illustrates the properties of the model, and, in particular, the non-monotonic relationship between the probability of entry and how much the incumbent lowers its prices, when we make specific assumptions about demand and costs. Section 2.3 briefly discusses limitations and extensions of the model.

2.1 A Dynamic Limit Pricing Model with Exogenous Marginal Costs

2.1.1 Overview

We consider a finite horizon dynamic game played in a single market, with periods $t = 1, ..., T$, although, as we explain below, we will make use of the limiting infinite horizon version of the model when performing computations. The discount factor is $0 < \beta < 1$. Consumer demand is static (i.e., it does not depend on past prices or availability), common knowledge and time invariant. There are two firms. An incumbent firm, I, is always in the market. Its marginal cost, $c_{I,t}$, lies on a compact interval and evolves over time according to a first-order Markov process. A long-lived potential entrant, E, with known and fixed marginal cost c_E, has to decide whether to enter the market each period. Entry requires payment of a sunk entry cost, κ_t, which is private information to E. If E enters, it is an active competitor in the next period. Before entry, I's marginal cost is private information. However, E can observe I's current period price, $p_{I,t}$, chosen from an interval $[\underline{p}, \overline{p}]$, and all previous prices before it decides whether to enter in t. I can therefore potentially choose its price to influence E's entry decision. Once E has entered, we assume that it will stay in the market for the rest of the game, that I's marginal cost will be observable and that both firms will choose prices simultaneously each period in a static Nash equilibrium. Our focus will therefore be on equilibrium strategies before entry occurs.

2.1.2 Cost Assumptions

The incumbent's marginal cost $c_{I,t}$ lies on a compact interval $[\underline{c_I}, \overline{c_I}]$ and evolves, exogenously, according to a first-order Markov process $\psi_I : c_{I,t-1} \to c_{I,t}$ with full support i.e., $c_{I,t-1}$ can evolve to any point on the support in the next period. Therefore E will view any value of $c_{I,t}$ on the support as being possible even if equilibrium play and what it has observed prior to t gives it a precise prior about the value of $c_{I,t}$. The conditional pdf is denoted $\psi_I(c_{I,t}|c_{I,t-1})$. We make the following assumptions.

Assumption 1 ***Marginal Cost Transitions***

1. *$\psi_I(c_{I,t}|c_{I,t-1})$ is continuous and differentiable (with appropriate one-sided derivatives at the boundaries).*

2. *$\psi_I(c_{I,t}|c_{I,t-1})$ is strictly increasing i.e., a higher type in one period implies higher types*

in the following period are more likely. Specifically, we will require that for all $c_{I,t-1}$ *there is some* c' *such that* $\frac{\partial \psi_I(c_{I,t}|c_{I,t-1})}{\partial c_{I,t-1}}|_{c_{I,t}=c'} = 0$ *and* $\frac{\partial \psi_I(c_{I,t}|c_{I,t-1})}{\partial c_{I,t-1}} < 0$ *for all* $c_{I,t} < c'$ *and* $\frac{\partial \psi_I(c_{I,t}|c_{I,t-1})}{\partial c_{I,t-1}} > 0$ *for all* $c_{I,t} > c'$. *Obviously it will also be the case that* $\int_{\underline{c_I}}^{\overline{c_I}} \frac{\partial \psi_I(c_{I,t}|c_{I,t-1})}{\partial c_{I,t-1}} dc_{I,t} = 0$.

To enter in period t, E has to pay a private information sunk entry cost, κ_t, which is an i.i.d. draw from a commonly-known time-invariant distribution $G(\kappa)$ (density $g(\kappa)$) with support $[\underline{\kappa} = 0, \overline{\kappa}]$.

Assumption 2 ***Entry Cost Distribution***

1. *$G(\cdot)$ is continuous and differentiable and the density $g(\kappa) > 0$ for all $\kappa \in [0, \overline{\kappa}]$.*
2. *$\overline{\kappa}$ is large enough so that, whatever the beliefs of the potential entrant, there is always some probability that it does not enter because the entry cost is too high.*

2.1.3 Pre-Entry Stage Game

The potential entrant does not observe $c_{I,t}$ prior to entering, but E does observe the whole history of the game to that point. The timing of the game in each pre-entry period is as follows:

1. I sets a price $p_{I,t}$, and receives flow profit

$$\pi_I^M(p_{I,t}, c_{I,t}) = q^M(p_{I,t})(p_{I,t} - c_{I,t}) \tag{1}$$

where $q^M(p_{I,t})$ is the demand function of a monopolist. Define

$$p_I^{\text{static monopoly}}(c_I) \equiv \text{argmax}_{p_I} q^M(p_I)(p_I - c_I) \tag{2}$$

The incumbent can choose a price from the compact interval $[\underline{p}, \overline{p}]$, although all of our theoretical results would hold when the monopolist sets a quantity. The choice of strategic variable in the duopoly game that follows entry may matter, as will be explained below.

2. E observes $p_{I,t}$ and κ_t, and then decides whether to enter (paying κ_t if it does so). If it enters, it is active at the start of the following period.

3. I's marginal cost evolves according to ψ_I.

Assumption 3 ***Monopoly Payoffs***

1. *$q^M(p_I)$, the demand function of a monopolist, is strictly monotonically decreasing in p_I, continuous and differentiable.*

2. *$\pi_I^M(p_I, c_I)$ has a unique optimum in price and for any $p_I \in [\underline{p}, \overline{p}]$ where $\frac{\partial^2 \pi_I^M(p_I, c_I)}{\partial p_I^2} > 0$, $\exists k > 0$ such that $\left| \frac{\partial \pi_I^M(p_I, c_I)}{\partial p_I} \right| > k$ for all c_I.*

3. *$\overline{p} \geq p_I^{\text{static monopoly}}(\overline{c_I})$ and $\underline{p}$ is low enough such that no firm would choose it (for any t) even if this would prevent E from entering whereas any higher price would induce E to enter with certainty.*[5]

The second condition is consistent with strict quasi-concavity of the profit function, and it is satisfied for most forms of demand, including the parameterized nested logit model used in our computations.

2.1.4 Post-Entry Stage Game

We assume that once E enters, marginal costs, which continue to evolve as before, are observed by both firms so that there is no scope for further signaling. The duopolists choose their strategic variables, $a_{I,t}$ and $a_{E,t}$, which could be prices or quantities, simultaneously.

Assumption 4 ***Duopoly Payoffs and Output***

[5]For some parameters, although not for the ones that we estimate in our calibration, this could require $\underline{p} < 0$. The purpose of this restriction is to ensure that the action space is large enough to allow all types to separate.

1. *firms use unique static Nash equilibrium strategies in each period following entry. Static per-period equilibrium profits are* $\pi_I^D(c_{I,t})$ *and* $\pi_E^D(c_{I,t})$*, and outputs* $q_I^D(c_{I,t})$ *and* $q_E^D(c_{I,t})$*.*

2. $\pi_I^D(c_I), \pi_E^D(c_I) \geq 0$ *for all* c_I*.*

3. $\pi_I^D(c_I)$ *and* $\pi_E^D(c_I)$ *are continuous and differentiable in their arguments, and* $\pi_I^D(c_I)$ *(*$\pi_E^D(c_I)$*) is monotonically decreasing (increasing) in* c_I*.*

4. $\pi_I^D(c_I) < \pi_I^M(p_I^{\text{static monopoly}}(c_I), c_I)$ *for all* c_I*.*

5. $q_I^D(c_I) - q^M(p_I^{\text{static monopoly}}(c_I)) - \frac{\partial \pi_I^D(c_I)}{\partial a_E}\frac{\partial a_E^*}{\partial c_I} < 0$ *for all* c_I*, where* a_E^* *is the equilibrium price or quantity choice of the entrant in the duopoly game.*

The second condition rationalizes why neither firm will exit once entry has occurred. Given that we are assuming that the post-entry game has complete information and a finite horizon, and that the firms have single products and constant marginal costs, uniqueness of the pricing equilibrium will be guaranteed under many standard demand formulations, such as linear, logit and nested logit (e.g., Mizuno (2003)). The fifth condition implies that a decrease in marginal cost is more valuable to a monopolist than a duopolist, and it is important in showing a single-crossing condition on the payoffs of an incumbent monopolist. Note that because $q^M(p_I)$ is decreasing in p_I, if this condition holds when a monopolist incumbent sets $p_I^{\text{static monopoly}}$ then it will also hold for lower limit prices, a fact that is used in our proof. The condition is easier to satisfy when the duopolists compete in prices (strategic complements), as $\frac{\partial \pi_I^D(c_I)}{\partial a_E}\frac{\partial a_E^*}{\partial c_I} > 0$ in this case, and when c_E is low relative to $\underline{c_I}$ (i.e., the potential entrant is always relatively efficient).[6] This makes sense in our empirical setting as Southwest is viewed as having had significantly lower costs than legacy carriers

[6] In his presentation of the two-period MR model, Tirole (1988) suggests a condition that a static monopolist produces more than a duopolist with the same marginal cost is reasonable. However, it will not hold in all models, such as one with homogeneous products and simultaneous Bertrand competition when the entrant has the higher marginal cost but it is below the incumbent's monopoly price.

during our sample period, and our estimates of the carriers' marginal costs are in line with this view.

2.1.5 Equilibrium: Existence, Uniqueness and Characterization

By assumption, there is a unique subgame perfect Nash equilibrium in the post-entry complete information duopoly game. Our equilibrium concept for the pre-entry period is Markov Perfect Bayesian Equilibrium (Toxvaerd (2008), Roddie (2012a)). In the finite horizon model, the specification of an MPBE requires, for each period:

- a period-specific pricing rule for I as a function of its marginal cost, $\varsigma_{I,t}(c_{I,t})$;
- a period-specific entry rule for E, as a function of its beliefs about I's marginal cost and its own entry cost draw; and,
- a specification of E's beliefs about I's marginal costs given all possible histories of the game.

To form an MPBE, E's entry rule must be optimal given its beliefs and its expected post-entry payoffs, and its beliefs should be consistent with I's pricing strategy and the application of (the continuous random variable version of) Bayes Rule on the equilibrium path. I's pricing rule must be optimal given what E will infer from I's price and how E will decide to enter. The Markovian restriction is that history only matters through how it affects E's beliefs about I's current marginal costs. These beliefs are payoff relevant because they affect E's expected future profits and its entry decision. To eliminate possible pooling equilibria we use the D1 refinement (Cho and Sobel (1990), Ramey (1996)), which restricts the inferences that a receiver can make if it observes off-the-equilibrium path actions, to eliminate pooling or partial pooling equilibria. Specifically, D1 requires the receiver to place zero posterior weight on a signaler having a type θ_1 if there is another type, θ_2, who would have a strictly greater incentive to deviate from the putative equilibrium for any set of post-signal beliefs that would give θ_1 an incentive to deviate.

The following theorem contains our main theoretical result for this model.

Theorem 1 *Consider the following strategies and beliefs:*

In the last period, $t = T$, a monopolist incumbent will set $p_{I,T} = p^{\text{static monopoly}}(c_{I,T})$, and the potential entrant will not enter whatever price the incumbent sets.

In all pre-entry periods $t < T$:

(i) E's entry strategy will be to enter if and only if its entry cost κ_t is lower than a threshold $\kappa_t^*(\widehat{c}_{I,t})$, where $\widehat{c}_{I,t}$ is E's point belief about I's marginal cost and

$$\kappa_t^*(\widehat{c}_{I,t}) = \beta\mathbb{E}_t[\phi_{t+1}^E|\widehat{c}_{I,t}] - \mathbb{E}_t[V_{t+1}^E|\widehat{c}_{I,t}] \tag{3}$$

where $\mathbb{E}_t[V_{t+1}^E|\widehat{c}_{I,t}]$ is E's expected value, at time t, of being a potential entrant in period $t+1$ (i.e., if it does not enter now) given equilibrium behavior at $t+1$, and $\mathbb{E}_t[\phi_{t+1}^E|\widehat{c}_{I,t}]$ is its expected value of being a duopolist in period $t+1$ (which assumes it has entered prior to $t+1$).[7] *The threshold $\kappa_t^*(\widehat{c}_{I,t})$ is strictly increasing in $\widehat{c}_{I,t}$;*

(ii) I's pricing strategy, $\varsigma_{I,t}(c_{I,t})$, will be the (unique) solution to a differential equation

$$\frac{\partial p_{I,t}^*}{\partial c_{I,t}} = \frac{\beta g(\kappa_t^*(c_{I,t}))\frac{\partial \kappa_t^*(c_{I,t})}{\partial c_{I,t}}\{\mathbb{E}_t[V_{t+1}^I|c_{I,t}] - \mathbb{E}_t[\phi_{t+1}^I|c_{I,t}]\}}{q^M(p_{I,t}) + \frac{\partial q^M(p_{I,t})}{\partial p_{I,t}}(p_{I,t} - c_{I,t})} \tag{4}$$

and an upper boundary condition $p_{I,t}^*(\overline{c_I}) = p^{\text{static monopoly}}(\overline{c_I})$. $\mathbb{E}_t[V_{t+1}^I|c_{I,t}]$ is I's expected value of being a monopolist at the start of period $t+1$ given current (t period) costs and equilibrium behavior at $t+1$. $\mathbb{E}_t[\phi_{t+1}^I|c_{I,t}]$ is its expected value of being a duopolist in period $t+1$. $\varsigma_{I,t}(c_{I,t})$ is strictly increasing in $c_{I,t}$, so it is fully separating and invertible;

(iii) E's beliefs: observing a price $p_{I,t}$, E believes that I's marginal cost is $\varsigma_{I,t}^{-1}(p_{I,t})$ if $p_{I,t}$ is in the range of $\varsigma_{I,t}(c_{I,t})$. For off-path beliefs, if $p_{I,t} > \varsigma_{I,t}(\overline{c_I})$ then E believes that $c_{I,t}$ equals $\overline{c_I}$. If $p_{I,t} < \varsigma_{I,t}(\underline{c_I})$ then E believes that $c_{I,t}$ equals $\underline{c_I}$.

This equilibrium exists, and these strategies form the unique MPBE strategies and

[7] We define values at the beginning of each stage. See the discussion in Appendix A for more details.

equilibrium-path beliefs consistent with a recursive application of the D1 refinement.

Proof. See Appendix A. ■

The existence and uniqueness results are established recursively, beginning with the last period of the model where there is no signaling.[8] We can then characterize the unique equilibrium in $T-1$, prove several properties of the firms' value functions implied by these strategies, and then use these properties to show existence and uniqueness of the equilibrium at $T-2$, and so on. We use well-known results from the literature on one-shot signaling models (in particular, Mailath and von Thadden (2013) and Ramey (1996)) to characterize the incumbent's unique equilibrium strategy in each period. To do this we show that the incumbent's expected payoff function satisfies conditions of type monotonicity (a price cut is more costly for an incumbent with higher marginal costs), belief monotonicity (the incumbent always benefits when the entrant believes that he has lower marginal costs so is less likely to enter) and a single-crossing condition (a lower cost incumbent is always willing to cut the current price slightly more in order to differentiate itself from a higher cost type). The more novel part of our results are that we show that these conditions will be satisfied throughout a multi-period dynamic game under the simple conditions on static payoffs and entry costs given in Assumptions 1-4. The fully separating equilibrium pricing strategy corresponds to the so-called Riley Equilibrium (Riley (1979)) where the incentive compatibility constraints consistent with full separation are satisfied at minimum cost to I in each period.

The fact that the incumbent's equilibrium strategy is fully separating, together with our assumption that there is complete information after entry so that there is no scope for E to time its entry to affect post-entry competition, implies that, on the equilibrium path, E's entry strategy (and choices) will be the same as in a model with complete information throughout the game. This property is very convenient because it means that we can solve for E's strategy without solving for I's limit pricing strategy.

[8] Note that our recursive approach means that, when we apply the D1 refinement, we are assuming that an off-the-equilibrium path action in a period before t cannot affect how an off-the-equilibrium path action in t is interpreted (Roddie (2012a)).

We can use equation (4) to understand what the incumbent's limit pricing schedule will look like. From (4) and the boundary condition, the incumbent's limit price will be lower than its static monopoly price, except in the final period, for all c_I below $\bar{c}$. We will call this reduction in price "price *shading*" in what follows. To understand what will affect the magnitude of shading it is useful to study a slightly re-written version of (4) for the first period of a $T = 2$ version of the model, when there is only one chance for E to enter,

$$\frac{\partial p^*_{I,1}}{\partial c_{I,1}} = \frac{\beta \frac{\partial \Pr(\text{E enters in period 1})}{\partial c_{I,1}} \{\mathbb{E}_{t=1}[\pi^M_I(p^{\text{static monopoly}}_I(c_{I,2}), c_{I,2})|c_{I,1}] - \mathbb{E}_{t=1}[\pi^D_I(c_{I,2})|c_{I,1}]\}}{q^M(p_{I,1}) + \frac{\partial q^M(p_{I,1})}{\partial p_{I,1}}(p_{I,1} - c_{I,1})}. \tag{5}$$

Holding the discount factor fixed, the pricing function will become steeper, implying greater shading when, all else equal, (i) there is a greater difference between I's static monopoly and duopoly profits (i.e., when the entrant will tend to be more competitive); (ii) E's entry decision, which will be to enter if the entry cost is less than $\kappa^*_1 = \mathbb{E}_{t=1}[\pi^D_E(c_{I,2})|c_{I,1}]$, is more sensitive to the incumbent's current marginal cost. This will be the case when I's marginal cost is more serially correlated and when the entry cost distribution has more mass around κ^*_1; and, (iii) the profit that the incumbent loses when it lowers its price is small, which will depend on the curvature of the static profit function. As the static profit function will be flat at the static monopoly price, quite large price decreases may be incentive compatible as long as the curvature is not too great.

In the multi-period model the difference in expected next period profits is replaced by $\mathbb{E}_t[V^I_{t+1}|c_{I,t}] - \mathbb{E}_t[\phi^I_{t+1}|c_{I,t}]$, where V^I and ϕ^I are the incumbent's continuation values as a monopolist and as a duopolist respectively. As we will now illustrate, the difference in continuation values can be much greater than the difference in static, one-period profits, because entry that is deterred in the current period may allow the incumbent to enjoy a number of periods of monopoly in the future. This can lead to substantial shading even if $c_{I,t}$ has only modest effects on the probability of entry.

2.2 Numerical Illustration and Cross-Market Comparisons

The previous analysis has focused on a single market. Our empirical analysis will focus on cross-market comparisons where exogenous variation in market characteristics, such as market size, will lead to variation in how likely Southwest is to enter when it becomes a potential entrant. To illustrate both the magnitude of shading that the model can generate and these cross-market relationships, we introduce the assumptions that we will make in the calibration.

Assumption 5 ***Calibration Assumptions***

1. *a firm's demand is determined by multiplying market size (M) by the firm's market share, which is determined, as a function of prices, by a static nested logit model.*

2. *I's marginal cost evolves according to AR(1) process with truncated normal innovations*

$$c_{I,t} = \rho^{AR} c_{I,t-1} + (1 - \rho^{AR}) \frac{\underline{c_I} + \overline{c_I}}{2} + \varepsilon_{I,t} \tag{6}$$

   where $\rho^{AR} > 0$, $\varepsilon_{I,t} \sim TRN(0, \sigma_c^2, \underline{c_I} - c_{I,t-1}, \overline{c_I} - c_{I,t-1})$ and the last two arguments give the lower and upper truncation points, and σ_c^2 is the variance of the untruncated distribution.

3. *E's entry costs have a truncated normal distribution, with a lower truncation point at zero and an upper truncation point that exceeds the maximum possible discounted variable profits of the potential entrant.*

The assumption that market size enters demand, and therefore profit functions, multiplicatively implies that, in our model, it has no effect on optimal monopoly or duopoly prices except through signaling incentives. Signaling incentives will vary because market size will affect the probability of entry, as, for a given entry cost, entry will be more attractive in larger markets. An extended model discussed in Section 6 will allow market size to also affect pricing through capacity choices.

Figure 1 is constructed using the demand parameters that we estimate to perform the calibration (Section 5). Consistent with earlier airline estimates they imply that an incumbent monopolist has substantial market power, and that the incumbent and Southwest (our E) are quite close substitutes once entry has occurred. To construct the figure we also assume that c_E=\$150, the range of c_I is \$170 to \$270, $\rho^{AR} = 0.97$ and that $\sigma_c = \$35$. The entry cost distribution has mean \$20 million and standard deviation \$2 million. The discount factor is 0.98, so that periods can be interpreted as quarters. While the finite structure of the model in Section 2.1 allows us to show existence and uniqueness, it also implies that strategies will change from period-to-period which complicates illustration. We will therefore solve for stationary strategies in the limiting infinite horizon version of the model. Appendix B.1 explains the computational procedure.

Panel (i) shows I's (signaling) pricing strategy in the dynamic model for a market size of $M = 20,000$ for $\rho^{AR} = 0.97$ (our baseline case) and $\rho^{AR} = 0.7$. The difference between the incumbent's strategy and the static monopoly price indicates the degree of shading. As the incumbent's current marginal cost is less informative about E's post-entry profits when $\rho^{AR} = 0.7$, there is less shading but, in both cases, the threat of entry causes the incumbent to significantly lower its price when $c_I < \overline{c_I}$. We can illustrate that shading yields a higher expected payoff than the static monopoly price by considering an example: for $\rho^{AR} = 0.97$ and $c_I = \$220$, the incumbent shades its price by \$59. As shown in panel (ii), this lower price reduces the incumbent's current profit by \$37,785 compared to the static optimal price of \$493. On the other hand, the difference in the incumbent's expected monopoly and duopoly continuation values is \$5.1 million, and charging the limit price reduces the entry probability from 0.143 to 0.131. As $(0.143 - 0.131) \times 5.1 > 0.038$, choosing the limit price increases the incumbent's payoff.

Panel (iii) shows how the equilibrium entry probability (measured at $c_I = \underline{c_I}$) and the average price change due to signaling (expressed as % of the static monopoly price) when we vary market size from 1,000 to 300,000 people. There is a monotonic and increasing relationship between market size and the probability of entry, and a non-monotonic relationship between market size and the degree of shading. The assumption that entry costs are normally distributed implies that, all else equal, E's entry decision will be most sensitive to I's marginal cost when the probability of entry takes on intermediate, rather than extreme, values. The implied non-monotonicity between the probability of entry (which here is varying because of market size) and the degree of shading is the relationship that we will observe in the data and our calibration.

One might have expected that I's marginal cost would need to have a large absolute effect on the probability of entry to generate significant shading. Panel (iv) shows that this is not necessarily the case in the dynamic model by plotting the relationship between the entry probability at $c_I = \underline{c_I}$ (x-axis), as we vary market size, the difference in the entry probabilities for $c_I = \overline{c_I}$ and $c_I = \underline{c_I}$ (left-axis) and the degree of shading (right-axis). The degree of shading can be large when the effect that c_I has on the entry probabilities is quite small. For example, for $M = 20,000$, the incumbent's cost can only reduce the entry probability from 0.143 to 0.119, but there is an average 11.6% reduction in the incumbent's price. The degree of shading is maximized, at 12.0% of the static profit maximizing price, when the entry probability for $c_I = \underline{c_I}$ is 0.291.

Panels (v) and (vi) help to explain why the dynamic model can generate significantly more shading than the two-period model. Panel (v) compares the average difference in the continuation values per unit of market size (i.e., $\frac{\mathbb{E}_t[V_{t+1}^I|c_{I,t}]-\mathbb{E}_t[\phi_{t+1}^I|c_{I,t}]}{M}$ averaged over $c_{I,t}$) in the first period of a two-period model and the dynamic model, as a function of the entry probability. Under Assumption 5, the difference in continuation values per market size unit in the two-period model is independent of market size. In the dynamic model the difference in continuation values depends on the probability of entry in future periods. When the probability of entry in future periods is very high, the difference between dynamic continuation values is essentially just the difference between one period profits. However, at very low entry probabilities the difference can be up to 50 ($=\frac{1}{1-0.98}$) times greater and, as a result, incentives to signal are strengthened. Panel (vi) compares, for given entry probabilities, equilibrium shading when the incumbent considers only payoffs in the next period, as it would in a two-period model, and when it considers dynamic continuation values.[9] Consistent with our discussion above, there is much less shading in equilibrium in the two-period model, unless entry probabilities are high. This difference is important for our empirical application because we observe large price cuts in markets where entry does not occur for quite long periods of time.

2.3 Extensions and Limitations

The model presented above is simple, and we wish to emphasize that it is possible to relax many of the assumptions. Our results would not change if E receives information that allows it to infer $c_{I,t}$ *after* it has taken its period t entry decision. This is relevant for our empirical setting where the Department of Transportation releases data that might help firms to understand their rivals' costs with a one or two quarter lag. Gedge, Roberts, and Sweeting (2014) show that all of the results hold when the potential entrant's marginal cost varies over time as long as it is publicly observed. We can also extend the model to allow for the incumbent's marginal cost to be partly endogenous, through being dependent on its capacity investment, and for the incumbent to be learning about the parameters of the entrant's entry cost distribution, as we show in Appendix F. However, in these cases we have not been able to show that simple conditions on the static primitives of the model are sufficient to guarantee existence and uniqueness of an equilibrium. Instead, we have to numerically verify conditions on value functions in each period of the game. We could also introduce the possibility that one of the firms may exit during the duopoly game which follows entry, although we have chosen not to focus on this more complicated case as in our sample of routes there is only one case where Southwest enters and then exits, and the

[9] To be precise, in both cases we use the entry probabilities implied by the infinite horizon dynamic model and compute the incumbent's pricing strategy using either (4) (dynamic model) or (5) (two-period model). We use this approach because there is no natural way to re-scale the entry cost distributions to generate comparable probabilities of entry.

incumbent is still active two years after Southwest enters on over 80% of routes. We may also be able to relax the assumption of complete information in the post-entry game: Sweeting, Tao, and Yao (2018), building on Mailath (1989), illustrate how multi-sided signaling in an oligopoly pricing game can significantly affect prices. However, the oligopoly signaling game is more challenging to solve than the one considered here.

Other features of the model appear more essential. In particular, tractability requires that the signaler has only one piece of private information per period.[10] This is a limitation as in many environments it is plausible that an incumbent has private information about both its costs and the level of demand. Some people have also suggested that the implications of our model are not intuitive. For example, when the degree of serial correlation is high, our model predicts that I will shade price significantly in every period, even though past prices will provide E with a quite tight prior over I's current marginal cost. Our result reflects a standard feature of fully separating equilibria in signaling models: the equilibrium distortion introduced by signaling does not depend on the receiver's prior but only on the range of values of the private information variable that are *possible*, and here our assumption that marginal costs can transition to any value on $[\underline{c}, \overline{c}]$ is important. As a result, there is a discontinuity in the equilibrium between the case where the receiver's prior has zero variance, in which case signaling may not be possible, and the case where the prior has a small, but positive, variance, where signaling can have a large effect on prices. One interpretation of this feature is that signaling is implausibly powerful in a model like ours, but one might also argue that the discontinuity reflects the fact that it is the complete information model that embodies the extreme assumption, generating predictions that are quite different from more plausible models where some asymmetry of information exists.

[10]When we allow for both pricing and capacity investments we specify a timing structure which means that capacity cannot be used as a signal.

3 Empirical Application and Data

We now examine whether our model can explain why dominant incumbent airlines lower prices when faced by the threat of entry by Southwest. In this section we introduce the empirical setting and describe the data, with additional details in Appendix C.

3.1 Empirical Application: Background

Several studies (e.g., Morrison and Winston (1987)) show that airline ticket prices tend to be lower when there are more potential competitors (defined as carriers serving one or both endpoints, but not yet serving the route), but "the most dramatic effects from potential competition arise in the case of Southwest Airlines, ... the dominant low-cost carrier" (Kwoka and Shumilkina (2010), p. 772). GS and Morrison (2001) estimate that potential competition from Southwest lowers incumbent prices by as much as 33% and 19-28%, respectively, consistent with observations in the media (e.g. Zuckerman (1999)). These are the largest estimated price effects of potential competition in any industry (Bergman (2002)), but the literature has provided no clear explanation for why incumbents lower prices when Southwest is a potential competitor, but has not yet entered. GS tentatively favor a deterrence explanation on the basis that, in their sample, observed price declines are smaller on routes where Southwest pre-announces its entry, although the difference with their remaining routes is not statistically significant. Based on the fact that incumbents do not tend to increase their capacities when entry is threatened, GS suggest that carriers may lower prices to increase customer loyalty, lowering Southwest's expected market share if it enters (GS, p. 1629). While we also find that capacities do not change, our preferred explanation involves incumbents signaling to Southwest.

Deterrence explanations are consistent with the comments of legacy carrier executives about the importance of preventing Southwest from entering routes, especially at their hub airports, which is where Bennett and Craun (1993) originally identified the "Southwest Effect".[11] They are also consistent with the comments of Southwest's managers that indicate that their entry decisions on at least some routes are sensitive to new information about incumbent prices and expected route profitability.[12] We present new evidence that favors a deterrence explanation, focusing on routes with a single dominant incumbent when entry is threatened, which are almost all routes from one of the dominant incumbent's hubs, as these routes come closest to the market structure assumed in models of strategic investment, including ours. We show that the data are particularly consistent with a limit pricing/signaling explanation, where incumbents use prices to signal information about the profitability of the route to Southwest. Most of our analysis will focus on the average price charged by a carrier, but results in Appendix C.4 and Appendix D.2.3 will show that we observe similar price changes across the price distribution, which theory predicts should happen if a limit pricing incumbent can price discriminate between different classes of customer (Pires and Jorge (2012)).

A critical feature of our story is that the incumbent must have some private information that will affect how tough it will be as a competitor. For an airline the marginal cost of selling a seat to a local passenger depends on the demand for seats on the same flight from connecting passengers (i.e., those traveling as part of longer itineraries). Edlin and Farrell (2004) and Elzinga and Mills (2005) document the difficulties of estimating marginal

[11]For example, when Southwest entered Philadelphia in 2004, then US Airways CEO David Siegel told employees "Southwest is coming for one reason: they are coming to kill us. They beat us on the West Coast, and they beat us in Baltimore. If they beat us in Philadelphia, they're going to kill us." (Business Travel News, March 25, 2004, "Philadelphia Could be US Airways' Last Stand").

[12]For example, "It's all based on customer demand. We're always evaluating markets to see if they are overpriced and underserved" (quote from Southwest spokesperson Brandy King, cited in an article "Southwest to Offer Flights between Sacramento and Orange County, CA" by Clint Swett, Knight Ridder Tribune Business News, 6 Mar 2002). Also, "Southwest does not have any hard and fast criteria dictating when it enters a market. The method is a cautious, reactive approach designed to take advantage of opportunities as they arrive" (quote from Brook Sorem, Southwest's manager of Schedule Planning, reported in a World Airport Week article "What Can Airports Do to Attract Southwest Airlines?", March 24, 1998). Herb Kelleher, longtime Chairman and CEO of Southwest, also admitted to having at least six different strategic plans for how Southwest might develop in the Northeastern United States, after its initial entry into Providence, R.I. (from Wall Street Journal article by Scott McCartney, "Turbulence Ahead: Competitors Quake as Southwest is Set to Invade the Northeast", October 23, 1996). Consistent with entry decisions becoming more sensitive to time-varying information, Boguslaski, Ito, and Lee (2004) show that fixed market characteristics explained fewer of Southwest's entry decisions over the 1990s.

costs on routes where connecting traffic is important, even with access to a carrier's internal data. Almost all of the routes in our dominant incumbent sample are routes from hubs where connecting traffic is especially important. We provide a model where the incumbent's private information is about the level of connecting demand and its marginal costs depend on this demand and endogenously chosen capacities in Appendix F.[13]

3.2 Data

Most of our data is drawn from the U.S. Department of Transportation's Origin-Destination Survey of Airline Passenger Traffic (Databank 1, DB1), a quarterly 10% sample of domestic tickets, and its T100 database that reports monthly carrier-segment level information on flights, capacity and the number of passengers carried on the segment (which may include connecting passengers). We aggregate the T100 data to the quarterly-level to match the structure of the DB1 data, and we include flights operated by and trips on regional affiliates operating for the primary carrier. From DB1, we drop itineraries with prices greater than $2,000 and less than $25 (for one-way trips we use half these amounts) and those involving more than one connection in either direction. Our data covers the period from Q1 1993-Q4 2010 (72 quarters).

Following GS, we define a market as a non-directional airport-pair with quarters as periods. We only consider pairs where, on average, at least 50 DB1 passengers are recorded as making return trips each period, possibly using connecting service, and in everything that follows a one-way trip is counted as half of a round-trip. We also exclude pairs where the round-trip distance is less than 300 miles. We define Southwest as having *entered* a route once it has at least 65 flights per quarter recorded in T100 and carries 150 direct passengers on the route in DB1, and we consider it to be a *potential entrant* once it serves at least one route nonstop out of each of the endpoint airports.[14]

[13] Of course, connecting traffic is likely to be correlated across routes and we have not tried to design a model where Southwest, or any other potential entrant, can make inferences from pricing behavior on multiple routes.

[14] The results are not sensitive to our 65 flight threshold as there are fewer than 2% of route-quarters where

Based on our potential entrant definition, there are 1,542 markets where Southwest becomes a potential entrant after the first quarter of our data and before Q4 2009. We choose this cutoff so that we can look at whether Southwest enters the following year. Southwest enters 337 of these markets during the period of our data. We will call these 1,542 markets our "full sample". However, we will focus most of our analysis on a subset of markets where one carrier is a *dominant incumbent* before Southwest enters. As we want to identify sustained dominance in a market, we use the following rules to identify a dominant carrier (where we treat a carrier on a route before and after a merger as the same carrier, even if the merger changes the carrier's name):

1. to be considered "active" in a route-quarter, a carrier must have at least 150 DB1 direct (i.e., not connecting) passengers;

2. once the carrier becomes active in a market, it is considered dominant in the market if three conditions are met: (i) it must be active in at least 70% of quarters before Southwest enters; (ii) in 80% of those quarters it must account for 80% of direct traffic and at least 50% of total traffic; and, (iii) during the time that Southwest is a potential entrant, Southwest must carry fewer than an average of 50 DB1 passengers per quarter. These thresholds are also chosen so that there are few observations close to them.

We identify 109 markets, listed in Appendix C.1, with a dominant incumbent before Southwest enters. However, Southwest enters some of these routes in the same quarter that it becomes a potential entrant, and for others Southwest is already a potential entrant when the incumbent meets our definition of dominance. As a result there are 65 markets where we observe a dominant incumbent both before Southwest is a potential entrant and after it is a potential entrant but before it actually entered. It is price changes on these routes that can identify how the entry threat changes the dominant incumbent's behavior, although we include all 109 routes in our "dominant incumbent" sample regressions to more precisely

Southwest has more than one flight but less than 100 flights per quarter.

identify the coefficients on the time effects and other controls.

Table 1 provides some summary statistics that allow a comparison of routes in the different samples. While all sets of routes have heterogeneous characteristics, dominant incumbent markets tend to be shorter with endpoint airports that are more likely to be primary airports in large cities. They are also larger by a measure of market size that we construct using an estimated generalized gravity model (see Appendix C.2) so that we capture how traffic varies systematically with both distance and the total number of passengers using the endpoint airports, in ways that more common population-based measures of market size do not. As we will use the market size variable as an exogenous determinant of the probability of Southwest's entry into a market, we base our explanatory variables on passenger flows in Q1 1993, the first quarter of our sample, when we estimate the gravity equation and when we predict market sizes for subsequent quarters. All of the markets in our dominant firm sample are shorter than the longest routes that Southwest flies nonstop (such as Las Vegas-Providence), so its entry should be feasible.

Our analysis will focus on how incumbent prices change when Southwest threatens entry. For each market, we split the sample quarters into three groups:

- "Phase 1": before Southwest is a potential entrant on the route;
- "Phase 2": when Southwest is a potential entrant on the route but it has not (yet) entered; and,
- "Phase 3": after Southwest has entered.

Table 2 reports, for our dominant incumbent markets, summary statistics for prices, capacities and passenger flows for each of these phases. The dominant carrier's average capacity and passenger numbers are higher for Phase 3 observations because Southwest only enters a selected set of markets. The statistics are consistent with Southwest's actual entry reducing the incumbent's price and its market share significantly, suggesting that an incumbent would be willing to make investments that reduce its current profits if doing so could deter or delay entry.

The summary statistics also suggest that incumbents lower prices by an average of almost \$90 (15%) when Southwest threatens entry (the comparison is most straightforward for the middle columns where the set of markets is the same). This is the pattern documented by GS using a regression analysis for a broader sample of markets from 1993 to 2004. We have repeated GS's regression analysis, which estimates price effects for quarters around when Southwest becomes a potential entrant and an actual entrant, controlling for market-incumbent fixed effects[15], quarter fixed effects and time-varying controls, using our dominant incumbent sample (Appendix C.4).

For both average yield (average price divided by route distance) and the log of average price measures, and percentiles of the price and yield distributions, we estimate that, on average, dominant incumbents lower prices by 10-14% when Southwest becomes a potential entrant and by an *additional* 30-45% if Southwest actually enters, relative to the incumbent's prices more than eight quarters before the start of Phase 2. The Phase 2 declines are slightly smaller than those estimated by GS, but the Phase 3 declines are larger, consistent with a dominant incumbent's Phase 1 prices reflecting significant market power. We also observe two other interesting patterns: first, incumbents start to lower prices two quarters *before* the start of Phase 2. This pattern is consistent with our model once we recognize that Southwest's entry is typically announced several months before it operates flights, and that incumbents should want to try to influence Southwest's choice of routes to enter from that date, whereas we have defined the start of Phase 2 based on when Southwest begins to operate flights at both endpoints.[16] Second, we estimate that, on average, incumbent prices fall by more over

[15]The name of the dominant carrier can change during the sample because of a merger. For example, the dominant incumbent on the Hartford-Minneapolis route was Northwest at the start of our sample and Delta at the end of our sample. In this analysis, and in our analysis in Section 4, we give the carrier the identity of the owner at the end of the sample. On this basis there is one incumbent for each of the dominant incumbent markets in our sample.

[16]For a sample of 24 airports where we could identify the exact dates that Southwest announced its entry and began flights, the average gap was 140 days. It is possible that rival airlines anticipate Southwest's entry some weeks before its entry is announced.

time during Phase 2, i.e., when Southwest does not actually enter. Additional investigation reveals that this feature is driven by a subset of the dominant incumbent markets in our data, and that both our basic model, and especially an extended version of our model, are able to explain this feature as well (Sections 5 and 6, and Appendix F).

Table 2 also reports a number of other statistics for the incumbent and Southwest. Over 80% of the incumbent's passengers on our route segments are making connections during Phase 2, suggesting that explanations for marginal cost opaqueness based on connecting passenger flows are appropriate. We can also see that during Phase 2 the incumbent's load factor tends to increase and that Southwest only carries a small share of the passengers on the route through its connecting service (of course, our rules for defining dominant incumbents were designed to make sure that Southwest is not a significant competitor when it is a potential entrant). These facts provide some preliminary evidence against explanations for Phase 2 price reductions that are based on the incumbent's marginal costs falling (marginal cost should increase in the load factor) or actual competition from Southwest once it serves the endpoint airports.

4 Non-Monotonic Relationship Between Incumbent Price Reductions and the Probability of Southwest Entry

In this section we show that in our data there is a non-monotonic relationship between the probability that Southwest enters a dominant incumbent market and how much the incumbent lowers its price in Phase 2. This is consistent with the roughly U-shaped relationship predicted in Figure 1(iv). We will argue that limit pricing is the explanation that best explains this relationship and other features of the data. Readers should refer to Appendix D and Sweeting, Gedge, and Roberts (2018) for additional discussion and results.

We estimate the relationship between the probability of entry and Phase 2 price reductions using a two-stage approach. Our second-stage specification is

$$\text{Price Measure}_{j,m,t} = \gamma_{j,m} + \tau_t + \alpha X_{j,m,t} + \dots$$
$$\beta_0 SWPE_{m,t} + \beta_1 \widehat{\rho_m} \times SWPE_{m,t} + \beta_2 \widehat{\rho_m}^2 \times SWPE_{m,t} + \epsilon_{j,m,t} \quad (7)$$

where $\widehat{\rho_m}$ is the predicted probability that Southwest will enter within four quarters. (7) is estimated only using observations on the dominant incumbent's prices during Phases 1 and 2 (i.e., before Southwest actually enters), and $SWPE_{m,t}$ is an indicator for Phase 2 observations, X includes dummies for the number of observed direct and connecting competitors on the route and jet fuel prices interacted with route distance, and $\gamma_{j,m}$ and τ_t are market-incumbent and quarter fixed effects, so that the β coefficients measure how the incumbent *changes* prices when entry is threatened as a function of $\widehat{\rho_m}$. We test for a non-monotonicity using a quadratic specification because of the small number of observations (in Appendix D.2.2 we show that a plot of the estimated price declines in each market against the probability of entry also indicates a non-monotonicity). A pattern where $\widehat{\beta_0} \approx 0$, $\widehat{\beta_1} < 0$ and $\widehat{\beta_2} > 0$ will be consistent with Figure 1(iv).

Specification (7) is essentially a cross-market regression of changes in one market outcome (the incumbent's price) on the predicted probability of another market outcome (whether Southwest enters). As we do not have an additional set of similar markets where entry was threatened but limit pricing was not possible that we can use as controls, we face a number of possible endogeneity concerns in interpreting the results as reflecting how the threat of entry causes limit pricing behavior. These concerns shape how we construct our $\widehat{\rho_m}$ and lead us to consider a range of possible alternative explanations for a U-shaped relationship.

$\widehat{\rho_m}$ is estimated in a first-stage using a probit specification. The dependent variable equals one if and only if Southwest enters the market within four quarters of becoming a potential entrant.[17] The explanatory variables include quarter dummies, measures of market size and

[17]We examine entry within four periods so that we do not have to deal with the truncation that results from different markets being exposed to the threat of entry for different numbers of periods. Our specification

concentration and measures of how the route fits into the networks of the incumbent and Southwest. We make two choices to reduce the possibility that Phase 2 price cuts could affect the entry decisions in our first-stage specification. First, the probit is estimated using the full sample *excluding* our dominant incumbent markets. Second, any variables based on passenger flows, which could be affected by prices, are calculated using Phase 1 quarters that are more than one year before the start of Phase 2.[18] Appendix D.2.3 shows that our second-stage results are robust to reducing the set of explanatory variables even further.

The probit estimates are presented in Appendix D.1 and they show that Southwest is more likely to enter shorter and larger markets, routes that include one of its focus airports, and markets that are more concentrated before it enters. When we apply the estimates to the 65 dominant incumbent markets with Phase 1 and Phase 2 observations, the predicted probabilities of entry within four quarters vary from $2.6\text{x}10^{-4}$ to 0.99, with the 20^{th}, 40^{th} and 60^{th} and 80^{th} percentiles at 0.02, 0.12, 0.28 and 0.54.

Columns (1) and (2) of Table 3 show the estimated second-stage coefficients for the log(average price) and average yield price measures (see Appendix Figure D.1 for graphical illustration). There is a U-shaped relationship between price changes and the probability of entry. The largest, and most significant, predicted price declines, of just under 15% relative to Phase 1 prices, happen when the probability of entry is in the region of 0.3 or 0.4. In both cases price declines for very high or low entry probabilities are predicted to be small and/or statistically insignificant.

This pattern is consistent with the prediction of our limit pricing model when we exogenously varied the probability of entry by changing market size, but there are several possible alternative explanations for why we observe this pattern in the data. Here we briefly summarize the arguments against these alternatives that are discussed in detail in Appendix D.2.3.

assumes that there is a positive and monotonic relationship between the probability that Southwest will enter within four quarters and the probability it will enter in later quarters if it has not already done so.

[18]For 474 of the 1,542 markets in the full sample we only have less than four Phase 1 quarters, and in this case we use all of the Phase 1 quarters that we do have.

Several explanations would involve the incumbent's prices falling in Phase 2 because its marginal costs are falling. One story would be that airport improvements (e.g., capacity increases) lower the incumbent's marginal costs and lead Southwest to consider entering the airport. If this is particularly pronounced for intermediate probability of entry markets then this could generate a U-shaped pattern. We address this possiblity by showing that the estimated non-monotonicity is robust to including airport $\times$ Phase 2 fixed effects, so that identification comes from variation in entry probabilities across routes within airports. We also find no evidence of a non-monotonicity at the end of Phase 1 which we might expect if airport developments cause incumbents to lower prices and Southwest to consider entering an airport. Alternative stories would involve the incumbent's marginal costs falling because it responds to the threat of entry by increasing its capacity, possibly to try to deter entry (e.g., Dixit (1980)), or because it loses customers, lowering its load factor, once consumers can fly Southwest to other destinations.[19] Columns (3)-(5) of Table 3 address these questions using our specification (7) and the natural logs of the incumbent's capacity, the total number of passengers on its flights and its average load factor as dependent variables. The estimated coefficients (and the plots available in Appendix Figure D.1) indicate that traffic and load factors increase in the intermediate probability of entry markets, while capacity does not change significantly. These results are not consistent with the incumbent's marginal costs falling. In Appendix D.2.3 we also present results suggesting that competition from the connecting service that Southwest can provide in Phase 2 does not explain the results.

A final alternative explanation is that incumbents lower prices to build up the loyalty of their customers, possibly by encouraging them to accumulate miles in frequent-flyer programs (FFPs).[20] Appendix D.3 discusses evidence that suggests loyalty-building is unlikely to be

[19]The model presented in Section 2 did not include capacity investment, and variation in a carrier's optimal capacity investment policy with market size when facing the possibility of new entry as market size varies, even without any deterrence incentives, could affect pricing. This is one reason why we discuss a model where capacity investment is an integral part of the model in Section 6.

[20]This type of strategy could be rationalized by either entry deterrence or entry accommodation incentives (loyalty could soften post-entry competition or increase the incumbent's demand), although the observed non-montonicity is consistent only with a deterrence explanation as accommodation would suggest that we should see the largest strategic investments in markets where entry is most likely.

the primary reason why prices fall. We observe significant non-monotonic price declines across the price distribution, not just for more expensive seats that will tend to be bought by business travelers who are most likely to be members of FFPs, and we are also not able to find any evidence that price reductions increase an incumbent's future demand as a loyalty story would suggest. It also seems unlikely that across-the-board reductions in ticket prices would be more effective at building loyalty or FFP participation than targeted rewards, such as double or triple miles promotions, which we cannot observe in the data.

5 Calibration

In this section we calibrate a version of the model from Section 2 where we allow for a more flexible model of mean entry costs to capture how entry probabilities vary across markets and over time. We choose the demand, marginal cost and entry cost parameters using *no information on how incumbent prices change during Phase 2.* We show that the calibrated model predicts a pattern of price declines that matches the non-monotonic pattern of price reductions in the data quite accurately. We use the calibrated model to quantify the welfare effects of limit pricing and of subsidies that would encourage Southwest to enter.

5.1 Parameter Estimation

5.1.1 Overview

Our dominant incumbent sample contains heterogeneous markets with different demands and costs that vary over time, and where many factors affect how likely Southwest is to enter. It is computationally infeasible to structurally estimate a version of the model that captures all of this heterogeneity. We therefore choose to use a single set of demand and marginal cost parameters, where dynamics enter only through marginal costs, and we create a transformed market size variable that allows us to capture cross-market variation in entry probabilities in a single dimension. In this subsection we describe how we choose the demand

and marginal cost parameters, how we transform market size and how we match empirical entry hazards to estimate the distribution of entry costs.

5.1.2 Demand Estimation

We model passenger demand using a one-level nested logit structure, where the incumbent and Southwest, once it enters, are in one nest and choosing not to travel or flying another carrier form the outside good. The indirect utility function is

$$\begin{aligned} u_{i,j,m,t} &= \mu_j + \tau_1 T_t + \tau_{2-4} Q_t + \gamma X_{j,m,t} - \alpha p_{j,m,t} + \xi_{j,m,t} + \zeta_{i,m,t}^{FLY} + (1-\lambda)\varepsilon_{i,j,m,t} \\ &\equiv \theta_{j,m,t} - \alpha p_{j,m,t} + \xi_{j,m,t} + \zeta_{i,m,t}^{FLY} + (1-\lambda)\varepsilon_{i,j,m,t} \end{aligned} \quad (8)$$

where we allow mean utility to depend on the number of other carriers who carry any passengers direct (the interpretation is that these carriers affect the value of the outside good), a linear time trend, quarter-of-year dummies, route distance and distance squared, dummies for routes involving a hub, a tourist destination or an endpoint in an MSA with multiple major airports, and dummies for Southwest and the major incumbent carriers. We estimate demand using the standard estimating equation for a nested logit model using aggregate data (Berry (1994)). Our observations are Phase 1 observations for the dominant incumbent and (where available) Phase 3 observations for the incumbent and Southwest from the 109 dominant incumbent markets. Table 4 reports the estimates for the price and nesting parameters using OLS and our preferred two-stage least squares specification, where we instrument for a carrier's price and a carrier's share of its nest using fuel prices interacted with route distance, and, for Southwest, a measure of the incumbent carrier's presence (measured by the proportion of traffic served) at the endpoint airports and whether an endpoint is a hub for the incumbent, and for the incumbent, an indicator for whether Southwest has entered and Southwest's presence at the endpoints. The 2SLS parameters imply that the incumbent and Southwest are quite close substitutes and the average Phase

3 own-price elasticity for an incumbent is -2.92.

5.1.3 Marginal Cost Estimation

We use the demand estimates and the first-order conditions associated with static, complete information profit-maximization for quarters in Phases 1 and 3, under the assumption that limit pricing only takes place in Phase 2, to infer the carriers' marginal costs in each quarter. The average implied marginal cost for the incumbent is \$258. On average, Southwest's implied marginal costs are 31% (or 5.4 cents per mile) lower than the incumbent's during Phase 3, which is consistent with differences between the average operating cost per available and per equivalent seat mile for legacy carriers and Southwest reported by the MIT Airline Data project based on data from the Department of Transportation's Form 41 (available at http://web.mit.edu/airlinedata/www/default.html). We estimate an AR(1) process using the implied marginal costs per mile

$$mc_{j,t} = \rho^{AR} mc_{j,t-1} + X_{j,t}\gamma + \mu_t + \mu_j + \varepsilon_{j,t} \tag{9}$$

where μ_t and μ_j are quarter and carrier dummies. The controls in X include interactions between the one-quarter lagged jet fuel price and distance, market size, average endpoint populations and a dummy for whether an endpoint airport is slot-controlled. Table 5 shows the estimates of p^{AR} from four specifications. In the 2SLS specifications we instrument for the lagged marginal cost using three previous lags as we recognize that our estimates of a carrier's marginal cost in any quarter are functions of noisy estimates of average prices and market share.

5.1.4 Choosing the Demand and Marginal Cost Parameters for the Entry Cost Calibration

As explained above, we use a single set of "representative market" demand and marginal cost parameters when performing the calibration.[21]

We assume a nested logit model of demand and use the estimated price and nesting coefficients of -0.45 and 0.8 respectively. The value of carrier quality for the incumbent, θ_I, is 0.75 and Southwest's is 0.66.[22] These qualities are treated as fixed over time, although this assumption could be relaxed at the cost of a much greater computational burden.

We assume that Southwest's marginal costs are fixed and equal to \$168. The incumbent's marginal costs are allowed to vary within a range of $\underline{c_I} = \$238$ and $\overline{c_I} = \$278$ around the mean of \$258. Based on the estimated AR(1) parameter we assume that

$$c_{I,t} = 0.97 * c_{I,t-1} + (1 - 0.97) * \frac{\underline{c_I} + \overline{c_I}}{2} + \varepsilon_{I,t} \qquad (10)$$

where $\varepsilon_{I,t} \sim TRN(0, \sigma_c^2, \underline{c_I} - c_{I,t-1}, \overline{c_I} - c_{I,t-1})$, and the untruncated standard deviation, σ_c, is \$36. This standard deviation allows us to match the interquartile range of the estimated innovations in marginal costs in column (2) of Table 5 based on a representative market distance of 1,200 miles. We acknowledge that there is some arbitrariness in our choices as we do not know what portion of the marginal cost innovations is unobserved by the potential entrant. However, we are assuming that the range of marginal costs is similar to the standard deviation of marginal cost innovations, implying that knowledge of the incumbent's current marginal cost should not be especially informative about whether its marginal cost in future periods will be high or low. Therefore one would expect our assumptions to generate only

[21] This is done partly to reduce the computational burden, but it is also done to avoid double counting how factors such as route distance affect how attractive a market is for Southwest to enter. As we describe below we will create a rescaled market size variable that accounts for how distance, and other variables, affect entry probabilities, and this adjustment should capture factors that influence the probability of entry through demand or marginal costs.

[22] During Phase 3 the average difference between the estimated $\theta_{j,m,t}$s of Southwest and the incumbent is -0.088, which is consistent with Southwest having a lower Phase 3 price but a similar market share (Table 2).

mild incentives for the incumbent to engage in limit pricing.[23]

5.1.5 Predicted Entry Probabilities and the Rescaling of Market Size

We now describe how we rescale market size to capture how many observable factors affect the probability that Southwest will enter and how we choose empirical entry hazards that will be matched when we estimate the distribution of entry costs.

We estimate a Weibull hazard model for Southwest's entry once it becomes a potential entrant using the full sample of data. The covariates include market size in the quarter Southwest becomes a potential entrant, the explanatory variables included in the probit model in Section 4 and a dummy for the market being in the dominant incumbent sample.[24] The Weibull structure allows us to capture the fact that the probability that Southwest enters in quarter t conditional on not entering previously tend to fall over time.

We use the estimated parameters on the market-level variables in the baseline hazard function to rescale the market size variable so that the hazards based on the rescaled variable alone are identical to those predicted by the estimated multivariate hazard model. The effect of this rescaling is illustrated in Table 6 for three markets that have Omaha as an endpoint. While Las Vegas-Omaha has a small market size, the probability of entry is relatively high because Las Vegas is a leisure destination and a Southwest focus city. This leads to its rescaled market size being larger than those for the other markets in the table. The table also shows that the implied hazard entry probabilities (i.e., the probability that Southwest will enter in a quarter conditional on not having entered in earlier quarters) decline over time over time, as well as being heterogeneous across markets. We use a more flexible model

[23]We also note that we did not impose that marginal costs can only lie on an interval when we estimated the AR(1) process. It would be hard to impose the truncation when dealing with markets of different lengths when we are allowing observable time-varying covariates, such as fuel prices, to affect the mean level of marginal costs in different ways in different markets.

[24]We include the dominant incumbent markets in the sample with a dummy explanatory variable so that we exactly match the average probability of entry for these markets. The time until Southwest enters is measured by the number of quarters since Southwest became a potential entrant plus 0.25, where the addition is required so that we can include those markets that Southwest entered in the same quarter that it entered the endpoint airports. As mentioned below, we will not try to match predicted probabilities for the first quarter where the chosen addition has a disproportionately large effect on the predicted hazard.

of mean entry costs than we assumed in Section 2 to fit this pattern.

5.1.6 Entry Cost Parameters

We assume that Southwest's entry costs in period t, where t measures the number of quarters since Southwest became a potential entrant, are normally distributed, $N(\mu_{m,t}, \sigma_\kappa^2)$. We use a single parameter for the standard deviation because this is an important parameter that directly affects shading through its effect on $g(\kappa)$ (see equation (4)). We allow a flexible model of the log of $\mu_{m,t}$ to fit the heterogeneity in the data. Specifically, it can vary with the log of rescaled market size, and it can increase by a factor of $(1+\gamma_{m,1})t^{\gamma_{m,2}}$ each quarter, where $\gamma_{m,1}$ is constrained to be positive. We interpret the variation with market size as reflecting the fact that our estimated entry cost should include the discounted value of future fixed costs, including the costs associated with capacity, that Southwest commits to when it enters. It is plausible that capacity costs will be larger in markets that are larger or where Southwest expects to have a larger market share. We assume that the increase in entry costs stops after 30 quarters, at which point the carriers play the limiting infinite horizon version of our model.[25] Both the incunbent and Southwest anticipate this increase, which provides Southwest with a strong incentive to enter early even when the increases in entry costs are small. We allow the logs of $\gamma_{m,1}$ and $\gamma_{m,2}$ to vary with a quadratic in rescaled market size.[26] The discount factor is 0.98, so that time periods can be interpreted as quarters.

We estimate the entry cost parameters by minimizing the sum of squared differences between the entry probabilities predicted by the model to the predictions from the estimated Weibull model for $t = 2, .., 20$, for every fifth dominant incumbent market, when we order markets by rescaled market size, so that we use 21 markets in total.[27] A nested fixed point

[25] Our estimates imply that mean entry costs rise very little after 15 quarters, and our results are almost identical if we allow mean entry costs to increase for 50 quarters rather than 30 quarters (see Appendix B and Appendix Figure E.2).

[26] We arrived at these specifications by initially calibrating entry cost distributions for five groups of markets split by rescaled market size with no cross-market heterogeneity in the parameters within each group. Our chosen specifications allow us to match how the estimated parameters varied across the five groups almost perfectly.

[27] The empirical hazard for the first quarter is sensitive to the ad-hoc addition to the timing of entry

approach is feasible because we can solve for equilibrium entry strategies using a complete information formulation of the model, so that there is no need to estimate equilibrium limit pricing strategies at each iteration.

Table 7 shows the estimated entry cost parameters. Figure 2 shows that we are able to match the predicted probabilities quite closely[28], and Appendix Figure E.1 shows how the implied entry cost parameters vary across markets. Mean initial entry costs vary almost linearly with rescaled market size in our data. For the median market, the mean initial entry cost ($\mu_{m,1}$) is \$44.2 million. An increase in rescaled market size of 1,000 people increases mean initial entry costs by around \$1.25 million or just over \$90 per Southwest passenger per quarter given Southwest's average post-entry market share. This compares with average variable Southwest profits per passenger of around \$110. If we assume that all of the variation in mean entry costs with market size reflects future fixed costs associated with capacity, we would infer that the remaining true sunk entry cost would be close to \$1.4 million, which seems plausible.[29] The standard deviation of entry costs is close to \$204,000, which does not seem unreasonable for the types of routes in our sample. Appendix Figure E.2 shows the implied path of the mean entry cost (including discounted fixed costs) and the probability of entry for the median market. The small increase in mean entry costs (less than 1% over six years) is sufficient to explain the large fall in entry probabilities. We can interpret this increase as reflecting the expiry of financial incentives, such as reduced landing fees and subsidized marketing, that are often available for the first few years after a carrier enters an airport, or a more behavioral explanation involving Southwest's managers being more

described in footnote 24 so we do not try to match it. We have also estimated the model using an objective function that is based on proportional (not absolute) differences between the implied and empirical entry probabilities. This produces very similar qualitative results, but larger welfare effects because the implied probability of entry rises in the smallest markets which generates greater shading.

[28]The figure is drawn for the 21 markets used in estimation. We have also examined the fit for the 65 markets which identified the non-monotonic relationship in Section 4. For the two largest markets our estimated model implies that entry probabilities are much lower than our hazard model predicts for periods after $t = 10$. However, this difference has almost no effect on our welfare calculations as the parameters imply that entry within one year is almost certain.

[29]This calculation is done assuming that the relationship all of the way down to a rescaled market size of zero is linear, which would not be consistent with the assumed functional form, even though the relationship is almost perfectly linear in the data (Appendix Figure E.1).

attentive to possible profitable route additions when they initially enter an airport.

5.2 Predicted Limit Pricing and Its Relationship with the Probability of Entry

Given the calibrated parameters, we solve for equilibrium limit pricing strategies for each market for each quarter after entry starts to be threatened (see Appendix B for the computational details). Figure 3(a) shows the relationship between the model-implied probability that Southwest enters in the first four quarters that it is a potential entrant and the expected change in the incumbent's price, relative to the static monopoly price, during these quarters if entry does not occur. Each circle represents a dominant incumbent market. Figure 3(b) shows the estimated change in log(average price) based on the coefficients in Table 3.

The obvious similarities are that both figures show a clear non-monotonic relationship between price changes and the probability of entry. The largest price decline predicted by the model (17%) is within the confidence intervals of the largest decline in price (15%) estimated from the data, with both occurring for intermediate probabilities of four quarter entry (0.55 and 0.31). The main difference is that the estimated curve predicts price increases for high probabilities, a feature that our model can never generate (a firm never has a reason to charge more than the static monopoly price). The problem here is with the extrapolation implied by the quadratic: we observe only a few markets with very high entry probabilities where we can identify price effects, and in these markets there is no evidence of large price increases (see Appendix D.2.2). Overall, we interpret the comparison as providing solid evidence that our limit pricing model provides a plausible explanation for why dominant incumbents lower prices when Southwest threatens entry.

5.3 Welfare Effects of Potential Competition under Asymmetric and Complete Information

We use the model to perform two types of calculation. The first calculation estimates the welfare effects of limit pricing in our dominant incumbent markets by comparing outcomes under asymmetric information and under complete information about the incumbent's marginal costs. The results are shown in Table 8 for three example markets and when we add all of the dominant incumbent markets together. Consumer surplus and incumbent profits are computed using our "true" market size measure, which is consistent with viewing the additional factors that enter rescaled market size as being ones that affect Southwest's entry costs. We assume that Southwest arrives as a potential entrant once the incumbent has chosen its static monopoly price in the first period and can choose to enter immediately, so that limit pricing begins in the second period if entry does not occur.

In the Hartford-Minneapolis market, Southwest is unlikely to enter and our model predicts that the threat of possible entry will reduce the incumbent's price by around \$20 (or 3.8%). However, using a quarterly discount factor of 0.98, this percentage reduction implies a present value of savings for consumers who would have traveled with monopoly pricing of \$4.32 million dollars (2009 dollars) while the incumbent remains a monopolist. As entry decisions would be the same under complete information, this number also measures the savings that consumers make in a model of asymmetric information. The increase in consumer surplus is slightly larger as lower fares cause some additional consumers to travel. As we are considering small reductions away from the profit-maximizing price, the reduction in the incumbent's profits is much smaller than the gain in consumer surplus.

Our model predicts much greater price shading when entry is threatened in the larger Manchester-Philadelphia market, but because limit pricing ends when entry happens, the present discounted value of consumer benefits from limit pricing increases by only 50% compared with Hartford-Minneapolis. For the largest markets, such as Las Vegas - San Jose, Southwest will likely enter before limit pricing can occur, so that the welfare effects of asymmetric information are limited. However, because most of our dominant incumbent markets are quite small, the present discounted value of limit pricing for consumers aggregated across the 109 markets in our sample is over $590 million, a substantial effect.

5.4 Welfare Effects of Entry Subsidies

The second calculation uses our model to investigate the welfare effects of small subsidies to Southwest when it serves a route. Many airports or local governments provide financial incentives for carriers to add routes, with Ryerson (2016) estimating that 26 US airports spent $171.5 million on "Airline Service Incentive Programs" between 2012 and 2015. For example, Columbus offers marketing subsidies of up to $100,000 and one year with no landing fees in a widely-praised program designed to encourage entry on a targeted set of routes (Port Columbus International Airport (2010), Kinney (2017)). These incentives are usually only granted to the first carrier serving a route, but our results will show that programs that encourage at least the possibility of additional entry could be valuable. We consider a subsidy that would pay Southwest $1,000 every quarter once it enters (implying a maximum present value of $50,000).

The lower section of Table 8 shows the effects of the subsidy on the probability of entry, the amount of shading, consumer surplus and the profits of the incumbent. We compare the effects of the subsidy program under complete information, where the effects only come from raising the probability of actual entry by the incumbent, and under asymmetric information. Whether the increase in consumer surplus is greater under complete or asymmetric information depends on two effects. First, as consumer surplus prior to actual entry is higher under asymmetric information, the value of increasing the probability of entry will tend to be greater under complete information, especially when there is more shading. Second, the subsidy can change the amount of shading that occurs.

In the Hartford-Minneapolis market, the increased probability of entry causes shading to increase (for example, from an average of $20 to $27 dollars in the first period that the incumbent can engage in limit pricing) and because the probability of entry is still low, the increase in consumer surplus is greater under asymmetric information. The welfare changes are also large: under asymmetric information, the present value of consumer surplus increases by \$8.5 million and the value of incumbent profits falls by \$4.0 million. The expected cost to the government is around \$7,000. To illustrate how the level of subsidy affects the size of the increase in consumer surplus, Figure 4 shows how the probability of entry, shading and the gain in consumer surplus change when we increase per-quarter subsidies from \$0 to \$100,000 per quarter. At the upper end of this range, it is almost certain that entry will happen quickly, and an increase in the subsidy will reduce any shading that does occur, so the welfare benefits of subsidies will be greater under complete information. At low entry probabilities, a small subsidy increases shading and subsidies raise consumer surplus more under asymmetric information.

For intermediate size markets, such as Manchester-Philadelphia, the subsidy continues to have large and positive welfare effects, although the gains are larger under complete information. In contrast, in the largest markets entry is almost certain without the subsidy, and the subsidy is effectively just a transfer to Southwest with any increases in consumer surplus having a similar scale to the cost of the subsidy.

Our results are consistent with the idea that subsidy programs should be targeted at markets that are truly marginal rather than ones where entry is very likely. However, our results also suggest that, especially in the presence of asymmetric information, there may be significant benefits to offering subsidies in markets where entry is quite unlikely, because even if entry does not occur, the market power of the incumbent can be constrained if small probabilities of entry are raised even slightly.

6 Extensions

As emphasized in Section 2, we focus on our basic model largely for reasons of tractability. There are two types of criticism that can be leveled at the simplicity of the model. The first criticism is that it cannot explain some features of incumbent's Phase 2 pricing, notably the fact that, on average, incumbents seem to cut prices by more over time when Southwest does not enter. While this can happen in some markets in the model that we calibrate (for example, as shown in Table 8, we predict that average shading would increase from 10.9% to 22.4% of the static monopoly price from the second to the twentieth period if entry does not occur in the Las Vegas-San Jose market where Southwest's entry probability is high), it does not happen on average. In Appendix F we show that the finding of additional price cuts in the data is driven by a subset of our markets, and that one way we can explain increasing price cuts is by extending our model to allow for the possibility that the incumbent is also learning about the probability that Southwest will enter (for example, because it is uninformed about the mean of Southwest's entry cost distribution). The introduction of two-way learning is an interesting extension to the literature in its own right.

The second criticism is that the model misses some key features of the airline industry. In particular, it is not clear what makes the incumbent's marginal cost opaque, and the exogeneity of the marginal cost innovations is inconsistent with the fact that marginal costs will depend on carriers' capacity investments, even if we do not observe large capacity changes in the data when entry is threatened. In Appendix F we address this criticism by building a model where marginal costs depend on endogenous capacities and the amount of demand that a carrier has from passengers who want to travel the route segment as part of a longer itinerary. As previously noted, Edlin and Farrell (2004) and Elzinga and Mills (2005), in the context of alleged predation, argue that it is difficult to assess a carrier's marginal costs when its flights are used to serve many connecting passengers. We have seen that connecting passengers fill the majority of seats on the dominant incumbent routes in our sample. Our extended model also allows the amount of connecting traffic available to Southwest to be correlated with the incumbent's demand, which provides the incumbent with an additional entry deterring motivation to signal that connecting demand is low. We show that this extended model continues to generate large price declines when entry is threatened and that these declines vary non-monotonically with the probability of entry. We also find that even though a carrier could choose to invest in greater (observed) capacity to try to deter entry in our model, predicted changes in capacity tend to be very small across the range of entry probabilities, and this is also consistent with our empirical results (Table 3 and Figure D.1).

7 Conclusion

We have presented theoretical and empirical frameworks for analyzing a classic form of strategic behavior, entry deterrence by setting a low price, in a dynamic setting. Our model assumes that an incumbent has an unobserved state variable that is serially correlated, but not perfectly persistent, over time. We show that under a standard refinement, our model has a unique Markov Perfect Bayesian Equilibrium in which the incumbent's pricing policy perfectly reveals its true type in each period. Our characterization of the equilibrium makes it straightforward to compute equilibrium pricing strategies, and we predict that an incumbent could keep prices low for a sustained period of time before entry occurs. The resulting tractability is striking given the perception in the applied literature that dynamic games with persistent asymmetric information are too intractable to be used in empirical work. We exploit this tractability to investigate whether a limit pricing model can explain why incumbent carriers lower prices significantly when routes are threatened with entry by Southwest. This is a natural setting to study, given that it provides the largest documented effect of potential competition on prices.

We show how the introduction of dynamics can lead to larger price reductions than in the canonical two-period model (Milgrom and Roberts (1982)), especially in markets where the probability of entry is not too high. In the application, this feature can explain why incumbent carriers keep prices low when Southwest remains a potential, but not an actual, entrant for quite long periods of time, and our model can also explain why incumbents cut prices even before Southwest has actually started operating at the endpoint airports. We provide new reduced-form evidence that a limit pricing explanation can explain why prices fall, by showing that there is a non-monotonic relationship between price changes and the probability of entry, and by providing evidence against explanations involving alternative entry deterring strategies, such as capacity investment. We show that when we calibrate our model, without using any information on price changes when entry is threatened, it predicts a pattern of price changes across markets that is qualitatively and quantitatively similar to the pattern in the data. The welfare effects of limit pricing are estimated to be substantial (increasing the present value of consumer surplus by over $590 million) even though we have focused on a sample of only 109 routes, most of which are fairly small. We illustrate how limit pricing may affect the value of a government subsidy program that encourages a carrier to consider entering as a second nonstop carrier. We have also shown that we can extend our model in several directions which preserve the prediction of significant and non-monotonic price reductions and can also allow us to explain additional features of the data.

As noted in Section 2, our model does have some limitations and it generates results which some readers may find unintuitive. For example, the incumbent may be willing to cut prices quite dramatically even when the equilibrium probability of entry is small (e.g., 0.03 or 0.04) and the potential entrant should already have a quite precise prior about the profitability of entry before it sees the incumbent's signal. But as we show, our results reflect the fact that in a dynamic model it can be very valuable to deter entry when future entry probabilities are low, because deterrence can lead to many future periods of monopoly, and the standard feature of signaling models that the precision of the receiver's prior does not affect equilibrium strategies when there is full separation. Indeed, we see a contribution of our paper as showing that signaling may provide a more powerful explanation for real-world phenomena than has been recognized in the empirical literature.

While we have explored one type of asymmetric information model and one application, we believe that there are many areas in which to explore how asymmetric information may impact firm behavior. For example, it is often claimed that predatory pricing is motivated by incumbents wanting to signal information on their costs or their intentions to both the current competitor and potential future competitors, and it would be interesting to compare how well this type of signaling story compares quantitatively against non-informational models of predation where the dominant incumbent makes observable investments (for instance, in capacity (Snider (2009), Williams (2012)), or learning-by-doing (Besanko, Doraszelski, and Kryukov (2014))) that commit it to lower future costs. Sweeting, Tao, and Yao (2018) show that when oligopolists are uncertain about each other's marginal costs, or alternatively how much weight each firm puts on profits and revenues when setting prices, equilibrium prices can be much higher than static models would predict, and static models may under predict how much mergers will raise prices. Closer to our current application, we would also like to explore whether there are assumptions under which a model with several incumbents has a tractable equilibrium with significant limit pricing behavior. This would allow us to expand our analysis in this paper to a broader set of industries and markets.

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Table 1: Comparison of Markets in the Full Sample and Dominant Incumbent Samples

			Dominant Incumbent Samples			
	Full Sample		109 Markets		65 Markets	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Mean endpoint population (m.)	2.509	1.918	2.834	1.923	3.218	2.112
Round-trip distance (miles)	2,525.11	1352.57	1,257.57	743.08	1,344.5	798.75
Constructed market size measure	33,005	46,389	65,637	68,589	52,325	62,642
Origin or destination is a:						
primary airport in multi-airport MSA	0.186	0.389	0.321	0.469	0.262	0.443
secondary airport in multi-airport MSA	0.316	0.465	0.321	0.469	0.369	0.486
airport in big city	0.643	0.479	0.844	0.364	0.877	0.331
leisure destination	0.108	0.311	0.110	0.314	0.092	0.292
slot controlled airport	0.039	0.193	0.064	0.246	0.108	0.312
Number of markets	1,542		109		65	

Notes: We define leisure destinations (primarily cities in Florida, Las Vegas, Charleston, SC and New Orleans) and big cities (top 30 MSAs excluding leisure destinations) following Gerardi and Shapiro (2009). We define New York JFK, LaGuardia and Newark, Washington Reagan and Chicago O'Hare as slot controlled, although slot controls are no longer in place at O'Hare. We identify metropolitan areas with more than one major airport using http://en.wikipedia.org/wiki/List_of_cities_with_more_than_one_airport, and identify the primary airport as the one with the most passenger traffic in 2012.

Table 2: Summary Statistics: Dominant Incumbent Sample

	Phase 1: $t < t_0$		Phase 1: $t < t_0$		Phase 2: $t_0 \leq t < t_e$		Phase 3: $t \geq t_e$	
	All markets		Markets with Phase 1 and Phase 2 Observations					
Variable	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Incumbent Pricing								
Yield (average fare per mile)	0.516	0.331	0.527	0.339	0.452	0.323	0.311	0.166
Average fare	476.77	135.18	514.55	144.44	426.06	117.68	261.83	60.65
Southwest Pricing								
Yield	-		-		0.296	0.150	0.235	0.072
Average fare	-		-		388.50	120.45	214.37	62.63
Passenger Shares								
Incumbent	0.797	0.213	0.743	0.235	0.840	0.122	0.461	0.198
Southwest	-		-		0.018	0.032	0.479	0.217
Incumbent Capacity and Traffic								
Capacity (seats performed)	75,760	52,459	72,785	49,012	69,770	47,066	90,877	52,314
Segment passengers (incl. connecting pass.)	46,072	32,141	44,174	29,814	48,478	31,677	64,385	38,585
Load factor	0.612	0.104	0.618	0.106	0.710	0.121	0.705	0.081
Proportion pass. connecting	0.837	0.114	0.847	0.109	0.830	0.115	0.774	0.107
Southwest Capacity and Traffic								
Capacity (seats performed)	-		-		-		80,751	62,207
Segment passengers (incl. connecting pass.)	-		-		-		52,713	39,195
Load factor	-		-		-		0.651	0.083
Proportion pass. connecting	-		-		-		0.701	0.101
Number of markets	109		65		65		59	

Table 3: Second-Stage Estimates of the Relationship Between the Probability that Southwest Enters and Changes in Incumbent Prices, Capacities, Segment Traffic and Load Factors

Dependent Variable	(1) Log Price	(2) Yield	(3) Log Capacity	(4) Log Passengers	(5) Log Load Factor
$SWPE_{m,t}$	-0.043*	-0.002	0.068	0.144***	0.076***
	(0.023)	(0.014)	(0.043)	(0.044)	(0.017)
$\widehat{\rho_m} * SWPE_{m,t}$	-0.693***	-0.732***	0.040	0.578	0.538***
	(0.182)	(0.142)	(0.362)	(0.413)	(0.142)
$\widehat{\rho_m}^2 * SWPE_{m,t}$	1.169***	1.046***	-0.820	-2.053***	-1.233***
	(0.256)	(0.219)	(0.619)	(0.749)	(0.236)
Observations	3,884	3,884	3,400	3,400	3,400

Notes: Heteroskedasticity robust Newey-West standard errors allowing for one period serial correlation and corrected for first-stage approximation error in the entry probabilities in parentheses. The number of observations reflect differences in the coverage and reporting in the DB1 and T100 data during our sample period. The predicted probability that Southwest enters within four quarters of becoming a potential entrant is based on estimates reported in Appendix D.1, and these specifications include market-incumbent and quarter fixed effects and time-varying controls listed in the text. ***, ** and * denote statistical significance at the 1, 5 and 10% levels respectively.

Table 4: Nested Logit Demand: Price and Nesting Parameters

	OLS	2SLS
Fare (\$00s, $\widehat{\alpha}$)	-0.317***	-0.446***
	(0.011)	(0.034)
Inside Share ($\widehat{\lambda}$)	0.748***	0.793***
	(0.033)	(0.072)
Observations	6,037	6,037
R^2	0.301	-

Notes: Specification also includes a linear time trend, quarter of year dummies, dummies for Southwest and the major incumbent carriers, market characteristics (distance, distance^2, indicators for whether the route includes a carrier's hub, a leisure destination or is in a city with another major airport) and dummies for the number of competitors offering direct service. The instruments used for 2SLS are described in the text. Robust standard errors in parentheses. ***,**,* denote statistical significance at the 1, 5 and 10% levels respectively.

Table 5: Marginal Cost Evolution: Estimates of Serial Correlation

	(1) OLS All Carriers	(2) 2SLS All Carriers	(3) 2SLS Southwest	(4) 2SLS Incumbents
MC $\widehat{\text{per mile}}_{j,m,t-1}$	0.916***	0.974***	0.978***	0.962***
	(0.037)	(0.013)	(0.039)	(0.012)
Observations	5,658	4,710	1,492	3,218
R^2	0.834	-	-	-

Notes: The dependent variable is MC $\widehat{\text{per mile}}_{j,m,t}$, carrier j's computed marginal cost per mile in market m in quarter t. The specification also includes market characteristics (market size, average population, distance and a dummy for whether one of the airports is slot constrained), quarter dummies, carrier dummies and the lagged price of jet fuel interacted with route distance. In columns (2)-(4) we use the third through fifth lags of marginal cost per mile to instrument for lagged marginal costs. Robust standard errors, corrected for the uncertainty in the demand estimates, are in parentheses. ***, **, * denote statistical significance at the 1, 5 and 10% levels respectively.

Table 6: Weibull Hazard Model: Predicted Hazard Rates and Rescaled Market Size for 3 Markets

Route	Original Market Size	$\widehat{h_{m,2}}$	$\widehat{h_{m,10}}$	Rescaled Market Size
Las Vegas - Omaha	19,820	0.208	0.098	46,462
Omaha - St Louis	36,568	0.092	0.042	37,402
Minneapolis - Omaha	38,763	0.037	0.017	27,948

Notes: The table shows, for three example markets, the original market size (constructed as described in Appendix C.2), estimated probabilities of entry after two and ten quarters ("hazard rates"), conditional on not having entered in an earlier period, and our rescaled market size which captures all of the observed variables entering the linear index of the hazard model. The hazard entry probabilities are calculated by finding the survival probability, $S_{m,t}$, for each quarter, and then calculating entry probability as $\frac{(S_{m,t-1}-S_{m,t})}{S_{m,t-1}}$.

Table 7: Calibration of Entry Costs: Parameter Estimates

	Constant	$\text{Log}(\frac{\text{Rescaled Market Size}}{100{,}000})$	
$\text{Log}\left(\frac{\text{Mean Entry Costs}}{10 \text{ million}}\right)$	2.524	0.968	
	(0.016)	(0.017)	
$\text{Log}\left(\frac{\text{Std. Dev. of Entry Costs}}{1 \text{ million}}\right)$	−1.588	-	
	(0.511)		
	Constant	$\frac{\text{Rescaled Market Size}}{100{,}000}$	$\left(\frac{\text{Rescaled Market Size}}{100{,}000}\right)^2$
$\text{Log}(\gamma_1)$	−6.790	9.050	−12.819
	(1.745)	(7.174)	(6.135)
γ_2	−1.940	−4.343	10.636
	(1.368)	(4.688)	(4.014)

Notes: Parameters minimize the sum of squared residuals comparing predicted hazard probabilities of entry with ones estimated from a Weibull hazard model based on 21 dominant carrier markets. The rescaling of market size is described in the text. Standard errors in parentheses only reflect uncertainty from the calibration stage of estimation, not from estimation of the Weibull hazard model, the carrier demand or marginal cost models, or the rescaling of market size.

Table 8: Welfare Effects of Limit Pricing and Counterfactual Fixed Cost Subsidies

Market	Hartford-Minneapolis	Manchester, NH-Philadelphia	Las Vegas-San Jose	All Dominant Incumbent Markets
Market Rank (by rescaled market size, out of 109 markets)	20	65	105	
Actual Market Size	33,828	45,481	136,861	total: 5.7 million
Model Predictions				
2^{nd} Quarter				
Prob. of Entry (if no entry in 1st quarter)	0.002	0.095	0.606	mean: 0.151
Shading ($, % relative to static monopoly price)	$20.07, 3.8%	$86.49, 16.6%	$57.04, 10.9%	mean: $59.83, 11.4%
20^{th} Quarter				
Probability of Entry (if no entry previously)	0.002	0.046	0.266	mean: 0.050
Shading ($, % relative to static monopoly price)	$16.87, 3.2%	$69.23, 13.3%	$117.06, 22.4%	mean: $52.44, 10.1%
Probability of Entry Within 4 Quarters	0.010	0.339	0.973	mean: 0.355
Welfare Effects of Limit Pricing (relative to complete information)				
PDV of Reduced Prices ($ms)	4.32	6.20	0.76	total: 538.74
PDV of Change in Consumer Surplus ($ms)	4.38	7.07	0.84	total: 592.27
PDV of Change in Incumbent Profits ($ms)	-0.18	-1.35	-0.13	total: -86.18
Impact of a $1,000 Per Quarter Subsidy				
Probability of Entry within 4 Quarters	0.018	0.372	0.974	mean: 0.374
2nd Period Shading ($, %)	$27.40, 5.3%	$89.62, 16.3%	$60.98, 10.9%	mean: $54.50, 10.5%
PDV of the Cost to Government ($ms)	0.007	0.039	0.048	total: 3.397
Changes Under Complete Information				
PDV of Change in Consumer Surplus ($ms)	7.136	4.127	0.078	total: 577.74
PDV of Change in Incumbent Profits ($ms)	-3.880	-2.239	-0.042	total: -314.15
Changes Under Asymmetric Information				
PDV of Consumer Surplus Gain ($ms)	8.553	3.264	0.059	total: 553.91
PDV of Change in Incumbent Profits ($ms)	-4.038	-2.083	-0.039	total: -312.14

Figure 1: Relationship Between Market Size, Entry Probabilities and Shading in the Dynamic Limit Pricing Model.

Figure 2: Match of Empirical Entry Probabilities (Conditional on Entry Having Not Already Occurred) and the Probabilities Predicted by the Calibrated Model for the 21 Markets Used in the Calibration.

Figure 3: Predicted and Estimated Relationships Between Price Changes and the Probability of Entry.

Figure 4: Predicted Effect of Fixed Cost Subsidies for Southwest on Entry, Incumbent Shading and Consumer Surplus in the Hartford-Minneapolis Market.

Figure 1: Relationship Between Market Size, Entry Probabilities and Shading in the Dynamic Limit Pricing Model.

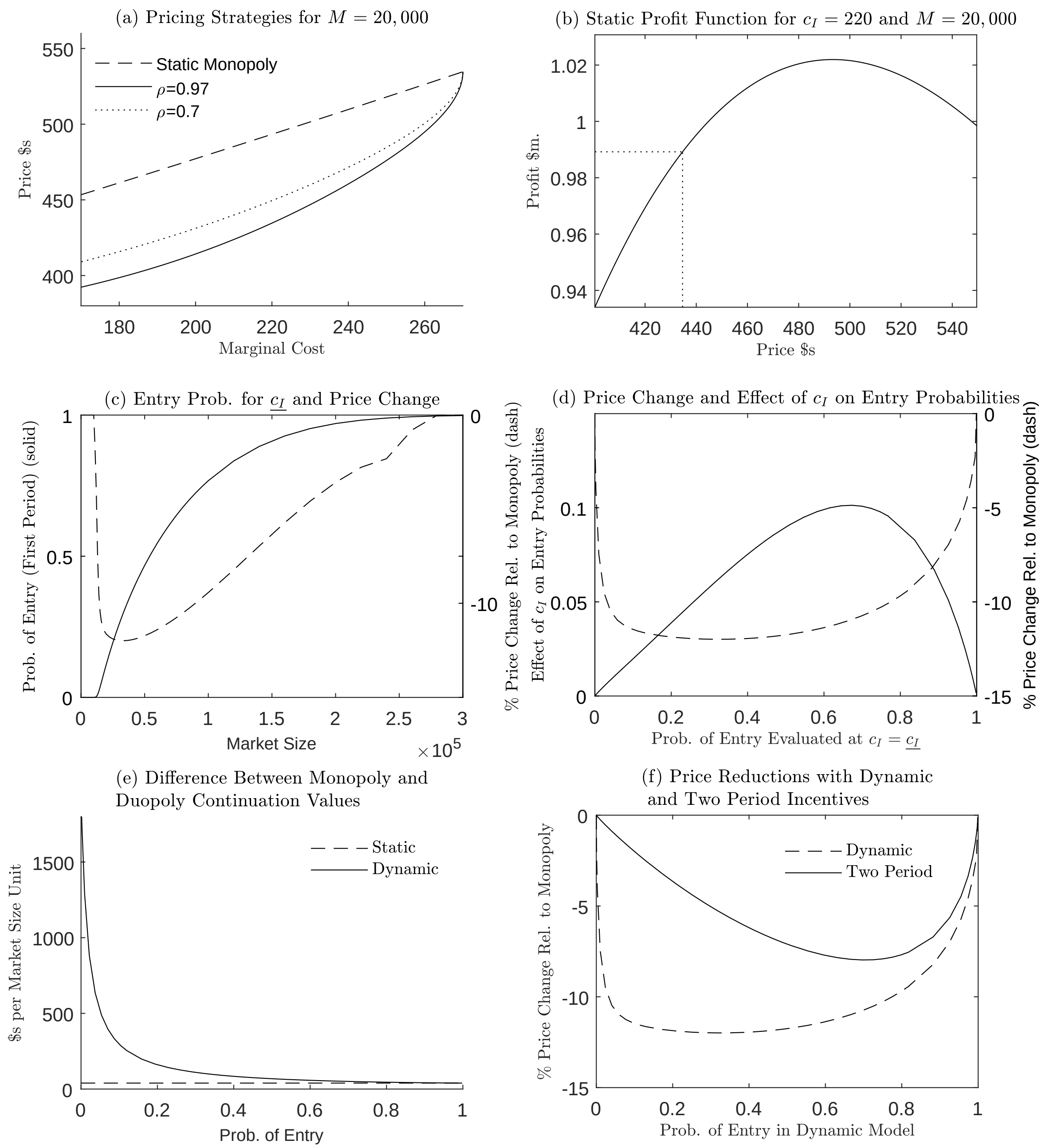


Figure 2: Match of Empirical Entry Probabilities (Conditional on Entry Having Not Already Occurred) and the Probabilities Predicted by the Calibrated Model for the 21 Markets Used in the Calibration.

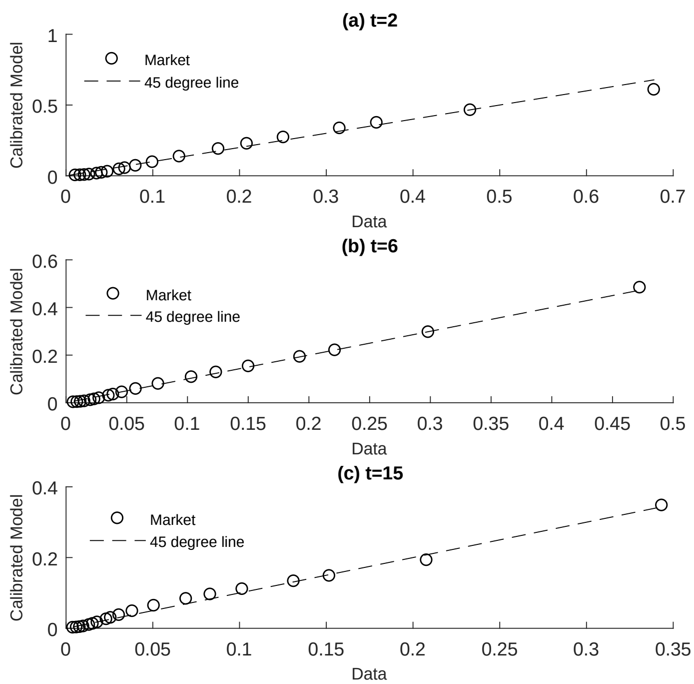


Figure 3: Predicted and Estimated Relationships Between Price Changes and the Probability of Entry.

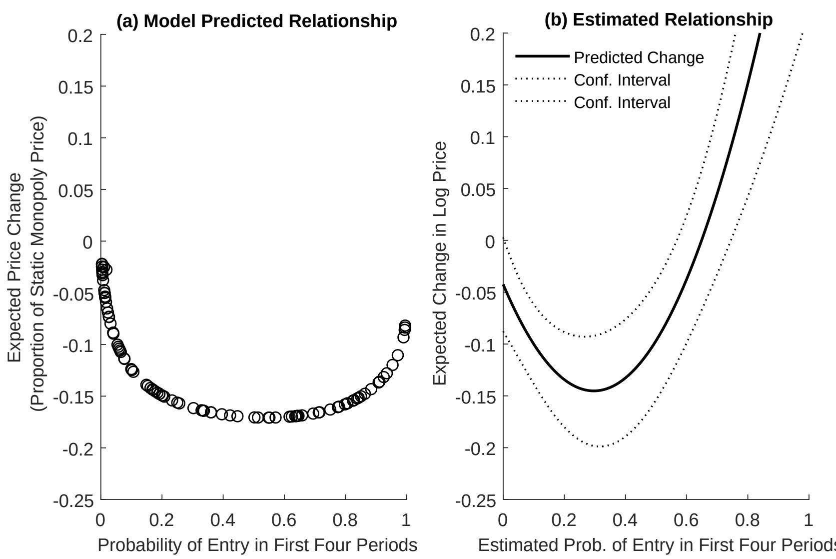
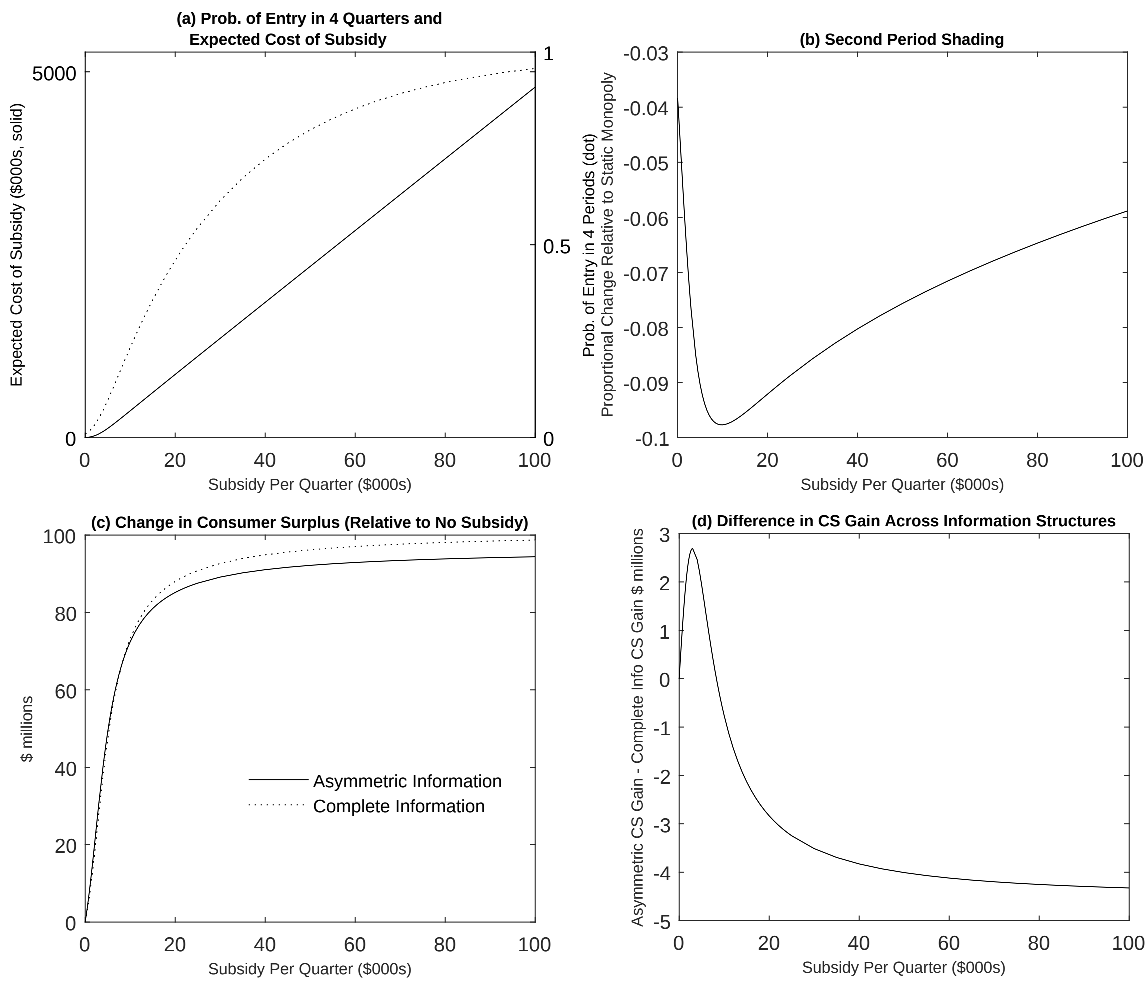


Figure 4: Predicted Effect of Fixed Cost Subsidies for Southwest on Entry, Incumbent Shading and Consumer Surplus in the Hartford-Minneapolis Market.



APPENDICES FOR ONLINE PUBLICATION

"A Model of Dynamic Limit Pricing with an Application to the Airline Industry"

by Andrew Sweeting, James W. Roberts and Chris Gedge

January 2019

These Appendices complement the material in the main paper. They are organized as follows.

Appendix A: Proof of Theorem 1.

Appendix B: Computational details for solving dynamic limit pricing models. We discuss the baseline model, the extended model with time-varying entry costs used in the calibration and the model with connecting traffic and capacity investment used in Appendix F.

Appendix C: Data Appendix with a list of the dominant incumbent sample markets and a description of the construction of the market size variable and a measure of connecting traffic. We also present results of regressions that repeat the analysis of Goolsbee and Syverson (2008) for our dominant incumbent markets to quantify how incumbents change prices when Southwest threatens entry and when it actually enters. We present results using average prices, yields and percentiles of the price and yield distribution.

Appendix D: Materials supplementing the reduced-form empirical analysis in Section 4, including (i) details and results from the estimation of the probability that Southwest will enter each market using the full sample; (ii) graphical illustrations of the estimated relationships between entry probabilities and changes in prices, capacities, passenger traffic and load factors; (iii) a "balance table" that compares how the value of observed market characteristics varies with the probability of entry; (iv) robustness checks on the results describing the non-monotonicity of price changes with respect to the probability of entry; and (v) empirical tests examining whether there is evidence that lower prices increase demand in future periods, as one would expect for incumbents to find it profitable to lower prices to increase customer loyalty.

Appendix E: Some additional information on the estimation of the demand parameters for the calibration, and figures illustrating how the entry costs implied by the estimates vary across markets and over time.

Appendix F: Discussion of extensions that allow for (i) unobserved demand from connecting passengers and marginal costs that depend on endogenous capacity investments; and (ii) incumbent learning about how profitable a market is to Southwest, which can help to explain why incumbents keep lowering prices when Southwest does not enter in some markets (it also shows that this phenomenon only happens in a subset of the markets in our data).

A Proof of Theorem 1

In this Appendix, we prove that the strategies described in Theorem 1 form a fully separating Markov Perfect Bayesian Equilibrium that is unique under a recursive application of the D1 Refinement. The proof uses induction and makes extensive use of theoretical results for one-shot signaling games from Mailath and von Thadden (2013) and Ramey (1996).

Overview. The proof is quite long, so it is useful to have a road map for how we will proceed. We begin by explaining how we define the values of the incumbent and the potential entrant in different periods of the game, and then prove two lemmas that will be used repeatedly. The main part of the proof uses induction. Assuming that value functions in period $t+1$ satisfy a set of properties, we characterize the strategies of the potential entrant and the incumbent (Section A.3). For the incumbent (Section A.3.2) we make use of the characterization of a unique separating equilibrium provided in Mailath and von Thadden (2013) and conditions from Ramey (1996) that allow us to eliminate pooling equilibria under the D1 refinement. We show that the strategies will imply the conditions on the potential entrant's value functions at the start of t that we will need in order to use the same approach in $t-1$ (Section A.3.3), and do the same for the incumbent (Section A.3.4). Finally we can show the required conditions hold for value functions in the final period T.

A.1 Notation and the Definition of Values

At many points in the proof we will make use of notation indicating expectations of a firm's value in a future period, e.g., $\mathbb{E}_t[V^E_{t+1}|\widehat{c}_{I,t}]$. We will use several conventions.

1. $\phi^E_t(c_{I,t})$ denotes E's expected present discounted future value when it is a duopolist at the beginning of period t, and I's marginal cost is $c_{I,t}$. Under our assumption that duopolists use unique static Nash equilibrium strategies in a complete information game, $\phi^E_t(c_{I,t})$ is uniquely defined.

2. $\phi_t^I(c_{I,t})$ denotes I's expected present discounted future value when it is a duopolist at the beginning of period t, and its marginal cost is $c_{I,t}$. Under our assumption that duopolists use unique static Nash equilibrium strategies in a complete information game, $\phi_t^I(c_{I,t})$ is uniquely defined.

3. $V_t^I(c_{I,t})$ denotes I's expected present discounted future value when it is an incumbent monopolist at the beginning of period t, and its marginal cost is $c_{I,t}$. The entry cost, κ_t, is not known when the value is defined, so that the value is the expectation over the different possible values of κ_t. This value will be dependent on the pricing strategy that I will use in period t, E's period t entry strategy and the strategies of both firms in future periods.

4. $V_t^E(c_{I,t})$ denotes E's expected present discounted future value when it is a potential entrant at the beginning of period t, and I's marginal cost is $c_{I,t}$. Of course, E does not know $c_{I,t}$ at the moment when this value is being defined (i.e., prior to I choosing a price) but defining values in this way is convenient because it both defines the value of both firms at the same moment each period (the beginning) and economizes on the amount of notation. κ_t is not known when the value is defined, so that the value is the expectation over the different possible values of κ_t.

When we write ϕ_t^E, ϕ_t^I, V_t^E or V_t^I to economize on notation, their dependence on $c_{I,t}$, or the entrant's beliefs about $c_{I,t}$, should be understood. For example, $\mathbb{E}_t[V_{t+1}^E|\widehat{c}_{I,t}]$ is the expected value of E as a potential entrant at the start of period $t+1$ given a belief that $c_{I,t}$ is exactly $\widehat{c}_{I,t}$. As in this example, when E has a point belief we will denote the believed value as $\widehat{c}_{I,t}$. If E does not have a point belief, we will denote their density as $q(\widetilde{c_{I,t}})$ and assume that only values on the interval $[\underline{c_I}, \overline{c_I}]$ can have positive density.

A.2 Useful Lemmas

We will make frequent use of several results:

Lemma 1 *Suppose that $f(x)$ is a strictly positive function, $g(x|w)$ is a strictly positive conditional pdf on $x, w \in [\underline{x}, \overline{x}]$. Further suppose that (i) for a given value of w $\exists x' \in (\underline{x}, \overline{x})$ such that $\frac{\partial g(x'|w)}{\partial w} = 0$, $\frac{\partial g(x|w)}{\partial w} < 0$ for $\forall x < x'$ and $\frac{\partial g(x|w)}{\partial w} > 0$ for $\forall x > x'$; and, (ii) $k \equiv \int_{\underline{x}}^{\overline{x}} f(x) \frac{\partial g(x|w)}{\partial w} dx$. If $\forall x$, $\frac{\partial f(x)}{\partial x} > 0$ then $k > 0$. On the other hand, if $\forall x$, $\frac{\partial f(x)}{\partial x} < 0$ then $k < 0$.*

Proof.

$$\begin{aligned}
k &\equiv \int_{\underline{x}}^{\overline{x}} f(x) \frac{\partial g(x|w)}{\partial w} dx \\
&= \int_{\underline{x}}^{x'} f(x) \frac{\partial g(x|w)}{\partial w} dx + \int_{x'}^{\overline{x}} f(x) \frac{\partial g(x|w)}{\partial w} dx \\
&> f(x') \left\{ \int_{\underline{x}}^{x'} \frac{\partial g(x|w)}{\partial w} dx + \int_{x'}^{\overline{x}} \frac{\partial g(x|w)}{\partial w} dx \right\} = 0 \text{ if } \frac{\partial f(x)}{\partial x} > 0 \\
\text{or} &< f(x') \left\{ \int_{\underline{x}}^{x'} \frac{\partial g(x|w)}{\partial w} dx + \int_{x'}^{\overline{x}} \frac{\partial g(x|w)}{\partial w} dx \right\} = 0 \text{ if } \frac{\partial f(x)}{\partial x} < 0
\end{aligned}$$

■

There are several useful corollaries of Lemma 1.

Corollary 1 *Suppose that $\phi^E_{t+1}(c_{I,t+1}) > V^E_{t+1}(c_{I,t+1})$, $\frac{\partial \{\phi^E_{t+1}(c_{I,t+1}) - V^E_{t+1}(c_{I,t+1})\}}{\partial c_{I,t+1}} > 0$ for all $c_{I,t+1}$ and $\frac{\partial \psi_I(c_{I,t+1}|\widehat{c}_{I,t})}{\partial \widehat{c}_{I,t}}$ satisfies Assumption 1, then*

$$\frac{\partial \mathbb{E}_t[\phi^E_{t+1}|\widehat{c}_{I,t}]}{\partial \widehat{c}_{I,t}} - \frac{\partial \mathbb{E}_t[V^E_{t+1}|\widehat{c}_{I,t}]}{\partial \widehat{c}_{I,t}} = \int_{\underline{c_I}}^{\overline{c_I}} \left[\phi^E_{t+1}(c_{I,t+1}) - V^E_{t+1}(c_{I,t+1})\right] \frac{\partial \psi_I(c_{I,t+1}|\widehat{c}_{I,t})}{\partial \widehat{c}_{I,t}} dc_{I,t+1} > 0.$$

Corollary 2 *Suppose that $V^I_{t+1}(c_{I,t+1}) > \phi^I_{t+1}(c_{I,t+1})$, $\frac{\partial \{V^I_{t+1}(c_{I,t+1}) - \phi^I_{t+1}(c_{I,t+1})\}}{\partial c_{I,t+1}} < 0$ for all $c_{I,t+1}$ and $\frac{\partial \psi_I(c_{I,t+1}|c_{I,t})}{\partial c_{I,t}}$ satisfies Assumption 1, then*

$$\frac{\partial \mathbb{E}_t[V^I_{t+1}|c_{I,t}]}{\partial c_{I,t}} - \frac{\partial \mathbb{E}_t[\phi^E_{t+1}|c_{I,t}]}{\partial c_{I,t}} = \int_{\underline{c_I}}^{\overline{c_I}} \left[V^I_{t+1}(c_{I,t+1}) - \phi^I_{t+1}(c_{I,t+1})\right] \frac{\partial \psi_I(c_{I,t+1}|c_{I,t})}{\partial c_{I,t}} dc_{I,t+1} < 0.$$

A further, very straightforward, result that will be referred to frequently is:

Lemma 2 *(a) Suppose that* $\phi^E_{t+1}(c_{I,t+1}) > V^E_{t+1}(c_{I,t+1})$ *for all* $c_{I,t+1}$ *and* ψ_I *satisfies Assumption 1, then*

$$\mathbb{E}_t[\phi^E_{t+1}|q(\widetilde{c_{I,t}})] - \mathbb{E}_t[V^E_{t+1}|q(\widetilde{c_{I,t}})] =$$
$$\int_{\underline{c_I}}^{\overline{c_I}}\int_{\underline{c_I}}^{\overline{c_I}} \left\{ \begin{array}{c} \left[\phi^E_{t+1}(c_{I,t+1}) - V^E_{t+1}(c_{I,t+1})\right] \times ... \\ \psi_I(c_{I,t+1}|\widetilde{c_{I,t}})q(\widetilde{c_{I,t}}) \end{array} \right\} dc_{I,t+1}d\widetilde{c_{I,t}} > 0$$

including the case where E has a point belief about I's marginal cost as a special case; and, (b) suppose that $V^I_{t+1}(c_{I,t+1}) > \phi^I_{t+1}(c_{I,t+1})$ *for all* $(c_{I,t+1})$ *and* ψ_I *satisfies Assumption 1, then*

$$\mathbb{E}_t[V^I_{t+1}|c_{I,t}] - \mathbb{E}_t[\phi^I_{t+1}|c_{I,t}] =$$
$$\int_{\underline{c_I}}^{\overline{c_I}} \left[V^I_{t+1}(c_{I,t+1}) - \phi^I_{t+1}(c_{I,t+1})\right] \psi_I(c_{I,t+1}|c_{I,t})dc_{I,t+1} > 0$$

Proof. Follows immediately from the assumptions as $\psi_I(c_{I,t+1}|\widehat{c}_{I,t}) > 0$ for all costs on $\left[\underline{c_I}, \overline{c_I}\right]$. ■

A.3 Proof for Period t Given Value Function Properties at $t+1$

We will assume that the entrant's value functions as defined at the start of period $t+1$ have the following properties:

E1^{t+1}. $\phi^E_{t+1}(c_{I,t+1}) > V^E_{t+1}(c_{I,t+1})$; and

E2^{t+1}. $\phi^E_{t+1}(c_{I,t+1})$ and $V^E_{t+1}(c_{I,t+1})$ are uniquely defined functions of $c_{I,t+1}$, and do not depend on κ_t or any earlier values of κ;

E3^{t+1}. $\phi^E_{t+1}(c_{I,t+1})$ and $V^E_{t+1}(c_{I,t+1})$ are continuous and differentiable in their arguments; and

E4^{t+1}. $\frac{\partial[\phi^E_{t+1}(c_{I,t+1})]}{\partial c_{I,t+1}} > \frac{\partial[V^E_{t+1}(c_{I,t+1})]}{\partial c_{I,t+1}}$

A.3.1 Potential Entrant Strategy in Period t

E will compare its expected continuation value if it enters, $\mathbb{E}_t[\phi^E_{t+1}|\widehat{c}_{I,t}]$ if it has a point belief and otherwise $\mathbb{E}_t[\phi^E_{t+1}|q(\widetilde{c_{I,t}})]$, less its entry cost, κ_t, with its expected continuation value if it does not enter, $\mathbb{E}_t[V^E_{t+1}|\widehat{c}_{I,t}]$ or $\mathbb{E}_t[V^E_{t+1}|q(\widetilde{c_{I,t}})]$. By E2^{t+1} these continuation values do not depend on κ_t or earlier entry costs, so that E's optimal entry strategy will be a period-specific threshold rule in its entry cost. Specifically, E will enter if and only if

$$\kappa_t < \kappa^*_t(\widehat{c}_{I,t}) = \beta\left\{\mathbb{E}_t[\phi^E_{t+1}|\widehat{c}_{I,t}] - \mathbb{E}_t[V^E_{t+1}|\widehat{c}_{I,t}]\right\}$$

if E has a point belief $\widehat{c}_{I,t}$; and otherwise its entry strategy will be to enter if and only if

$$\kappa_t < \kappa^*_t(q(\widetilde{c_{I,t}})) = \beta\left\{\mathbb{E}_t[\phi^E_{t+1}|q(\widetilde{c_{I,t}})] - \mathbb{E}_t[V^E_{t+1}|q(\widetilde{c_{I,t}})]\right\}$$

To derive the incumbent's strategy we also need to show that the threshold has certain properties. Specifically, we need it to be the case that $\kappa^*_t > \underline{\kappa} = 0$ and $\kappa^*_t < \overline{\kappa}$; and, that if E has a point belief, its threshold κ^*_t is continuous and differentiable and strictly increasing in $\widehat{c}_{I,t}$. $\kappa^*_t > \underline{\kappa} = 0$ follows from combining E1^{t+1} and Lemma 2(a). $\kappa^*_t(\widehat{c}_{I,t})$ will be continuous and differentiable if $\phi^E_{t+1}(c_{I,t+1})$ and $V^E_{t+1}(c_{I,t+1})$ are continuous and differentiable (E3^{t+1}), and ψ_I is continuous and differentiable (Assumption 1). $\kappa^*_t(\widehat{c}_{I,t})$ is strictly increasing in $\widehat{c}_{I,t}$ if $\frac{\partial \mathbb{E}_t[\phi^E_{t+1}|\widehat{c}_{I,t}]}{\partial \widehat{c}_{I,t}} - \frac{\partial \mathbb{E}_{t-1}[V^E_{t+1}|\widehat{c}_{I,t}]}{\partial \widehat{c}_{I,t}} > 0$, which follows from E4^{t+1} and Corollary 1.

A.3.2 Incumbent Strategy in Period t

Existence of a Unique Separating Signaling Strategy To show the existence of a unique separating strategy for the incumbent we will rely on Theorem 1 of Mailath and von Thadden (2013), which is a useful generalization of the results in Mailath (1987). This theorem imposes conditions on the incumbent's 'signaling payoff function' $\Pi^{I,t}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t})$ where, in this application, the first argument is the incumbent's marginal cost, the second argument is E's (point) belief about the I's marginal cost, and $p_{I,t}$ is the price that I sets.

Theorem [Based on Mailath and von Thadden (2013)] *If (MT-i)* $\Pi^{I,t}(c_{I,t}, c_{I,t}, p_{I,t})$ *has a unique optimum in* $p_{I,t}$*, and for any* $p_{I,t} \in [\underline{p}, \overline{p}]$ *where* $\Pi^{I,t}_{33}(c_{I,t}, c_{I,t}, p_{I,t}) > 0$*, there* $\exists k > 0$ *such that* $\left|\Pi^{I,t}_3(c_{I,t}, c_{I,t}, p_{I,t})\right| > k$ *for all* $c_{I,t}$*; (MT-ii)* $\Pi^{I,t}_{13}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t}) \neq 0$ *for all* $(c_{I,t}, \widehat{c}_{I,t}, p_{I,t})$*; (MT-iii)* $\Pi^{I,t}_2(c_{I,t}, \widehat{c}_{I,t}, p_{I,t}) \neq 0$ *for all* $(c_{I,t}, \widehat{c}_{I,t}, p_{I,t})$*; (MT-iv)* $\frac{\Pi^{I,t}_3(c_{I,t}, \widehat{c}_{I,t}, p_{I,t})}{\Pi^{I,t}_2(c_{I,t}, \widehat{c}_{I,t}, p_{I,t})}$ *is a monotone function of* $c_{I,t}$ *for all* $\widehat{c}_{I,t}$ *and all* $p_{I,t}$ *below the static monopoly price; (MT-v)* $\overline{p} \geq p^{\text{static monopoly}}(\overline{c_I})$ *and* $\Pi^{I,t}(\underline{c_{I,t}}, \underline{c_{I,t}}, \underline{p}) < \max_p \Pi^{I,t}(\underline{c_{I,t}}, \overline{c_{I,t}}, p)$*, then I's period t unique separating pricing strategy is differentiable on the interior of* $[\underline{c_I}, \overline{c_I}]$ *and satisfies the differential equation*

$$\frac{\partial p^*_{I,t}}{\partial c_{I,t}} = -\frac{\Pi^{I,t}_2}{\Pi^{I,t}_3}$$

with boundary condition that $p^*_{I,t}(\overline{c_I}) = p^{\text{static monopoly}}(\overline{c_I})$.

We now show that the conditions (MT-i)-(MT-v) hold assuming that

I1^{t+1}. $V^I_{t+1}(c_{I,t+1}) > \phi^I_{t+1}(c_{I,t+1})$;

I2^{t+1}. $V^I_{t+1}(c_{I,t+1})$ and $\phi^I_{t+1}(c_{I,t+1})$ are continuous and differentiable; and,

I3^{t+1}. $\frac{\partial V^I_{t+1}(c_{I,t+1})}{\partial c_{I,t+1}} < \frac{\partial \phi^I_t(c_{I,t+1})}{\partial c_{I,t+1}}$

as well as the conditions on E's period t entry threshold that were derived above.

Condition (MT-v) is simply a condition on the support of prices, with the second part requiring that $\underline{p}$ is so low that I would always prefer to set some higher price even if this resulted in E having the worst (i.e., highest) possible beliefs about I's marginal cost whereas setting price $\underline{p}$ would have resulted in E having the best (i.e., lowest) possible beliefs. This is implied by Assumption 3.

The signaling payoff function is defined as

$$\Pi^{I,t}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t}) = q^M(p_{I,t})(p_{I,t} - c_{I,t}) + ...$$
$$\beta((1 - G(\kappa^*_t(\widehat{c}_{I,t})))\mathbb{E}_t[V^I_{t+1}|c_{I,t}] + G(\kappa^*_t(\widehat{c}_{I,t}))\mathbb{E}_t[\phi^I_{t+1}|c_{I,t}])$$

where $G(\kappa_t^*(\widehat{c}_{I,t}))$ is the probability that E enters given its entry strategy.

Condition (MT-i): $\Pi^{I,t}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t})$ only depends on $p_{I,t}$ through the static monopoly profit function $\pi_{I,t}^M = q^M(p_{I,t})(p_{I,t} - c_{I,t})$. The assumptions on the monopoly profit function in Assumption 3 therefore imply that (MT-i) is satisfied.

Condition (MT-ii): Differentiation of $\Pi^{I,t}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t})$ gives

$$\Pi_{13}^{I,t}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t}) = -\frac{\partial q^M(p_{I,t})}{\partial p_{I,t}} \tag{11}$$

$\Pi_{13}^{I,t}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t}) \neq 0$ for all $(c_{I,t}, \widehat{c}_{I,t}, p_{I,t})$ because monopoly demand is strictly downward sloping on $[\underline{p}, \overline{p}]$ (Assumption 3).

Condition (MT-iii): Differentiating $\Pi^{I,t}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t})$ gives

$$\Pi_2^{I,t}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t}) = -\beta g(\kappa_t^*(\widehat{c}_{I,t}))\frac{\partial \kappa_t^*(\widehat{c_{I,t}})}{\partial \widehat{c}_{I,t}} \left\{\mathbb{E}_t[V_{t+1}^I | c_{I,t}] - \mathbb{E}_t[\phi_{t+1}^I | c_{I,t}]\right\} \tag{12}$$

$\Pi_2^{I,t}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t}) \neq 0$ for all $(c_{I,t}, \widehat{c}_{I,t}, p_{I,t})$ as $g(\kappa_t^*(\widehat{c}_{I,t})) > 0$ (which is true given Assumption 2 and the previous result that $\underline{\kappa} < \kappa_t^*(\widehat{c}_{I,t}) < \overline{\kappa}$), $\frac{\partial \kappa_t^*(\widehat{c}_{I,t})}{\partial \widehat{c}_{I,t}} > 0$ for all $\widehat{c}_{I,t}$ (true given the previous result on the monotonicity of E's entry threshold rule in perceived incumbent marginal cost), and $\mathbb{E}_t[V_{t+1}^I | c_{I,t}] - \mathbb{E}_t[\phi_{t+1}^I | c_{I,t}] > 0$ (assumption I1^{t+1} and Lemma 2(b)).

Condition (MT-iv): Using equations (11) and (12) we have

$$\frac{\Pi_3^{I,t}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t})}{\Pi_2^{I,t}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t})} = \frac{\left[q^M(p_{I,t}) + \frac{\partial q^M(p_{I,t})}{\partial p_{I,t}}(p_{I,t} - c_{I,t})\right]}{\left(-\beta g(\kappa_t^*(\widehat{c}_{I,t}))\frac{\partial \kappa_t^*(\widehat{c}_{I,t})}{\partial \widehat{c}_{I,t}} \left\{\mathbb{E}_t[V_{t+1}^I | c_{I,t}] - \mathbb{E}_t[\phi_{t+1}^I | c_{I,t}]\right\}\right)}$$

Differentiation with respect to $c_{I,t}$ gives

$$\frac{\partial \frac{\Pi_3^{I,t}(c_{I,t},\widehat{c}_{I,t},p_{I,t})}{\Pi_2^{I,t}(c_{I,t},\widehat{c}_{I,t},p_{I,t})}}{\partial c_{I,t}} = \frac{\frac{\partial q^M(p_{I,t})}{\partial p_{I,t}}}{\left(\beta g(\kappa_t^*(\widehat{c}_{I,t}))\frac{\partial \kappa_t^*(\widehat{c}_{I,t})}{\partial \widehat{c}_{I,t}}\left\{\mathbb{E}_t[V_{t+1}^I] - \mathbb{E}_t[\phi_{t+1}^I]\right\}\right)} + \ldots$$

$$\frac{\left[q(p_{I,t}) + \frac{\partial q^M(p_{I,t})}{\partial p_{I,t}}(p_{I,t} - c_{I,t})\right]\frac{\partial\left\{\mathbb{E}_t[V_{t+1}] - \mathbb{E}_t[\phi_{t+1}^I]\right\}}{\partial c_{I,t}}\left(\beta g(\kappa_t^*(\widehat{c}_{I,t}))\frac{\partial \kappa_t^*(\widehat{c}_{I,t})}{\partial \widehat{c}_{I,t}}\right)}{\left(\beta g(\kappa_t^*(\widehat{c}_{I,t}))\frac{\partial \kappa_t^*(\widehat{c_{I,t}})}{\partial \widehat{c}_{I,t}}\left\{\mathbb{E}_t[V_{t+1}^I] - \mathbb{E}_t[\phi_{t+1}^I]\right\}\right)^2}$$

where $\mathbb{E}_t[V_{t+1}^I|c_{I,t}]$ and $\mathbb{E}_t[\phi_{t+1}^I|c_{I,t}]$ have been written as $\mathbb{E}_t[V_{t+1}^I]$ and $\mathbb{E}_t[\phi_{t+1}^I]$ to save space.

Sufficient conditions for $\frac{\partial \frac{\Pi_3^{I,t}(c_{I,t},\widehat{c}_{I,t},p_{I,t})}{\Pi_2^{I,t}(c_{I,t},\widehat{c}_{I,t},p_{I,t})}}{\partial c_{I,t}}$ to be < 0 (implying $\frac{\Pi_3^{I,t}(c_{I,t},\widehat{c}_{I,t},p_{I,t})}{\Pi_2^{I,t}(c_{I,t},\widehat{c}_{I,t},p_{I,t})}$ is monotonic in $c_{I,t}$) are: $\left\{\mathbb{E}_t[V_{t+1}^I|c_{I,t}] - \mathbb{E}_t[\phi_{t+1}^I|c_{I,t}]\right\} > 0$ (follows from assumption I1^{t+1} and Lemma 2(b));

$\frac{\partial\left\{\mathbb{E}_t[V_{t+1}^I|c_{I,t}] - \mathbb{E}_t[\phi_{t+1}^I|c_{I,t}]\right\}}{\partial c_{I,t}} < 0$ (assumption I3^{t+1} and Corollary 2);

$\left[q(p_{I,t}) + \frac{\partial q^M(p_{I,t})}{\partial p_{I,t}}(p_{I,t} - c_{I,t})\right] \geq 0$ for all prices below the monopoly price (implied by strict quasi-concavity of the profit function); $g(\kappa_t^*(\widehat{c}_{I,t})) > 0$ (Assumption 2 and the previous result that $\underline{\kappa} < \kappa_t^*(\widehat{c}_{I,t}) < \overline{\kappa}$); $\frac{\partial \kappa_t^*(\widehat{c}_{I,t})}{\partial \widehat{c}_{I,t}} > 0$ (proved above); and, $\frac{\partial q^M(p_{I,t})}{\partial p_{I,t}} < 0$ (Assumption 3).

Uniqueness of the Separating Strategy under the D1 Refinement The Mailath and von Thadden theorem allows us to show that there is only one fully separating strategy, but it does not show that there can be no pooling equilibria. To show this, we use the D1 Refinement and Theorem 3 of Ramey (1996).

Theorem [Based on Ramey (1996)] *Take I's signaling payoff $\Pi^{I,t}(c_{I,t}, \kappa_t', p_{I,t})$ where κ_t' is E's entry threshold. If conditions (R-i) $\Pi_2^{I,t}(c_{I,t}, \kappa_t', p_{I,t}) \neq 0$ for all $(c_{I,t}, \kappa_t', p_{I,t})$; (R-ii) $\frac{\Pi_3^{I,t}(c_{I,t},\kappa_t',p_{I,t})}{\Pi_2^{I,t}(c_{I,t},\kappa_t',p_{I,t})}$ is a monotone function of $c_{I,t}$ for all κ_t'; and (R-iii) $\overline{p} \geq p^{\text{static monopoly}}(\overline{c_I})$ and $\Pi^{I,t}(\underline{c_{I,t}}, \overline{\kappa}, \underline{p}) < \max_p \Pi^{I,t}(\underline{c_{I,t}}, \underline{\kappa}, p)$ for all t, then an equilibrium satisfying the D1 refinement will be fully separating.*

The signaling payoff function in this theorem is defined based on E's threshold, not its point belief, to allow for the fact that, with pooling, E's beliefs may not be a point. (R-iii) is a condition on the support of prices, as it says that I would always prefer to use some price above $\underline{p}$ even if doing this led to certain entry when setting $\underline{p}$ would prevent entry from happening. Once again, it is implied by Assumption 3. Essentially replicating the proofs of (MT-iii) and (MT-iv) above, we now show that conditions (R-i) and (R-ii) hold.

Condition (R-i): $\Pi_2^{I,t}(c_{I,t}, \kappa_t, p_{I,t}) = -\beta g(\kappa_t)\left\{\mathbb{E}_t[V_{t+1}^I|c_{I,t}] - \mathbb{E}_t[\phi_{t+1}^I|c_{I,t}]\right\}$. The right-hand side will not be equal to zero if $g(\cdot) > 0$ (true given Assumption 2 and the condition that an equilibrium level of κ_t' will satisfy $\underline{\kappa} < \kappa_t' < \overline{\kappa}$), and $\left\{\mathbb{E}_t[V_{t+1}^I|c_{I,t}] - \mathbb{E}_t[\phi_{t+1}^I|c_{I,t}]\right\} > 0$ (follows from assumption I1^{t+1} and Lemma 2(b)).

Condition (R-ii): as before, we have

$$\frac{\Pi_3^{I,t}(c_{I,t}, \kappa_t, p_{I,t})}{\Pi_2^{I,t}(c_{I,t}, \kappa_t, p_{I,t})} = \frac{\left[q^M(p_{I,t}) + \frac{\partial q^M(p_{I,t})}{\partial p_{I,t}}(p_{I,t} - c_{I,t})\right]}{\left(-\beta g(\kappa_t)\left\{\mathbb{E}_t[V_{t+1}^I|c_{I,t}] - \mathbb{E}_t[\phi_{t+1}^I|c_{I,t}]\right\}\right)}$$

Differentiation with respect to $c_{I,t}$ yields

$$\frac{\partial \frac{\Pi_3^{I,t}(c_{I,t},\kappa_t,p_{I,t})}{\Pi_2^{I,t}(c_{I,t},\kappa_t,p_{I,t})}}{\partial c_{I,t}} = \frac{\frac{\partial q^M(p_{I,t})}{\partial p_{I,t}}}{\beta g(\kappa_t)\mathbb{E}_t[V_{t+1}^I|c_{I,t}] - \mathbb{E}_t[\phi_{t+1}^I|c_{I,t}]} + \ldots$$
$$\frac{\left[q(p_{I,t}) + \frac{\partial q^M(p_{I,t})}{\partial p_{I,t}}(p_{I,t} - c_{I,t})\right]\frac{\partial\left\{\mathbb{E}_t[V_{t+1}^I|c_{I,t}] - \mathbb{E}_t[\phi_{t+1}^I|c_{I,t}]\right\}}{\partial c_{I,t}}(\beta g(\kappa_t))}{\left(\beta g(\kappa_t)\left\{\mathbb{E}_t[V_{t+1}^I|c_{I,t}] - \mathbb{E}_t[\phi_{t+1}^I|c_{I,t}]\right\}\right)^2}$$

Sufficient conditions for $\frac{\partial \frac{\Pi_3^{I,t}(c_{I,t},\kappa_t,p_{I,t})}{\Pi_2^{I,t}(c_{I,t},\kappa_t,p_{I,t})}}{\partial c_{I,t}}$ to be < 0 (implying $\frac{\Pi_3^{I,t}(c_{I,t},\kappa_t,p_{I,t})}{\Pi_2^{I,t}(c_{I,t},\kappa_t,p_{I,t})}$ monotonic in $c_{I,t}$) are: $\left\{\mathbb{E}_t[V_{t+1}^I|c_{I,t}] - \mathbb{E}_t[\phi_{t+1}^I|c_{I,t}]\right\} > 0$ (follows from assumption I1^{t+1} and Lemma 2(b));
$\frac{\partial\left\{\mathbb{E}_t[V_{t+1}^I|c_{I,t}] - \mathbb{E}_t[\phi_{t+1}^I|c_{I,t}]\right\}}{\partial c_{I,t}} < 0$ (assumption I3^{t+1} and Corollary 2);
$\left[q(p_{I,t}) + \frac{\partial q^M(p_{I,t})}{\partial p_{I,t}}(p_{I,t} - c_{I,t})\right] \geq 0$ for all prices below the monopoly price (implied by quasi-concavity of the profit function); $g(\kappa_t^*(\widehat{c}_{I,t})) > 0$ (Assumption 2 and the previous result that $\underline{\kappa} < \kappa_t^*(\widehat{c}_{I,t}) < \overline{\kappa}$); and, $\frac{\partial q^M(p_{I,t})}{\partial p_{I,t}} < 0$ (Assumption 3).

As noted by Fudenberg and Tirole (1991), p. 460, the application of the D1 refinement, while primarily used to eliminate pooling equilibria, may also imply some restrictions on the beliefs that the receiver should have following off-path actions in a separating equilibrium, even if a separating equilibrium could be supported by multiple different sets of beliefs. Applying their logic to our setting, it follows that E should interpret a price strictly above $\varsigma^*_{I,t}(\overline{c_I})$ as coming from an incumbent with cost $\overline{c_I}$ and a price below $\varsigma^*_{I,t}(\underline{c_I})$ as coming from an incumbent with cost $\underline{c_I}$.

A.3.3 Properties of the Potential Entrant's Value Functions for Period t

We now show that, given these strategies (in particular the fact that I's pricing strategy is fully revealing), which depend on the assumed properties of value functions in period $t+1$, that the value functions at the start of period t will have these same properties. For the potential entrant we have to prove:

E1^t. $\phi^E_t(c_{I,t}) > V^E_t(c_{I,t})$;

E2^t. $\phi^E_t(c_{I,t})$ and $V^E_t(c_{I,t})$ are uniquely defined functions of $c_{I,t}$, and do not depend on κ_{t-1} or any earlier values of κ;

E3^t. $\phi^E_t(c_{I,t})$ and $V^E_t(c_{I,t})$ are continuous and differentiable in both arguments; and

E4^t. $\frac{\partial \phi^E_t(c_{I,t})}{\partial c_{I,t}} > \frac{\partial V^E_t(c_{I,t})}{\partial c_{I,t}}$

From the above, we have that

$$\phi^E_t(c_{I,t}) = \pi^D_E(c_{I,t}) + \beta \int_{\underline{c_I}}^{\overline{c_I}} \phi^E_{t+1}(c_{I,t+1})\psi_I(c_{I,t+1}|c_{I,t})dc_{I,t+1} \tag{13}$$

$$V^E_t(c_{I,t}) = \int_0^{\kappa^*(c_{I,t})} \int_{\underline{c_I}}^{\overline{c_I}} \left\{\beta\phi^E_{t+1}(c_{I,t+1})\psi_I(c_{I,t+1}|c_{I,t}) - \kappa\right\} g(\kappa)dc_{I,t+1}d\kappa + ... \tag{14}$$

$$\int_{\kappa^*(c_{I,t})}^{\overline{\kappa}} \int_{\underline{c_I}}^{\overline{c_I}} \beta V^E_{t+1}(c_{I,t+1})\psi_I(c_{I,t+1}|c_{I,t})g(\kappa)dc_{I,t+1}d\kappa$$

where we are exploiting the fact that the entrant has correct beliefs about I's marginal cost when taking its entry decision in equilibrium.

Continuity and differentiability of (13) and (14) follows from ϕ^E_{t+1} and V^E_{t+1} being continuous and differentiable (E3^{t+1}), $\psi_I(c_{I,t+1}|c_{I,t})$ being continuous and differentiable (Assumption 1) and $\kappa^*(c_{I,t})$ being continuous and differentiable as shown above. The fact that both (13) and (14) are uniquely defined and do not depend on κ_{t-1} or any earlier values of κ follows from inspection of these equations and, in particular, the fact that I's signaling strategy perfectly reveals its current cost so that E's entry threshold in period t does not depend on earlier information. As $\phi^E_{t+1}(c_{I,t+1}) > V^E_{t+1}(c_{I,t+1})$, (14) implies

$$V^E_t(c_{I,t}) < \beta \int_{\underline{c_I}}^{\overline{c_I}} \phi^E_{t+1}(c_{I,t+1})\psi_I(c_{I,t+1}|c_{I,t})dc_{I,t+1},$$

and therefore,

$$\phi^E_t(c_{I,t}) - V^E_t(c_{I,t}) > \pi^D_E(c_{I,t}) > 0$$

by our assumption on duopoly profits, so that $\phi^E_t(c_{I,t}) > V^E_t(c_{I,t})$.

To show that $\frac{\partial[\phi^E_t(c_{I,t})]}{\partial c_{I,t}} > \frac{\partial[V^E_t(c_{I,t})]}{\partial c_{I,t}}$, it is convenient to write

$$\phi^E_t(c_{I,t}) - V^E_t(c_{I,t}) = \pi^D_E(c_{I,t}) + \int_0^{\overline{\kappa}} \min\{\kappa, \mathbb{E}_t[\phi^E_{t+1}|c_{I,t}] - \mathbb{E}_t[V^E_{t+1}|c_{I,t}]\}g(\kappa)d\kappa$$

so that

$$\frac{\partial[\phi^E_t(c_{I,t})]}{\partial c_{I,t}} - \frac{\partial[V^E_t(c_{I,t})]}{\partial c_{I,t}} = \frac{\partial \pi^D_E(c_{I,t})}{\partial c_{I,t}} + \ldots$$

$$\beta \frac{\partial \int_0^{\overline{\kappa}} \min\{\kappa, \mathbb{E}_t[\phi^E_{t+1}|c_{I,t}] - \mathbb{E}_t[V^E_{t+1}|c_{I,t}]\}g(\kappa)d\kappa}{\partial c_{I,t}} > 0$$

where the inequality follows from $\frac{\partial \pi_E^D(c_{I,t})}{\partial c_{I,t}} > 0$ (Assumption 4), $0 < \kappa^* < \overline{\kappa}$ and $\frac{\partial \mathbb{E}_t[\phi_{t+1}^E | c_{I,t}]}{\partial c_{I,t}} - \frac{\partial \mathbb{E}_t[V_{t+1}^E | c_{I,t}]}{\partial c_{I,t}} > 0$ (E4^{t+1} and Corollary 1).

A.3.4 Properties of the Incumbent's Value Functions for Period t

For the incumbent we have to prove:

I1^t. $V_t^I(c_{I,t}) > \phi_t^I(c_{I,t})$;

I2^t. $V_t^I(c_{I,t})$ and $\phi_t^I(c_{I,t})$ are continuous and differentiable; and,

I3^t. $\frac{\partial V_t^I(c_{I,t})}{\partial c_{I,t}} < \frac{\partial \phi_t^I(c_{I,t})}{\partial c_{I,t}}$.

Condition I1^t:

$$V_t^I(c_{I,t}) = \max_{p_{I,t}} q^M(p_{I,t})(p_{I,t} - c_{I,t}) + ... \tag{15}$$
$$\beta \begin{bmatrix} (1 - G(\kappa_t^*(\varsigma_{I,t}^{-1}(p_{I,t}))))\mathbb{E}_t[V_{t+1}^I | c_{I,t}] \\ +G(\kappa_t^*(\varsigma_{I,t}^{-1}(p_{I,t})))\mathbb{E}_t[\phi_{t+1}^I | c_{I,t}] \end{bmatrix}$$
$$\phi_t^I(c_{I,t}) = \pi_I^D(c_{I,t}) + \beta \mathbb{E}_t[\phi_{t+1}^I | c_{I,t}] \tag{16}$$

Now, given I1^{t+1} and Lemma 2(b),

$$\beta \begin{bmatrix} (1 - G(\kappa_t^*(\varsigma_{I,t}^{-1}(p_{I,t}))))\mathbb{E}_t[V_{t+1}^I | c_{I,t}] + \\ G(\kappa_t^*(\varsigma_{I,t}^{-1}(p_{I,t})))\mathbb{E}_t[\phi_{t+1}^I | c_{I,t}] \end{bmatrix} > \beta \mathbb{E}_t[\phi_{t+1}^I | c_{I,t}]$$

for any $p_{I,t}$ (including the static monopoly price). But, as $q^M(p_{I,t})(p_{I,t} - c_{I,t}) > \pi_I^D(c_{I,t})$ (Assumption 4) when the static monopoly price is chosen, it follows that $V_t^I(c_{I,t}) > \phi_t^I(c_{I,t})$ when a possibly different price is chosen by the incumbent.

Condition I2^t: continuity and differentiability of $V_t^I(c_{I,t})$ and $\phi_t^I(c_{I,t})$ follows from expressions (15) and (16), and the continuity and differentiability of the static and duopoly profit functions, the incumbent's equilibrium pricing function, the entry threshold function,

$\kappa_t^*(c_{I,t})$, the cdf of entry costs G, the cost transition conditional probability function ψ_I, and the following period value functions $V_{t+1}^I(c_{I,t+1})$ and $\phi_{t+1}^I(c_{I,t+1})$ (I2^{t+1}).

Condition I3^t:

$$\frac{\partial V_t^I(c_{I,t})}{\partial c_{I,t}} = \frac{\partial \pi^M(p^*, c_{I,t})}{\partial c_{I,t}} + \beta \frac{\partial \mathbb{E}_t[\phi_{t+1}^I | c_{I,t}]}{\partial c_{I,t}} - ...$$
$$\beta \frac{\partial \kappa^*(c_{I,t})}{\partial c_{I,t}} g(\kappa_t^*(c_{I,t})) \left\{ \mathbb{E}_t[V_{t+1}^I | c_{I,t}] - \mathbb{E}_t[\phi_{t+1}^I | c_{I,t}] \right\} + ...$$
$$\beta(1 - G(\kappa^*(c_{I,t}))) \left[\frac{\partial \mathbb{E}_t[V_{t+1}^I | c_{I,t}] - \mathbb{E}_t[\phi_{t+1}^I | c_{I,t}]}{\partial c_{I,t}} \right]$$

$\frac{\partial \pi^M(p^*, c_{I,t})}{\partial c_{I,t}} = -q^M(p^*) + \frac{\partial p^*(c_{I,t})}{\partial c_{I,t}} \left\{ q^M(p^*) + \frac{\partial q^M(p^*)}{\partial p}(p^* - c_{I,t}) \right\}$. But from the unique equilibrium strategy of the incumbent (recall that $V_t^I(c_{I,t})$ is the value to being an incumbent at the beginning of period t allowing for equilibrium play in that period),

$$\frac{\partial p^*}{\partial c_{I,t}} \left\{ q^M(p^*) + \frac{\partial q^M(p^*)}{\partial p}(p^* - c_{I,t}) \right\} = \beta g(\kappa_t^*(c_{I,t})) \frac{\partial \kappa_t^*}{\partial c_{I,t}} \left\{ \mathbb{E}_t[V_{t+1}^I | c_{I,t}] - \mathbb{E}_t[\phi_{t+1}^I | c_{I,t}] \right\}$$

so

$$\frac{\partial V_t^I(c_{I,t})}{\partial c_{I,t}} = -q^M(p^*) + \beta \frac{\partial \mathbb{E}_t[\phi_{t+1}^I | c_{I,t}]}{\partial c_{I,t}} + ...$$
$$\beta(1 - G(\kappa^*(c_{I,t}))) \left[\frac{\partial \mathbb{E}_t[V_{t+1}^I | c_{I,t}] - \mathbb{E}_t[\phi_{t+1}^I | c_{I,t}]}{\partial c_{I,t}} \right]$$

and

$$\frac{\partial \phi_t^I(c_{I,t})}{\partial c_{I,t}} = \frac{\partial \pi^D(c_{I,t})}{\partial c_{I,t}} + \beta \frac{\partial \mathbb{E}_t[\phi_{t+1}^I | c_{I,t}]}{\partial c_{I,t}}$$
$$= -q_I^D(c_{I,t}) + \frac{\partial \pi_I^D}{\partial a_E^D} \frac{\partial a_E^D}{\partial c_{I,t}} + \beta \frac{\partial \mathbb{E}_t[\phi_{t+1}^I | c_{I,t}]}{\partial c_{I,t}} < 0$$

where the inequality follows from the assumption that $\frac{\partial \pi^D(c_{I,t})}{\partial c_{I,t}} < 0$ (Assumption 4). Therefore,

$$\frac{\partial V_t^I(c_{I,t})}{\partial c_{I,t}} - \frac{\partial \phi_t^I(c_{I,t})}{\partial c_{I,t}} = q_I^D(c_{I,t}) - q^M(p^*(c_{I,t})) - \frac{\partial \pi_I^D}{\partial a_E^D}\frac{\partial a_E^D}{\partial c_{I,t}} + ...$$
$$\beta(1-G(\kappa^*(c_{I,t})))\left[\frac{\partial\{\mathbb{E}_t[V_{t+1}^I|c_{I,t}] - \mathbb{E}_t[\phi_{t+1}^I|c_{I,t}]\}}{\partial c_{I,t}}\right] < 0$$

where the inequality follows from Assumption 4, as $q^M(p^*(c_{I,t})) > q^M(p^{\text{static monopoly}})$ because the limit price will be below the static monopoly price and demand slopes downwards (Assumption 3), and I3^{t+1} and Corollary 2.

A.4 Proof for Period T

We now turn to showing that the value functions defined at the start of period T have the required properties. Of course, this is trivial because the game ends after period T so that if I is a monopolist in period T then it should just set the static monopoly price, and E should not enter for any positive entry cost. Therefore, $\phi_T^E(c_{I,T}) = \pi_E^D(c_{I,T})$, $V_T^E(c_{I,T}) = 0$, $\phi_T^I(c_{I,T}) = \pi_I^D(c_{I,T})$ and $V_T^I(c_{I,T}) = q(p^{\text{static monopoly}}(c_{I,T}))(p^{\text{static monopoly}}(c_{I,T}) - c_{I,T})$. Under our assumptions $\phi_T^E(c_{I,T}) > V_T^E(c_{I,T})$, $V_T^I(c_{I,T}) > \phi_T^I(c_{I,T})$, $\frac{\partial \phi_T^E}{\partial c_{I,T}} > \frac{\partial V_T^E}{\partial c_{I,T}} = 0$, $\frac{\partial V_T^I(c_{I,T})}{\partial c_{I,T}} < \frac{\partial \phi_T^I(c_{I,T})}{\partial c_{I,T}} < 0$.[30]

[30] $\frac{\partial V_T^I(c_{I,T})}{\partial c_{I,T}} - \frac{\partial \phi_T^I(c_{I,T})}{\partial c_{I,T}} = q_I^D(c_{I,T}) - q^M(p^{\text{static monopoly}}(c_{I,T})) - \frac{\partial \pi_I^D}{\partial a_E^D}\frac{\partial a_E^{*D}}{\partial c_{I,T}} < 0$ by Assumption 4.

B Computational Methods for Solving Dynamic Limit Pricing Models

In this Appendix we explain how we solve our dynamic limit pricing model. We first explain how we solve the game where marginal costs evolve exogenously, considering both the finite horizon and the limiting infinite horizon models. We then discuss how we solve the extended model where capacity choices and marginal costs are endogenous.

B.1 Model with Exogenous Marginal Costs

This subsection explains how we solve models with exogenously evolving incumbent marginal costs, which are used both in illustrating properties of the model and in our calibration. We begin with the case where the distribution of entry costs is time invariant.

B.1.1 Preliminaries

We start by specifying a 25-point grid of values for the incumbent's marginal cost (results are almost identical using 50 or 100 points) and a 1000-point grid of values for the incumbent's price, where the highest value is above the static monopoly price of the incumbent with the highest possible marginal cost and the lowest price is much lower than the monopoly price associated with the lowest possible marginal cost. For each value on the cost grid we solve for:

- I's profits and prices as a static monopolist;
- I and E's profits in static duopoly ($\pi_j^D(c_I)$); and,
- the gradient of I's static monopoly profits with respect to its price for each price on the price grid, $\frac{\partial \pi_I^M(p_I,c_I)}{\partial p_I} = q^M(p_I) + \frac{\partial q^M(p_I)}{\partial p_I}(p_I - c_I)$.

We also verify that the sufficient condition for single-crossing

$$\left(q_I^D(c_I, c_E) - q^M(p_I^{\text{static monopoly}}(c_I)) - \frac{\partial \pi_I^D(c_I, c_E, p_E)}{\partial p_E} \frac{\partial p_E^*}{\partial c_I} < 0\right)$$

for all c_I.

B.1.2 Entry Strategies

E has a stochastic optimal stopping problem where its decision is to enter, as once it enters it simply receives the associated flow of static duopoly profits for the rest of the game. In a finite horizon structure, signify its entry strategy as $\kappa_t^*(c_I)$ where we are exploiting the fact that, in equilibrium, it will know the true value of I's marginal cost, and we specify E's values as a potential entrant and as a duopolist in the final period of the game as $V_T^E(c_I) = 0$ and $\phi_T^E(c_I) = \pi_E^D(c_I)$. These values are measured once c_I has evolved to its final time period value.

We can now go to the penultimate time period $(T-1)$. We use the assumed form of the transition processes for c_I to calculate the value of $\mathbb{E}_{T-1}[\phi_T^E|c_{I,T-1}]$ for each value of $c_{I,T-1}$ on the cost grid. The integration is done using the trapezium rule. As $\mathbb{E}_{T-1}[V_T^E|c_{I,T-1}] = 0$, $\kappa_{T-1}^*(c_{I,T-1}) = \beta\mathbb{E}_{T-1}[\phi_T^E|c_{I,T-1}]$. We compute $g(\kappa_{T-1}^*)$ and $\frac{\partial \kappa_{T-1}^*(c_{I,T-1})}{\partial c_{I,T-1}}$ for each grid point. We can use the implied entry probabilities to compute the entrant's expected values at the beginning of period $T-1$, i.e.,

$$\phi_{T-1}^E(c_{I,T-1}) = \pi_E^D(c_{I,T-1}) + \beta\mathbb{E}_{T-1}[\phi_T^E|c_{I,T-1}]$$

$$V_{T-1}^E(c_{I,T-1}) = \beta G(\kappa_{T-1}^*(c_{I,T-1}))\mathbb{E}_{T-1}[\phi_T^E|c_{I,T-1}] + ...$$

$$\beta(1 - G(\kappa_{T-1}^*(c_{I,T-1})))\mathbb{E}_{T-1}[V_T^E|c_{I,T-1}] - \int_0^{\kappa^*(c_{I,T-1})} \kappa g(\kappa) d\kappa$$

where the integration to calculate the expected value of the entry cost conditional on entry being optimal can be done analytically when the distribution of entry costs is normal.

We can now proceed to $T-2$ and all earlier periods. We use exactly the same procedure apart from recognizing that

$$\kappa^*_{T-2}(c_{I,T-2}, c_{E,T-2}) = \beta\{\mathbb{E}_{T-2}[\phi^E_{T-1}|c_{I,T-2}, c_{E,T-2}] - \mathbb{E}_{T-2}[V^E_{T-1}|c_{I,T-2}, c_{E,T-2}]\}, \quad (17)$$

as there is positive value associated with being a potential entrant at $T-1$.

B.1.3 Limit Pricing Strategies

In a finite horizon game, we solve for the incumbent's value functions and its limit pricing strategies recursively.

In the final time period, the incumbent will set the optimal static price, so that $V^I_T = \pi^{*M}_I(c_I)$ and $\phi^I_T = \pi^D_I(c_I)$. In the penultimate period, we calculate $\mathbb{E}_{T-1}[V^I_T|c_{I,T-1}]$ and $\mathbb{E}_{T-1}[\phi^I_T|c_{I,T-1}]$ as expected values to being a monopolist or duopolist in the next period, given the assumed form of the cost transition. We then use the values of $g(\kappa^*_{T-1})$ and $\frac{\partial\kappa^*_{T-1}(c_{I,T-1})}{\partial c_{I,T-1}}$ that we calculated when solving the potential entrant's problem to solve for the pricing strategy of the incumbent. Starting from the boundary condition, where an incumbent with the highest marginal cost should set the static monopoly price, we use

$$\frac{\partial p^*_{I,T-1}}{\partial c_{I,T-1}} = \frac{\beta g(\kappa^*_{T-1})\frac{\partial\kappa^*_{T-1}(c_{I,T-1})}{\partial c_{I,t}}\{\mathbb{E}_{T-1}[V^I_T|c_{I,T-1}] - \mathbb{E}_{T-1}[\phi^I_T|c_{I,T-1}]\}}{\frac{\partial\pi^M_I(p_{I,T-1},c_{I,T-1})}{\partial p_{I,T-1}}}$$

to find the equilibrium pricing schedule. This is done using `ode45` in MATLAB.[31] As we solve the differential equation we interpolate, using cubic splines, the values of $g(\kappa^*_{T-1})$, $\frac{\partial\kappa^*_{T-1}(c_{I,T-1})}{\partial c_{I,t}}$, $\{\mathbb{E}_{T-1}[V^I_T|c_{I,T-1}] - \mathbb{E}_{T-1}[\phi^I_T|c_{I,T-1}]\}$ and $\frac{\partial\pi^M_I(p_{I,T-1},c_{I,T-1})}{\partial p_{I,T-1}}$ from the relevant grid points.

We use the resulting pricing function to calculate the incumbent's profits in period $T-1$ given this strategy, $\pi^M_I(c_I, p^{\text{DLP}}_{T-1}) = (p^{\text{DLP}}_{T-1}(c_I) - c_I)Q(p^{\text{DLP}}_{T-1})$. The incumbent's value functions at the beginning of period $T-1$ are then calculated as

[31] We have used a variety of differential equation solvers with essentially identical results. We use `ode45`, so we can use MATLAB Coder to translate a function of which solving the differential equation is a part into C, which greatly speeds computation.

$$\phi^I_{T-1}(c_{I,T-1}) = \pi^D_I(c_{I,T-1}) + \beta\mathbb{E}_{T-1}[\phi^I_T|c_{I,T-1}]$$

$$V^I_{T-1}(c_{I,T-1}) = \pi^M_I(c_I, p^{\text{DLP}}_{T-1}) + \beta G(\kappa^*_{T-1}(c_{I,T-1}))\mathbb{E}_{T-1}[\phi^I_T|c_{I,T-1}] + ...$$

$$\beta(1 - G(\kappa^*_{T-1}(c_{I,T-1})))\mathbb{E}_{T-1}[V^I_T|c_{I,T-1}].$$

With these value functions in hand, we can then proceed back to the previous period and repeat the calculations, before proceeding backwards through the rest of the game.

B.1.4 Infinite Horizon Game (used in numerical illustration and calibration)

In the limiting infinite horizon version of the model, this procedure of solving for period-specific pricing strategies is unnecessary. Our first step is to the recursion for solving the potential entrant's strategy until the values of ϕ^E_t, V^E_t and κ^*_t have converged for all values on the cost grid. These will be the stationary strategies in the infinite horizon of the game. Next, we calculate the incumbent's value function as a duopolist (ϕ^I) in an infinitely repeated static game. We then use an iterative procedure where we solve for differential equations and pricing functions repeatedly to find a fixed points in the incumbent's value function as a monopolist (V^I) and its pricing function, taking into account that limit pricing affects the incumbent's value of being a monopolist rather than a duopolist in the future. This procedure usually converges in less than 20 iterations so that it saves significant time compared to solving the pricing game for a large number of periods of a finite horizon game.

B.1.5 Increasing Mean Entry Costs

When we calibrate the model we allow for the mean of the entry cost distribution to increase with the number of periods since E became a potential entrant. We implement this model by creating an additional discrete state variable, $Z = 1, 2, ..., \overline{Z}$, whose value determines the mean of the entry cost distribution, and by specifying a matrix P^Z that describes the transition of Z from period to period. For our calibration, we assume a deterministic transition where Z always increases by one, until it arrives in the absorbing state $\overline{Z}$, and we set $\overline{Z} = 30$. We match entry probabilities from the first 20 quarters that Southwest is a potential entrant, so that the effect of this upper bound is not too great (the probabilities for the first 20 periods are essentially identical if we use $\overline{Z} = 50$).

We now solve for infinite horizon values for E's value functions and entry thresholds where these functions will now depend on the value of Z as well c_I. The procedure is identical to the one used above, except for the fact that when we take expectations over values in the next period we need to recognize that Z will have transitioned if $Z < \overline{Z}$, and we need to check convergence for a set of value functions, entry strategies and pricing strategies, rather than a single vector.

B.2 Extension with Capacity Investment and Endogenous Marginal Costs

We start by specifying grids for the state variables. For the post-entry game, the grid is three-dimensional $(\theta_I^{NL}, K_I, K_E)$. For the pre-entry game it is two-dimensional. (θ_I^{NL}, K_I). In calculating the results in our base parameterization in Section 6, we use a 30-point grid for $\theta_I^{NL} \in [150,000, 250,000]$, a 40-point grid for $K_I \in [8,000, 58,000]$, and a 38-point grid for $K_E \in [4,000, 52,000]$. In addition, we specify a 237-point grid for the incumbent's local price (p_I^L) which runs from \$250 below the lowest monopoly price for local traffic (i.e., the monopoly price with maximum capacity and least connecting traffic) to just above the highest monopoly price. Finally, we create a $(\theta_I^{NL}, \widehat{\theta_I^{NL}}, K_I, p_I^L)$ grid that we will use in verifying the single-crossing condition.

For each of the duopoly grid points we solve for profits in the duopoly stage game (denote these $\pi_j^D(\theta_I^{NL}, K_I, K_E)$). With logit or nested logit demands and marginal costs that increase monotonically in a carrier's load factor, this pricing game has a unique equilibrium. For each point on the monopoly grid, we calculate the static monopoly prices, for both local and connecting traffic, and variable profits. We also calculate the derivative of the incumbent's profit with respect to its local price at every point on the price grid $\left(\frac{\partial \pi_I^M(p_I^L, p_I^{*NL}(p_I^L), \theta_I^{NL}, K_I)}{\partial p_I^L}\right)$, where we account for the fact that when the monopolist has a local price that is below the monopoly price, it will optimally set a higher connecting price (p_I^{NL}) in order to reduce its marginal cost. These derivatives will be used when solving the differential equations for the incumbent's limit pricing strategy. We can also use it to verify that the first condition in the Malaith and von Thadden theorem (Appendix A), which only relates to the shape of the monopoly profit function, is satisfied.[32] The second condition can be confirmed analytically as, holding prices and capacity fixed, marginal costs increase in θ_I^{NL}.

We then turn to solving the dynamic game, where we need to compute investment strategies under both monopoly and duopoly and the incumbent's pricing strategy before entry has occurred. Because we are not able to verify that the conditions needed for existence and uniqueness of equilibrium strategies will always hold prior to solving the game, we are reliant on a recursive approach where we start from the end of the game and verify that the conditions hold in every period.

B.2.1 Final Period (T)

Given our assumptions on the timing of when costs are incurred, in the final period there will be no changes to capacity; no entry; and, an incumbent monopolist will set static monopoly prices for both types of traffic. We use these to define the following value functions:

1. the value of a monopolist incumbent at the start of period T, $V_T^I(\theta_{I,T}^{NL}, K_{I,T})$, for each monopoly grid point. This is equal to the variable profit from serving both types of traffic at static monopoly prices, less the capacity cost, $\gamma_I^K K_{I,T}$.

2. the value of a potential entrant at the start of period T, $V_T^E(\theta_{I,T}^{NL}, K_{I,T}) = 0$, for each monopoly grid point.

[32]In this model, the relevant Mailath and von Thadden theorem replaces $c_{I,t}$ with the unobserved factor $\theta_{I,t}^{NL}$, and the price with the price set for local traffic.

3. the values of duopolists at the start of period T, $\phi_T^I(\theta_{I,T}^{NL}, K_{I,T}, K_{E,T})$ and $\phi_T^E(\theta_{I,T}^{NL}, K_{I,T}, K_{E,T})$, which are equal to duopoly variable profits less capacity costs.

B.2.2 Earlier Period (t)

We then proceed through all earlier periods recursively. For each period, we work as follows:

Capacity Choice.

Monopoly. We first solve the capacity choice, $K_{I,t+1}^*(\theta_{I,t}^{NL}, K_{I,t})$, of a monopolist incumbent that decides to change its capacity. For each $(\theta_{I,t}^{NL}, K_{I,t})$ grid point we can calculate the expected continuation value from each $K_{I,t+1}$ (on the same grid) taking into account the non-fixed component of the adjustment cost.

$$CV_I(K_{I,t+1}|\theta_{I,t}^{NL}, K_{I,t}) = \beta \int_{\underline{\theta_I^{NL}}}^{\overline{\theta_I^{NL}}} V_{t+1}^I(\theta_{I,t+1}^{NL}, K_{I,t+1})\psi(\theta_{I,t+1}^{NL}|\theta_{I,t}^{NL})d\theta_{I,t+1}^{NL} - \zeta(K_{I,t+1} - K_{I,t})^2$$

where the integration is performed using the trapezium rule. We then find $K_{I,t+1}^*(\theta_{I,t}^{NL}, K_{I,t})$ by maximizing this continuation value, interpolating over the grid points using a cubic spline (so that a capacity choice that is not at one of the grid points can be optimal). With $K_{I,t+1}^*(\theta_{I,t}^{NL}, K_{I,t})$ in hand, we can then compute the probability that the incumbent changes its capacity given the distribution of fixed adjustment costs, the expected fixed adjustment cost given that it chooses to change capacity $(\eta_{I,t}^*(K_{I,t+1}^*, \theta_{I,t}^{NL}, K_{I,t}))$ and the incumbent's expected value (which we call the intermediate value function) before the adjustment cost is drawn:

$$V_{int-t}^I(\theta_{I,t}^{NL}, K_{I,t}) = \Pr(\text{capacity change}) \times [CV_I(K_{I,t+1}^*|\theta_{I,t}^{NL}, K_{I,t}) - \eta_{I,t}^*(K_{I,t+1}^*, \theta_{I,t}^{NL}, K_{I,t})] + ...$$
$$(1 - \Pr(\text{capacity change})) \times CV_I(K_{I,t}|\theta_{I,t}^{NL}, K_{I,t})$$

We also calculate the value, before the adjustment cost is drawn, of the potential entrant

$$V^E_{int-t}(\theta^{NL}_{I,t}, K_{I,t}) = \Pr(\text{capacity change}) \times \beta \int_{\underline{\theta^{NL}_I}}^{\overline{\theta^{NL}_I}} V^E_{t+1}(\theta^{NL}_{I,t+1}, K^*_{I,t+1})\psi(\theta^{NL}_{I,t+1}|\theta^{NL}_{I,t})d\theta^{NL}_{I,t+1} + ...$$

$$(1 - \Pr(\text{capacity change})) \times \beta \int_{\underline{\theta^{NL}_I}}^{\overline{\theta^{NL}_I}} V^E_{t+1}(\theta^{NL}_{I,t+1}, K_{I,t})\psi(\theta^{NL}_{I,t+1}|\theta^{NL}_{I,t})d\theta^{NL}_{I,t+1}$$

Duopoly. Under duopoly we have to solve for the capacity policies of both firms at each $(\theta^{NL}_{I,t}, K_{I,t}, K_{E,t})$ grid point. To do this, we simultaneously solve the pair of first-order conditions that define optimal choices if capacity is changed. In our presented examples, we assume that E has no adjustment costs, but we also find the probability that I will change its capacity. For E, the continuation value given a capacity choice $K_{E,t+1}$, where I chooses $K^*_{I,t+1}$ if it changes its capacity, is

$$CV_E(K_{I,t+1}, K_{E,t+1}|\theta^{NL}_{I,t}, K_{I,t}, K_{E,t}) = \left[\begin{array}{c} \Pr(I \text{ capacity change}) \times ... \\ \beta \int_{\underline{\theta^{NL}_I}}^{\overline{\theta^{NL}_I}} \phi^E_{t+1}(\theta^{NL}_{I,t+1}, K_{I,t+1}, K_{E,t+1})\psi(\theta^{NL}_{I,t+1}|\theta^{NL}_{I,t})d\theta^{NL}_{I,t+1} \end{array} \right] + ...$$

$$\left[\begin{array}{c} (1 - \Pr(I \text{ capacity change})) \times ... \\ \beta \int_{\underline{\theta^{NL}_I}}^{\overline{\theta^{NL}_I}} \phi^E_{t+1}(\theta^{NL}_{I,t+1}, K_{I,t}, K_{E,t+1})\psi(\theta^{NL}_{I,t+1}|\theta^{NL}_{I,t})d\theta^{NL}_{I,t+1} \end{array} \right]$$

where we perform integration using the trapezium rule and then calculate numerical derivatives to find the value of the first-order condition $\left(\frac{\partial CV_E(K_{I,t+1}, K_{E,t+1}|\theta^{NL}_{I,t}, K_{I,t}, K_{E,t})}{\partial K_{E,t+1}}\right)$ at each of the grid points. To find the value of the first-order conditions at $(K_{I,t+1}, K_{E,t+1})$ values that are not on the grid we use MATLAB's piecewise cubic Hermite interpolation. Of course, we would like there to be a unique equilibrium in the capacity choice game. We have examined the shape of the reaction functions for many parameters and periods and have consistently found that the reaction functions of both firms have been quite linear in the other firm's capacity. Under linearity, there will almost necessarily be a single equilibrium. Having solved for the capacity choices, we then calculate the values $\phi^I_{int-t}(\theta^{NL}_{I,t}, K_{I,t}, K_{E,t})$ and $\phi^E_{int-t}(\theta^{NL}_{I,t}, K_{I,t}, K_{E,t})$, which are defined prior to I's fixed adjustment cost being drawn, in a similar fashion to above.

Entry. We calculate E's entry strategy at each point on the monopoly grid when it has not yet entered the market.[33] E will want to enter whenever $\phi^{E}_{int-t}(q^{NL}_{I,t}, K_{I,t}, 0) - \kappa_t > V^{E}_{int-t}(\theta^{NL}_{I,t}, K_{I,t})$, where κ_t is the draw of entry costs, so that $\kappa^*_t(\theta^{NL}_{I,t}, K_{I,t}) = \phi^{E}_{int-t}(\theta^{NL}_{I,t}, K_{I,t}, 0) - V^{E}_{int-t}(\theta^{NL}_{I,t}, K_{I,t})$. We assume that κ_t is drawn from a distribution $G(\kappa)$ on $[0, \overline{\kappa}]$ where we set $\overline{\kappa}$ =\$100 million. To generate a fully separating equilibrium we need the probability of entry to be on the (0,1) interval and to be strictly monotonically increasing in $\theta^{NL}_{I,t+1}$, properties that we verify.[34] We then calculate the pdf function $g(\kappa^*_t(\theta^{NL}_{I,t}, K_{I,t}))$ and $\frac{\partial \kappa^*_t(\theta^{NL}_{I,t}, K_{I,t})}{\partial \theta^{NL}_{I,t}}$ (numerically) for every grid point, together with the expected entry cost if the firm enters.

Pricing/Market Competition.

Duopoly. For the duopoly game we have already calculated the equilibrium profits for each $(\theta^{NL}_{I,t}, K_{I,t}, K_{E,t})$ combination. Therefore, we can simply calculate the beginning of period firm values at each grid point as

$$\phi^{j}_{t}(\theta^{NL}_{I,t}, K_{I,t}, K_{E,t}) = \pi^{D}_{j}(\theta^{NL}_{I,t}, K_{I,t}, K_{E,t}) + \phi^{j}_{int-t}(\theta^{NL}_{I,t}, K_{I,t} K_{E,t})$$

Monopoly. Here we have to solve for the limit pricing schedule having verified that the signaling payoff function satisfies the properties of belief monotonicity, type monotonicity and single-crossing. The signaling payoff function is

$$\begin{aligned}\Pi^{I,t}(\theta^{NL}_{I,t}, \widehat{\theta^{NL}_{I,t}}, p^{L}_{I,t}, K_{I,t}) = \pi^{M}_{I}(p^{L}_{I,t}, p^{*NL}_{I}(p^{L}_{I,t}), \theta^{NL}_{I,t}, K_{I,t}) + ...\\ (1 - G(\kappa^*_t(\widehat{\theta^{NL}_{I,t}}, K_{I,t}))V^{I}_{int-t}(\theta^{NL}_{I,t}, K_{I,t}) + ...\\ G(\kappa^*_t(\widehat{\theta^{NL}_{I,t}}, K_{I,t}))\phi^{I}_{int-t}(\theta^{NL}_{I,t}, K_{I,t}, 0)\end{aligned}$$

[33] Note that here the θ^{NL}_{I} grid is being interpreted as the entrant's beliefs about the incumbent's connecting traffic. Of course, in a fully separating equilibrium, these beliefs are correct.

[34] Note that in the last periods of the game where the entry cost will typically be much bigger than the PDV value of profits of a new entrant, the probability of entry may be numerically indistinguishable from zero due to rounding error. In this case, the incumbent's pricing strategy is set equal to static monopoly pricing.

Given a value of $K_{I,t}$, we can verify, numerically, the remaining conditions of the Mailath and von Thadden theorem (Appendix A) required for uniqueness of a fully separating equilibrium. These are: (i) $\Pi_2^{I,t}(\theta_{I,t}^{NL}, \widehat{\theta_{I,t}^{NL}}, p_{I,t}^L, K_{I,t}) \neq 0$ for all $(\theta_{I,t}^{NL}, \widehat{\theta_{I,t}^{NL}}, p_{I,t}^L, K_{I,t})$, which, given the monotonicity of $\kappa_t^*(\widehat{\theta_{I,t}^{NL}}, K_{I,t})$ simply involves verifying that $V_{int-t}^I(\theta_{I,t}^{NL}, K_{I,t}) > \phi_{int-t}^I(\theta_{I,t}^{NL}, K_{I,t}, 0)$ [belief monotonicity]; and (ii) $\frac{\Pi_3^{I,t}(\theta_{I,t}^{NL}, \widehat{\theta_{I,t}^{NL}}, p_{I,t}^L, K_{I,t})}{\Pi_2^{I,t}(\theta_{I,t}^{NL}, \widehat{\theta_{I,t}^{NL}}, p_{I,t}^L, K_{I,t})}$ is a monotone function of $\theta_{I,t}^{NL}$ for all, $\widehat{\theta_{I,t}^{NL}}$ and all $p_{I,t}^L$ below the local static monopoly price [single-crossing]. For each $(\theta_{I,t}^{NL}, \widehat{\theta_{I,t}^{NL}}, K_{I,t})$ grid point we first compute

$$\frac{\Pi_3^{I,t}(\theta_{I,t}^{NL}, \widehat{\theta_{I,t}^{NL}}, p_{I,t}^L, K_{I,t})}{\Pi_2^{I,t}(\theta_{I,t}^{NL}, \widehat{\theta_{I,t}^{NL}}, p_{I,t}^L, K_{I,t})} = \frac{\frac{\partial \pi_I^M(p_{I,t}^L, p_I^{*NL}(p_{I,t}^L), \theta_{I,t}^{NL}, K_{I,t})}{\partial p_{I,t}^L}}{-g(\kappa_t)\left\{V_{int-t}^I(\theta_{I,t}^{NL}, K_{I,t}) - \phi_{int-t}^I(\theta_{I,t}^{NL}, K_{I,t}, 0)\right\}}$$

at each of our 300 incumbent local price grid points (recall that we have already calculated the numerator). For each $(\widehat{\theta_{I,t}^{NL}}, K_{I,t}, p_{I,t}^L)$ grid point (for local prices below the static monopoly price), we then take differences with respect to $\theta_{I,t}^{NL}$ and verify that there are no changes in sign. The same calculations show that the single-crossing condition in the Ramey theorem in Appendix A, will also be satisfied.

If these conditions hold, we can then calculate the equilibrium limit pricing schedule for a given $K_{I,t}$, by solving the Mailath and von Thadden (2013) differential equation with a boundary condition where a firm with connecting traffic equal to $\overline{\theta_I^{NL}}$ charges the static monopoly price. The form of the differential equation is

$$\frac{\partial p_{I,t}^{*L}(\theta_{I,t}^{NL}, K_{I,t})}{\partial \theta_{I,t}^{NL}} = \frac{g(\kappa_t^*(\theta_{I,t}^{NL}, K_{I,t}))\frac{\partial \kappa_t^*(\theta_{I,t}^{NL}, K_{I,t})}{\partial \theta_{I,t}^{NL}}\{V_{int-t}^I(\theta_{I,t}^{NL}, K_{I,t}) - \phi_{int-t}^I(\theta_{I,t}^{NL}, K_{I,t}, 0)\}}{\frac{\partial \pi_I^M(p_{I,t}^L, p_I^{*NL}(p_{I,t}^L), \theta_{I,t}^{NL}, K_{I,t})}{\partial p_{I,t}^L}}$$

All of the terms in this expression have already been calculated for points on the grids, so when we solve the differential equation we interpolate them. The denominator is interpolated using a cubic spline, while the other terms are interpolated using piecewise cubic Hermite interpolation. The differential equation itself is solved in MATLAB using the `ode45` routine.

We then calculate the beginning of period firm values as:

$$\begin{aligned}
V_t^I(\theta_{I,t}^{NL}, K_{I,t}) = \pi_I^M(p_{I,t}^{*L}, p_I^{NL}(p_{I,t}^{*L}), \theta_{I,t}^{NL}, K_{I,t}) - \gamma_I^K K_{I,t} + ... \\
(1 - G(\kappa_t^*(\theta_{I,t}^{NL}, K_{I,t}))V_{int-t}^I(q_{I,t}^{NL}, K_{I,t}) + ... \\
G(\kappa_t^*(\theta_{I,t}^{NL}, K_{I,t}))\phi_{int-t}^I(q_{I,t}^{NL}, K_{I,t}, 0) \\
V_t^E(\theta_{I,t}^{NL}, K_{I,t}) = (1 - G(\kappa_t^*(\theta_{I,t}^{NL}, K_{I,t}))V_{int-t}^E(\theta_{I,t}^{NL}, K_{I,t}) + ... \\
G(\kappa_t^*(\theta_{I,t}^{NL}, K_{I,t}))\phi_{int-t}^E(\theta_{I,t}^{NL}, K_{I,t}, 0)
\end{aligned}$$

At this point we can then move on to capacity choices in the previous period.

C Data Appendix

This Appendix supplements the material in Section 3 in the main paper.

C.1 List of Dominant Incumbent Markets

In the following list (*) identifies markets in the subset of 65 markets where Southwest is observed for at least some quarters as a potential, but not an actual, entrant. Carrier names reflect those at the end of the sample (so, for example, Northwest routes are listed under Delta).

American (AA): Nashville-Raleigh, Burbank-San Jose, Colorado Springs-St Louis(*), Las Vegas-San Jose, Los Angeles-San Jose(*), Reno-San Jose(*), Louisville-St Louis, Omaha-St. Louis(*), San Jose-Orange County(*), St. Louis-Tampa

Alaska (AS): Boise-Portland, Boise-Seattle, Eugene-Seattle, Spokane-Portland(*), Spokane-Seattle, Oakland-Portland, Oakland-Seattle, Oakland-Orange Country(*)

Continental (CO): Baltimore-Houston(Bush)(*), Cleveland-Palm Beach(*), Fort Lauderdale-Houston(*), Houston- Jackson, MS(*), Houston-Jacksonville(*), Houston-Orlando(*), Houston-Omaha(*), Houston-Palm-Beach(*), Houston-Raleigh(*), Houston-Seattle(*), Houston-Orange County(*), Houston-Tampa(*), Houston-Tucson(*)

Delta (DL): Albuquerque-Minneapolis(*), Albany-Detroit(*), Albany-Minneapolis(*), Hartford-Minneapolis(*), Boise-Minneapolis(*), Boise-Salt Lake City, Buffalo-Detroit(*), Colorado Springs-Salt Lake City, Detroit-Milwaukee(*), Detroit-Norfolk, VA(*), Fresno-Reno(*), Fresno-Salt Lake City(*), Fort Lauderdale-Minneapolis(*), Spokane-Minneapolis(*), Spokane-Salt Lake City, Jacksonville-LaGuardia(*), Los Angeles-Salt Lake City, LaGuardia-New Orleans(*), LaGuardia-Southwest Florida(*), LaGuardia-Tampa(*), Kansas City-Salt Lake City(*), Minneapolis-New Orleans(*), Minneapolis-Oklahoma City(*), Minneapolis-Omaha(*), Minneapolis-Providence(*), Minneapolis-Orange County(*), Oakland-Salt Lake City, Portland-Salt Lake City, Reno-Salt Lake City, San Diego-Salt Lake City, Seattle-Salt Lake City, San Jose-Salt Lake City, Salt Lake City-Sacramento, Salt Lake City-Orange County, Salt Lake City-Tucson

United (UA): Hartford-Washington Dulles(*), Nashville-Washington Dulles(*), Boise-San Francisco(*), Eugene-San Francisco(*), Washington Dulles-Indianapolis(*), Washington Dulles- Jacksonville(*), Washington Dulles-LaGuardia(*), Washington Dulles-Raleigh(*), Washington Dulles-Tampa

US Airways (US): Albany-Baltimore, Hartford-Baltimore, Hartford-Philadelphia(*), Buffalo-Baltimore, Buffalo-LaGuardia(*), Buffalo-Philadelphia(*), Baltimore-Jacksonville, Baltimore-

Orlando, Baltimore-Norfolk, Baltimore-Palm Beach, Baltimore-Pittsburgh(*), Baltimore-Providence, Baltimore-Tampa, Columbus-Philadelphia(*), Jacksonville-Philadelphia(*), Colorado Springs-Phoenix(*), Las Vegas-Omaha, Las Vegas-Pittsburgh, Las Vegas-Tucson, LaGuardia-Pittsburgh(*), Manchester-Philadelphia(*), New Orleans- Philadelphia(*), Norfolk-Philadelphia(*), Omaha-Phoenix, Philadelphia-Pittsburgh, Philadelphia-Providence, Phoenix-Orange County(*), Sacramento-Orange County(*)

Other Carriers: Midwest Airlines (YX): Columbus-Milwaukee(*), Kansas City-Milwaukee; Airtran (FL): Baltimore-Milwaukee; Midway Airlines (JI): Jacksonville-Raleigh(*); ATA (TZ): Chicago Midway-Philadelphia, Chicago Midway-Southwest Florida.

C.2 Construction of Market Size

A simple approach to defining the size of an airline market is to assume that it is proportional to the arithmetic or geometric average population of the endpoint cities (e.g., Berry and Jia (2010)). However, the number of passengers traveling on a route also varies systematically with distance, time and the number of people who use the endpoint airports.[35] Recognizing this fact, like Benkard, Bodoh-Creed, and Lazarev (2010) amongst others, we try to create a better measure of market size, that we use when estimating demand in Section 5 (see also Appendices D.3 and E) and also as one of the variables, in addition to average endpoint population, that can predict the probability of entry by Southwest in Section 4 (Appendix D.1).

We estimate a generalized gravity equation using our full sample of markets, where the expected number of passengers (we use a three quarter moving average of DB1 passengers) traveling on a route is allowed to be a function of time, distance, the number of originating and final destination passengers at both of the endpoint airports as well as interactions between these variables and distance, and origin and destination fixed effects. The originating and destination variables are measured in the first quarter of our data (Q1 1993) in order to avoid potential endogeneity problems arising from passenger flows later in our sample being

[35]This can reflect either the fact that customers in some cities may be able to choose between multiple airports, which may be more or less convenient, but also that some destinations, such as vacation destinations, receive many more visitors than would be expected based on their populations.

affected by Southwest's route-level entry decisions and incumbents' responses to them.[36]

$$\mathbb{E}\left[\text{Passengers}_{o,d,t}\right] = \exp\left\{\begin{array}{c} \tau_t + \beta_1 \text{Longtrip}_{o,d} + \beta_2 \log(\text{Distance}_{o,d}) + \beta_3 \log(\text{Distance}^2_{o,d})... \\ +\beta_4 \log(\text{Originating}_{d,1993}) + \beta_5 \log(\text{Originating}_{o,1993})... \\ +\beta_6 \log(\text{Destination}_{o,1993}) + \beta_7 \log(\text{Destination}_{d,1993})... \\ + \sum_{j=1}^{3} \beta_{8,j} \log(\text{Originating}_{o,1993}) \log(\text{Distance}_{o,d})^j ... \\ + \sum_{j=1}^{3} \beta_{9,j} \log(\text{Destination}_{d,1993}) \log(\text{Distance}_{o,d})^j ... \\ \text{and } o \text{ and } d \text{ fixed effects and their interactions with Longtrip}_{o,d} \end{array}\right\}$$

where τ_t are quarter fixed effects, o is the origin airport, d is the destination airport, and $\text{Longtrip}_{o,d}$ is a dummy variable for whether the round-trip distance exceeds 2,300 miles. $\text{Originating}_{j,1993}$ is the number of DB1 passengers in Q1 1993 with itineraries originating at $j = \{o, d\}$. $\text{Destination}_{j,1993}$ is the number of DB1 passengers in Q1 1993 with itineraries where $j = \{o, d\}$ is the final destination. The specification is estimated using the Poisson Pseudo-Maximum Likelihood estimator, as suggested by Silva and Tenreyro (2006), because estimates from a log-linearized regression will be inconsistent when the residuals are heteroskedastic. The estimates of several coefficients are shown in Table C.1.

With the estimates in hand, we calculate the predicted value of the number of passengers for each market-quarter and then form our estimate of market size by multiplying this estimate by 3.5,[37] so that, on average, the market share of all carriers combined (as a share of the potential market) is between 25% and 40%.

[36]Our measure does vary across quarters because of the quarter dummies included in the specification, which should pick up aggregate/national trends in air travel.

[37]In the event that the number of passengers traveling on a route in a quarter exceeds this scaled market size number we set the market size for that quarter equal to the average market size for that origin and destination pair, which only affects 0.3% of the observations.

Table C.1: Selected Coefficients from the Gravity Equation Used to Estimate Market Size

	DB1 Passengers
Longtrip	0.330***
	(0.062)
log(Dist)	10.166***
	(1.606)
$\log(\text{Dist})^2$	-0.666***
	(0.111)
$\log(\text{Destination}_{d,1993})$	-5.187**
	(2.632)
$\log(\text{Destination}_{o,1993})$	0.570***
	(0.036)
$\log(\text{Originating}_{o,1993})$	-3.964
	(2.589)
$\log(\text{Originating}_{d,1993})$	-0.049**
	(0.020)
Observations	148,158
Pseudo-R^2	0.732

Note: ***, ** and * denote statistical significance at the 1, 5 and 10% levels respectively.

C.3 Calculation of Connecting Traffic

As mentioned in the text, we view connecting traffic as being an important source of asymmetric information between a dominant incumbent operating on a route out of one of its hubs and a potential entrant. We report some statistics on estimates of the amount of connecting traffic carried on routes in our sample. The estimate of the number of connecting passengers is formed by subtracting ten times the number of passengers traveling the route in DB1 from the total number of passengers reported as traveling on the carrier-segment in T100.

There are several sources of possible error in this number. First, DB1 is only a sample of passengers, so we may not measure the number of nonstop passengers accurately. Second, while we include traffic on regional affiliates in our T100 number, these affiliates did not report in T100 throughout the sample. Third, additional error arises from some passengers who are non-connecting in DB1 traveling on one-stop service with no change of planes so, contrary to what we assume, they would not appear in T100. These concerns are one reason why we do not attempt to calibrate our model using connecting traffic information.

C.4 Price Changes when Southwest Becomes a Potential Entrant: Replicating the Analysis of Goolsbee and Syverson (2008) for the Dominant Incumbent Sample

Goolsbee and Syverson (2008) show that incumbent airline prices fall when Southwest threatens entry on a route and when it actually enters. Their analysis uses a broad sample of markets (not restricted to markets with a dominant incumbent) from 1993 to 2004. In the Appendix we repeat their regression-based analysis for our longer dominant incumbent sample.

The specification is

$$\text{Price Measure}_{j,m,t} = \gamma_{j,m} + \tau_t + \alpha X_{j,m,t} + ...$$
$$\sum_{\tau=-8}^{8+} \beta_\tau SWPE_{m,t_0+\tau} + \sum_{\tau=0}^{3+} \beta_\tau SWE_{m,t_e+\tau} + \varepsilon_{j,m,t} \tag{18}$$

where $\gamma_{j,m}$ are market-incumbent fixed effects and τ_t are quarter fixed effects. Only observations for the dominant incumbent are included in the regression. Controls, X, include counts of the number of other direct or connecting carriers serving the market, and interactions between spot prices for jet fuel and route distance. t_0 and t_e are the quarters in which Southwest becomes a potential and actual entrant, and the $SWPE_{m,t_0+\tau}$ and $SWE_{m,t_e+\tau}$ dummies allow us to measure how prices change around these events. We use observations for up to three years (12 quarters) before Southwest becomes a potential entrant, and the β coefficients measure price changes relative to those quarters that are more than eight quarters before Southwest becomes a potential entrant or, if Southwest becomes a potential entrant within the first eight quarters that the dominant carrier is observed in the data, the first quarter that the market is observed.

Table C.2: Incumbent Pricing In Response to Southwest's Actual and Potential Entry

		Phase 1		*Phase 2*		*Phase 3*
<u>Fare</u>						
	$t_0 - 8$	-0.046	t_0	-0.089^{***}	t_e	-0.438^{***}
		(0.028)		(0.029)		(0.064)
	$t_0 - 7$	-0.022	$t_0 + 1$	-0.119^{***}	$t_e + 1$	-0.549^{***}
		(0.027)		(0.035)		(0.070)
	$t_0 - 6$	-0.048	$t_0 + 2$	-0.129^{***}	$t_e + 2$	-0.555^{***}
		(0.030)		(0.032)		(0.076)
	$t_0 - 5$	-0.050	$t_0 + 3$	-0.128^{***}	$t_e + 3$	-0.603^{***}
		(0.032)		(0.031)		(0.079)
	$t_0 - 4$	-0.021	$t_0 + 4$	-0.144^{***}	$t_e + 4$	-0.619^{***}
		(0.031)		(0.033)		(0.082)
	$t_0 - 3$	-0.015	$t_0 + 5$	-0.142^{***}	$t_e + 5$	-0.611^{***}
		(0.027)		(0.039)		(0.080)
	$t_0 - 2$	-0.059^{**}	$t_0 +$ 6-12	-0.203^{***}	$t_e +$ 6-12	-0.584^{***}
		(0.026)		(0.050)		(0.080)
	$t_0 - 1$	-0.064^{***}	$t_0 + 13+$	-0.309^{***}	$t_e + 13+$	-0.581^{***}
		(0.024)		(0.052)		(0.084)
<u>Yield</u>						
	$t_0 - 8$	-0.026^{*}	t_0	-0.045^{***}	t_e	-0.251^{***}
		(0.015)		(0.017)		(0.050)
	$t_0 - 7$	-0.007	$t_0 + 1$	-0.050^{**}	$t_e + 1$	-0.295^{***}
		(0.015)		(0.022)		(0.053)
	$t_0 - 6$	-0.022	$t_0 + 2$	-0.060^{***}	$t_e + 2$	-0.296^{***}
		(0.016)		(0.020)		(0.057)
	$t_0 - 5$	-0.014	$t_0 + 3$	-0.059^{***}	$t_e + 3$	-0.313^{***}
		(0.017)		(0.019)		(0.058)
	$t_0 - 4$	-0.013	$t_0 + 4$	-0.072^{***}	$t_e + 4$	-0.324^{***}
		(0.016)		(0.021)		(0.060)
	$t_0 - 3$	-0.009	$t_0 + 5$	-0.070^{***}	$t_e + 5$	-0.330^{***}
		(0.015)		(0.023)		(0.059)
	$t_0 - 2$	-0.034^{**}	$t_0 +$ 6-12	-0.114^{***}	$t_e +$ 6-12	-0.326^{***}
		(0.016)		(0.029)		(0.060)
	$t_0 - 1$	-0.035^{**}	$t_0 + 13+$	-0.179^{***}	$t_e + 13+$	-0.349^{***}
		(0.015)		(0.034)		(0.066)

Notes: Estimates of specification (18) with the dependent variable as either the log of the mean passenger-weighted fare on the dominant incumbent ("Fare") or this fare divided by the nonstop route distance ("Yield"). Specifications include market-incumbent fixed effects, quarter fixed effects and controls for the number of other competitors on the route (separately for direct or connecting), fuel prices and fuel prices×route distance. Standard errors clustered by route-carrier are in parentheses. ***, ** and * denote statistical significance at the 1, 5 and 10% levels respectively. Number of observations is 4,167 and the adjusted R^2s are 0.78 ("Fare") and 0.85 ("Yield"). Phases are defined in the text.

Table C.2 presents two sets of coefficient estimates, using the log of the average ticket price and the yield, which is equal to the average price divided by the length of the route, as alternative price measures. Both measures are informative, and they have the potential to show different results when price changes are different on routes of different length. However, in our regressions, both measures show similar proportional effects across phases, with prices falling by 10-14% when Southwest becomes a potential entrant and an additional 30-45% when Southwest enters (the average yield in Phase 1 is 0.544). Our Phase 2 price declines are slightly smaller than those identified by GS, but our Phase 3 declines are larger, presumably reflecting the greater market power that dominant incumbents have prior to Southwest's entry. One striking feature is that prices appear to fall more over time during Phase 2, i.e., if Southwest does not actually enter. We discuss the ability of our basic model and extensions to explain this pattern in Section 6 and Appendix F. Another feature is that prices start declining two quarters *before* Southwest becomes a potential entrant. This pattern is consistent with our model once one takes into account that Southwest typically announces its entry into airports several months before it actually starts to operate flights, which is what is measured by t_0, as rivals should try to affect Southwest's subsequent decisions about which routes to serve.

Tables C.3-C.5 present the results of the same regressions using the 25^{th}, 50^{th} or 75^{th} percentiles of the price/yield distribution for the dominant incumbent to form the dependent variable, rather than the average fare. We see that there are significant Phase 2 and 3 price declines across the price distribution for both measures, although the percentage declines are somewhat larger at higher percentiles where margins will tend to be bigger. The pattern that prices decline across the fare distribution in Phase 2 is consistent with the predictions of a limit pricing model where the incumbent can price discriminate across different classes of customers (Pires and Jorge (2012)).

Table C.3: Incumbent Pricing In Response to Southwest's Actual and Potential Entry: 25th Percentile of Prices

		Phase 1		*Phase 2*		*Phase 3*
<u>Fare</u>						
	t_0-8	-0.047	t_0	-0.049	t_e	-0.455^{***}
		(0.029)		(0.038)		(0.073)
	t_0-7	0.006	t_0+1	-0.095^{**}	t_e+1	-0.519^{***}
		(0.033)		(0.045)		(0.077)
	t_0-6	-0.033	t_0+2	-0.110^{**}	t_e+2	-0.530^{***}
		(0.031)		(0.044)		(0.078)
	t_0-5	-0.040	t_0+3	-0.136^{***}	t_e+3	-0.562^{***}
		(0.034)		(0.040)		(0.082)
	t_0-4	0.030	t_0+4	-0.101^{**}	t_e+4	-0.581^{***}
		(0.036)		(0.040)		(0.086)
	t_0-3	0.009	t_0+5	-0.110^{**}	t_e+5	-0.577^{***}
		(0.034)		(0.047)		(0.085)
	t_0-2	-0.029	$t_0+6\text{-}12$	-0.169^{***}	$t_e+6\text{-}12$	-0.522^{***}
		(0.029)		(0.054)		(0.084)
	t_0-1	-0.031	t_0+13+	-0.282^{***}	t_e+13+	-0.506^{***}
		(0.025)		(0.057)		(0.086)
<u>Yield</u>						
	t_0-8	-0.027^{**}	t_0	-0.017	t_e	-0.185^{***}
		(0.013)		(0.018)		(0.040)
	t_0-7	0.013	t_0+1	-0.020	t_e+1	-0.202^{***}
		(0.017)		(0.020)		(0.042)
	t_0-6	-0.017	t_0+2	-0.035^{*}	t_e+2	-0.201^{***}
		(0.014)		(0.019)		(0.045)
	t_0-5	-0.015	t_0+3	-0.045^{**}	t_e+3	-0.205^{***}
		(0.014)		(0.019)		(0.043)
	t_0-4	0.017	t_0+4	-0.038^{*}	t_e+4	-0.211^{***}
		(0.016)		(0.021)		(0.045)
	t_0-3	0.011	t_0+5	-0.043^{**}	t_e+5	-0.221^{***}
		(0.015)		(0.021)		(0.046)
	t_0-2	-0.008	$t_0+6\text{-}12$	-0.069^{***}	$t_e+6\text{-}12$	-0.216^{***}
		(0.015)		(0.025)		(0.049)
	t_0-1	-0.008	t_0+13+	-0.112^{***}	t_e+13+	-0.232^{***}
		(0.015)		(0.034)		(0.052)

Notes: Estimates of specification (18) when dependent variable is log of the 25th percentile passenger-weighted fare ("Fare") or this fare divided by the nonstop route distance ("Yield"). The adjusted R^2s are 0.71 ("Fare") and 0.74 ("Yield"). Other notes from Table C.2 apply here.

Table C.4: Incumbent Pricing In Response to Southwest's Actual and Potential Entry: 50th Percentile of Prices

		Phase 1		Phase 2		Phase 3
Fare						
	$t_0 - 8$	-0.039	t_0	-0.088^{**}	t_e	-0.545^{***}
		(0.032)		(0.034)		(0.092)
	$t_0 - 7$	-0.015	$t_0 + 1$	-0.108^{**}	$t_e + 1$	-0.655^{***}
		(0.036)		(0.046)		(0.091)
	$t_0 - 6$	-0.030	$t_0 + 2$	-0.117^{***}	$t_e + 2$	-0.658^{***}
		(0.036)		(0.041)		(0.097)
	$t_0 - 5$	-0.013	$t_0 + 3$	-0.127^{***}	$t_e + 3$	-0.722^{***}
		(0.037)		(0.040)		(0.103)
	$t_0 - 4$	-0.036	$t_0 + 4$	-0.164^{***}	$t_e + 4$	-0.713^{***}
		(0.038)		(0.040)		(0.107)
	$t_0 - 3$	-0.018	$t_0 + 5$	-0.168^{***}	$t_e + 5$	-0.672^{***}
		(0.035)		(0.049)		(0.106)
	$t_0 - 2$	-0.082^{**}	$t_0 + 6\text{-}12$	-0.237^{***}	$t_e + 6\text{-}12$	-0.616^{***}
		(0.032)		(0.053)		(0.105)
	$t_0 - 1$	-0.065^{**}	$t_0 + 13+$	-0.347^{***}	$t_e + 13+$	-0.602^{***}
		(0.032)		(0.062)		(0.109)
Yield						
	$t_0 - 8$	-0.024	t_0	-0.047^{**}	t_e	-0.303^{***}
		(0.017)		(0.022)		(0.065)
	$t_0 - 7$	-0.003	$t_0 + 1$	-0.041	$t_e + 1$	-0.341^{***}
		(0.021)		(0.028)		(0.066)
	$t_0 - 6$	-0.014	$t_0 + 2$	-0.056^{**}	$t_e + 2$	-0.342^{***}
		(0.024)		(0.026)		(0.069)
	$t_0 - 5$	0.007	$t_0 + 3$	-0.065^{***}	$t_e + 3$	-0.362^{***}
		(0.022)		(0.024)		(0.071)
	$t_0 - 4$	-0.023	$t_0 + 4$	-0.085^{***}	$t_e + 4$	-0.372^{***}
		(0.022)		(0.028)		(0.074)
	$t_0 - 3$	-0.007	$t_0 + 5$	-0.081^{***}	$t_e + 5$	-0.371^{***}
		(0.023)		(0.030)		(0.075)
	$t_0 - 2$	-0.053^{**}	$t_0 + 6\text{-}12$	-0.143^{***}	$t_e + 6\text{-}12$	-0.366^{***}
		(0.023)		(0.035)		(0.077)
	$t_0 - 1$	-0.040^{*}	$t_0 + 13+$	-0.212^{***}	$t_e + 13+$	-0.389^{***}
		(0.023)		(0.050)		(0.085)

Notes: Estimates of specification (18) when dependent variable is log of the median passenger-weighted fare ("Fare") or this fare divided by the nonstop route distance ("Yield"). The adjusted R^2s are 0.70 ("Fare") and 0.81 ("Yield"). Other notes from Table C.2 apply here.

Table C.5: Incumbent Pricing In Response to Southwest's Actual and Potential Entry: 75th Percentile of Prices

		Phase 1		*Phase 2*		*Phase 3*
<u>Fare</u>						
	t_0-8	-0.051	t_0	-0.125^{***}	t_e	-0.480^{***}
		(0.032)		(0.042)		(0.089)
	t_0-7	-0.051	t_0+1	-0.160^{***}	t_e+1	-0.622^{***}
		(0.034)		(0.042)		(0.092)
	t_0-6	-0.065^{*}	t_0+2	-0.179^{***}	t_e+2	-0.617^{***}
		(0.038)		(0.044)		(0.098)
	t_0-5	-0.060	t_0+3	-0.163^{***}	t_e+3	-0.683^{***}
		(0.039)		(0.043)		(0.105)
	t_0-4	-0.040	t_0+4	-0.194^{***}	t_e+4	-0.700^{***}
		(0.041)		(0.044)		(0.103)
	t_0-3	-0.041	t_0+5	-0.181^{***}	t_e+5	-0.672^{***}
		(0.036)		(0.049)		(0.103)
	t_0-2	-0.081^{**}	t_0+ 6-12	-0.228^{***}	t_e+ 6-12	-0.653^{***}
		(0.037)		(0.060)		(0.102)
	t_0-1	-0.073^{**}	t_0+13+	-0.372^{***}	t_e+13+	-0.614^{***}
		(0.034)		(0.069)		(0.111)
<u>Yield</u>						
	t_0-8	-0.029	t_0	-0.079^{***}	t_e	-0.354^{***}
		(0.022)		(0.028)		(0.079)
	t_0-7	-0.031	t_0+1	-0.091^{***}	t_e+1	-0.423^{***}
		(0.021)		(0.032)		(0.079)
	t_0-6	-0.030	t_0+2	-0.102^{***}	t_e+2	-0.429^{***}
		(0.023)		(0.031)		(0.083)
	t_0-5	-0.028	t_0+3	-0.089^{***}	t_e+3	-0.455^{***}
		(0.024)		(0.031)		(0.086)
	t_0-4	-0.035	t_0+4	-0.117^{***}	t_e+4	-0.471^{***}
		(0.024)		(0.033)		(0.088)
	t_0-3	-0.038^{*}	t_0+5	-0.115^{***}	t_e+5	-0.469^{***}
		(0.023)		(0.036)		(0.086)
	t_0-2	-0.061^{**}	t_0+ 6-12	-0.169^{***}	t_e+ 6-12	-0.472^{***}
		(0.025)		(0.045)		(0.086)
	t_0-1	-0.056^{**}	t_0+13+	-0.274^{***}	t_e+13+	-0.494^{***}
		(0.023)		(0.052)		(0.098)

Notes: Estimates of specification (18) when dependent variable is log of the 75th percentile passenger-weighted fare ("Fare") or this fare divided by the nonstop route distance ("Yield"). The adjusted R^2s are 0.72 ("Fare") and 0.84 ("Yield"). Other notes from Table C.2 apply here.

D Supplement to Evidence of a Non-Monotonic Relationship Between the Probability of Entry and Incumbent Price Reductions

This Appendix supplements Section 4 in the main paper.

D.1 Estimation of Southwest's Route-Level Entry Probabilities

As outlined in Section 4, we test for non-monotonicity in two stages where the first stage involves the prediction of the probability that Southwest will enter each of the routes in our sample. We estimate a probit model using 1,415 non-dominant incumbent markets in the full sample. There is one observation per market, and the dependent variable ($\text{Entry4}_{m,t}$) is equal to 1 if Southwest enters market m within four quarters of starting to operate at both endpoint airports (i.e., within four quarters of becoming a potential entrant). We measure entry over a short fixed interval so that we do not need to account for the fact that we observe markets that are exposed to the possibility of entry for different numbers of periods (although to calibrate the model we use a very similar specification to estimate a hazard model using information on entry in any period in our data). Southwest enters close to 53% of the routes that it enters during our sample within one year of becoming a potential entrant, and 6% and 2% of routes over the next two years.

$$\Pr(\text{Entry4}_{m,t}|X,t) = \Phi(\tau_t + \alpha X_{m,t})$$

where τ_t contains a full set of quarter dummies. The explanatory variables X_m contain the following market characteristics:

- Distance: round-trip distance between the endpoint airports (also Distance^2);
- Long Distance: a dummy that is equal to 1 for markets with a round-trip distance

greater than 2,000 miles;

- Average Pop.: geometric average population for the endpoint MSAs (also Average Pop.^{2});

- Market Size: the Phase 1 average of our estimated market size variable[38] (also Market Size^2), excluding the last four quarters of Phase 1. For those markets where there are less than or equal to four quarters observed for Phase 1, we average over all of the Phase 1 quarters in the data for that market;

- Slot: a dummy that is equal to 1 if either endpoint airport is a slot-controlled airport (New York JFK, LaGuardia and Newark, Washington Reagan and Chicago O'Hare);

- Leisure Destination: a dummy that is equal to 1 if either endpoint city is a leisure destination as defined by Gerardi and Shapiro (2009);

- Big City: a dummy that is equal to 1 if either endpoint city is a large city, following the population-based definition of Gerardi and Shapiro (2009);

- Southwest Alternate Airport: a dummy equal to 1 in cases where Southwest already serves one of the endpoint airports from an airport that is in the same city as the other endpoint airport;

- HHI: the Phase 1 average HHI for the route, based on passenger numbers, excluding the last four quarters of Phase 1. For those markets where there are less than or equal to four quarters observed for Phase 1, we average over all of the Phase 1 quarters in the data for that market.

For each of the endpoint airports separately, we also include:

- Primary Airport: a dummy equal to 1 for the largest airport (measured by passenger traffic in 2012) in a multiple airport city;

[38]See Appendix C.2 for details.

- Secondary Airport: a dummy equal to 1 for an airport other than the largest in a multiple airport city;

- Incumbent Presence: the Phase 1 average of the average proportion of all passenger originations accounted for by the incumbents on route m at the airport, excluding the last four quarters of Phase 1 (also Incumbent Presence^2). For those markets where there are less than or equal to four quarters observed for Phase 1, we average over all of the Phase 1 quarters in the data for that market;

- Southwest Presence: the Phase 1 average of the proportion of all passenger originations accounted for by Southwest at the airport, excluding the last four quarters of Phase 1 (also Southwest Presence^2). For those markets where there are less than or equal to four quarters observed for Phase 1, we average over all of the Phase 1 quarters in the data for that market.

The estimated coefficients are reported in Table D.1, where by "origin" we simply mean the airport with the three-letter IATA airport code that is alphabetically first for the airport-pair. Larger market sizes, shorter distances, leisure destinations and more concentrated markets are all more likely to attract entry.

D.2 Second-Stage Estimates

D.2.1 Graphical Illustration of the Estimated Changes in Table 3

Figure D.1 show the estimated quadratic relationships for the five regression specifications in Table 3. The dashed lines indicate 95% confidence intervals, which are corrected to allow for the uncertainty in the estimated probabilities as well as allowing for heteroskedasticity and first-order serial correlation in the second-stage residuals.

Table D.1: Probit Model of Southwest's Entry

	Entry by Southwest Within Four Quarters	
Distance	-0.545*	
	(0.280)	
Distance^2	0.022	
	(0.045)	
Long Distance	-0.006	
	(0.221)	
Average Pop.	-0.210	
	(0.142)	
Average Pop.^{2}	0.017**	
	(0.008)	
Market Size	0.297***	
	(0.052)	
Market Size^2	-0.008***	
	(0.002)	
Slot	-1.715***	
	(0.525)	
Leisure Destination	0.724***	
	(0.212)	
Big City	-0.210	
	(0.168)	
Southwest Alternate Airport	-0.104	
	(0.261)	
HHI	0.592	
	(0.387)	
Airport-Specific Variables	Origin	Destination
Primary Airport	0.579*	0.521*
	(0.343)	(0.278)
Secondary Airport (origin)	0.753***	0.214
	(0.261)	(0.271)
Incumbent Presence	-7.157	-9.974
	(11.260)	(6.522)
Incumbent Presence^2	30.848	22.419*
	(33.441)	(11.717)
Southwest Presence	2.338**	0.364
	(1.157)	(1.226)
Southwest Presence^2	-2.893**	-0.485
	(1.338)	(1.462)
Observations	1,415	
Pseudo-R^2	0.368	

Notes: Specification also includes dummies for the quarter in which Southwest becomes a potential entrant. Robust standard errors in parentheses. ***,**,* denote statistical significance at the 1, 5 and 10% levels respectively.

Figure D.1: Quadratic Relationships with the Predicted Probability of Southwest's Entry in the Regressions in Table 3

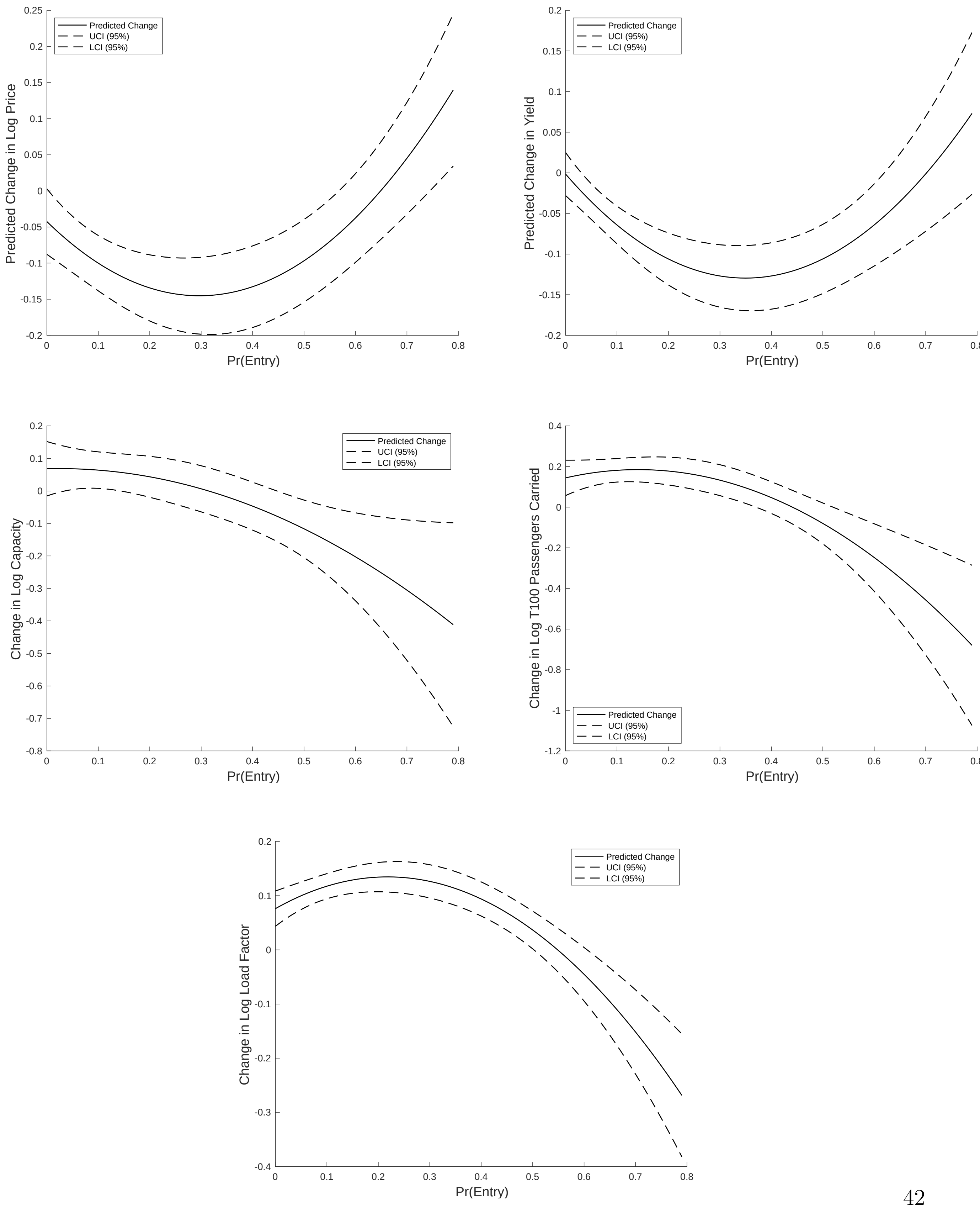
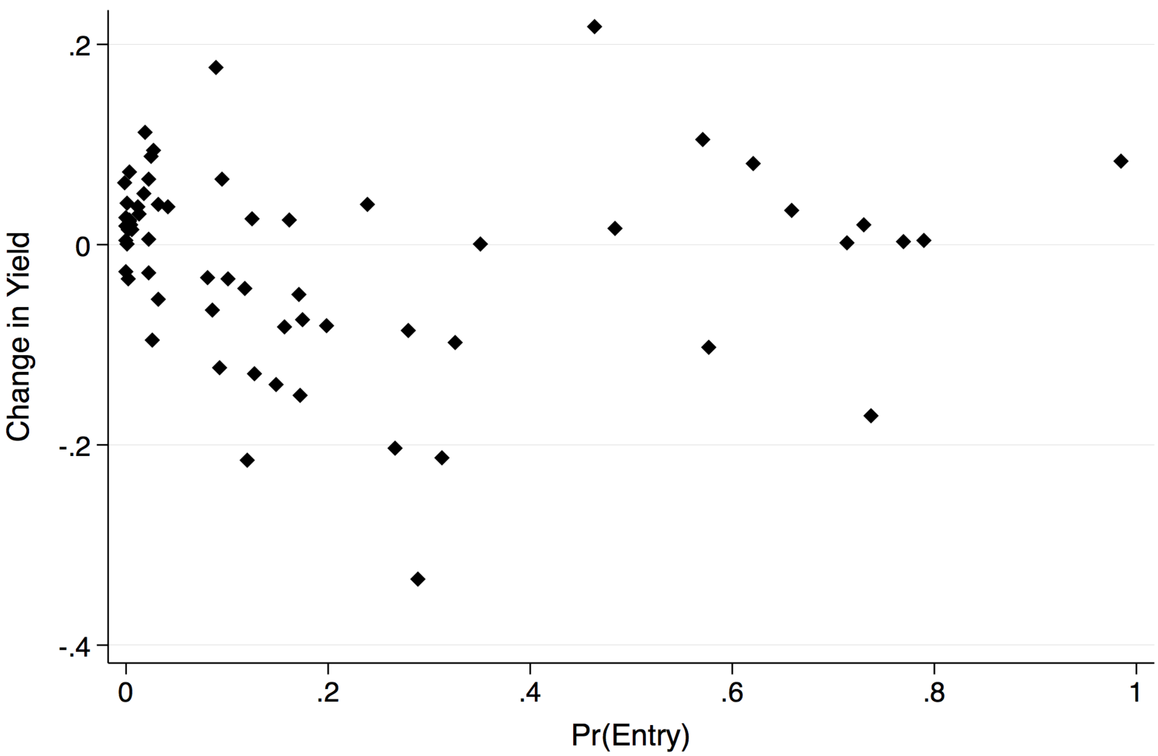


Figure D.2: Estimated Phase 2 Yield Changes Market-by-Market as a Function of Southwest's Predicted Probability of Entry



D.2.2 Estimates of Market-By-Market Price Declines

In the text we report the estimated quadratic relationship between the probability of entry and incumbent price changes in Phase 2. This is a simple and parsimonious way of testing for non-monotonicity given the limited number of market observations, but it relies on a parametric functional form which our model does not imply. In order to show we are not being drawn to a misleading conclusion, we estimate the price change *in each market* by replacing the three $SWPE_{m,t}$ terms in specification (7) with $SWPE_{m,t}\times$market m dummy interactions. The coefficients, when average yield is the price measure, on these interactions are plotted in Figure D.2 against the first-stage probability of entry for the relevant market (excluding one off-the-chart observation with an estimated yield change of -0.617 and an entry probability of 0.142). While there is heterogeneity in how prices change for a given predicted entry probability, which could reflect both random variation in pricing and imprecise estimates of entry probabilities in different markets, the clear pattern is that prices do not tend to decrease during Phase 2 in markets with high or very low entry probabilities, while they tend to fall significantly in most of the markets in between. The feature that there is no significant change for markets with the highest entry probabilities is noteworthy because the estimated quadratic specifications reported in columns (1) and (2) of Table 3 predicted price *increases* in these markets, whereas our calibrated model, like these market-by-market estimates, does not (see Section 5 for more discussion).

D.2.3 Robustness Checks on Estimated Non-Monotonic Relationship Between Changes in Prices and the Probability of Entry

Table D.2 presents the coefficient estimates for yield regressions when we make a number of changes to investigate the robustness and the interpretation of the baseline results which appear in column (1) of Table 3, and are repeated in the first column here. We focus on the yield results, but we would reach similar conclusions looking at prices.

In order to reduce the concern that Phase 2 price changes in dominant incumbent markets

Table D.2: Robustness Checks on the Incumbent Yield Results Reported in Table 3

	(1) Baseline	(2) Include Dom. Inc. Mkts. in 1st Stage	(3) Exclude Pass. Flow Vars. from 1st Stage	(4) Incl. Phase 2 $\times$Airport Fixed Effects
$SWPE_{mt}$	-0.002	-0.012	0.013	-
	(0.014)	(0.015)	(0.014)	
$\widehat{\rho_m} \times SWPE_{mt}$	-0.732***	-0.555***	-0.859***	-1.015***
	(0.142)	(0.120)	(0.154)	(0.248)
$\widehat{\rho_m}^2 \times SWPE_{mt}$	1.046***	0.738***	1.268***	1.176***
	(0.219)	(0.162)	(0.236)	(0.340)

	(5) Allow for Quadratic for $t_0 - 8$ to $t_0 - 2$		(6) Allow for Separate Effects with Phase 2 Duration		(7) Control for Conv. of WN Connections
	Phase 1 Effect	Phase 2 Effect	First 12 Qtrs.	After 12 Qtrs.	
Constant	-0.045***	-0.017	-0.013	0.014	0.011
	(0.015)	(0.015)	(0.013)	(0.015)	(0.014)
$\widehat{\rho_m}\times$...	0.226	-0.680***	-0.436***	-1.425***	-0.512***
	(0.138)	(0.152)	(0.140)	(0.174)	(0.150)
$\widehat{\rho_m}^2\times$...	-0.211	1.005***	0.623***	2.298***	0.823***
	(0.201)	(0.237)	(0.210)	(0.292)	(0.202)

Notes: Heteroskedasticity robust Newey-West standard errors allowing for one period serial correlation and corrected for first-stage approximation error in the entry probabilities in parentheses. All specifications include market-incumbent fixed effects and the additional controls included in the specifications in Table 3, and specification (7) has controls for the convenience of connecting on Southwest. In specification (5) the constant, $\widehat{\rho_m}$ and $\widehat{\rho_m^2}$ are interacted with a dummy variable for Phase 1 and a dummy variable for Phase 2. In specification (6) they are interacted with dummies for the first 12 quarters of Phase 2 and later quarters. In specification (7) they are interacted with dummies for Phase 2, as in the first four specifications. ***, ** and * denote statistical significance at the 1, 5 and 10% levels respectively. All specifications are estimated using 3,884 incumbent-market-quarter observations.

affect the probability of entry, our baseline specifications do not include dominant incumbent markets in the sample of markets used for the estimation of the entry probabilities and explanatory variables that are based on passenger flows are defined based on data from one year before the start of Phase 1. Column (2) shows that we get a similar estimated relationship if we include the 109 dominant incumbent markets in the estimation sample. Column (3) shows the results when we exclude all of the passenger flow-based variables (HHI and the carrier presence variables) from the first-stage estimation (market size which is based on passenger flows in Q1 1993 remains included). The absolute magnitude of the linear and quadratic terms increases in this case.

As discussed in the text, an alternative concern is that airport developments, such as capacity increases, reduce the incumbent's marginal costs at the same time as attracting Southwest to enter the airport, so that it becomes a potential entrant. In column (4) we add a set of interactions between the Phase 2 dummy variable and airport-specific fixed effects in the second-stage specification, so that the quadratic is identified from variation in entry probabilities across routes at given airports.[39] The estimated quadratic coefficients are also larger than the baseline in this case, and they remain statistically significant even though the standard errors increase as the number of fixed effects rises. In lower specification (5) we address the same concern by trying to test whether there is a detectable non-monotonicity between price changes and the entry probability towards the end of Phase 1 as might be expected if airport changes both induce Southwest to enter the airport and cause the incumbent's static optimal price to fall. As we think that Southwest's arrival has some effect on prices before it begins operations, we do so by estimating a separate quadratic in the probability of entry for the quarters $t_0 - 8$ to $t_0 - 2$ (i.e., two to eight quarters before Southwest becomes a potential entrant). We find no evidence of a non-monotonic relationship at the end of Phase 1, while the estimated Phase 2 coefficients remain close to the baseline.

[39] For example, a dummy for Las Vegas in Phase 2 that is equal to 1 for any route during Phase 2 which has Las Vegas as an endpoint, so that there will be two airport dummies equal to one for each Phase 2 observation.

Table D.3: Balance Table for Dominant Firm Sample

Variable Description	Market Probability of Southwest Entry Low	Intermediate	High	p-value for 2-Sided Test of Equality of Means Low and Int.	Int. and High	All Three
Market entered by	0.194	0.528	0.892	0.003	0.000	0.000
Southwest (dummy)	(0.401)	(0.506)	(0.315)			
Incumbent is a legacy	0.944	0.833	0.730	0.137	0.291	0.047
carrier (dummy)	(0.232)	(0.378)	(0.450)			
Nonstop Distance	1,747.1	1,094.7	939.8	0.000	0.298	0.000
(round-trip)	(722.6)	(719.8)	(524.6)			
Market Size	29,119	50,072	116,313	0.006	0.000	0.000
	(20,124)	(39,397)	(89,416)			
Average endpoint	2,663,055	2,582,668	3,245,342	0.857	0.161	0.286
city population	(1,740,231)	(2,023,390)	(1,975,970)			
One or both endpoint airports is hub	0.917	0.833	0.622	0.292	0.043	0.006
for dominant incumbent	(0.280)	(0.378)	(0.492)			
One or both endpoint cities is	0.500	0.444	0.757	0.643	0.006	0.015
multi-airport market	(0.507)	(0.504)	(0.435)			
One or both endpoints is a	0.056	0.111	0.162	0.401	0.533	0.354
leisure destination	(0.232)	(0.319)	(0.374)			
Phase 1 route HHI	0.608	0.767	0.851	0.001	0.038	0.000
	(0.208)	(0.182)	(0.157)			
Phase 1 proportion of traffic	0.858	0.853	0.800	0.807	0.064	0.102
making connections	(0.094)	(0.089)	(0.143)			
Phase 1 load factor	0.642	0.591	0.603	0.054	0.594	0.123
	(0.114)	(0.105)	(0.088)			
Incumbent Phase 1	529.86	462.58	431.56	0.038	0.299	0.006
Direct Fare ($)	(140.73)	(129.12)	(124.26)			
Phase 2 Southwest	0.031	0.009	0.001	0.009	0.037	0.000
share	(0.041)	(0.016)	(0.003)			
Phase 2 Southwest	0.013	0.009	0.001	0.466	0.037	0.004
share, excluding Minneapolis routes	(0.020)	(0.016)	(0.003)			
Number of markets	36	36	37			

Notes: The left-hand columns report the mean of the variable during Phase 1 (before Southwest is a potential entrant), unless otherwise noted, where we first average across quarters for each market and then report the average across markets. The standard deviation (in parentheses) is the across-market standard deviation. The right-hand columns report the p-values from t-tests for equality of the means for low/intermediate and intermediate/high groups, and a test for equality of all three means (implemented using `mvtest means` in STATA). We assume that, under the null hypothesis, the variances may be heterogeneous across the three groups for continuous variables such as population and market size, and that they are the same across groups for dummy variables such as whether the market was entered.

A further way of testing whether the results could be explained by markets with intermediate entry probabilities having particular characteristics is using a balance table where observed market characteristics can be compared. Table D.3 presents this type of table where we break the 109 dominant incumbent markets into three groups of almost equal size based on the estimated probability of entry. Obviously we would not expect variables that affect the attractiveness of entry to be the same across the groups, so the main thing we are looking for is whether there are significant non-monotonicities in observed market characteristics, especially those that might suggest that different competitive factors may be at work. For each market, we first calculate the mean of the variable across Phase 1 observations (i.e., before Southwest is a potential entrant, with two exceptions noted below), and the reported means are averages across these market-level means. Standard deviations are in parentheses and the right-hand columns present p-values from tests that the means of the variables are the same across the three groups.

In most cases, the mean values for the intermediate probability of entry markets lie between those for the low and high probability markets (e.g., HHI, market size, and average incumbent Phase 1 fare). In other cases, for example average endpoint population and load factor, we cannot reject the hypothesis that the means for the three different groups are the same. For multi-airport endpoints the p-value is 0.015 but the difference between the low and intermediate probability of entry markets is small. We discuss the final rows below.

As mentioned in Appendix C.4, the magnitude of the Phase 2 price decline seems to increase over time. In lower specification (6) of Table D.2 we test whether the non-monotonicity is a feature of the data both in the first three years after Southwest becomes a potential entrant and in later quarters. The quadratic coefficients are economically and statistically significant for both sets of time periods.[40] See Appendix F for further discussion of what may generate the increasing price decline in the data.

One possible non-strategic explanation for Phase 2 price declines is that once South-

[40]For example, if $\rho = 0.4$ then the expected yield decrease will be 0.09 for the first 12 quarters and 0.19 for subsequent quarters, compared with an average Phase 1 yield of 0.53 for these markets.

west serves both endpoints, it is able to provide *actual* competition, because it can provide connecting service that is a partial substitute for the incumbent's direct service.[41] Several pieces of evidence suggest that actual competition does not explain why prices fall in our data. First, as shown in Table 2, Southwest's share of traffic is very small in Phase 2, compared with the incumbent's Phase 2 share or Southwest's own share in Phase 3. Its average Phase 2 prices are also quite high ($389 compared to $426 for the incumbent) suggesting that it is typically not seeking to compete aggressively in the threatened markets in Phase 2. It is therefore unlikely that there is enough competitive pressure in Phase 2 to cause the incumbent's static optimal price to fall significantly. The penultimate row of the balance table (Table D.3) shows that Southwest's Phase 2 market share in the intermediate probability of entry markets, where we observe prices falling, is less than 1%, whereas it is highest in the low probability of entry markets where we do not see prices decline. Connecting traffic is especially high on a set of routes from Minneapolis, reflecting the ability of passengers to make convenient connections at Southwest's focus airport at Chicago Midway.

Second, the fact that the incumbent's prices start to decline two quarters before Southwest actually starts being active at both endpoints, which is consistent with a strategic investment story, is not consistent with prices falling due to actual competition, which could only start when service begins, at least if we assume that consumers do not substitute intertemporally (e.g., delaying travel in anticipation that Southwest's reasonably high connecting fares will soon be available).

Third, connecting service on Southwest is likely to be most attractive for price sensitive, leisure travelers. Assuming that these customers will also tend to buy the cheapest fares on the incumbent (for example, because they buy restricted tickets far in advance of departure), one would expect actual competition to drive the largest price reductions on these low priced fares. As shown in Table D.4, prices decline significantly for the 25^{th}, the 50^{th} and the

[41] The limited literature on connecting service (in general, not specifically focused on Southwest) indicates that it provides only a partial constraint on the market power of a carrier that provides direct service (Reiss and Spiller (1989), Dunn (2008)).

Table D.4: Second-Stage Analysis of the Relationship Between the Probability of Entry and Price Changes with Percentiles of the Yield Distribution

	(1) 25^{th} percentile	(2) 50^{th} percentile	(3) 75^{th} percentile
$SWPE_{m,t}$	-0.001	0.020	-0.003
	(0.013)	(0.018)	(0.021)
$\widehat{\rho_m} \times SWPE_{m,t}$	-0.681***	-0.904***	-1.087***
	(0.154)	(0.210)	(0.199)
$\widehat{\rho_m}^2 \times SWPE_{m,t}$	1.067***	1.149***	1.527***
	(0.248)	(0.335)	(0.281)
Observations	3,884	3,884	3,884

Notes: Specification equivalent to specification (1) in Table D.2 except that a percentile of the yield distribution replaces the average yield as the dependent variable.

75^{th} percentiles of the price distribution, and for each of them we observe a statistically and economically U-shaped price decline with respect to the estimated probability of entry. While it seems unlikely that limited low-end actual competition would produce this result, it is consistent with a limit pricing story. For example, Pires and Jorge (2012) consider a model where an incumbent has a common marginal cost across several markets and only one market is threatened by entry. They show that in a limit price, signaling equilibrium, the incumbent lowers prices in all markets.

Fourth, we can provide additional evidence by directly controlling for the convenience of connecting service on Southwest. To do so, we augment the baseline specification, in lower specification (7) of Table D.2, by including interactions between the Phase 2 dummy and additional dummies that split our dominant incumbent markets into quintiles based on the proportional increase in the distance that a traveler would have to fly (relative to the nonstop distance) if she made a connection via the most convenient Southwest focus airport (Baltimore, Chicago Midway, Las Vegas or Phoenix). While this change does reduce the magnitude of the quadratic coefficients, they remain significant and, counter-intuitively, the coefficients on the new variables indicate that yields fall most on routes where connections on Southwest are least convenient.

D.3 Analysis of Demand Dynamics

As explained in Section 4, one interpretation of Phase 2 price cuts is that incumbents are trying to increase customer loyalty. This strategy could help deter entry by reducing Southwest's expected demand. It could, alternatively, be an accommodation strategy that increases the incumbent's expected profits in the duopoly game that follows entry.[42] In this Appendix we provide some evidence that suggests that lower prices do not significantly raise an incumbent's own demand in future quarters.

We estimate a simple nested logit demand model of the incumbent's demand, where the outside good is 'not flying' and different carriers flying the route are gathered in the single nest (see Appendix E.1 where we use the same demand model specification to estimate demand and marginal cost parameters for our calibration of the dynamic limit pricing model in Section 5). Our market size measure is described in Appendix C.2. Our estimating equation is the standard one used with aggregate data, following Berry (1994), and given that we are focused here on understanding whether the incumbent can increase its future demand by lowering prices, we estimate the model using only (average) price and share observations for the incumbent. However, as well as the carrier's average price in the current period, we also include prices in previous quarters, and, if there is a significant loyalty effect, then we expect the coefficients on these lagged prices to also be negative. Our instruments for the current average price and the inside share are the one-quarter lagged jet fuel price, the interaction of this price and the nonstop route distance, the carrier's presence at the endpoints and a dummy for whether Southwest has entered the market. When we include price lags, we introduce appropriately lagged values of these variables as additional instruments. Our sample consists of observations on the dominant incumbent, from Phases 1 and 3, and in

[42] Our empirical evidence in Section 4 indicates that price cuts are motivated by deterrence and not accommodation, as we do not observe large price cuts in the dominant incumbent sample markets where entry is most likely. Of course, an incumbent might not want to increase consumer loyalty if it expects entry, if this would cause the entrant to price more aggressively.

some specifications Phase 2.[43]

The estimated coefficients are shown in Table D.5. Columns (1)-(4) use observations from Phases 1 and 3 only, with the specifications including different lagged price variables. The F-statistics in the first-stage regressions (not reported) are all greater than 45. We observe that none of the coefficients on the lagged prices are statistically significant at the 5% level[44] and that they vary in sign, while the coefficient on the current price remains significant. Columns (5)-(8) repeat this analysis using observations from all phases to illustrate the robustness of our findings that lower current incumbent prices do not increase its future demand.

These estimates provide some evidence against demand dynamics being important and they complement the evidence from the distribution of prices (we see price declines throughout the distribution not merely for the types of expensive ticket purchased by the most valuable frequent flyers) and the existing literature on frequent-flyer programs. For example, Uncles, Dowling, and Hammond (2003) suggests that even business travelers, who are often viewed as being the most locked into these programs, substitute between carriers frequently because they choose to be members of multiple programs at once. There are, however, at least two caveats to our regression results. First, the standard errors on the lagged variables are large enough that we cannot formally reject quite substantial demand dynamics even though our point estimates are generally small. Second, a more explicitly dynamic demand model estimated using individual-level data, which might include information on frequent-flyer program participation, might have more statistical power and be able to detect non-trivial dynamics for at least some consumers.[45]

[43]Note that to understand whether induced loyalty could deter entry it might also be interesting to ask whether the incumbent's lagged prices affect the demand of other carriers including Southwest. However, these effects would be even harder to identify than effects on the carrier's own demand.

[44]The p-value for the coefficient on the one-year lagged price in column (4) is 0.10, but the coefficient is positive, i.e. it has the 'wrong' sign.

[45]For example, it is possible that the future demand of some especially valuable travelers responds to price discounts in a way that we cannot detect with our data.

Table D.5: Nested Logit Demand Estimates for the Incumbent with Lagged Prices

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Fare ($100s)	-0.453***	-0.195	-0.473***	-0.468***	-0.431***	-0.218*	-0.473***	-0.449***
	(0.0417)	(0.140)	(0.134)	(0.0662)	(0.0387)	(0.130)	(0.133)	(0.0635)
Inside Share	0.787***	0.845***	0.727***	0.747***	0.774***	0.828***	0.767***	0.782***
	(0.103)	(0.109)	(0.121)	(0.114)	(0.0959)	(0.102)	(0.117)	(0.109)
Fare_{t-1}		-0.236*	0.0564			-0.193	0.109	
		(0.138)	(0.222)			(0.127)	(0.225)	
Fare_{t-2}			-0.0502				-0.0680	
			(0.239)				(0.234)	
Fare_{t-3}			0.193				0.138	
			(0.232)				(0.221)	
Fare_{t-4}			-0.0458	0.0923*			-0.0231	0.0741
			(0.138)	(0.0550)			(0.130)	(0.0509)
Phases	1 & 3	1 & 3	1 & 3	1 & 3	All	All	All	All
Observations	4,244	4,007	3,453	3,614	5,297	4,979	4,286	4,551

Notes: Specifications also include a linear time trend, carrier dummies, a dummy for whether the incumbent is a hub carrier on the route, quarter of year dummies, market characteristics (distance, distance^2, indicators for whether the route includes a leisure destination or is in a city with another major airport) and dummies for the number of competitors offering direct service. The instruments are described in the text. The first four specifications use only observations from Phases 1 and 3, while the last four use observations from all phases. Robust standard errors in parentheses. ***,** ,* denote statistical significance at the 1, 5 and 10% levels respectively.

E Calibration

In this Appendix, we provide some additional details and results for our calibration. Our goal is to see whether our model predicts significant price shading, which varies with the probability of entry in the same way as in our data (Section 4) when we use parameters appropriate for the markets in our sample. We estimate the key parameters without using any information on the incumbent's pricing when it is threatened with entry in Phase 2. We use the estimated model to test whether it predicts a pattern of price declines similar to the one observed in the data.

E.1 Demand

We estimate a static nested logit model of passenger demand on non-directional route markets using the dominant incumbent sample for Phases 1 and 3 (i.e., before Southwest becomes a potential entrant, and after Southwest enters, if it enters).[46] Travel on carriers other than the dominant incumbent and Southwest is included in the outside good but we include the number of other carriers that fly any passengers direct as a control in our specification of mean utility. The specification of mean utility is given in equation (8) in the text.

We estimate the model using the standard estimating equation for a nested logit model with aggregate data (Berry (1994)):

$$\log\left(\frac{s_{j,m,t}}{s_{0,m,t}}\right) = \mu_j + \tau_1 T_t + \tau_{2-4} Q_t + \gamma X_{j,m,t} - \alpha p_{j,m,t} + \lambda \log(\overline{s}_{j,m,t|FLY}) + \xi_{j,m,t}$$

where $\overline{s}_{j,m,t|FLY}$ is carrier j's share of passengers flying the route on the incumbent or Southwest and $s_{j,m,t}$ is firm j's market share.

Appendix Table E.1, an enlarged version of Table 4, presents OLS and 2SLS estimates of the demand model.[47] Controlling for endogeneity increases the estimated price elasticity of demand (the median elasticity implied by the column (2) estimates is -2.70) and, consistent with previous research, consumers are estimated to prefer traveling on a carrier with a hub at one of the endpoints.

E.2 Marginal Costs and Entry Cost Parameters

The estimation of marginal costs and the entry cost parameters is described in the text.

[46] We also restrict ourselves to Phase 1 observations where the dominant incumbent has at least 50 direct DB1 passengers and Phase 3 observations where the formerly dominant incumbent and Southwest have 50 DB1 passengers and Phase 3 observations more than one quarter after Southwest enters. We also drop observations where the outside market share is less than 0.05 and observations where the formerly dominant incumbent's market share falls below 0.05 after Southwest enters, although these restrictions have little impact on the demand estimates.

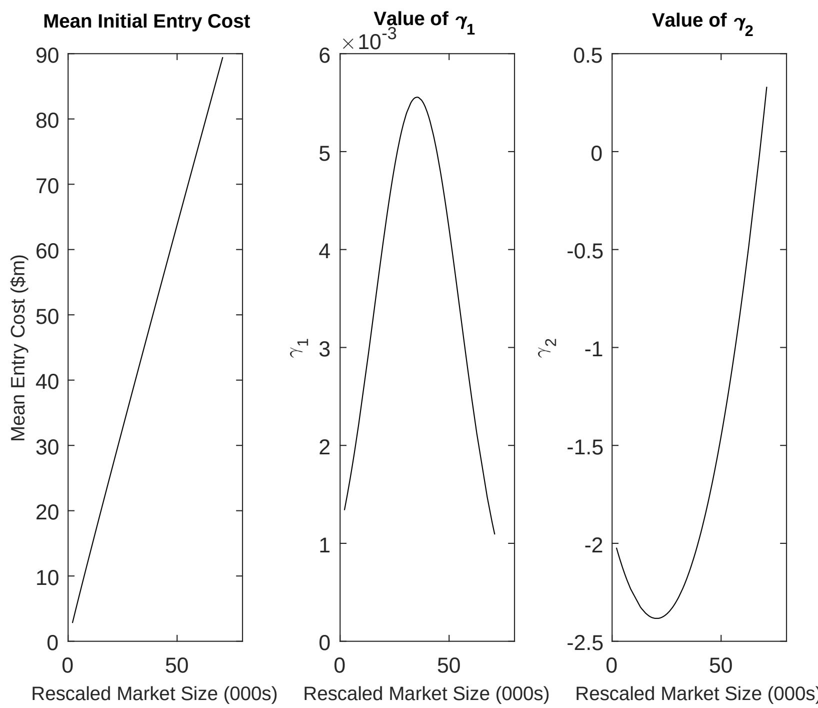
[47] The 2SLS estimates are qualitatively similar to those reported in Appendix D.3 where we only use observations on the incumbent, but also include observations from Phase 2.

Table E.1: Nested Logit Demand: Selected Coefficient Estimates

	OLS	2SLS
Fare (\$00s, $\widehat{\alpha}$)	-0.317***	-0.446***
	(0.011)	(0.034)
Inside Share ($\widehat{\lambda}$)	0.748***	0.793***
	(0.033)	(0.072)
Hub Carrier	0.207***	0.247***
	(0.026)	(0.028)
Selected Carrier Dummies		
American	-0.029	-0.026
	(0.056)	(0.061)
Continental	0.143*	0.318***
	(0.085)	(0.099)
Delta	-0.154***	-0.176***
	(0.042)	(0.044)
Northwest	0.339***	0.613***
	(0.045)	(0.077)
United	-0.272***	-0.204***
	(0.075)	(0.077)
US Airways	0.096**	0.249***
	(0.044)	(0.055)
Southwest	0.155***	0.078
	(0.041)	(0.047)
Observations	6,037	6,037
R^2	0.301	-

Notes: Specification also includes a linear time trend, quarter of year dummies, dummies for some additional, smaller carriers, market characteristics (distance, distance^2, indicators for whether the route includes a leisure destination or is in a city with another major airport) and dummies for the number of competitors offering direct service. The instruments used for 2SLS are described in the text. Robust standard errors in parentheses. ***,** ,* denote statistical significance at the 1, 5 and 10% levels respectively.

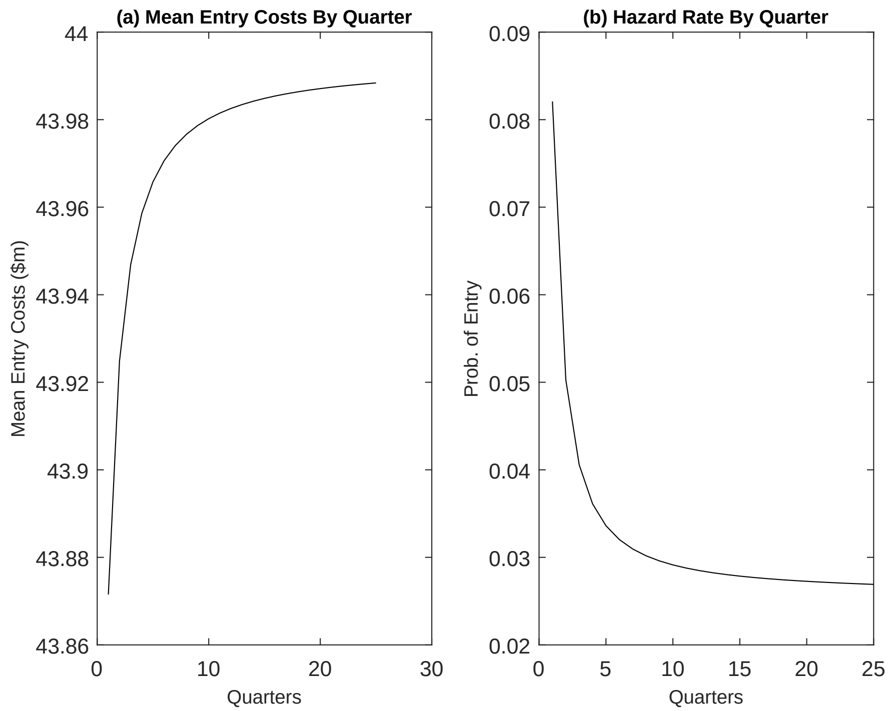
Figure E.1: Variation of Initial Mean Entry Costs and Parameters Affecting Increase in Entry Costs over Time With Rescaled Market Size



E.3 Estimated Entry Costs

The estimates of the entry cost parameters are presented in text Table 7. Figure E.1 shows how initial entry costs and the γ parameters vary with the size of the market. The striking features are that mean initial entry costs (i.e., those in the first period that Southwest can enter) are almost perfectly linear in rescaled market size. The values of γ_1 and γ_2 indicate that increases mean entry costs from period to period are typically small. However, these increases have substantial effects on the entry probabilities, as can be seen in Figure E.2, which shows the implied path of the mean entry cost, which includes the discounted value of expected fixed costs in our model, and the probability of entry for the median market. The entry probability declines quickly even though the increase in entry costs is very small, because the expectation of a future increase in entry costs reduces the value of waiting.

Figure E.2: Variation of Mean Entry Costs and Entry Probabilities Over Time for the Median Market



F Extensions to the Model

The model presented in the text assumes that the incumbent's marginal cost is the one piece of private information and that it evolves exogenously. This gives us a tractable model but it has two limitations. First, it does not capture some important characteristics of the airline industry, such as the fact that marginal costs depend on carriers' capacity choices. The mechanism through which factors such as connecting traffic may cause an incumbent to behave as if its marginal cost is private information is also unclear. We address these issues by sketching an extension to our model, and we show that this more complicated model continues to generate significant limit pricing. Second, we have not analyzed whether the simple model can explain why, on average, prices fall over time in Phase 2. We also discuss this issue and formulations of the model that can help to explain it.

F.1 Limit Pricing with Connecting Traffic and Capacity Investment

Our first extension allows for endogenous capacity investment and an asymmetry of information about how many people are interested in flying on the incumbent as part of a longer trip (i.e., connecting passenger demand). Recall that the majority of passengers that the incumbent carries on our routes are connecting passengers (Table 2) and that the economics of network flows are usually viewed as being fairly opaque (Edlin and Farrell (2004)). Here we outline the model and describe its implications for pricing and capacity investment for a given set of parameters.[48]

F.1.1 Specification and Parameterization

On a given route, carriers use their available capacity (measured by seats) to serve two mutually exclusive types of travelers: local customers (L), who are only traveling between the endpoints, and non-local (connecting) customers (NL) who are making longer journeys. We assume that the incumbent and an entrant would compete for local customers, but that they serve distinct markets for connecting customers.[49] The incumbent's connecting demand is not observed by the potential entrant, but the profitability of entry can be affected by it in two ways: first, the incumbent's marginal cost will increase in its capacity utilization so that high connecting demand will lead to it setting higher local prices, for a given level of capacity; and, second, the connecting demand of the two carriers can be positively correlated. For both reasons, the incumbent may want to signal that its connecting demand is low to deter entry. We assume that the incumbent's connecting prices are not observed by the potential

[48]We leave estimation of this model to future research, which would need to overcome the data issues concerning data on connecting passengers described in Appendix C.3.

[49]We have in mind that people connecting on Southwest may tend to be going to different places than people connecting on legacy carriers, and that, in either case, connecting customers will typically have a number of different connecting options involving other routes so it will not be the case that the incumbent and the entrant compete head-to-head for connecting traffic. One supporting piece of evidence for this assumption is that the average incumbent connecting fare in Phase 3 (once Southwest has entered), \$381.77, is almost the same as in Phase 2, \$388.99, when Southwest is just a potential entrant on the route. This suggests that Southwest's entry onto the route does not affect an incumbent's connecting demand too much.

entrant, but that it can observe the incumbent's local price.[50] We are interested in how local prices may change when entry is threatened.

Demand. We assume that local demand has a similar form the one used in Section 5 5, but we consider only a single market size of 52,361. We assume that, whether entry has occurred or not, the incumbent faces non-local demand of

$$q_{I,t}^{NL}(p_{I,t}^{NL},\theta_{I,t}^{NL})=\theta_{I,t}^{NL}\frac{\exp(\beta_I^{NL}-\alpha^{NL}p_{I,t}^{NL})}{1+\exp(\beta_I^{NL}-\alpha^{NL}p_{I,t}^{NL})} \tag{19}$$

where $p_{I,t}^{NL}$ is the incumbent's chosen price (here we are simplifying by assuming that a single connecting price is chosen). $\theta_{I,t}^{NL}$, which acts like the market size variable in a standard discrete choice analysis of firm demand, lies on a compact interval $[\underline{\theta_I^{NL}},\overline{\theta_I^{NL}}]$, and is not observed by a potential entrant, although it is observed post-entry. Reflecting the changing travel options available to connecting passengers, it evolves according to a stationary, first-order AR(1) process

$$\theta_{I,t}^{NL}=\rho^{NL}\theta_{I,t-1}^{NL}+(1-\rho^{NL})\frac{\underline{\theta_I^{NL}}+\overline{\theta_I^{NL}}}{2}+\varepsilon_t \tag{20}$$

where the normal distribution of ε_t is truncated to keep the parameter on the support. We assume that $\beta_I^{NL}=0.727$, $\underline{\theta_I^{NL}}=150,000$, $\overline{\theta_I^{NL}}=250,000$, $\rho^{NL}=0.9$[51] and the standard deviation of ε is 15,000. $\alpha^{NL}=0.0066$ (for a price in dollars), which is 50% larger than its value for local demand. We assume that, if it enters, the entrant will have non-local demand

$$q_{E,t}^{NL}(p_{E,t}^{NL},\theta_{E,t}^{NL})=(\theta_E^{NL}+\tau\theta_{I,t}^{NL})\frac{\exp(\beta_E^{NL}-\alpha^{NL}p_{E,t}^{NL})}{1+\exp(\beta_E^{NL}-\alpha^{NL}p_{E,t}^{NL})} \tag{21}$$

[50] In practice, so many connections use a particular segment that the entrant would have to monitor hundreds of connecting prices and then infer how these were being affected by demand on a particular segment.

[51] When we estimate an AR(1) using the incumbent's realized connecting traffic (measured with caveats discussed in Section 3.2), we find a serial correlation parameter between 0.85 and 0.9. Of course, realized connecting traffic will depend on costs on other segments and operational considerations as well as underlying demand, so it should be recognized that this statistic does not exactly correspond to the serial correlation that we assume in our model.

where, in our baseline, $\tau = 0.25$ and $\theta_E^{NL} = 16,667$, so that, on average, $(\theta_E^{NL} + \tau\theta_{I,t}^{NL})$ is roughly one-third of the value of $\theta_{I,t}^{NL}$.[52] $\beta_E^{NL} = 0.627$.

Carrier Costs. Carriers have observable capacities, $K_{j,t}$ and carrier j's period t costs are equal to

$$C_j(q_{j,t}^L, q_{j,t}^{NL}, K_{j,t}) = \gamma_j^K K_{j,t} + \gamma_{j,1}^L q_{j,t}^L + \gamma_{j,1}^{NL} q_{j,t}^{NL} + \gamma_{j,2}\left(\frac{q_{j,t}^{NL} + q_{j,t}^L}{K_{j,t}}\right)^{\upsilon}(q_{j,t}^L + q_{j,t}^{NL}) \qquad (22)$$

so that there are soft capacity constraints and marginal costs increase in the load factor. This specification also implies that if entry lowers the incumbent's demand then its marginal costs will tend to fall as well. We assume that $\gamma_{I,1}^L = 45$, $\gamma_{I,1}^{NL} = \gamma_{E,1}^L = \gamma_{E,1}^{NL} = 0, \gamma_{j,2} = 100$ and $\nu = 10$, so the marginal costs of carrying additional passengers are only high when the load factor is high. $\gamma_I^K = \$180$ and $\gamma_E^K = \$120$ per seat. Therefore, the entrant tends to have an advantage through lower marginal and capacity costs. This advantage plays a role in making sure that the single-crossing condition, which is required for a unique equilibrium, holds.

We also assume that the incumbent has to pay additional costs when it changes its capacity,

$$C_{I,t}^A(K_{I,t}, K_{I,t+1}) = \zeta(K_{I,t+1} - K_{I,t})^2 + \mathcal{I}(K_{I,t+1} \neq K_{I,t}) \times \eta_{I,t} \qquad (23)$$

where the first term is a deterministic convex adjustment cost, with $\zeta = 0.25$ in the baseline, and the second component is a fixed adjustment cost, which is an i.i.d. draw from an exponential distribution with a mean, in the baseline, of \$50,000. We assume that the entrant does not have any adjustment costs for capacity. This is partly for computational simplicity, but it also reflects the fact that operational constraints at an incumbent's hub may mean that it is more difficult for it to reschedule capacity.

Timing. We assume a finite horizon structure. Within each period t prior to entry, timing is as follows.

[52] Of course, the entrant may carry more connecting passengers than this proportion would suggest because its costs tend to be lower.

1. I observes $\theta^{NL}_{I,t}$ and $K_{I,t}$.

2. I chooses its prices $p^L_{I,t}$ and $p^{NL}_{I,t}$, receives ticket revenues and pays the cost of transporting passengers, and the linear capacity cost.

3. E observes its entry cost, which is an i.i.d. draw from a commonly known distribution, $p^L_{I,t}$ and $K_{I,t}$, and decides whether to enter, paying the entry cost if does so.

4. If E has entered, both firms simultaneously choose their capacities for $t+1$, and pay any relevant adjustment costs. If E has not entered, I makes its capacity choice.

5. $\theta^{NL}_{I,t}$ evolves to its value $\theta^{NL}_{I,t+1}$.

After entry, we assume that $\theta^{NL}_{I,t}$ is publicly observed by both firms, but that otherwise the timing is unchanged, except that step 3 is removed and both firms choose their prices simultaneously in step 2.

Discount Factor. For the calculations reported below, we assume a discount factor of 0.95, so that we can identify strategies that are essentially stationary once we have gone back 50 or 60 periods.[53]

F.1.2 Equilibrium

The equilibrium in this model is comprised of beliefs and an entry rule for the potential entrant, a pre-entry pricing strategy for the incumbent and post-entry pricing strategies for both firms, and also capacity investment strategies. For this richer model there is no simple static condition that ensures that there will be a unique signaling equilibrium under refinement, so we numerically verify the conditions required for existence and uniqueness during the solution process, which is described in Appendix B.2.

Several features of this model are worth highlighting. The incumbent has incentives to signal that its connecting demand is low, which it can only do by setting a low local

[53]We stop the recursion when, looking across the entire state space, no price changes by more than 1 cent and no entry probability changes by more than 1e-4.

price. Capacity cannot be used as a signal because we assume that $K_{I,t}$ is chosen before $\theta_{I,t}^{NL}$ is known to the incumbent, and $K_{I,t+1}$ is chosen after the entry decision has been made. On the other hand, the incumbent could try to deter entry by building up excess capacity to the extent that adjustment costs mean that it will not immediately reduce its capacity once entry occurs. On the other hand, there is also an incentive to lower capacity in order to soften competition if entry does occur.[54] Capacity choices may also interact with limit pricing in subtle ways. For example, an incumbent can lower the cost of cutting the local price by increasing capacity, but because capacity is observed, a capacity increase may also require the incumbent to lower local prices even more for its signal to be credible. In this model, the cost of lowering the local price by a given amount is reduced by the fact that the incumbent can simultaneously increase $p_{I,t}^{NL}$, reducing $q_{I,t}^{NL}$, so that its marginal costs do not increase too much. Of course, this feature also implies that greater price reductions are required for the signal to be credible.

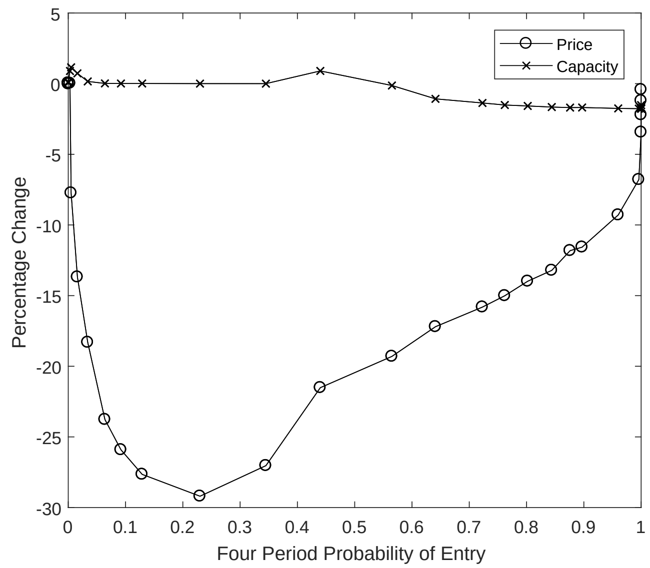
F.1.3 Results

Figure F.1 shows the relationship between the probability that entry occurs within four periods, the expected percentage first period price change and the expected percentage change in capacity over the first four periods (assuming that entry does not occur). The changes are measured relative to the prices and capacities charged in the last period before the entry threat is introduced, based on 1,000 simulations.[55] As we are holding market size fixed, the entry probability is varied by adding a fixed amount, which can vary from −\$12 million to \$5

[54]Adjustment costs also affect incentives to signal, because, if they are low, the potential entrant knows that even if the incumbent has either a high or low pre-entry marginal cost, it would be able to adjust it rapidly once entry occurs.

[55]These statistics are calculated using a two-stage process. In the first stage, we solve for equilibrium strategies in the game presented above and in a variant where entry is assumed to be blockaded. In the second stage, we first use strategies from the blockaded game to simulate 1,000 paths for capacities, prices and $\theta_{I,t}^{NL}$ for 100 periods starting from randomly chosen initial states. The states at the end of these paths are used as starting points for a further set of simulations, for 20 periods, using converged strategies from the early periods of the game where the entry threat is present. We then compare changes in prices and capacities with prices and capacities from the period before the entry threat is introduced.

Figure F.1: Predicted Price and Capacity Changes When Entry is Threatened in a Model with Endogenous Marginal Costs and Endogenous Capacity Investment



million to the entrant's per-period profits.[56] Entry cost draws are assumed to be distributed normally with mean \$20 million and standard deviation \$4 million, and we assume that this distribution does not change over time in order to have a manageable computational burden.

The results are striking. The incumbent responds to the threat of entry by reducing prices significantly, unless entry is almost certain. There is a clear non-monotonic relationship between the probability of entry and the magnitude of the price change. On the other hand, capacity changes are very small, with slight increases at very low entry probabilities and declines for higher entry probabilities. Note that this lack of capacity changes does not reflect the existence of excessively large adjustment costs, because, on average, the incumbent's capacity drops by 0.5% or more in a single period when entry occurs.[57] This basic pattern is consistent with the results of the empirical analysis (Table 3, Table D.2 and Figure D.1) in the sense that there are large price reductions in intermediate probability of

[56]We vary entry probabilities in this way because, if market size is varied, we would also need to vary the grids used for connecting traffic and carrier capacities in an appropriate way.

[57]We have examined what happens when adjustment costs are lowered. Capacity changes are also small in this case. It is not surprising that the incumbent does not try to deter entry by investing in capacity when adjustment costs are low, because there is no reason for the potential entrant to expect the incumbent to keep its capacity high if it enters.

entry markets and no significant changes in capacity in low or intermediate probability of entry markets. In the data, capacity in high probability of entry markets declines slightly. This may reflect the fact that in these markets, which typically involve a Southwest focus airport, the incumbent anticipates a significant loss of both local and connecting (which we did not allow for in the model) passengers when Southwest's entry occurs.

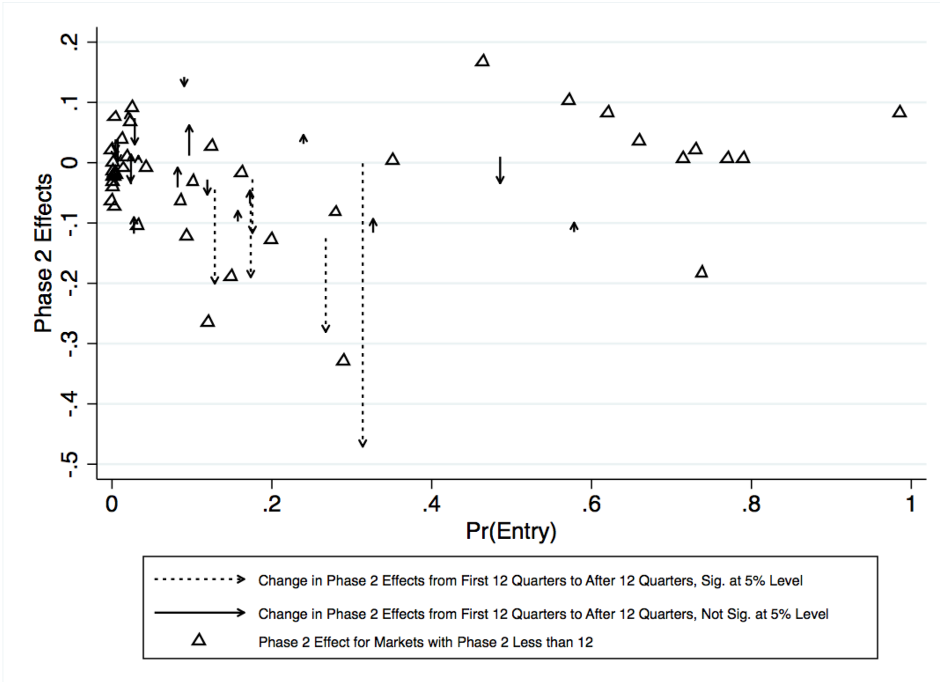
F.2 Limit Pricing and Increasing Price Reductions over Time

The estimates in Tables C.2 and D.2 show that, on average, prices and yields continue to decline the longer markets remain in Phase 2 (i.e., when entry is threatened but does not occur). We now consider this pattern, and potential explanations, in more detail.

A closer analysis reveals that this pattern is driven by some large yield decreases in a small number of intermediate probability of entry markets. This is illustrated in Figure F.2, which is similar to Figure D.2, but which distinguishes between incumbent yield changes within twelve quarters of Southwest becoming a potential entrant and later quarters. Markets that do not have more than twelve Phase 2 quarters (either because Southwest enters, the sample ends or the incumbent ceases to meet the criteria for dominance) are marked by triangles. Yield changes for markets with more than twelve Phase 2 quarters are represented by arrows with the yield change (relative to Phase 1) after more than 12 quarters at the arrow's tip and the initial price decline at the other end.

We observe that there are large, statistically and economically significant price declines *during Phase 2* in five intermediate entry probability markets, and no statistically significant increases. This suggests that we should not look for a mechanism that would cause prices to fall in all markets. Broadly speaking, there are two different kinds of explanations that are worth considering. The first type of explanation is that, once entry is threatened, incumbents make investments that lower their marginal costs. These investments may complement limit pricing as an entry deterrence strategy. One example might be US Airways's 1998 introduction of its MetroJet-branded service on many routes from Baltimore-Washington

Figure F.2: Yield Changes During Phase 2 For Markets in the Dominant Firm Sample



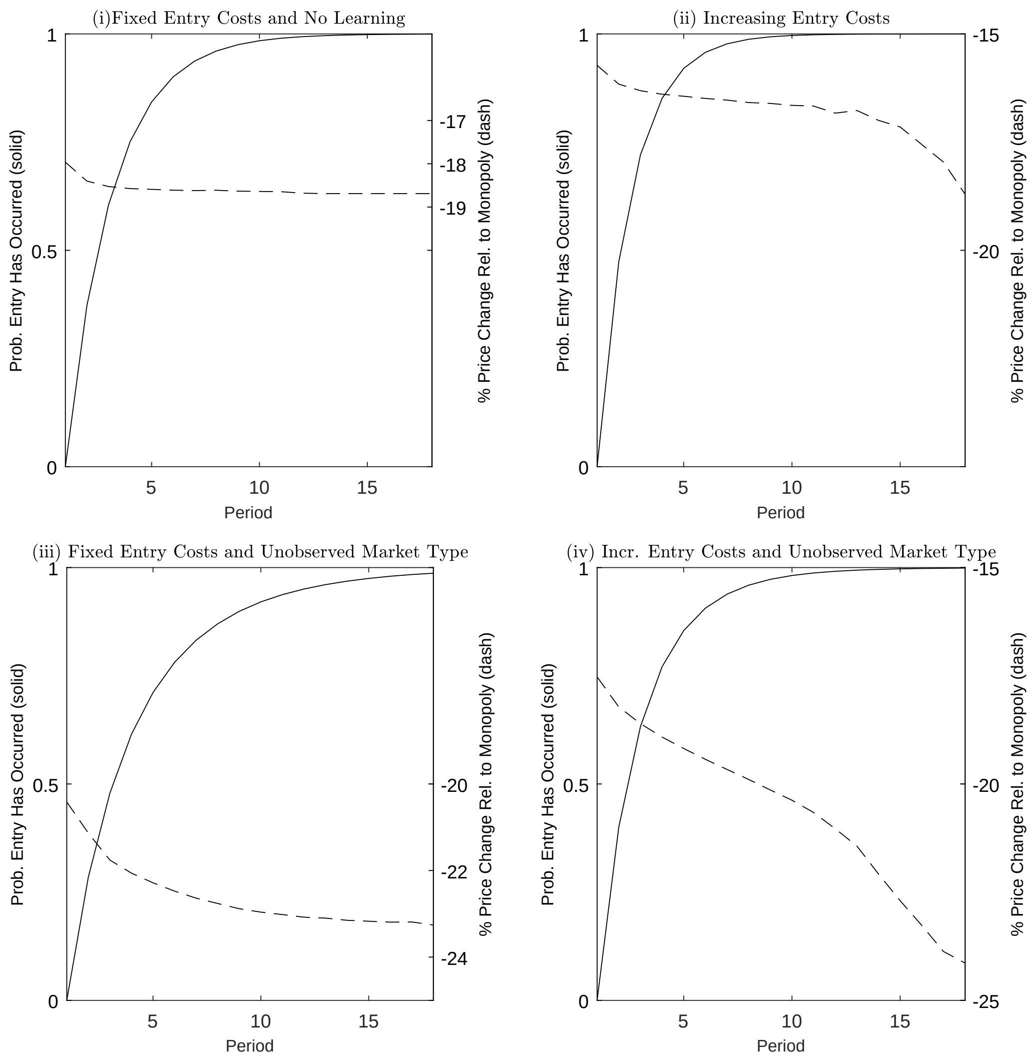
International (BWI) in response to Southwest's growth at the airport.[58] US Airways executives indicated that MetroJet had significantly lower costs than its parent, which had previously flown the same routes, so that its optimal monopoly and limit prices would have fallen.[59] However, we note that this type of investment cannot explain all of the Phase 2 price declines in our data: it took US Airways 5 years to introduce MetroJet after Southwest entered BWI whereas we observe price declines as soon as Southwest threatens entry. It is also worth noting that MetroJet was terminated in late 2001, having never been profitable.

The second type of explanation is that decreasing prices can arise in a limit pricing model without any change in static demand or marginal cost primitives. Recall that in our model price declines tend to be maximized when the per period probability of entry is quite low (see text Figure 1). Therefore, if the probability of entry perceived by the incumbent is

[58]Note that MetroJet cannot explain any of the significant price changes in Figure F.2 because only one BWI route in the dominant firm sample remains in Phase 2 for more than twelve quarters, and that route (to Houston Intercontinental, IAH) was a route where Southwest had a low predicted probability of entry reflecting Southwest's limited presence at IAH.

[59]US Airways CEO David Siegel was quoted in Business Travel News on October 28, 2001 as saying "We tried small fixes [to combat the growth of Southwest], and we know those don't work. MetroJet was about an eight-cent [per seat-mile] carrier and we know what happened to MetroJet."

Figure F.3: Price Changes over Time in A Model With Limit Pricing, Incumbent Learning and Increasing Entry Costs



initially reasonably high but falls over time, then the amount of shading may increase. In our calibrated model this can occur because of the increase in entry costs, as can been seen from considering the Las Vegas-San Jose market in text Table 8. Expected shading more than doubles, from 10.9% to 22.4% of the static monopoly price, from the second to the twentieth period, if entry does not occur.

This type of entry cost increase can be complemented by other features that can be incorporated into the model.[60] One example is learning by the incumbent about how likely

[60]It could also be complemented by investments that reduce the incumbent's marginal cost, as in the

the potential entrant is to enter. To be specific, suppose that a market is either attractive or unattractive for entry (maybe because of how much connecting traffic will be supplied to its network if it enters the route), but that this is not observed by the incumbent, which initially attaches equal probability to each market type. If entry does not initially occur, the incumbent will update its beliefs using Bayes Rule, and will expect a lower probability of entry which could cause it to lower its price. In this model there is two-way learning, which cannot be a feature of a two-period model where there is only one opportunity for the potential entrant to enter the market, but the model remains tractable as long as it is assumed that post-entry competition is not affected by how the potential entrant times its entry decision.

For a given set of parameters, Figure F.3 illustrates the effect of introducing learning into the model.[61] In panel (i), we assume that mean entry costs do not increase over time and that the incumbent knows how attractive the market is for the potential entrant, although the potential entrant does not know the incumbent's marginal cost so that there is still limit pricing. Given the parameters, there is significant limit pricing and a *small* increase in the magnitude of the price decline over time as the entry process tends to lead the incumbent being more likely to have a low marginal cost. In panel (ii) we introduce an increasing mean entry cost (an increase of \$2 million spread uniformly over twenty periods, when the initial mean entry cost is \$48 million). This lowers the initial degree of shading, because it increases the initial probability of entry, but it causes the degree of shading to increase over time.[62] In panel (iii), we introduce our unobserved market type. We lower the potential entrant's per-period profits in an unattractive market by \$200,000, which is 15% of its average profit. This lowers the probability of entry, and it also causes shading to increase over time as the

MetroJet example.

[61]As in our other examples, passenger demand has a nested logit structure, with a price coefficient of $\alpha = 0.4$ (prices are measured in hundreds of dollars) and the nesting parameter is 0.75. The incumbent's marginal cost can range from \$160 to \$280, and the innovation process is the same as the one used in the calibration. The entrant's marginal cost is \$150. Entry costs are normally distributed with an initial mean of \$48 million and a standard deviation of \$1.25 million. Market size is 50,000.

[62]The slight shakiness in the pattern is due to simulation error.

incumbent revises its beliefs. For example, if entry has not occurred after 5 periods, the incumbent's posterior is, on average, that the market is unattractive with probability 0.89. However, most of the increase in shading happens fairly quickly, reflecting the fact that only a small number of periods is required for the incumbent to become pretty confident about how attractive the market is to Southwest.[63] Finally, in panel (iv), we combine incumbent learning and increasing entry costs, and together these factors combine to produce a sustained increase, of over 7 percentage points of the expected static monopoly price, in the degree of shading. Therefore, limit pricing combined with both learning and small increases in entry costs may provide an explanation for the increasing price reductions observed in the data.

[63] Of course we would expect the attractiveness of a real market to potentially evolve over time, so that the incumbent may remain more uncertain than our model allows.