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

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Abstract

Theoretical models of strategic investment often assume that information is asymmetric, creating incentives for incumbent firms to signal information to deter entry or encourage exit. However, the simple one-shot nature of existing models limits our ability to test whether these models quantitatively, or even qualitatively, fit the data. We develop a dynamic model with persistent asymmetric information, where a monopolist incumbent has incentives to repeatedly signal information about its costs to a potential entrant by setting a price below the static profit-maximizing level. The model has a unique Markov Perfect Bayesian Equilibrium under a standard form of refinement, and equilibrium strategies can be computed easily, making it well suited for empirical work. We calibrate our model using parameters estimated from airline data to test whether it can explain the stylized fact that incumbent airlines cut prices substantially when Southwest becomes a potential entrant, but not an actual entrant, on a route. We show that our model can generate price shading that is consistent with the size of the price cuts that are observed when Southwest becomes a potential entrant, as well as providing new reduced-form evidence that incumbents cut prices to try to deter entry.

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1 Introduction

In markets where entry costs are significant, a dominant incumbent firm may have an incentive to take actions that deter entry by rivals. Since at least the work of Bain (1949), many theoretical models have explored possible examples of entry deterring strategies (Tirole (1994), Belleflamme and Peitz (2009)). However, although these models form much of the core of theoretical IO, there is very little evidence that that these models can explain real world data, either qualitatively or quantitatively. This is both intellectually unsatisfying and an impediment to any antitrust authority that wanted to build a case against a practice that they suspect may be aimed at deterring entry. One reason for the lack of evidence is that it is unclear what very stylized two-period theoretical models predict should be observed in real-world settings where incumbents and potential entrants interact repeatedly. The lack of both evidence and any understanding of what would happen with repeated interaction are particularly striking for models where strategic behavior is driven by an asymmetry of information between incumbents and entrants, as in the case of the limit pricing model of Milgrom and Roberts (1982) (MR hereafter).

In this paper we develop a dynamic version of the MR model. In our model an incumbent monopolist's costs, which are private information, are correlated over time, but are not perfectly persistent. A long-lived potential entrant observes the price set by the incumbent and its quantity, and, as in the MR model, the incumbent can try to signal that it has a low cost by setting a low price. The imperfect persistence of the incumbent's costs create an incentive for limit pricing in every period until entry occurs, at which point we assume (like MR) that the game becomes one of complete information, where the duopolists observe each other's costs.

Although the model is a dynamic game with persistent asymmetric information, it is actually very tractable. In particular, we show, using results from the theoretical literature on signaling models, that under some simple and plausible conditions on the primitives of the model, that Markov Perfect Bayesian Equilibrium strategies and beliefs on the equilibrium path are unique under refinement. The incumbent's pricing strategy perfectly reveals its costs in every period. Equilibrium pricing and entry strategies, described by a differential equation and threshold rule respectively, can be easily computed.

Having developed the model, we explore whether it can can explain the phenomenon that incumbent airlines' prices decline significantly when Southwest, the most well-known U.S. low-cost carrier, becomes a potential entrant on an airport-pair route (meaning that it serves both endpoint airports) but is not yet active on the route. As documented by Morrison (2001) and Goolsbee and Syverson (2008) (GS) these price declines can be very large: up to 20% of previous prices, and of roughly the same size as the additional declines that take place if and when Southwest actually enters. The questions of interest are whether these declines are caused by incumbents trying to deter entry (rather than, for example, trying to accommodate entry by taking actions that soften post-entry competition) and, more specifically, whether our dynamic limit pricing model provides a potential explanation.

We provide two types of empirical evidence. First, we provide new evidence that the declines are being caused by incumbents' trying to deter entry. To do so we follow Ellison and Ellison (2011) (EE) who show that entry deterrence incentives may lead to a non-monotonic relationship between the level of investment and factors that determine the attractiveness of entry. Intuitively, incumbents will be more willing to sacrifice short-term profit to try to deter entry in markets of intermediate attractiveness to entrants, rather than in markets where entry is very unlikely or almost certain. In our data, we are able to estimate how exogenous market characteristics affect the probability of entry by Southwest, and, when we focus on those markets with a dominant incumbent prior to Southwest becoming the potential entrant, which provide the best match to the assumptions of our model, we find that the price declines are only statistically significant and are largest in magnitude in those markets where these characteristics predict an intermediate probability of Southwest entering. In contrast, if incumbents cut prices in markets of intermediate attractiveness to entrants, where entry decisions are potentially sensitive to small changes in beliefs about the incumbent's costs, then we would expect to see the largest declines in those markets where entry is most likely. This logic is also strengthened by the fact that we observe declines throughout the price distribution, which intuitively is more consistent with signaling costs rather than trying to affect the loyalty of a specific group of consumers. We also provide evidence against alternative explanations of price declines on these routes, involving reductions in marginal costs due to either Southwest's activity at the endpoint airports or additional incumbent investments in capacity when faced by the threat of entry.

Second, exploiting the tractability of our model, we perform a calibration exercise to see whether it can predict that incumbents should lower prices below the monopoly level by as much as we see incumbents cutting prices when Southwest becomes a potential entrant. To do so we estimate demand and marginal cost parameters using observations where we would not expect limit pricing to be important. Our results indicate that, for a average market in our data, our model can predict price decreases of the observed magnitude (e.g., 10-20%), and, consistent with the EE logic, it would predict smaller effects in markets where entry was either very likely or very unlikely to occur.

Our paper is related, and makes contributions to, at least five distinct literatures. The first is the theoretical literature on models of limit pricing and, more generally, strategic investment under asymmetric information. The idea that firms might set low prices to deter rivals from entering a market has its origins in the work of Kaldor (1935), Clark (1940) and Bain (1949). The obvious question is why a pre-entry price could affect a potential entrant's expectations of its post-entry profits. One approach was that potential entrants might view the incumbent as committed to the pre-entry price even if entry occurs (e.g., Gaskins (1971), Kamien and Schwartz (1971), Baron (1973), De Bondt (1976) and Lippman (1980)), although the reason why the potential entrant would regard the incumbent as committed was left unclear. (Friedman (1979)). This criticism was addressed by the MR model which explained why limit pricing could be an equilibrium in a fully rational model with flexible prices by allowing for asymmetric information about the profitability of entry, creating the possibility that pre-entry prices could be used to signal information about demand or costs which would affect the profitability of entry. In this setting, limit pricing may enhance efficiency by reducing prices while moving entry decisions closer to what they would be under full information.

Our theoretical resullts build on the second related literature, the more general theoretical literature on signaling models. Specifically we use results from Mailath (1987), Mailath and von Thadden (forthcoming) and Ramey (1996) which characterize equilibria and refinements in the context of two-period models, where there is only one opportunity to signal. We use these results recursively in the context of a finite period dynamic game, showing that doing so only requires simple and weak conditions on static payoffs and quantity choices. Some recent work on signaling models has also investigated what happens in multiple periods. Kaya (2009) and Toxvaerd (2010) consider models where the sender's type is fixed over time, and they show that, at least in the equilibria that they focus on, signaling happens only for a limited number of periods at the start of the game after which the type of the sender is credibly established. In contrast, we allow the sender's type to evolve over time, according to a Markov process, which generates an incentive for repeated signaling. This is also true in Roddie (2012a) and Roddie (2012b) who considers a quantity-setting game between duopolists one of whom has a marginal cost that is private information. Roddie specifies high-level conditions on payoff functions that imply that there is a unique fully separating Markov Perfect Bayesian equilibrium under a recursive application of the D1 refinement, and he shows how the privately informed firm ends up looking like a Stackelberg leader. Our theoretical work differs from Roddie in that we use a slightly different set of high-level conditions, partly reflecting the different structure of our game, and, more importantly, that we show that these high-level conditions are satisfied throughout our game under a set of relatively weak restrictions on the static monopoly and duopoly payoffs and quantity outcomes in the stage game of our model.

The third related literature is the limited empirical work that has looked for evidence of strategic entry deterrence. A number of papers have provided evidence by showing differences in the investment decisions of different types of firm (e.g., Lieberman (1987)) or correlations between incumbent investments and subsequent entry decisions (e.g., Chevalier (1995)) without identifying the precise mechanism involved or showing that investment is motivated by deterrence.[1] Smiley (1988) takes a different approach by conducting a survey of managers in order to identify which strategies they believe are used to deter entry. In this survey some managers do report using (limit) pricing to either prevent entry or limit the growth of rivals. EE develop and apply a different, but still qualitative, approach to testing for strategic behavior which will be used below, which has been applied by both EE and Dafny (2005).

However, we go beyond this qualitative test to consider whether our specific model can generate the size of the price changes observed in the airline data. In this regard we are closer to three recent structural empirical papers, Snider (2009), Williams (2012) and Chicu (2012), that estimate dynamic oligopoly models with complete information (at least up to iid payoff shocks), in the spirit of Ericson and Pakes (1995), to try to quantify the effectiveness of capacity investment to deter entry. We differ from these papers in considering a dynamic model with asymmetric information and deriving conditions under which the equilibrium that we look at is unique. We also approach our empirical exercise by calibrating our model rather than imposing our model, which is certainly a simplification of reality, on the data. We regard this as a sensible approach given our primary interest is in testing whether a dynamic limit pricing model can explain the main patterns in the data rather than performing counterfactuals.

The fourth related literature has looked at the response of incumbents to potential entry in the airline industry. As mentioned above, Morrison (2001) and GS document what has sometimes been called the "Southwest effect," where the emergence of Southwest as a potential, but not yet an actual, entrant on the route leads to a substantial decline in prices. Entry leads to further price declines. In their analyses, however, the exact mechanism which leads prices to fall is not identified. We provide new evidence in favor of a deterrence explanation, at least in the subset of markets which, prior to Southwest entry, are dominated by single incumbent.[2] While we focus on explaining price

[1] Salvo (2010) argues that Brazilian cement producers set prices at a level that prevents imports from being profitable. However, this setting differs from standard models of strategic investment where a potential entrant has to pay a sunk cost to enter the market.

[2] GS examine a much broader range of markets, including those with several incumbent firms. In the theoretical literature, some models (e.g., Waldman (1983), McLean and Riordan (1989)) show that when there are several incumbents, the incentive of any one incumbent to engage in strategic investment to deter entry is severely limited due the free-rider problem (deterrence is a public good for the incumbents). While this argument seems intuitive, several alternative

declines, Goetz and Shapiro (2012) argue that incumbent airlines also respond to the threat of entry by Southwest by agreeing codesharing arrangement with other carriers. In our set of markets, we also find this response but it occurs primarily in markets where entry is most likely indicating that it may primarily be a tactic used by incumbents to try to accommodate entry.

The final related literature is the general literature on the modeling of dynamic games. Almost all of the existing literature follows the seminal paper of Ericson and Pakes (1995) in assuming that firms either observe all payoff-relevant variables or observe them up to some payoff shocks that are iid over time. Given these assumptions, there is no scope for firms to signal information about the future profitability of entry or any need for potential entrants to form beliefs about their opponents' types. This obviously rules out important types of strategic investment behavior proposed in the two-period theoretical literature. In a recent paper, Fershtman and Pakes (2012) (FP) provide a general framework for modeling a dynamic game with persistent incomplete information. As they argue, it can be very difficult to solve these models keeping track of players' beliefs over the whole state-space given all possible histories. They suggest circumventing this computational problem using an alternative solution concept, Experience Based Equilibrium (EBE). This concept does not involve the specification of players' beliefs about their opponents' types, but only their expectations about payoffs from how their own actions depend on some limited observed history of the game. They also only require optimality on an endogenously determined recurrent class of states. In this paper we consider a very specific model of a dynamic game with asymmetric information where we are able to characterize a PBE that has a very simple, tractable and computationally-convenient form which allows us to avoid the computational problems that they identify. While our approach lacks the generality of the FP approach, for our goal of studying dynamic limit pricing in an empirical setting, the fact we are able to retain the PBE concept has two important advantages. First, because beliefs are explicitly modeled, it is natural to speak of signaling which presumably operates through beliefs about how effective the incumbent will be as a competitor. Second, we can apply standard techniques to prove uniqueness of equilibrium which makes empirical work much more straightforward. In contrast, there will typically be multiple EBEs and, to date, there is currently no approach to choosing between them.[3]

The rest of the paper is organized as follows. Section 2 lays out our model of dynamic limit pricing

models show that there are circumstances in which oligopolists can still engage in substantially entry deterring behavior (e.g., Gilbert and Vives (1986), Waldman (1987), Kirman and Masson (1986)). Extending our model to the case with several incumbents is an interesting direction for future work.

[3]FP consider a model with finite state and action spaces. This may also limit a player's ability to signal its type, by requiring at least some pooling when there are more types than possible actions. In contrast, we consider a game where the signaling firm chooses a continuous action (price).

and characterizes the equilibrium. Section 3 describes the airline data. Section 4 provides the reduced-form (GS and EE-style) evidence in favor of deterrence, and Section 5 describes the calibration exercise. Section 6 concludes. Appendix A contains all proofs and Appendix B presents tables of additional reduced form results referred to throughout the paper.

2 Model

In this section we develop our theoretical model of a dynamic entry deterrence game with serially correlated asymmetric information. We describe the Markov Perfect Bayesian Equilibrium (MPBE) of the model where incumbents perfectly reveal their type each period and explain the conditions under which this equilibrium both exists and is unique under a dynamic version of the D1 refinement (proofs are in Appendix A). Finally we explain how equilibrium strategies are computed using a recursive algorithm.

We present the model in an abstract way, so that we can be clear about what features of our results are general, rather than dependent on specific parametric choices that we make to calibrate our model using airline data. In the next section we explain why we believe it is reasonable to apply the model to study the "Southwest effect".

2.1 Model Specification

There is an finite sequence of discrete time periods, $t = 1, ..., T$, two long-lived firms and a common discount factor of β. We assume finite T so that we can apply backwards induction to prove certain properties of the model, but, when illustrating strategies in our calibration exercise below, we will assume that T is fairly large and focus on the strategies that will be almost stationary in the early part of the game.[4]

At the start of the game, firm I is an incumbent, who is assumed to remain in the market forever, and firm E is a long-lived potential entrant. It is assumed that E will remain as a potential entrant until it enters, and that, once it enters, it will also remain in the market forever. The marginal costs of the firms, c_{Et} and c_{It} lie on compact intervals $C_E := [\underline{c_E}, \overline{c_E}]$ and $C_I := [\underline{c_I}, \overline{c_I}]$ and evolve, independently, according to Markov processes $\psi_I : c_{It-1} \to c_{It}$ and $\psi_E : c_{Et-1} \to c_{Et}$, with full support (i.e., costs can evolve to any point on the support in the next period), and we will denote the conditional probability density functions (pdfs) $\psi_I(c_{It}|c_{It-1})$ and $\psi_E(c_{Et}|c_{Et-1})$. We will assume the following:

[4] We could follow Toxvaerd (2008) who argues for the properties for an infinite horizon game by taking the $T \to \infty$ limit of finite horizon games for which properties can be shown using backwards induction.

1. $\psi_I(c_{It}|c_{It-1})$ and $\psi_E(c_{Et}|c_{Et-1})$ are continuous and differentiable (with appropriate sided derivatives at the boundaries).

2. $\psi_I(c_{It}|c_{It-1})$ and $\psi_E(c_{Et}|c_{Et-1})$ are strictly increasing i.e., a higher cost in one period implies that higher costs in the following period are more likely. Specifically, we will require that for all c_{jt-1} there is some x' such that $\frac{\partial\psi_j(c_{jt}|c_{jt-1})}{\partial c_{jt-1}}|_{c_{jt}=x'} = 0$ and $\frac{\partial\psi_j(c_{jt}|c_{jt-1})}{\partial c_{jt-1}} < 0$ for all $c_{jt} < x'$ and $\frac{\partial\psi_j(c_{jt}|c_{jt-1})}{\partial c_{jt-1}} > 0$ for all $c_{jt} > x'$. Obviously it will also be the case that $\int_{\underline{c_j}}^{\overline{c_j}} \frac{\partial\psi_j(c_{jt}|c_{jt-1})}{\partial c_{jt-1}} dc_{jt} = 0$.

To enter in period t, E has to pay a private-information sunk entry cost κ_t, which is an iid draw from a time-invariant distribution $G(\cdot)$ (density $g(\cdot)$) defined over $\underline{\kappa} = [0, \overline{\kappa}]$. We will assume that $\overline{\kappa}$ 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. Demand is assumed to be common knowledge and fixed, although it would be straightforward to extend the model to allow for time-varying demand as long as it is observed by both firms. Similarly one can allow for an observed common-element of costs (e.g., fuel prices) that changes over time, with the Markov processes described above only affecting the idiosyncratic component of costs.

2.1.1 Pre-Entry Game

Before E has entered, so that I is a monopolist, E does not observe c_{It}. E does observe the whole history of the game to that point. The timing of the game in each of these periods is as follows:

1. I and E observe c_{Et} (the entrant's marginal cost).

2. E observes κ_t (I does not).

3. I sets a price p_{It}, and receives profit

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

where $q^M(p_{It})$ is the downward-sloping demand function of a monopolist. Define $p_I^{\text{static monopoly}}(c) = \text{argmax}_{p_I} q^M(p_I)(p_I - c)$. The incumbent can choose a price from the compact interval $[\underline{p}, \overline{p}]$ where $\overline{p}$ is above $p_I^{\text{static monopoly}}(\overline{c_I})$, the static monopoly price that an incumbent with cost $\overline{c_I}$ would choose. $\underline{p}$ is low enough such that in equilibrium no incumbent would want to choose it, whatever effects this had on the beliefs of the potential entrant.[5] We will assume that $\pi_I^M(p_{It}, c_{It})$ always has a unique maximum in price, is concave in price at this maximum and is strictly quasi-concave for all prices $[\underline{p}, \overline{p}]$. This will be true for standard demand functions such as linear demand and the multinomial choice logit and nested logit discrete-choice models.

4. E observes p_{It}.

5. E decides whether to enter (paying κ_t if it does so). If it enters, it is active at the start of the following period.

6. Marginal costs of both firms evolve independently according to ψ_I and ψ_E.

2.1.2 Post-Entry Game

We assume that once E enters both firms observe both marginal costs, so there is no scope for further signaling, and that they receive static equilibrium flow profits $\pi_I^D(c_{It}, c_{Et})$ and $\pi_E^D(c_{Et}, c_{It})$, where the different functions allow for fixed quality differences between the firms. The firms' equilibrium outputs are $q_I^D(c_{It}, c_{Et})$ and $q_E^D(c_{Et}, c_{It})$. The choice variables of the firms in the static duopoly game are a_{It} and a_{Et} (which could be prices or quantities). We make a number of assumptions on the duopoly game:

1. $\pi_I^D(c_{It}, c_{Et}), \pi_E^D(c_{Et}, c_{It}) \geq 0$ for all c_{It}, c_{Et}. This assumption also rationalizes why neither firms exits.

2. $\pi_I^D(c_{It}, c_{Et})$ and $\pi_E^D(c_{Et}, c_{It})$ are continuous and differentiable in both arguments.

3. $q_I^D(c_{It}, c_{Et}) - q^M(p_I^{\text{static monopoly}}(c_{It})) - \frac{\partial \pi_I^D(c_{It}, c_{Et})}{\partial a_{Et}} \frac{\partial a_{Et}}{\partial c_{It}} < 0$ for all (c_{It}, c_{Et}). This is the key condition that we use to show that a single crossing property will hold in our model in every period. The sign of the last term will depend on whether the duopolists compete in strategic complements (prices) or substitutes (quantities), with the condition being easier to satisfy when they compete in prices as an increase in the incumbent's marginal cost will lead to the entrant setting a higher price, which is good for the incumbent.[6]

[5] Note that this could require $\underline{p} < 0$. The purpose of this restriction is that we have to allow a large enough range of prices that all types are able to separate. We could also describe our model as one where the incumbent chooses a quantity q on $[0, \overline{q}]$ where $\overline{q}$ is sufficiently high. All of our theoretical results would hold when the monopolist sets a quantity, but we choose not to present our model in this way because it is more natural to assume price-setting when talking about limit pricing.

[6] In his presentation of the two-period MR model, Tirole (1994) 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 homogenous products and Bertrand competition when the entrant has the higher marginal cost but it is below the incumbent's monopoly price.

2.1.3 Comparison with Milgrom and Roberts (1982, MR)

MR provide the classic two-period model of limit pricing in which one firm (our I) is a monopolist in the first period, and a second firm (E) can observe its price or output before deciding whether to enter in the second period. In the model on which they focus, the marginal costs of both firms are private information in the first period while E's entry cost is commonly known. The marginal costs of both firms, which in their case do not vary over time, are publicly revealed if E enters, so that, with entry, second period competition is static Cournot or Bertrand. I can attempt to deter entry by using its first-period quantity/price choice to signal its marginal cost to E.

Our cost assumptions differ in two respects. First, in our model the incumbent's marginal costs can evolve over time, specifically in a positively serially correlated way. We need correlation (which takes an extreme form in the MR model) in order for the monopolist to have something that will affect an entrant's profit from entering to signal. On the other hand, we need the incumbent's marginal costs to be able to change from period-to-period in order to generate an incentive for the incumbent to engage in limit pricing in every period before entry occurs. As a comparison, Kaya (2009) and Toxvaerd (2010) consider dynamic models in which the incumbent's type is fixed over time, where the natural equilibrium to consider involves the incumbent signaling only in initial periods after which point the receiver is convinced of the sender's type.

Second, we assume that the entrant's marginal costs, which we allow to be serially correlated, are observed, but that its entry costs, which are iid draws, are not. The key features of our model are that only one player (E) is learning and entry is probabilistic from the perspective of the incumbent. In these respects we are just like MR. In contrast, if we assumed that E had a serially correlated unobserved state variable (either marginal costs or entry costs) then the incumbent would be able to draw inferences about that variable from E's entry decisions, leading to a two-way model of learning. This would significantly complicate the model, and, because of the discrete nature of the action space, the equilibrium could not be fully revealing as a failure to enter could only imperfectly reveal E's costs. We could, however, assume that either entry costs are observed with c_{Et} unobserved and iid over time, or that entry costs are unobserved and iid while marginal costs are observed and possibly serially correlated. We chose the second option for two reasons: first, in the entry games literature it is quite standard to treat entry cost draws as being private information and independent; and, second, it seems natural to allow for serial correlation in the entrant's marginal costs given our assumptions on I's marginal costs and our estimation results. We will also argue below that Southwest's business model, which involves a simpler network structure than legacy carriers, adds some plausibility to the idea that Southwest's operating costs might be more transparent than those of other carriers.

2.2 Equilibrium

Unique Nash equilibrium behavior post entry, where two firms play a complete information duopoly game, is assumed.[7] We are therefore interested in characterizing play before E enters. Our basic equilibrium concept is MPBE (Roddie (2012a), Toxvaerd (2008)). The definition of a MPBE requires, for each period:

- a time-specific pricing strategy for I, as a function of both firms' marginal costs $\varsigma_{It} : (c_{It}, c_{Et}) \rightarrow p_{It}$;
- a time-specific entry rule for E, as a function of its beliefs about I's marginal cost, denoted with a $\widehat{c}_{It}$, its own marginal costs and its own entry cost draw, $\sigma_{Et} : (\widehat{c}_{It}, c_{Et}, \kappa_t) \rightarrow$ {Enter, Stay Out}; and
- a specification of E's beliefs about I's marginal costs given all possible histories of the game.

In an equilibrium, for all possible c_{Et} and c_{It}, E's entry rule should be optimal given its beliefs, its beliefs should be consistent with I's strategy on the equilibrium path, and the evolution of marginal costs, and I's pricing rule must be be optimal given what E will infer from I's price and how E will react based on these inferences.

Fully Separating Riley Equilibrium (FSRE). We will consider an equilibrium where I's price perfectly reveals its current marginal cost, i.e., there is full separation, and where signaling is achieved at minimum cost to I subject to the incentive compatibility constraints being satisfied (i.e. the 'Riley equilibrium' (Riley (1979)).

The following proposition contains our main theoretical results

Proposition 1 *Consider the following strategies and beliefs:*

(i) E's entry strategy will be to enter if and only if entry costs κ_t *are lower than a threshold* $\kappa_t^*(\widehat{c}_{It}, c_{Et})$*, where* $\widehat{c_{It}}$ *is E's (point) belief about I's marginal cost and*

$$\kappa_t^*(\widehat{c}_{It}, c_{Et}) = \beta[\mathbb{E}_t(\phi_{t+1}^E | \widehat{c}_{It}, c_{Et}) - \mathbb{E}_t(V_{t+1}^E | \widehat{c}_{It}, c_{Et})] \quad (2)$$

[7] Existence and uniqueness will depend on the particular form of demand assumed, and will hold for the common demand specifications (e.g., linear, logit, nested logit) with single product firms and linear marginal cost.

where $\mathbb{E}_t(V^E_{t+1}|\widehat{c}_{It}, c_{Et})$ *is* E*'s expectation, at time* t *to being a potential entrant in period* $t+1$ *(i.e., if it does not enter now) given equilibrium behavior at* $t+1$ *and* $\mathbb{E}_t(\phi^E_{t+1}|\widehat{c}_{It}, c_{Et})$ *is its expected value to being a duopolist in period* $t+1$ *(which assumes it has entered prior to* $t+1$*).*[8] *The threshold* $\kappa^*_t(\widehat{c}_{It}, c_{Et})$ *is strictly decreasing in* c_{Et} *and strictly increasing in* $\widehat{c}_{It}$*;*

(ii) I*'s pricing strategy* $\varsigma_{It} : (c_{It}, c_{Et}) \to p^*_{It}$ *will be the solution to a differential equation*

$$\frac{\partial p^*_{It}}{\partial c_{It}} = \frac{\beta g(\cdot)\frac{\partial \kappa^*_t(c_{It},c_{Et})}{\partial c_{It}}\{\mathbb{E}_t[V^I_{t+1}|c_{It}, c_{Et}] - \mathbb{E}_t[\phi^I_{t+1}|c_{It}, c_{Et}]\}}{q^M(p_{It}) + \frac{\partial q^M(p_{It})}{\partial p_{It}}(p_{It} - c_{It})} \tag{3}$$

and an upper boundary condition $p^*_{It}(\overline{c_I}) = p^{static\ monopoly}(\overline{c_I})$*.* $\mathbb{E}_t[V^I_{t+1}|c_{It}, c_{Et}]$ *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* $t+1$*.* $\mathbb{E}_t[\phi^I_{t+1}|c_{It}, c_{Et}]$ *is its expected value of being a duopolist in period* $t+1$*;*

(iii) E*'s on-the-equilibrium path beliefs: observing an output* q_{It}*,* E *believes that* I*'s marginal cost is* $\varsigma^{-1}_{It}(p_{It}, c_{Et})$*.*

This equilibrium exists and the above form the unique MPBE strategies and equilibrium-path beliefs consistent with a recursive application of the D1 refinement. For completeness we assume that if E *observes a price which is not in the range of* $\varsigma_{It}(c_{It}, c_{Et})$ *it believes that the incumbent has marginal cost* $\overline{c_I}$*.*

Proof. See Appendix A. ■

Our proofs use results from the theoretical literature on signaling models. The first result that we use is from Mailath and von Thadden (forthcoming). They provide conditions on signaling payoffs[9] that lead to a unique separating equilibrium, where the signaler's strategy is determined by a differential equation and a boundary condition.[10] The key conditions are type monotonicity (a given price reduction always implies a greater loss in current payoffs for an incumbent with higher marginal costs), belief monotonicity (the incumbent always benefits when the entrant believes that he has lower c_{It}, which reflects the monotonicity of the entrant's entry rule) and a single crossing condition (implies

[8] When we define values we have to do so at specific points in the stage game. Both firms values as duopolists are defined once they know the current period values of both firms' marginal costs. For the pre-entry game, E's value is defined at point 2 in the stage game defined above where E knows its own marginal cost and its entry cost for the period. The value for the incumbent is defined after point 1, when it knows its own marginal cost and the marginal cost of the entrant.

[9] The signaling payoff function can be written as $\Pi_{It}(c_{It}, \widehat{c}_{It}, p_{It}, c_{Et})$ where $\widehat{c}_{It}$ is E's point belief about the incumbent's marginal cost when taking its period t entry decision. An alternative way of writing the payoff function that is used when ruling out pooling equilibria is $\Pi_{It}(c_{It}, \kappa_{Et}, p_{It}, c_{Et})$ where κ_{Et} is the threshold used by the potential entrant.

[10] We use Theorem 1 of Mailath and von Thadden (forthcoming), which is effectively a re-statement of a result from Mailath (1987).

that a lower cost incumbent is always willing to cut price slightly more in order to differentiate itself from higher cost incumbents). Our contribution is to show that our assumptions on the primitives of the model (or more precisely, static monopoly and duopoly quantities and payoffs) are *sufficient* for I's signaling payoff function to satisfy these conditions in every period by applying backwards induction. Our conditions are not necessary so that our equilibrium may exist more generally.

Mailath and von Thadden's results do not rule out the possible existence of pooling equilibria. To do so we recursively apply the D1 refinement (Cho and Sobel (1990), Ramey (1996)), which is a restriction on the possible inferences that E could make when observing off-the-equilibrium-path actions. Specifically, in a one-shot signaling game, D1 restricts how off-the-equilibrium-path signals are interpreted by requiring 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. Theorem 3 of Ramey (1996) shows that as long as a pool does not involve signalers choosing (in our setting) the lowest possible price, pooling equilibria can be eliminated when the signaling payoff function satisfies a single crossing condition.

Applying D1 in a setting with repeated signaling is potentially complicated by the possibility that an off-the-equilibrium path signal in one period could change how the receiver interprets signals in future periods. Here we follow Roddie (2012a) in applying a recursive version of D1, where we work backwards through the game, applying the refinement in each period, assuming refined equilibrium behavior and inferences in future periods.

2.3 Solving the Model

Given values of the parameters, the supports and the form of the differential equation describing the incumbent's pricing strategy it is straightforward to compute pricing strategies and entry probabilities. The solution algorithm is as follows.

Step 1. Specify a grid for c_{It} and c_{Et}.

Step 2. For each of these points calculate each firm's single-period profits in the specified full information duopoly game that follows entry.

Step 3. Consider period T. Calculate the incumbent's static monopoly profits for each discretized value of c_{It} (in this period it does not face the threat of entry and so prices as a static monopolist). The incumbent's static monopoly and duopoly profits define V_T^I and ϕ_T^I for each value on the grid. For the potential entrant $V_T^E = 0$ and ϕ_T^E is the static duopoly profit.

Step 4. Consider period $T-1$.

For a given value of c_{ET-1} we use the known transition matrix of costs to calculate the value of $\mathbb{E}_{T-1}[\phi_T^E | c_{IT-1}, c_{ET-1}]$ for each value of c_{IT-1}. As $\mathbb{E}_{T-1}[V_T^E | c_{IT-1}, c_{ET-1}] = 0$, $\kappa_{T-1}^*(c_{IT-1}, c_{ET-1}) = \beta \mathbb{E}_{T-1}[\phi_T^E | c_{IT-1}, c_{ET-1}]$, and we can compute $g(\cdot)$ and $\frac{\partial \kappa_{T-1}^*(c_{IT-1}, c_{ET-1})}{\partial c_{IT-1}}$ for each of these values. Next we solve for the pricing strategy of the incumbent as a function of its marginal cost, by solving the differential equation starting from the boundary solution that the firm with the highest marginal cost sets the static monopoly price

$$\frac{\partial p_{IT-1}^*}{\partial c_{IT-1}} = \frac{\beta g(\kappa_{T-1}^*) \frac{\partial \kappa_{T-1}^*(c_{IT-1}, c_{ET-1})}{\partial c_{It}} \{\mathbb{E}_{T-1}[V_T^I | c_{IT-1}, c_{ET-1}] - \mathbb{E}_{T-1}[\phi_T^I | c_{IT-1}, c_{ET-1}]\}}{q^M(p_{IT-1}) + \frac{\partial q^M(p_{IT-1})}{\partial p_{IT-1}}(p_{IT-1} - c_{IT-1})} \tag{4}$$

This is done using `ode113` in MATLAB. Given known demand, the denominator can be computed exactly for any value of c_{IT-1} considered by the differential equation solver. We store this result, and then repeat for all other values of c_{ET-1}.

Given the entry and pricing strategies we can calculate $V_{T-1}^i(c_{IT-1}, c_{ET-1})$ and $\phi_{T-1}^i(c_{IT-1}, c_{ET-1})$ for both firms (i.e., the values of each firm as a monopolist/potential entrant/duopolist) as appropriate given the cost state.

Step 5. Consider period $T-2$. Here we proceed using the same steps as in Step 4, except that $\kappa_{T-2}^*(c_{IT-2}, c_{ET-2}) = \beta\{\mathbb{E}_{T-2}[\phi_{T-1}^E | c_{IT-2}, c_{ET-2}] - \mathbb{E}_{T-2}[V_{T-1}^E | c_{IT-2}, c_{ET-2}]\}$.

Step 6. Repeat for all previous periods.

3 Can Our Limit Pricing Model Explain the "Southwest Effect"?

We now turn to the question of whether our dynamic limit pricing model can explain why incumbent carriers cut prices substantially when Southwest becomes a potential entrant on an airline route. We present two types of evidence. First, in Section 4, we show reduced form evidence that indicates, for the routes that match the assumptions of our model, that incumbents cut prices because they want to try to deter entry, and that it is price, rather than route capacity, that is their strategic variable of choice. Second, in Section 5, we perform a calibration exercise that shows that our model can generate price cuts consistent with the price changes observed in the data, where we use demand and cost parameters estimated using airline data. In this section we introduce our data and explain why we believe that it is plausible that our model may capture important features of at least a subset of airline markets.

3.1 Relevance of Our Model to the Southwest Effect

Competition in airline markets, which we define as routes between airport-pairs[11], is heterogenous with routes between small cities often having no non-stop service, while large markets may have several carriers competing non-stop. While previous analysis of the Southwest effect (e.g., in GS) has drawn on this wide range of markets, we will test our model, which assumes an incumbent monopolist, by focusing on a subset of markets with one dominant incumbent when Southwest is a potential entrant (defined as Southwest serving both of the endpoint airports but not the route itself) and we will focus on this carrier's pricing and how Southwest responds to it. In our markets there are usually several potential entrants in addition to Southwest but we believe that it is plausible to focus on Southwest because its rapid growth during our data (1993-2010) and the large effect that it has on prices when it actually enters make it plausible that incumbents would be particularly concerned to try to prevent Southwest's entry.[12]

The most obvious reason to believe that our model cannot describe what happens in the airline industry is that we are making very strong assumptions about the observability of costs. Specifically, we have assumed that, prior to entry, the incumbent's marginal cost is private information, while the potential entrant's marginal costs are public information but its entry costs are unobserved. We note that, while it would complicate solving our model by adding additional state variables, we could allow for additional factors, such as fuel costs or changes in the economy, that affect marginal costs or demand and are observed by both firms, so what is really critical is that there is an idiosyncratic portion of the incumbent's costs that are private information and serially correlated.

Why is it reasonable to believe that some part of the incumbent's marginal cost is not publicly observed? The dominant incumbents in our sample are almost all legacy carriers operating hub-and-spoke networks where one of the endpoint airports is a hub. As has been well-documented in cases of alleged predation (Edlin and Farrell (2004), Elzinga and Mills (2005)), the effective marginal opportunity cost of a seat on a particular segment on this type of route depends on how people who might travel on the segment as part of a longer route fly over the rest of the carrier's network and the profitability of these onward journeys. These opportunity cost can be difficult to determine unambiguously even ex-post and with access to the carrier's internal cost data. Therefore, the

[11] We follow GS in defining markets as airport-pairs. An alternative approach is to use city-pairs.

[12] Wu (2012) compares the effects that potential entry by Southwest and JetBlue have on incumbent prices. He finds that JetBlue has a substantially smaller effect.

incumbent's current marginal cost should be somewhat opaque to other firms making contemporaneous decisions about entry, and that the unobserved component is likely to be time-varying (as travelers options to use other routes for connections change) but serially correlated.[13] In contrast, Southwest's marginal costs, which we assume are observed, are likely to be relatively transparent because it operates a simpler point-to-point network using a fleet composed entirely of Boeing 737s. In our view, the two informational assumptions that are actually harder to justify are that Southwest's current entry costs are unobserved to the incumbent and that the incumbent's marginal costs are observed once the potential entrant enters. The first assumption is designed to capture the idea that, even if an incumbent knows factors that might affect entry, such as the availability of gates, it is likely difficult for it to determine exactly when Southwest will enter routes that appear likely to be marginal in terms of Southwest's profitability. In the context of our model one could interpret this type of uncertainty as uncertainty about Southwest's entry cost. The second assumption is primarily for convenience in the sense that we could follow Roddie (2012a) and allow for a duopoly game with asymmetric information post-entry, although in doing so we would move further away from the the spirit of the MR model. In general it also seems plausible that operating on a route should give an entrant a clearer view of the incumbent's marginal costs than it has a potential entrant.

While we can defend our cost assumptions, there are clearly important features of the industry that our model abstracts away from. In particular, a carrier's marginal costs on different routes are likely to be correlated so that a potential entrant should try to make inferences about costs on a particular route from pricing on other routes as well. Our model is a model of a single route and cannot capture this. On a particular route a carrier also sets many prices (first or business class and economy tickets, and tickets with and without restrictions that may be available on different dates before departure). Our model ignores this feature, assuming that the incumbent sets a single price. However, we will provide evidence that, on at least the routes that fit the assumptions of our model, incumbent carriers cut prices across the entire distribution of fares, which, at least intuitively, seems consistent with the idea of a carrier trying to signal that its marginal cost of filling a seat is low. This fact will also provide some evidence against explanation against alternative explanations for why incumbents cut prices when Southwest becomes a potential entrant.

[13] One might object that firms can use publicly collected data to understand these network flows. However, the Department of Transportation only releases these data with a lag of at least three months, and our theoretical results hold even if we assume that the incumbent marginal costs are revealed to the entrant after it has made its entry decision.

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), 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), that we aggregate to the quarterly level. Our data covers the period from Q1 1993-Q4 2010 (72 quarters).[14]

Following GS, we define a market to be 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 define Southwest as a potential entrant on a route when it serves at least one other route directly (defined by having at least 65 flights per quarter recorded in T100, or 50 non-stop passengers in DB1) out of both of the endpoint airports, but it does not serve directly the route itself. We define Southwest as having entered once it has at least 65 flights recorded in T100 and carries 150 non-stop passengers on the route in DB1.

Based on our potential entrant definition there are 1,872 markets where Southwest becomes a potential entrant after the first quarter of our data and before Q4 2009, a cut-off that we use so we can see whether Southwest enters the market in the following year, an observed outcome that we will use to estimate which market characteristics make entry more likely. Southwest enters 339 of these markets during the period of our data. We will call this the full sample. Most of our analysis will focus on the subset of these markets where there is one carrier that is a *dominant incumbent* before Southwest enters. As we want to identify only carriers that are committed to a market rather than just serving it briefly, we use the following rules to identify a dominant carrier:

1. to be active in a quarter it must carry at least 150 DB1 non-stop passengers;

2. once it becomes active in a market the carrier must be active in at least 70% of quarters before Southwest enters, and in 80% of those quarters it must account for 80% of direct traffic on the market and at least 50% of total traffic.[15]

[14] There are some changes in reporting requirements and practices over time. For example, prior to 1998 operating and ticketing carriers are not distinguished in DB1, making it difficult to analyze codesharing. Prior to 2002 regional affiliates, such as American Eagle or Air Wisconsin operating as United Express, were not required to report T100 data, which provides some limits on our ability to look at capacity.

[15] To apply this definition we have to deal with carrier mergers (for example, Northwest was the dominant carrier on the Minneapolis to Oklahoma City route before it merged with Delta in 2008, after which Delta is the dominant carrier). In our baseline specifications we treat the dominant carrier before and after a merger as the same carrier.

Table 1: Summary Stats: Southwest as a Potential Entrant

	Full Sample		Dominant Firm Samples			
	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev
Mean endpoint population (m)	2.373	1.974	2.850	1.894	3.155	2.081
Distance (miles)	2,548.48	1,327.04	1,251.44	749,58	1,315.1	803.07
Primary city airport (Origin)	0.061	0.24	0.198	0.4	0.185	0.391
Primary city airport (Dest.)	0.106	0.308	0.17	0.377	0.138	0.348
Second city airport (Origin)	0.153	0.36	0.179	0.385	0.169	0.378
Second city arport (Dest.)	0.173	0.378	0.179	0.385	0.231	0.425
O or D is a big city	0.587	0.492	0.858	0.35	0.877	0.331
O or D is a leisure destination	0.093	0.291	0.113	0.318	0.108	0.312
O or D is slot controlled	0.033	0.179	0.057	0.23	0.092	0.292
WN presence (Origin)	0.318	0.285	0.27	0.246	0.225	0.213
WN presence (Dest.)	0.272	0.244	0.159	0.17	0.163	0.174
Market Size	27,320	41,380	53,019	44,107	44,675	40,896
Numb. of markets	1872		106		65	

We identify 106 markets with a dominant incumbent before Southwest enters, but in some of these markets Southwest enters at the same time as it becomes a potential entrant (i.e., the market is one of the first ones it enters when it enters one of the endpoint airports) and in a few of them the dominant incumbent becomes active only after Southwest is a potential entrant on the route. Therefore in 65 markets we observe quarters where the incumbent carrier is dominant both before Southwest becomes a potential entrant and after it is a potential entrant but before it actually entered. It is data from these routes that will identify the effects of the potential entry threat on the price set by a dominant incumbent, although the other routes are useful in controlling for quarter effects and several other observed factors that we allow to affect pricing.

Table 1 presents summary statistics for the full sample, the 106 markets and the subset of 65 markets. The origin (destination) label here just refers to the airport that has a code earlier (later) in the alphabet.[16] Relative to the full sample, both groups of dominant incumbent markets tend to be shorter with larger endpoint cities measured either by average population or by one of the cities being a city that Gerardi and Shapiro (2009) identify as a 'big city' in their analysis of airline fare distributions. As only large cities have multiple airports, the dominant incumbent markets are also more likely to involve an airport identified as a primary or secondary airport.[17] On the other hand,

[16] So for Boston Logan (BOS) to Raleigh-Durham (RDU), BOS would be the origin and RDU the destination

[17] They define big cities based on MSA population, and they use a fairly wide range including cities such as Kansas City. We also follow them in defining 'leisure' destinations, which include cities such as New Orleans and Charleston, SC as well as several Florida airports and Las Vegas. We define slot controlled airports as JFK, LaGuardia and Newark in the New York area, Washington National and Chicago O'Hare, although O'Hare is no longer slot controlled. We identify metropolitan areas with more than one major airport using

the standard deviations show that both sets of markets are quite heterogeneous with respect to market characteristics.

The bottom row of the table contains our estimate of market size. We form this estimate as the predicted value from an OLS gravity model regression where, using data for Q1 1993, we regress the log of the total number of round-trip passengers on a route on the logs of total enplanements at each of the endpoint airports and the log of non-stop round trip distance. This prediction is multiplied by 3.5 to give a rough-and-ready approximation of the total number of people who might travel on a route if prices were low enough.[18]

Table 2 reports summary statistics for variables that vary over time for the dominant firm markets, such as average prices and market shares. Quarters are aggregated into three groups: Phase 1 - before Southwest is a potential entrant, Phase 2 - after Southwest is potential entrant but before it enters and Phase 3 - after Southwest enters. The latter set of markets is a selected sample of markets, which explains why, in Phase 3, the number of seats that the incumbent has scheduled and the number of passengers it carries on these routes is significantly larger than for the broader set of markets in Phases 1 and 2. In these summary statistics we observe that the incumbent's prices tend to be lower in Phase 2 than Phase 1, consistent with the Southwest Effect. If Southwest enters, incumbents tend to charge prices that are slightly above Southwest but still tend to maintain a larger market share. This is consistent with incumbents being viewed by consumers as having higher quality.

The summary statistics also provide some evidence against an alternative story for why prices fall in Phase 2. Recall that in Phase 2, Southwest serves both endpoint airports so that it is plausible that a passenger might choose to travel using connecting service on Southwest, so that Southwest might really be a competitor rather than just a potential entrant. However, from the table we see that Southwest's average market share in Phase 2 is less than 2%, compared with the dominant carrier's share of over 80%, suggesting that the degree of direct competitive pressure that Southwest exerts in Phase 2 is fairly small. This contrasts with the much larger share that Southwest typically attains if it enters the market.

The bottom section of the table shows the number of carriers providing indirect service (to count a carrier must carry at least 6.5 DB1 return passengers), the total number of potential entrants (carriers serving both endpoints) and a measure of the importance of code-sharing on the route, measured

http://en.wikipedia.org/wiki/List_of_cities_with_more_than_one_airport, and identify the primary airport in a city as the one with the most passenger traffic in 2012.

[18] The advantage of this approach is that it adjusts for distance (as more people travel between closer cities) and, for multi-airport cities, endpoint enplanements allow us to get a better prediction of the number of people traveling that just using endpoint city populations.

either by at least one of the passengers in DB1 being identified as a codesharing passenger (operating carrier is the dominant incumbent but the ticketing carrier is different) or the number of codeshared passengers. Goetz and Shapiro (2012) argue that one of the responses to the threat of entry by Southwest is that incumbents increase codesharing. For our dominant firm sample, we also see the proportion of code-shared routes increasing in Phase 2. However, we will show below that this occurs primarily in markets where Southwest's actual entry is most likely, which is different from the set of routes where we observe the largest price decreases.

4 Evidence of Limit Pricing in the Dominant Incumbent Sample

We begin our analysis by confirming that we do find a statistically significant Southwest Effect, i.e., that prices fall in Phase 2 when Southwest becomes a potential entrant, for our dominant incumbent sample once we control for market fixed effects, quarter dummies and other controls. To do so, we follow GS, who used markets with any number of incumbents, by utilizing the following regression specification:

$$\begin{aligned} ln(p_{j,m,t}) &= \gamma_m + \tau_t + \alpha X_{j,m,t} \\ &+ \sum_{\tau=-8}^{8+} \beta_\tau SWPE_{m,t_0+\tau} + \sum_{\tau=0}^{3+} \beta_\tau SWE_{m,t_e+\tau} + \varepsilon_{j,m,t} \end{aligned} \quad (5)$$

where $p_{j,m,t}$ is the passenger-weighted mean fare charged by dominant incumbent carrier j in market m in quarter t, γ_m are market-carrier fixed effects[19] and τ_t are quarter fixed effects. Carriers other than the dominant carrier are not included in our version of the regression. X includes the number of firms serving the market (with direct or connecting service) as well as interactions between the jet fuel price and route distance. t_0 is the quarter in which Southwest becomes a potential entrant, so $SWPE_{m,t_0+\tau}$ is an indicator for Southwest being a potential entrant into market m at quarter $t_0 + \tau$. If Southwest enters it does so at t_e, and $SWE_{m,t_e+\tau}$ is an indicator for Southwest being direct entrant into the market at quarter $t_e + \tau$. We use observations for up to 3 years (12 quarters) before Southwest becomes a potential entrant, and the β coefficients measure price changes relative to those quarters

[19] Note that when the dominant firm is involved in a merger (for example, the merger between Delta and Northwest in 2008) we use the same fixed effect before and after the merger even though the name of the dominant carrier may change (e.g., from Northwest to Delta on the Minneapolis to Omaha route).

Table 2: Summary Stats: Dominant Carrier Sample

	Phase 1: $t < t_0$		Phase 2: $t_0 \leq t < t_e$		Phase 3: $t \geq t_e$	
Variable	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev
Incumbent Pricing						
Mean fare	511.92	162.89	447.65	120.33	259.88	73.24
Southwest Pricing						
Mean fare	-		371.95	78.01	223.34	64.19
Incumbent Traffic						
T100 Seats scheduled	76,798	55,087	76,570	44,969	115,405	63,096
T100 Segment passengers	49,092	34,165	56,694	35,701	82,277	45,059
Incumbent Market Share						
Total share	0.74	0.264	0.83	0.15	0.517	0.228
Southwest Market Share						
Total share	-		0.0137	0.0332	0.434	0.232
Route Characteristics						
Competitors indirect	1.87	1.58	1.85	1.33	0.97	1.25
Potential entrants	7.83	1.71	8.25	1.62	8.55	1.88
Incumbent code-shared route	0.151	0.357	0.354	0.478	0.470	0.499
Incumbent code-shared passengers (DB1B)	4	29.29	4.54	13.42	20.89	79.76
Number markets	106		65		54	

that are more than 8 quarters before Southwest becomes a potential entrant or, if Southwest becomes a potential entrant within the first 8 quarters that the dominant carrier is observed in the data, the first quarter that it is observed. We estimate separate coefficients for the quarters immediately around the entry events, but aggregate those quarters further away from the event where we have fewer observations. Standard errors are clustered at the market-carrier level to allow for correlation in the error terms over time. We report results where markets are weighted equally, but the results are very similar if, like GS, we weight markets by the average number of passengers carried.

Table 4 presents the coefficient estimates. Consistent with GS's results using a broader sample and the summary statistics discussed above, Southwest's presence as a potential entrant, as well as its actual entry, is associated with large falls in the dominant incumbent's price. Southwest's presence as a potential entrant leads to price declines of around 10-14% in the six quarters after Southwest becomes a potential entrant. These price declines are maintained over time, i.e., they do not disappear if Southwest fails to enter the route. This is consistent with our model where, because the incumbent's marginal cost can change over time, there is an incentive to continue signal. In fact the decline seems to increase over time: this is also consistent with our model because of the way that those incumbents who repeatedly deter entry will tend to be those who receive the most favorable cost draws so that both their profit-maximizing and their deterring prices will tend to be lower. Like GS, prices start to fall about two quarters before Southwest becomes a potential entrant, presumably reflecting the fact that Southwest's airport entry is either announced or otherwise anticipated several months before it actually begins flying routes. If Southwest enters the market, average prices decline by an *additional* 30-45%, giving a decline of 45-60% relative to prices in Phase 1. This post-entry decline is larger than the one in GS, presumably reflecting the fact that dominant incumbents have more market power prior to Southwest's entry than the average incumbent in GS's sample.

We now address the question of whether our model of entry deterrence through limit pricing can explain the price declines that occur when Southwest becomes a potential entrant. We begin by using the approach to detecting strategic investment suggested by EE to identify whether the price declines are likely due to the dominant incumbents trying to deter entry. In the context of a fairly general incomplete information model of strategic investment EE argue that, when strategic incentives are present, they lead to a prediction that the relationship across markets between the level of investment and factors that affect the attractiveness of entry and investment should be non-monotonic. In the context of our model, the logic would apply in the following way. Suppose that we can identify how attractive markets are to Southwest based on exogenous market characteristics. When Southwest

Table 3: Incumbent Responses to the Threat of Entry - Logged Average Fare

β Estimates					
Before WN is PE:		WN is PE:		WN is E:	
$t_0 - 8$	-0.047	t_0	-0.105^{***}	t_e	-0.416^{***}
	(0.029)		(0.031)		(0.066)
$t_0 - 7$	-0.022	$t_0 + 1$	-0.115^{***}	$t_e + 1$	-0.514^{***}
	(0.0307)		(0.034)		(0.069)
$t_0 - 6$	-0.040	$t_0 + 2$	-0.131^{***}	$t_e + 2$	-0.539^{***}
	(0.034)		(0.032)		(0.077)
$t_0 - 5$	-0.041	$t_0 + 3$	-0.131^{***}	$t_e + 3$	-0.602^{***}
	(0.034)		(0.032)		(0.080)
$t_0 - 4$	-0.015	$t_0 + 4$	-0.135^{***}	$t_e + 4$	-0.608^{***}
	(0.033)		(0.034)		(0.082)
$t_0 - 3$	-0.009	$t_0 + 5$	-0.137^{***}	$t_e + 5$	-0.577^{***}
	(0.029)		(0.038)		(0.084)
$t_0 - 2$	-0.0761^{**}	$t_0 +$ 6-12	-0.206^{***}	$t_e +$ 6-12	-0.589^{***}
	(0.029)		(0.047)		(0.081)
$t_0 - 1$	-0.0874^{***}	$t_0 +$ 13+	-0.309^{***}	$t_e +$ 13+	-0.589^{***}
	(0.029)		(0.051)		(0.086)
Market-Carrier Fixed Effects:			Yes		
Quarter Fixed Effects:			Yes		
Time-varying Controls:			Yes		
N	3,904				
adj. R^2	0.81				

Dependent variable is log of the mean passenger-weighted fare. Standard errors are in parentheses and are clustered by route-carrier. *** denotes significance at the 1% level, ** at 5% and * at 10%.

becomes a potential entrant, an incumbent will not choose to cut prices (very much) in markets where entry is very unattractive to Southwest, because it is likely only to be sacrificing monopoly profits. A low price is also unlikely to deter entry in markets where entry is very attractive, so the monopolist will, once again, not want to sacrifice short-run profits that it can make before Southwest enters. Instead, the incumbent will only be willing to cut prices substantially in markets of intermediate attractiveness to Southwest, where its entry decision might plausibly be tipped away from entry, towards delay, if it believes that the incumbent has low marginal costs. On the other hand, if, instead of being motivated by deterrence, incumbents cut prices to accommodate entry, i.e., to generate outcomes that are more favorable for the incumbent once entry occurs, then we would expect to see the size of the price declines to increase monotonically with how attractive markets are to the entry of Southwest.[20]

[20]GS consider a simpler version of this analysis where they compare pricing behavior, in the quarters immediately prior to Southwest becoming a potential entrant on routes where Southwest had already announced it would enter and

The EE approach is implemented in two stages (second stage standard errors are corrected for first stage estimation error using a bootstrap where we resample markets). In the first stage, we estimate a probit model using the full sample, where an observation in a market and the dependent variable is equal to 1 if Southwest entered within four quarters of becoming a potential entrant.[21]

$$\Pr(entry4_m = 1|X, Z, t) = \Phi(\tau_t + \alpha X_m) \tag{6}$$

t is the quarter that WN became a PE, and τ_t are time dummies. The X_m variables are exogenous market characteristics such as measures of market population, route distance and whether one of the endpoints is a big city, a tourist destination or a primary/secondary airport in a large city, and measures of both the dominant incumbent's presence and Southwest's presence. We also include our measure of market size (divided by 10 in this case). The estimates are in Table 4, and the signs on most of the coefficients are sensible so that, for example, there is more entry in both larger and shorter markets. The fit of the model is also good for an entry model, with a pseudo-R^2 of 0.37.

In the second stage, we take the dominant firm sample and use the first-stage estimates and the exogenous characteristics of these markets to predict the probability of entry. We then divide these markets into terciles based on the probability of entry, and estimate the following regression:

$$ln(p_{j,m,t}) = \gamma_m + \tau_t + \alpha X_{m,t} + \sum_{s=1}^{3} \beta_s I[\hat{\rho}_m \in Terc_s] * SWPE_{m,t} + \epsilon_{j,m,t} \tag{7}$$

where $\hat{\rho}_m$ is the predicted probability of entry (within one year) on market m and, as before, $p_{j,m,t}$ is the passenger-weighted mean fare charged by the dominant incumbent carrier j in market m in quarter t. $X_{m,t}$ is defined as the same as before. All of the specifications we consider include market-carrier and quarter fixed effects. We focus on the results where we use fuel interacted with distance and deviation from mean distance squared to control for how jet fuel prices and distance affect carriers costs, but the results are robust to using different controls. Only observations from Phases 1 and 2 are included in the regression, and the β_s coefficients measure how much prices decline in Phase 2 as a function of the probability of entry. The results are similar if we use quintiles rather than terciles, although the individual coefficients tend to be less significant because of the smaller number of markets

routes where it had not. They observe larger declines in prices on routes where entry had not been pre-announced, but the differences are generally not statistically significant. However, the direction of their results is consistent with our findings.

[21] It would be inappropriate to use a dummy for Southwest ever entering because, in our relatively long sample, different markets are exposed to the possibility of entry for different periods of time. Using a 4 quarter rule also means that we minimize the truncation problem associated with the end of the sample while still having a significant number of observations.

Table 4: First Stage

	(1)
	entry4
Secondary airportO	0.542**
	(0.237)
Secondary airportD	0.0383
	(0.233)
Primary airportO	0.688***
	(0.254)
Primary airportD	0.558***
	(0.211)
$WNpresORG$	2.455**
	(0.983)
$WNpresORG^2$	-2.245**
	(0.940)
$WNpresDEST$	0.187
	(1.045)
$WNpresDEST^2$	-0.0427
	(1.101)
$INCpresORG$	2.174
	(1.743)
$INCpresORG^2$	-2.085
	(1.683)
$INCpresDEST$	-4.076
	(4.223)
$INCpresDEST^2$	6.253
	(7.521)
Slot controlled	-1.801***
	(0.543)
$Tourist$	1.003***
	(0.174)
Big city	-0.0134
	(0.146)
$Distance$	-0.668***
	(0.204)
$Distance^2$	0.0385
	(0.0344)
$Population$	-0.0952
	(0.109)
$Population^2$	0.0117*
	(0.00637)
$MarketSize$	0.237***
	(0.0404)
$MarketSize^2$	-0.00745***
	(0.00165)
N	1872
pseudo R^2	0.372

Standard errors in parentheses

Additional controls included (e.g. quarter dummies for when Southwest becomes a potential entrant)

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

in each group.

The results in the first column of Table 5 indicate that the price declines are only significantly different from zero, and are largest, in the middle tercile. In contrast, declines are small, at most, in markets where entry is either likely or unlikely. This pattern is consistent with a limit pricing deterrence story, but not an accommodation story.

Table 5: Ellison and Ellison Analysis: Second Stage

	(1) log(Fare)	(2) log(T100 pass.)	(3) log(Load)	(4) Codeshare route	(5) Prop. Codeshare	(6) log(Capacity)
$Tercile1$	-0.0426	0.132*	0.0779**	-0.00953	0.00368	0.0799
	(0.0589)	(0.069)	(0.033)	(0.0986)	(0.0047)	(0.0756)
$Tercile2$	-0.142**	0.209**	0.164***	0.165	0.0114	0.0390
	(0.0677)	(0.0933)	(0.037)	(0.174)	(0.0128)	(0.1097)
$Tercile3$	-0.0692	0.00960	-0.00953	0.444***	0.0551***	0.0329
	(0.091)	(0.009)	(0.0466)	(0.148)	(0.0186)	(0.0997)
N	3622	3100	3100	2185	2185	3085
R^2	0.729	0.817	0.690	0.505	0.326	0.730

Bootstrapped standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

One can also take other approaches to examining the empirical plausibility of explanations based on entry accommodation. For example, the accommodation story that has been mentioned to us most frequently is that incumbents may cut prices in order to build up the loyalty of their frequent flyers in order to retain as much of their custom as possible if and when Southwest enters.[22] If so, it seems plausible that we would see price reductions targeted at the types of high-priced tickets that are usually purchased by frequent flyers when traveling for business. In the Appendix Tables B.1-B.3, we report the GS results using the logs of the 25^{th}, 50^{th} and 75^{th} percentiles of the fare distribution as dependent variables rather than the log of the mean fare. Comparing prices in phases 1 and 2, we see significant and substantial declines across the price distribution, although the proportional declines are admittedly larger for higher priced tickets. While this seems inconsistent with an accommodation story based on the dynamics of frequent-flyer demand it does seem intuitively consistent with a limit pricing deterrence story where the incumbent is trying to signal that its marginal cost of a seat is low, whichever type of customer purchases it.[23]

[22]Specifically an accommodation story requires that there is a state variable that the incumbent can affect by its pricing behavior prior to Southwest's entry that will affect its demand or costs after Southwest enters. Frequent flyer mileage provides this type of state variable.

[23]The percentile results also provide some additional evidence against the argument that prices fall because Southwest

An alternative explanation for why prices decline is that the presence of Southwest at both endpoints is correlated with an actual reduction in the incumbent carrier's marginal costs on the route, because it affects how traffic flows over the incumbent's network (e.g., it affects how many people fly the route as a segment on a longer journey). While it is not obvious why this would primarily affect routes with intermediate entry probabilities (e.g., the middle tercile), we can also assess this explanation directly by repeating the tercile specification using the log of total passenger traffic for the dominant incumbent on the segment, as measured in T100, as the dependent variable.[24] The results are reported in the second column of Table 5. We observe that once Southwest becomes a potential entrant segment traffic tends to increase, on average, across all of the terciles although the increases are not significant on markets where entry is most likely. The finding that traffic increases, and that there is not a dramatic difference between markets with intermediate entry probabilities and those with low entry probabilities, provides evidence against the argument that prices fall because of marginal cost changes.

In the third column of Table 5 we also use the log of the incumbent carrier's load factor on a route as the dependent variable. The load factor is measured as the number of passengers carried on the segment divided by the number of seats scheduled (there are a handful of observations where no seats were scheduled but some were performed, which explains why the number of observations in column (3) is slightly less than the number of observations in column (2)). In the sixth column the log of the number of scheduled seats is used as the dependent variable. Even if segment traffic increases, the carrier's marginal cost could fall if it adds so much capacity that there are more empty seats. In particular, one might argue that this is exactly what would happen if incumbent carriers use capacity as their strategic variable, as assumed in the models of predatory pricing by airlines proposed by Snider (2009) and Williams (2012).[25] In this case falling prices would be a consequence of an entry deterring strategy, that might well be focused on markets with intermediate entry probabilities, rather than the deterring strategy itself. However, we observe that load factors actually tend to increase once Southwest becomes a potential entrant in markets with intermediate entry probabilities, while

is providing actual competition because it is able to offer connecting service on the route. If so, one would probably expect to see the declines concentrated in the lower part of the fare distribution as the types of price-sensitive consumer who are most likely to be willing to use connecting service on Southwest are also likely to be buy the cheapest, most restrictive tickets on the incumbent carrier. Instead we observe similar declines across the price distribution.

[24]We have fewer observations in this regression because of incomplete coverage of flights operated by regional affiliates in T100 prior to 2001.

[25]For example, suppose that the incumbent's marginal cost is publicly observed and a decreasing function of its capacity on a route, that it is costly for the incumbent to adjust its route capacity and that Southwest's post-entry profits are decreasing in the incumbent's route capacity. In this case, the incumbent may invest in more capacity to try to deter in the intermediate entry probability markets, and the incumbent's price would tend to fall as a result even when it just sets a static profit-maximizing price given the capacity that it has.

capacities do not change. This suggests both that marginal costs should not be falling differentially on these routes and that, if incumbents are trying to deter entry, it is price rather than capacity that is used as the strategic variable. This result is also consistent with GS's finding that incumbent capacity does not systematically increase when Southwest becomes a potential entrant.

Goetz and Shapiro (2012) suggest that incumbents also respond to the threat of entry by Southwest by increasing codesharing with other carriers, although it is not clear whether this is a strategy that they use to try to deter or to accommodate entry. To understand whether codesharing is a strategy that changes in a similar way to pricing we repeat the tercile regressions using two measures of codesharing as the dependent variable. The first dependent variable is a dummy variable that is equal to 1 if any DB1 passengers are recorded as flying on the incumbent carrier (as an operating carrier) but with a different airline as the ticketing carrier during the quarter. This is the Goetz and Shapiro (2012) measure of codesharing. The second dependent variable is the proportion of passengers carried by the incumbent that have a different ticketing carrier, which may do a better job of capturing how important codesharing actually is. We restrict our analysis to quarters after 1998 when operating and ticketing carriers are distinguished in DB1. The results, reported in the fourth and fifth columns of Table 5, are interesting because they indicate that, once Southwest becomes a potential entrant, codesharing increases substantially only in markets where Southwest's actual entry is most likely. This suggests that, unlike price reductions, codesharing is likely used as part of an entry accommodation strategy.

5 Can Our Model Predict the Size of the Observed Price Declines?

While the reduced-form evidence is consistent with prices being lowered in an attempt to deter entry (limit pricing), this does not mean that our model can explain the quite large price declines that are observed. In this section we therefore calibrate our model using estimated demand and cost parameters to test whether a limit pricing explanation can generate price declines as large as those that are actually observed. We stay as close as we can to the theoretical model presented above, and our model has the following features:

- a nested logit demand structure where the nests are 'fly' and 'not fly' , and the product quality of the incumbent and Southwest are held constant. The nesting parameter, price coefficient and product qualities are estimated from the data, given the definition of market size from Section 3.

- marginal costs of both firms that evolve according to independent AR(1) processes (with truncated normal innovations) on supports that are different for Southwest and the incumbent, although we use the same AR(1) parameter for both firms. We estimate the serial correlation parameter, and choose the supports based on the distribution of marginal costs that we estimate.

- a truncated normal entry cost distribution for Southwest which we choose (i.e., we do not, currently, recover this from estimating a dynamic entry model). We briefly discuss the plausibility of the assumed values below.

To estimate demand and marginal costs we use the dominant firm sample data for Phases 1 and 3 (i.e., before Southwest becomes a potential entrant, and after Southwest enters, if it enters). We do this principally because we want to recover marginal costs using periods when the standard Bertrand Nash first order conditions may apply, without using periods when the more complicated, dynamic limit pricing first order conditions might be appropriate. We also restrict attention to only the dominant incumbent and Southwest (Phase 3), including more marginal carriers who may fly some passengers on the route in the outside good.

Demand Estimation

We assume a standard nested logit indirect utility specification (e.g., Berry (1994))

$$\begin{aligned} u_{i,j,m,t} &= \mu_j + \tau_1 T_t + \tau_2 Q2_t + \tau_3 Q3_t + \tau_4 Q4_t + \gamma X_{j,m,t} + \alpha p_{j,m,t} + \xi_{j,m,t} + \zeta^{FLY}_{i,m,t} + (1-\lambda)\varepsilon_{i,j,m,t} \\ &\equiv \theta_{j,m,t} + \alpha p_{j,m,t} + \xi_{j,m,t} + \zeta^{FLY}_{i,m,t} + (1-\lambda)\varepsilon_{i,j,m,t} \end{aligned} \tag{8}$$

where μ_j is firm j's mean quality, T_t is a time trend, and $Q2$, $Q3$ and $Q4$ are seasonal dummies. $p_{j,m,t}$ is the passenger weighted average round trip fare for firm j on market m in quarter t and $\xi_{j,m,t}$ is the unobserved (to the econometrician) characteristic. In this specification $\xi_{j,m,t}$ varies across time for the same carrier in a given market, but when we do the calibration we will hold the qualities of the incumbent and Southwest fixed at their estimated mean values. $X_{j,m,t}$ includes an indicator for whether the market is a hub for carrier j, together with market characteristics such as distance and whether one of the airports is a primary or secondary airport. However, because market size is defined using a regression model which already includes factors such as airport enplanements and distance, we do not necessarily expect these characteristics to have significant effects on demand, and in practice their effects are statistically insignificant or small. Being a hub carrier may raise demand because of frequent flyer programs or gate access.

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

$$ln\left(\frac{s_{j,m,t}}{s_{0,m,t}}\right) = \mu_j + \tau_1 T_t + \tau_2 Q2_t + \tau_3 Q3_t + \tau_4 Q4_t + \gamma X_{j,m,t} - \alpha p_{j,m,t} + \lambda ln(\overline{s}_{j,m,t|FLY}) + \xi_{j,m,t} \quad (9)$$

where $\overline{s}_{j,m,t|FLY}$ is firm j's market share conditional on flying and $s_{j,m,t}$ is firm j's market share, and market size is defined as in Section 3.

As both $p_{j,m,t}$ and $\overline{s}_{j,m,t|FLY}$ should be endogenous, we instrument for them in our preferred specification using the one-period lagged value price of jet fuel[26] both on its own and interacted with route distance, each carrier's competitor's average presence at the endpoints in that quarter and for the incumbent whether Southwest has entered the market and for Southwest whether the route involves a hub for the incumbent.

Table 6 presents estimates of demand when we use OLS and 2SLS. As expected, estimated demand is more elastic controlling for endogeneity, and the median elasticity in the second column is 3.13, which is comparable to estimates in other studies of airline demand (e.g., Berry and Jia (2010), Snider (2009)). Southwest's quality is estimated to be slightly lower than most of the legacy carriers, consistent with the fact that post-entry they typically have similar market shares while Southwest has lower prices. Consistent with Borenstein (1989) and Berry (1992), consumers are estimated to prefer a carrier that has a hub at one of the endpoints.

When we simulate the calibrated model of dynamic limit pricing below, we will set $\lambda = 0.878$ and the values of θ for each firm by setting Southwest's quality to be its estimated value ($\theta_{WN} = -0.216$), and the incumbent to have quality equal to the average of the legacy carriers ($\theta_{INC} = 0.196$).[27]

Marginal Costs

With the 2SLS demand estimates in hand, we back out the incumbent's and Southwest's marginal costs in each period using the standard static Bertrand Nash pricing first-order conditions (recall, Phase 2, where we believe our limit pricing model may apply is not used for estimation). The median

[26]Specifically, U.S. Gulf Coast Kerosene-Type Jet Fuel Spot Price FOB (in $/gallon).

[27]Distance is set equal to its mean, while the hub, primary and secondary airport parameters are set equal to zero.

Table 6: Nested Logit Demand Estimates

	OLS	2SLS
$\widehat{\alpha}$	-0.124***	-0.346***
	(0.012)	(0.033)
$\widehat{\lambda}$	0.722***	0.878***
	(0.021)	(0.044)
$\widehat{\mu}$:		
AA	-0.061	-0.024
	(0.047)	(0.058)
AS	-0.023	-0.108**
	(0.045)	(0.049)
CO	0.047	0.344***
	(0.09)	(0.113)
DL	-0.171***	-0.223***
	(0.043)	(0.044)
NW	-0.075	0.412***
	(0.056)	(0.102)
UA	-0.502***	-0.372***
	(0.071)	(0.080)
US	0.015	0.264***
	(0.044)	(0.068)
WN	-0.029	-0.194***
	(0.042)	(0.043)
$\widehat{\gamma}$:		
HUB	0.312***	0.396***
	(0.021)	(0.025)
N	6,893	6,893

Market characteristics (e.g., distance, distance^2), a linear time trend and quarter-of-year dummies are also included. In the second specification we include one-period-lagged value of the average cost of jet fuel, the lagged cost of jet fuel interacted with distance, each carrier's competitor's average presence at the endpoints in that quarter and for the incumbent whether Southwest has entered the market and for Southwest whether the route involves a hub for the incumbent as instruments for $p_{j,m,t}$ and $\overline{s}_{j,m,t|FLY}$. Standard errors are in parentheses. *** denotes significance at the 1% level, ** at 5% and * at 10%.

implied marginal cost is \$0.16/mile, which is comparable to the \$0.14 of total operating expenses per available seat mile that airlines reported on DOT form 41 in 2010. To estimate the persistence in marginal costs we then regress the implied costs on lagged costs, market-carrier fixed effects, quarter-of-year dummies, a time trend, the jet fuel price and the jet fuel price interacted with distance.[28] The estimated AR(1) parameter is shown in the first column of Table 7. As the implied marginal costs are likely to be measured with error (partly because market shares and prices are based on a sample of DB1 data), in the second column we instrument for the lagged marginal cost with the previous (i.e., $t-2$) marginal cost and the value of $\widehat{\rho}$ increases to 0.818, indicating that marginal cost shocks are quite persistent. The estimated standard deviation of the marginal cost innovations is \$25.

Table 7: Marginal Cost Evolution Estimates

	OLS	2SLS
$\widehat{mc}_{j,m,t-1}$	0.747^{***} (0.021)	0.818^{***} (0.013)
N	6,623	6,379

The dependent variable is $\widehat{mc}_{j,m,t}$, carrier j's computed marginal cost in market m in quarter t. The specification also includes one period lagged fuel price, included separately and also interacted with distance, three quarter dummies and a quarterly trend. We also include carrier market fixed effects. In the second column we instrument for $\widehat{mc}_{j,m,t-1}$ with $\widehat{mc}_{j,m,t-2}$. Standard errors are in parentheses. *** denotes significance at the 1% level, ** at 5% and * at 10%.

We set the bounds on marginal costs by choosing values which are approximately at the 25th and 75th percentiles of the estimated marginal costs. For incumbents this gives bounds of [\$150,\$400], and for Southwest bounds of [\$90,\$200], which reflects the fact that Southwest's observed prices are lower across markets. We specify the unconditional mean for each firm's marginal cost to be the center point of these intervals.

Entry Costs

We use these estimated demand and cost parameters to calibrate our model of dynamic limit pricing to predict an incumbent's pricing behavior in a medium-sized market when it faces a new potential entry threat by Southwest. We consider a case where the market size is equal to its mean value for the dominant firm markets and set $T = 20$ and the quarterly discount factor β to 0.98.[29]. In our

[28] When we perform the calibration we do not include the effects of time varying fuel costs or time effects in the model.

[29] Given our assumptions on entry costs the incumbent's equilibrium pricing strategy is quite stable across the early periods for $T = 20$.

calibration, we set $\kappa \sim TRN(\$15\text{m}, \$9\text{m}, \$0, \$100\text{m})$.[30] To put the mean entry costs in perspective, we estimate that the average quarterly variable profit for the observations in the dominant firm sample data in Phases 1 and 3 (based on imputed marginal costs) is \$1.66m (Berry and Jia (2010) estimate this number for all flights and fare classes to be \$1.45m in 2006), a figure that implies that for a firm considering entering in the first period, that an entry cost of \$15m represents about 54% of the present discounted value of future variable profits.

Calibration Results

Figure 1 illustrates the magnitude of price cuts that our calibrated model of limit pricing predicts relative to the static monopoly pricing schedule in the first period of the game when Southwest's marginal cost is at its median (\$150). At this point, the most efficient incumbent faces a probability of entry of 0.2406 in the next period and the least efficient faces a probability of entry of 0.3265. This level and variance of probability of entry generates shading of 4.7% for an incumbent with marginal cost equal to \$394, (the weakest type, with a marginal cost of \$400, sets the Nash price) and maximum shading by an incumbent of 18.5%; weighted-average shading[31] is 15.5%. Recalling that the price cuts that we observe in the data when Southwest becomes a potential entrant are in the range of 10-15% , our results suggest that a reasonably parameterized version of the dynamic limit pricing model generates is capable of generating the type of price changes observed in the data.

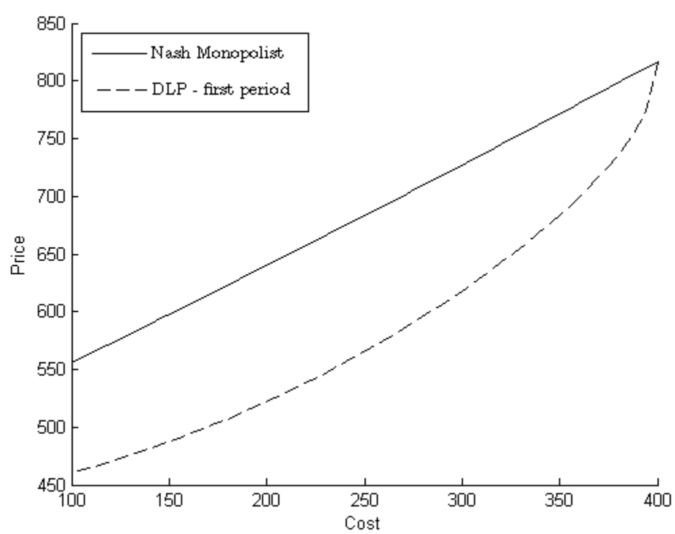

Figure 1: Pricing Strategies, $t = 1$ out of $T = 20$, $c_{WN} = 150$.

[30]Where $TRN(\mu, \sigma, a, b)$ indicates a normal distribution with mean μ, standard deviation σ that is truncated below at a and above at b.

[31]Where weights are determined by the probability of each marginal cost combination in the steady state distributions of costs.

As a further test of the model, in the spirit of EE, we can also examine how incumbents' price cutting changes in markets that are much smaller or larger than the average (we do this by considering market sizes at the 10th and 90th percentiles observed in our sample). In these markets we expect to see much smaller price reductions as deterrence is either largely unnecessary (smaller markets) or unlikely to be effective (larger ones). Figure 2 confirms these intuitions, as we see weighted average deviations from static monopoly pricing of 2-3% for each type of market, with corresponding probabilities of entry of 93-99% and 2-3% for the large and small markets, respectively.

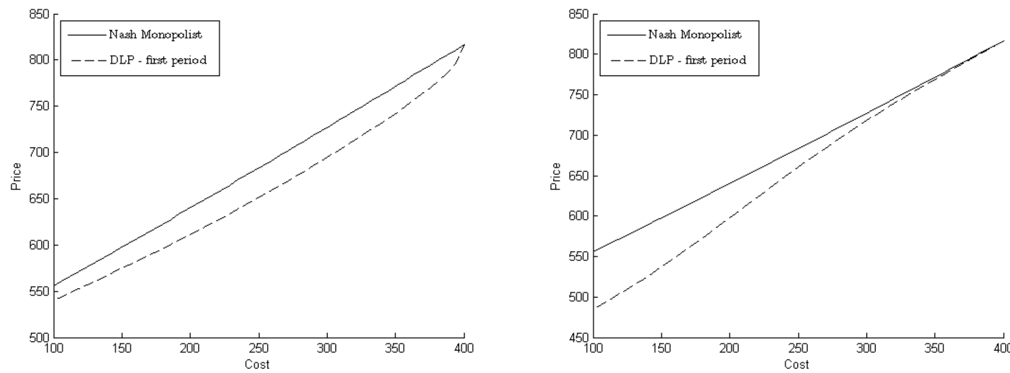

Figure 2: Pricing Strategies, $t = 1$ out of $T = 20$, $c_{WN} = 150$. The right-hand figure is for a large market size and the left-hand figure is for the small market size.

6 Conclusion

We have proposed a framework for analyzing a classic form of strategic behavior, entry deterrence by setting a low price, in a dynamic setting. Under some weak conditions on the primitives and a standard refinement, our model has a unique Markov Perfect Bayesian Equilibrium in which the incumbent's pricing policy reveals his marginal cost each period. This characterization of the equilibrium makes it straightforward to compute equilibrium policies. The resulting tractability stands in contrast to the widely-held belief that dynamic games with persistent asymmetric information are too intractable to be studied or tested empirically, at least when using standard equilibrium concepts. While our model is a special case in many respects, and uniqueness of a dynamic MPBE is certainly not general, it is the natural extension of one of the most widely cited static theory models (Milgrom and Roberts (1982)), and it seems quite plausible that there are other interesting models with structures that would also make them tractable for dynamic analysis.

We exploit tractability to study whether our model of dynamic limit pricing can explain the so-called "Southwest effect" where incumbent carriers cut prices when Southwest becomes a potential entrant on a particular airline route. Here we provide new evidence, both in the reduced form and through a calibration of our structural model, that limit pricing can explain both the qualitative pattern and the quantitative size of the price cuts. We believe that this type of exercise, which combines different types of empirical analysis, provides a potentially profitable direction for testing models of strategic investment.

We hope to extend our analysis in several directions in future work. One priority is to allow for there to be multiple incumbents and to see whether we can also get tractability in this context, and under what conditions. This would be an important extension because there are multiple incumbents in many settings that interest IO economists, including some airline markets where the "Southwest effect" may be observed.

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A Proof of the Conditions Required for Existence and Uniqueness of the FSRE

In this appendix, we prove that our model satisfies the conditions required for existence and uniqueness of the FSRE equilibrium.

We will make frequent use of the following result:

Lemma 1 *Suppose $f(x,y)$, $g(x|w)$ and $h(y)$ are functions where (i) $\int_{\underline{x}}^{\overline{x}} \frac{\partial g(x|w)}{\partial w}dx = 0$, (ii) for a given value of w $\exists x' \in (\underline{x}, \overline{x})$ such that $\frac{\partial g(x'|w)}{\partial w} = 0$, $\frac{\partial g(x|w)}{\partial w} < 0$ $\forall x < x'$ and $\frac{\partial g(x|w)}{\partial w} > 0$ for $\forall x > x'$, (iii) $h(y) > 0$ and $\int_{\underline{x}}^{\overline{x}} h(y)dy = 1$, (iv) $f(x,y) > 0$, and (v) $k = \int_{\underline{y}}^{\overline{y}}\int_{\underline{x}}^{\overline{x}} f(x,y)\frac{\partial g(x|w)}{\partial w}h(y)dxdy$. If,$\forall x, y$ $\frac{\partial f(x,y)}{\partial x} > 0$ then $k > 0$, and if, $\forall x, y$ $\frac{\partial f(x,y)}{\partial x} < 0$ then $k < 0$.*

Proof.

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

■

We proceed by breaking down Proposition 1 into two parts based on the entrant's and the incumbent's strategy.

A.1 Existence and Monotonicity of the Potential Entrant's Threshold Rule

Proposition 2 *Assume that E has the point belief that I's current marginal cost is $\widehat{c}_{It} \in [\underline{c_I}, \overline{c_I}]$. E's entry strategy will be to enter if entry costs κ are lower than a uniquely defined period-specific threshold*

$\kappa_t^*(\widehat{c}_{It}, c_{Et})$. *The threshold is defined by*

$$\kappa^* = \beta \mathbb{E}_t[\phi_{t+1}^E | \widehat{c}_{It}, c_{Et}] - \mathbb{E}_t[V_{t+1}^E | \widehat{c}_{It}, c_{Et}]$$

where V_{t+1}^E *is* E*'s value to being a potential entrant in period* $t+1$ *(i.e., if it does not enter now) and* ϕ_{t+1}^E *is* E*'s value to being a duopolist in period* $t+1$ *(which assumes it has entered prior to* $t+1$*). The threshold* κ^* *is strictly decreasing in* c_{Et} *and strictly increasing in* $\widehat{c}_{It}$*.*

Proof. The following conditions, implied by the assumptions of our model, are sufficient for this proposition to hold:

(i) $\mathbb{E}_t[\phi_{t+1}^E | \widehat{c}_{It}, c_{Et}] - \mathbb{E}_t[V_{t+1}^E | \widehat{c}_{It}, c_{Et}] > \underline{\kappa} = 0$ for all $(\widehat{c}_{It}, c_{Et})$ (there is always some possibility of entry);

(ii) $\mathbb{E}_t[\phi_{t+1}^E | \widehat{c}_{It}, c_{Et}] - \mathbb{E}_t[V_{t+1}^E | \widehat{c}_{It}, c_{Et}] < \overline{\kappa}$ for all $(\widehat{c}_{It}, c_{Et})$ (there is always some possibility of no entry);

(iii) $\mathbb{E}_t[V_{t+1}^E | \widehat{c}_{It}, c_{Et}]$ and $\mathbb{E}_t[\phi_{t+1}^E | \widehat{c}_{It}, c_{Et}]$ are continuous and differentiable in both arguments. For $t < T$, $\mathbb{E}_t[\phi_{t+1}^E | \widehat{c}_{It}, c_{Et}]$ is strictly increasing in $\widehat{c}_{It}$ and decreasing in c_{Et}. For $t < T-1$, $\mathbb{E}_t[V_{t+1}^E | \widehat{c}_{It}, c_{Et}]$ is strictly increasing in $\widehat{c}_{It}$ and decreasing in c_{Et}. For $t = T-1$, $\mathbb{E}_{T-1}[V_T^E | \widehat{c}_{IT-1}, c_{ET-1}] = 0$; and

(iv) $\frac{\partial \mathbb{E}_t[\phi_{t+1}^E | \widehat{c}_{It}, c_{Et}]}{\partial \widehat{c}_{It}} > \frac{\partial \mathbb{E}_t[V_{t+1}^E | \widehat{c}_{It}, c_{Et}]}{\partial \widehat{c}_{It}}$ and $\frac{\partial \mathbb{E}_t[V_{t+1}^E | \widehat{c}_{It}, c_{Et}]}{\partial c_{Et}} > \frac{\partial \mathbb{E}_t[\phi_{t+1}^E | \widehat{c}_{It}, c_{Et}]}{\partial c_{Et}}$. This means that a change in either firm's marginal cost hasa greater effect on E's value when it is in the market than when it is only a potential entrant.

Under conditions (iii) and (iv) the geometry of the expected value functions will resemble those in Figure 3 (although in reality they would not be linear), where the gap between expected value functions defines the threshold level of the entry cost required to induce entry.

We now show that conditions (i), (iii) and (iv) hold in our model. (ii) requires a minimum upper bound on $\overline{\kappa}$ (specifically we need $\mathbb{E}_t[\phi_{t+1}^E | \overline{c_I}, \underline{c_E}] - \mathbb{E}_t[V_{t+1}^E | \overline{c_I}, \underline{c_E}] < \overline{\kappa}$, as the value of being in the market already is maximized when the entrant has the largest possible marginal cost advantage).

We first establish the conditions for period $T-1$.

(i) $\mathbb{E}_{T-1}[\phi_T^E | \widehat{c}_{IT-1}, c_{ET-1}] = \mathbb{E}_{T-1}[\pi_E^D | \widehat{c}_{IT-1}, c_{ET-1}] > \mathbb{E}_{T-1}[V_T^E | \widehat{c}_{IT-1}, c_{ET-1}] = 0$ as all $\pi_E^D > 0$ by assumption and there is no value to being a potential entrant in the last period.

(iii)

$$\mathbb{E}_{T-1}[\phi_T^E | \widehat{c}_{IT-1}, c_{ET}] = \int_{\underline{c_I}}^{\overline{c_I}} \int_{\underline{c_E}}^{\overline{c_E}} \pi_E^D(c_{ET}, c_{IT}) \psi_I(c_{IT} | \widehat{c}_{IT-1}) \psi_E(c_{ET} | c_{ET-1}) dc_{ET} dc_{IT}$$

Continuity and differentiability of $\mathbb{E}_{T-1}[\phi_T^E | \widehat{c}_{IT-1}, c_{ET}]$ follows from continuity and differentiability of

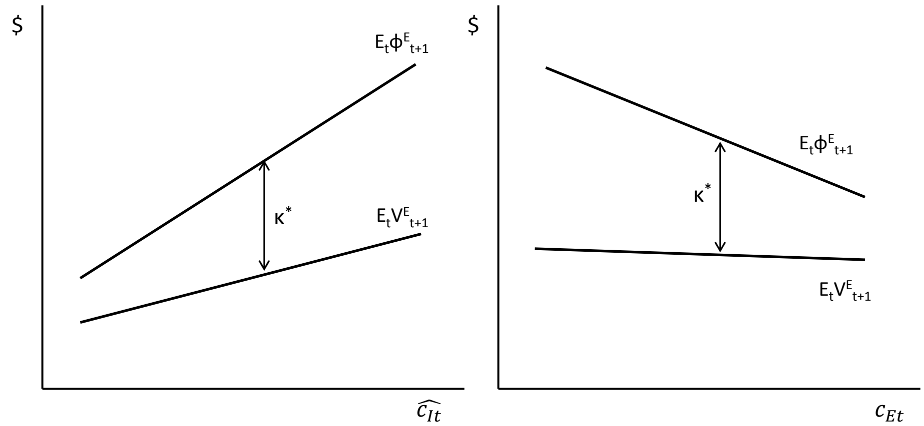

Figure 3: Illustrative expected value functions for the potential entrant

$\pi_E^D(c_{IT}, c_{ET})$ and the continuity and differentiability of the Markov transition functions $\psi_I(c_{IT}|c_{IT-1})$ and $\psi_E(c_{ET}|c_{ET-1})$ with respect to their conditioning variables.

(iv) $\frac{\partial \mathbb{E}_{T-1}[\phi_T^E|\widehat{c}_{IT-1}, c_{ET-1}]}{\partial \widehat{c}_{IT-1}} = \frac{\partial \mathbb{E}_{T-1}[\pi_{ET}^D|\widehat{c}_{IT-1}, c_{ET-1}]}{\partial \widehat{c}_{IT-1}} = \int\limits_{\underline{c_I}}^{\overline{c_I}} \int\limits_{\underline{c_E}}^{\overline{c_E}} \pi_E^D(c_{ET}, c_{IT}) \frac{\partial \psi_I(c_{IT}|\widehat{c}_{IT-1})}{\partial \widehat{c}_{IT-1}} \psi_E(c_{ET}|c_{ET-1}) dc_{ET} dc_{IT}$.

Application of Lemma 1 implies that $\frac{\partial \mathbb{E}_{T-1}[\phi_T^E|\widehat{c}_{IT-1}, c_{ET-1}]}{\partial \widehat{c}_{IT-1}} > 0$. Also, we have $\frac{\partial \mathbb{E}_{T-1}[\phi_T^E|\widehat{c}_{IT-1}, c_{ET-1}]}{\partial \widehat{c}_{IT-1}} > \frac{\partial \mathbb{E}_{T-1}[V_T^E|\widehat{c}_{IT-1}, c_{ET-1}]}{\partial \widehat{c}_{IT-1}} = 0$.

Application of the same lemma shows that $\frac{\partial \mathbb{E}_{T-1}[\phi_T^E|\widehat{c}_{IT-1}, c_{ET-1}]}{\partial c_{ET-1}} < \frac{\partial \mathbb{E}_{T-1}[V_T^E|\widehat{c}_{IT-1}, c_{ET-1}]}{\partial c_{ET-1}} = 0$ as $\pi_E^D(c_{Et}, c_{It})$ is decreasing in c_{Et}, the entrant's own marginal cost.

Since $\mathbb{E}_{T-1}[V_T^E|\widehat{c}_{IT-1}, c_{ET-1}] = 0$, we prove the following at $T-2$. First $\frac{\partial \mathbb{E}_{T-2}[V_{T-1}^E|\widehat{c}_{IT-2}, c_{ET-2}]}{\partial \widehat{c}_{IT-2}} > 0$ because

$$\mathbb{E}_{T-2}[V_{T-1}^E|\widehat{c}_{IT-2}, c_{ET-2}] = \int\limits_{\underline{c_I}}^{\overline{c_I}} \int\limits_{\underline{c_E}}^{\overline{c_E}} \int\limits_{\underline{\kappa}}^{\overline{\kappa}} \max\{\beta \mathbb{E}_{T-1}[V_T^E|c_{IT-1}, c_{ET-1}], \beta \mathbb{E}_{T-1}[\phi_T^E|c_{IT-1}, c_{ET-1}] - \kappa_{T-1}\} ...$$

$$\psi_I(c_{IT-1}|\widehat{c}_{IT-2}) \psi_E(c_{ET-1}|c_{ET-2}) g(\kappa_{T-1}) dc_{IT-1} dc_{ET-1} d\kappa_{T-1}$$

$$= \int\limits_{\underline{c_I}}^{\overline{c_I}} \int\limits_{\underline{c_E}}^{\overline{c_E}} \int\limits_{\underline{\kappa}}^{\overline{\kappa}} \max\{0, \beta \mathbb{E}_{T-1}[\pi_E^D|c_{IT-1}, c_{ET-1}] - \kappa_{T-1}\} ...$$

$$\psi_I(c_{IT-1}|\widehat{c}_{IT-2}) \psi_E(c_{ET-1}|c_{ET-2}) g(\kappa_{T-1}) dc_{IT-1} dc_{ET-1} d\kappa_{T-1}.$$

Therefore

$$\frac{\partial \mathbb{E}_{T-2}[V^E_{T-1}|\widehat{c}_{IT-2},c_{ET-2}]}{\partial \widehat{c}_{IT-2}} = \int\limits_{\underline{c_I}}^{\overline{c_I}}\int\limits_{\underline{c_E}}^{\overline{c_E}} \left\{ \int\limits_{\underline{\kappa}}^{\beta \mathbb{E}_{T-1}[\pi^D_E|c_{IT-1},c_{ET-1}]} \left(\beta \mathbb{E}_{T-1}[\pi^D_E|c_{IT-1},c_{ET-1}] - \kappa_{T-1}\right) g(\kappa_{T-1}) d\kappa_{T-1} \right\} ...$$

$$\frac{\partial \psi_I(c_{IT-1}|\widehat{c}_{IT-2})}{\partial \widehat{c}_{IT-2}} \psi_E(c_{ET-1}|c_{ET-2}) dc_{IT-1} dc_{ET-1} > 0$$

by Lemma 1 as $\left\{ \int\limits_{\underline{\kappa}}^{\beta \mathbb{E}_{T-1}[\pi^D_E|c_{IT-1},c_{ET-1}]} \left(\beta \mathbb{E}_{T-1}[\pi^D_E|c_{IT-1},c_{ET-1}] - \kappa_{T-1}\right) g(\kappa_{T-1}) d\kappa_{T-1} \right\} > 0$, and is increasing in $\widehat{c}_{IT-1}$. $\frac{\partial \mathbb{E}_{T-2}[V^E_{T-1}|\widehat{c}_{IT-2},c_{ET-2}]}{\partial c_{ET-2}} < 0$ follows from application of the same lemma. Continuity and differentiability of $\mathbb{E}_{T-2}[V^E_{T-1}|\widehat{c}_{IT-2},c_{ET-2}]$ follows from the continuity of $\mathbb{E}_{T-1}[\pi^D_E|\widehat{c}_{IT-1},c_{ET-1}]$ and continuity and differentiability of $\psi_I(c_{IT-1}|\widehat{c}_{IT-2})$ and $\psi_E(c_{ET-1}|c_{ET-2})$.

Now consider a period $t < T-1$. Suppose that the conditions hold at t. We show that this implies that they hold at $t-1$.

(i) As $\kappa_t \geq \underline{\kappa} = 0$ and (by the induction hypothesis) $\beta \mathbb{E}_t[\phi^E_{t+1}|\widehat{c}_{It},c_{Et}] - \beta \mathbb{E}_t[V^E_{t+1}|\widehat{c}_{It},c_{Et}] > 0$, $\phi^E_t - V^E_t > 0$ for all $(\widehat{c}_{It},c_{Et})$. Therefore $\mathbb{E}_{t-1}[\phi^E_t - V^E_t|\widehat{c}_{It-1},c_{Et-1}] > 0$.

(iii)

$$\mathbb{E}_{t-1}[\phi^E_t|\widehat{c}_{It-1},c_{Et-1}] = \int\limits_{\underline{c_I}}^{\overline{c_I}}\int\limits_{\underline{c_E}}^{\overline{c_E}} \pi^D_t(c_{It},c_{Et})\psi_I(c_{It}|\widehat{c}_{It-1})\psi_E(c_{Et}|c_{Et-1}) dc_{It} dc_{Et} + ...$$

$$\beta \int\limits_{\underline{c_I}}^{\overline{c_I}}\int\limits_{\underline{c_E}}^{\overline{c_E}} \mathbb{E}_{t-1}[\phi^E_{t+1}|c_{It},c_{Et}]\psi_I(c_{It}|\widehat{c}_{It-1})\psi_E(c_{Et}|c_{Et-1}) dc_{It} dc_{Et}$$

$$\mathbb{E}_{t-1}[V^E_t|\widehat{c}_{It-1},c_{Et-1}] = \int\limits_{\underline{c_I}}^{\overline{c_I}}\int\limits_{\underline{c_E}}^{\overline{c_E}}\int\limits_{\underline{\kappa}}^{\overline{\kappa}} \max\{\beta \mathbb{E}_t[V^E_{t+1}|c_{It},c_{Et}], \beta \mathbb{E}_t[\phi_{t+1}|c_{It},c_{Et}] - \kappa_t\}...$$

$$\psi_I(c_{It}|\widehat{c}_{It-1})\psi_E(c_{Et}|c_{Et-1}) g(\kappa_t) dc_{It} dc_{Et} d\kappa_t$$

Continuity and differentiability of $\mathbb{E}_{t-1}[\phi^E_t|\widehat{c}_{It-1},c_{Et-1}]$ and $\mathbb{E}_{t-1}[V^E_t|c_{It-1,}c_{Et-1}]$ follow from continuity and differentiability of π^D_E (assumed), ψ_I and ψ_E (assumed) and $\mathbb{E}_t[V^E_{t+1}|c_{It},c_{Et}]$ and $\beta \mathbb{E}_t[\phi^E_{t+1}|c_{It},c_{Et}]$ (induction hypothesis).

(iv)

$$\mathbb{E}_{t-1}[\phi_t^E|\widehat{c}_{It-1}, c_{Et-1}] - \mathbb{E}_{t-1}[V_t^E|\widehat{c}_{It-1}, c_{Et-1}] = \int_{\underline{c_I}}^{\overline{c_I}}\int_{\underline{c_E}}^{\overline{c_E}} \pi_t^D(c_{It}, c_{Et})\psi_I(c_{It}|\widehat{c}_{It-1})\psi_E(c_{Et}|c_{Et-1})dc_{It}dc_{Et} + ...$$

$$+ \int_{\underline{c_I}}^{\overline{c_I}}\int_{\underline{c_E}}^{\overline{c_E}}\int_{\underline{\kappa}}^{\overline{\kappa}} \min\{\kappa_t, \beta\mathbb{E}_t[\phi_{t+1}^E|c_{It}, c_{Et}] - \beta\mathbb{E}_t[V_{t+1}^E|c_{It}, c_{Et}]\}...$$

$$\psi_I(c_{It}|\widehat{c}_{It-1})\psi_E(c_{Et}|c_{Et-1})g(\kappa_t)dc_{It}dc_{Et}d\kappa_t$$

so that

$$\frac{\partial\mathbb{E}_{t-1}[\phi_t^E|\widehat{c}_{It-1}, c_{Et-1}]}{\partial\widehat{c}_{It-1}} - \frac{\partial\mathbb{E}_{t-1}[V_t^E|\widehat{c}_{It-1}, c_{Et-1}]}{\partial\widehat{c}_{It-1}} = \int_{\underline{c_I}}^{\overline{c_I}}\int_{\underline{c_E}}^{\overline{c_E}} \pi_{Et}^D(c_{It}, c_{Et})\frac{\partial\psi_I(c_{It}|\widehat{c}_{It-1})}{\partial\widehat{c}_{It-1}}\psi_E(c_{Et}|c_{Et-1})dc_{It}dc_{Et}$$

$$+ \int_{\underline{c_I}}^{\overline{c_I}}\int_{\underline{c_E}}^{\overline{c_E}}\int_{\underline{\kappa}}^{\overline{\kappa}} \min\{\kappa_t, \beta\mathbb{E}_t[\phi_{t+1}|c_{It}, c_{Et}] - \beta\mathbb{E}_t[V_{t+1}^E|c_{It}, c_{Et}]\}...$$

$$\frac{\partial\psi_I(c_{It}|\widehat{c}_{It-1})}{\partial\widehat{c_{It-1}}}\psi_E(c_{Et}|c_{Et-1})g(\kappa_t)dc_{It}dc_{Et}d\kappa_t$$

Considering the terms in the second integral: $\kappa_t \geq 0$, and from the induction hypotheses $\beta\mathbb{E}_t[\phi_{t+1}^E|c_{It}, c_{Et}] - \beta\mathbb{E}_t[V_{t+1}^E|c_{It}, c_{Et}] > 0$ and is increasing in c_{It}. Application of Lemma 1 then implies that the second integral is ≥ 0.

Considering the term on the right-hand side of the first row: $\pi_E^D(c_{It}, c_{Et}) > 0$ and is strictly increasing in c_{It}. Application of Lemma 1 then implies that this term is > 0. Therefore, $\frac{\partial\mathbb{E}_{t-1}[\phi_t^E|\widehat{c}_{It-1}, c_{Et-1}]}{\partial\widehat{c}_{It-1}} - \frac{\partial\mathbb{E}_{t-1}[V_t^E|\widehat{c}_{It-1}, c_{Et-1}]}{\partial\widehat{c}_{It-1}} > 0$ as required.

The proof that $\frac{\partial\mathbb{E}_{t-1}[\phi_t^E|\widehat{c}_{It-1}, c_{Et-1}]}{\partial c_{Et-1}} < \frac{\partial\mathbb{E}_{t-1}[V_t^E|\widehat{c}_{It-1}, c_{Et-1}]}{\partial c_{Et-1}} < 0$ follows exactly the same logic, using the facts that $\frac{\partial\pi_E^D}{\partial c_{Et}} < 0$ and the induction hypothesis that $\beta\mathbb{E}_t[\phi_{t+1}|c_{It}, c_{Et}] - \beta\mathbb{E}_t[V_{t+1}^E|c_{It}, c_{Et}]$ is decreasing in c_{Et}. ■

A.2 Incumbent's Payoff Functions Satisfies the Conditions for Existence of the FSRE and and Uniqueness under the D1 Refinement

Let I's signaling payoff be denoted $\Pi^{It}(c_{It}, \widehat{c}_{It}, p_{It}, c_{Et})$, where $\widehat{c}_{It}$ is E's (point) belief about I's marginal cost. Given the structure of the game,

$$\Pi^{It}(c_{It}, \widehat{c}_{It}, p_{It}, c_{Et}) = q^M(p_{It})(p_{It} - c_{It}) + ... \tag{10}$$
$$\beta((1 - G(\kappa_t^*(\widehat{c}_{It}, c_{Et})))\mathbb{E}_t[V_{t+1}^I | c_{It}, c_{Et}] + G(\kappa_t^*(\widehat{c}_{It}, c_{Et}))\mathbb{E}_t[\phi_{t+1}^I | c_{It}, c_{Et}])$$

where $\mathbb{E}_t[V_{t+1}^I | c_{It}, c_{Et}]$ and $\mathbb{E}_t[\phi_{t+1}^I | c_{It}, c_{Et}]$ are the expected value to being a monopolist and duopolist in period $t+1$ given current marginal costs. Given E's threshold rule for entry, $\Pr(E \text{ not enter} | \widehat{c}_{It}, c_{Et}) = (1 - G(\kappa_t^*(\widehat{c}_{It}, c_{Et})))$.

Based on Theorem 1 of Mailath and von Thadden (forthcoming) (which is based on Mailath (1987)), we have the following result.

Proposition 3 *If (i) $\Pi^{It}(c_{It}, c_{It}, p_{It}, c_{Et})$ has a unique optimum in p_{It}, and for any $p_{It} \in [\underline{p}, \overline{p}]$ where $\Pi_{33}^{It}(c_{It}, c_{It}, p_{It}, c_{Et}) > 0$ $\exists k > 0$ such that $\left|\Pi_3^{It}(c_{It}, c_{It}, p_{It}, c_{Et})\right| > k$ for all (c_{It}, c_{Et}); (ii) $\Pi_{13}^{It}(c_{It}, \widehat{c}_{It}, p_{It}, c_{Et}) \neq 0$ for all $c_{It}, \widehat{c}_{It}, p_{It}, c_{Et}$; (iii) $\Pi_2^{It}(c_{It}, \widehat{c}_{It}, p_{It}, c_{Et}) \neq 0$ for all $c_{It}, \widehat{c}_{It}, p_{It}, c_{Et}$; (iv) $\frac{\Pi_3^{It}(c_{It}, \widehat{c}_{It}, p_{It}, c_{Et})}{\Pi_2^{It}(c_{It}, \widehat{c}_{It}, p_{It}, c_{Et})}$ is a monotone function of c_{It} for all $\widehat{c_{It}}$, c_{Et}; (v) $\overline{p} \geq p^{static\ monopoly}(\overline{c_I})$ and $\Pi^{It}(\underline{c_{It}}, \underline{c_{It}}, \underline{p}, c_{Et}) < \max \Pi^{It}(\underline{c_{It}}, \overline{c_{It}}, \underline{p}, c_{Et})$ for all t, c_{Et}, 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 given*

$$\frac{\partial p_{It}^*}{\partial c_{It}} = -\frac{\Pi_2^{It}}{\Pi_3^{It}}$$

with boundary condition that $p_{It}^*(\overline{c_I}) = p^{static\ monopoly}(\overline{c_I})$.

Proof. We show that our game satisfies conditions (i)-(iv). The second part of condition (v) is a condition that $\underline{p}$ is so low that no firm would ever want to choose it.

(i) $\Pi^{It}(c_{It}, \widehat{c}_{It}, p_{It}, c_{Et})$ only depend on p_{It} through the static monopoly profit function $\pi_{It}^M = q^M(p_{It})(p_{It} - c_{It})$. The profit function will satisfy the conditions if it is continuous, concave at the profit maximizing price and strictly quasi-concave in p_{It} on $[\underline{p}, \overline{p}]$, as assumed.

(ii) Differentiation of the payoff function gives

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

$\Pi_{13}^{It}(c_{It}, \widehat{c}_{It}, p_{It}, c_{Et}) \neq 0$ as long as monopoly demand is downward sloping on $[\underline{p}, \overline{p}]$.

(iii) Differentiation of the payoff function gives

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

$\Pi_2^{It}(c_{It}, \widehat{c}_{It}, p_{It}, c_{Et}) \neq 0$ if $g(\kappa_t^*(\widehat{c}_{It}, c_{Et})) > 0$ (which depends on entry costs having sufficient support), $\frac{\partial \kappa_t^*(\widehat{c}_{It}, c_{Et})}{\partial \widehat{c}_{It}} > 0$ for all $(\widehat{c}_{It}, c_{Et})$ (which follows from monotonicity of E's entry threshold rule in perceived incumbent marginal cost that was just proved), and $\left\{\mathbb{E}_t[V_{t+1}^I|c_{It}, c_{Et}] - \mathbb{E}_t[\phi_{t+1}^I|c_{It}, c_{Et}]\right\} > 0$ (expected continuation value as a monopolist greater than as a duopolist). This last property will be shown below.

(iv) Using equations (11) and (12) we have

$$\frac{\Pi_3^{It}(c_{It}, \widehat{c}_{It}, p_{It}, c_{Et})}{\Pi_2^{It}(c_{It}, \widehat{c}_{It}, p_{It}, c_{Et})} = \frac{\left[q^M(p_{It}) + \frac{\partial q^M(p_{It})}{\partial p_{It}}(p_{It} - c_{It})\right]}{\left(-\beta g(\kappa_t^*(\widehat{c}_{It}, c_{Et}))\frac{\partial \kappa_t^*(\widehat{c}_{It}, c_{Et})}{\partial \widehat{c}_{It}} \left\{\mathbb{E}_t[V_{t+1}^I|c_{It}, c_{Et}] - \mathbb{E}_t[\phi_{t+1}^I|c_{It}, c_{Et}]\right\}\right)} \tag{13}$$

Differentiation with respect to c_{It} gives

$$\frac{\partial \frac{\Pi_3^{It}(c_{It}, \widehat{c}_{It}, p_{It}, c_{Et})}{\Pi_2^{It}(c_{It}, \widehat{c}_{It}, p_{It}, c_{Et})}}{\partial c_{It}} = \frac{\frac{\partial q^M(p_{It})}{\partial p_{It}}}{\left(\beta g(\kappa_t^*(\widehat{c}_{It}, c_{Et}))\frac{\partial \kappa_t^*(\widehat{c}_{It}, c_{Et})}{\partial \widehat{c}_{It}} \left\{\mathbb{E}_t[V_{t+1}^I|c_{It}, c_{Et}] - \mathbb{E}_t[\phi_{t+1}^I|c_{It}, c_{Et}]\right\}\right)} + ... \tag{14}$$
$$\frac{\left[q(p_{It}) + \frac{\partial q^M(p_{It})}{\partial p_{It}}(p_{It} - c_{It})\right] \frac{\partial\left\{\mathbb{E}_t[V_{t+1}^I|c_{It}, c_{Et}] - \mathbb{E}_t[\phi_{t+1}^I|c_{It}, c_{Et}]\right\}}{\partial c_{It}} \left(\beta g(\kappa_t^*(\widehat{c}_{It}, c_{Et}))\frac{\partial \kappa_t^*(\widehat{c}_{It}, c_{Et})}{\partial \widehat{c}_{It}}\right)}{\left(\beta g(\kappa_t^*(\widehat{c}_{It}, c_{Et}))\frac{\partial \kappa_t^*(\widehat{c_{It}}, c_{Et})}{\partial \widehat{c}_{It}} \left\{\mathbb{E}_t[V_{t+1}^I|c_{It}, c_{Et}] - \mathbb{E}_t[\phi_{t+1}^I|c_{It}, c_{Et}]\right\}\right)^2}$$

Sufficient conditions for $\frac{\partial \frac{\Pi_3^{It}(c_{It}, \widehat{c}_{It}, p_{It}, c_{Et})}{\Pi_2^{It}(c_{It}, \widehat{c}_{It}, p_{It}, c_{Et})}}{\partial c_{It}}$ to be < 0 (implying $\frac{\Pi_3^{It}(c_{It}, \widehat{c}_{It}, p_{It}, c_{Et})}{\Pi_2^{It}(c_{It}, \widehat{c}_{It}, p_{It}, c_{Et})}$ monotonic in c_{It}) are:

(a) $V_{t+1}^I(c_{It+1}, c_{Et+1}) - \phi_{t+1}^I(c_{It+1}, c_{Et+1}) > 0$ for all (c_{It+1}, c_{Et+1}), which implies $\left\{\mathbb{E}_t[V_{t+1}^I|c_{It}, c_{Et}] - \mathbb{E}_t[\phi_{t+1}^I|c_{It}, c_{Et}]\right\} > 0$;

(b) $\frac{\partial\left\{V_t^I(c_{It}, c_{Et}) - \phi_t^I(c_{It}, c_{Et})\right\}}{\partial c_{It}} < 0$ for all (c_{It}, c_{Et}), which implies $\frac{\partial\left\{\mathbb{E}_t[V_{t+1}^I|c_{It}, c_{Et}] - \mathbb{E}_t[\phi_{t+1}^I|c_{It}, c_{Et}]\right\}}{\partial c_{It}}$ by Lemma 1[32];

(c) $\left[q(p_{It}) + \frac{\partial q^M(p_{It})}{\partial p_{It}}(p_{It} - c_{It})\right] \geq 0$ for all prices below the monopoly price (given quasi-concavity

[32] $\frac{\partial \mathbb{E}_t[V_{t+1}^I|c_{It}, c_{Et}]}{\partial c_{It}} - \frac{\partial \mathbb{E}_t[\phi_{t+1}^I|c_{It}, c_{Et}]}{\partial c_{It}} = \int_{\underline{c_I}}^{\overline{c_I}} \int_{\underline{c_E}}^{\overline{c_E}} \left\{V_{t+1}^I(c_{It+1}, c_{Et+1}) - \phi_{t+1}^I(c_{It+1}, c_{Et+1})\right\} \frac{\partial \psi_I(c_{It+1}|c_{It})}{\partial c_{It}} \psi_E(c_{Et+1}|c_{Et}) dc_{It} dc_{Et}$

of the profit function);

(d) $\frac{\partial \kappa_t^*(\widehat{c}_{It}, c_{Et})}{\partial \widehat{c}_{It}} > 0$ (just proved); and

(e) $\frac{\partial q^M(p_{It})}{\partial p_{It}} < 0$ (assumed).

We now establish (a) and (b) by backwards induction.

(a) $V_{t+1}^I(c_{It}, c_{Et}) - \phi_{t+1}^I(c_{It}, c_{Et}) > 0$.

In the final period, payoffs are simply static (no signaling) monopoly and duopoly profits, so, from our assumptions on π_I^D, $V_T^I - \phi_T^I > 0$ for all c_{IT}, c_{ET}.

Now consider any period $t < T$. Assume that $V_{t+1}^I(c_{It+1}, c_{Et+1}) - \phi_{t+1}^I(c_{It+1}, c_{Et+1}) > 0$. We show that $V_t^I(c_{It}, c_{Et}) - \phi_t^I(c_{It}, c_{Et}) > 0$ is implied.

$$\begin{aligned}
V_t^I(c_{It}, c_{Et}) &= \max_{p_{It}} q^M(p_{It})(p_{It} - c_{It}) + ... \\
&\quad \beta \left[\begin{array}{c} (1 - G(\kappa_t^*(\varsigma_t^{-1}(p_{It}), c_{Et})))\mathbb{E}_t[V_{t+1}^I | c_{It}, c_{Et}] \\ +G(\kappa_t^*(\varsigma_t^{-1}(p_{It}), c_{Et}))\mathbb{E}_t[\phi_{t+1}^I | c_{It}, c_{Et}] \end{array} \right] \\
\phi_t^I(c_{It}, c_{Et}) &= \pi_I^D(c_{It}, c_{Et}) + \beta \mathbb{E}_t[\phi_{t+1}^I | c_{It}, c_{Et}]
\end{aligned}$$

Now, under the assumption that $V_{t+1}^I(c_{It+1}, c_{Et+1}) - \phi_{t+1}^I(c_{It+1}, c_{Et+1}) > 0$ for all c_{It+1}, c_{Et+1},

$$\beta \left[\begin{array}{c} (1 - G(\kappa_t^*(\varsigma_t^{-1}(p_{It}), c_{Et})))\mathbb{E}_t[V_{t+1}^I | c_{It}, c_{Et}] + \\ G(\kappa_t^*(\varsigma_t^{-1}(p_{It}), c_{Et}))\mathbb{E}_t[\phi_{t+1}^I | c_{It}, c_{Et}] \end{array} \right] > \beta \mathbb{E}_t[\phi_{t+1}^I | c_{It}, c_{Et}]$$

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

(b) $\frac{\partial \left\{ V_t^I(c_{It}, c_{Et}) - \phi_t^I(c_{It}, c_{Et}) \right\}}{\partial c_{It}} < 0$ for all (c_{It}, c_{Et}).

In the final period, a monopolist will produce the static monopoly output so that $\frac{\partial V_T^I(c_{IT}, c_{ET})}{\partial c_{IT}} = -q^{\text{static monopoly}}(c_{IT})$. For the duopolist, $\frac{\partial \phi_T^I(c_{IT}, c_{ET})}{\partial c_{IT}} = -q_I^D(c_{IT}, c_{ET}) + \frac{\partial \pi_I^D}{\partial a_E^D} \frac{\partial a_E^D}{\partial c_{IT}}$. Therefore

$$\frac{\partial \{ V_T^I(c_{IT}, c_{ET}) - \phi_T^I(c_{IT}, c_{ET}) \}}{\partial c_{IT}} = q_I^D(c_{IT}, c_{ET}) - q^{\text{static monopoly}}(c_{IT}) - \frac{\partial \pi_I^D}{\partial a_E^D} \frac{\partial a_E^D}{\partial c_{IT}}$$

Under our assumptions on the duopoly game, this expression will be negative as required.

Consider a period $t < T$:

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

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

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

so

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

and

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

Therefore,

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

We need this expression to be negative. If $\frac{\partial\left\{V_{t+1}^I(c_{It+1},c_{Et+1}) - \phi_{t+1}^I(c_{It+1},c_{Et+1})\right\}}{\partial c_{It+1}} < 0$ (the induction hypothesis), then the term in square brackets is negative. Therefore a sufficient condition is that $q_I^D(c_{It},c_{Et}) - q^M(p^*(c_{It,}c_{et})) - \frac{\partial \pi_I^D}{\partial a_E^D}\frac{\partial a_E^D}{\partial c_{IT}}$ is negative. As the limit pricing output $q^M(p^*(c_{It,}c_{Et}))$ will be *greater* than the static monopoly output, a sufficient condition for the whole expression to be negative is simply the sufficient conditions that we had for period T, which we know are satisfied for our duopoly game. ■

Based on Theorem 3 of Ramey (1996) we have the following result.

Proposition 4 *Take the signaling payoff* $\Pi^{It}(c_{It}, \kappa_t, p_{It}, c_{Et})$ *where* κ_t *is E's threshold. If Conditions (i)* $\Pi_2^{It}(c_{It}, \kappa_t, p_{It}, c_{Et}) \neq 0$ *for all* $c_{It}, \kappa_t, p_{It}, c_{Et}$*; (ii)* $\frac{\Pi_3^{It}(c_{It},\kappa_t,p_{It},c_{Et})}{\Pi_2^{It}(c_{It},\kappa_t,p_{It},c_{Et})}$ *is a monotone function of* c_{It} *for all* κ*,* c_{Et}*; and (iii)* $\overline{p} \geq p^{\text{static monopoly}}(\overline{c_I})$ *and* $\Pi^{It}(\underline{c_{It}}, \overline{\kappa}, \underline{p}, c_{Et}) < \max \Pi^{It}(\underline{c_{It}}, \underline{\kappa}, \underline{p}, c_{Et})$ *for all* t, c_{Et}*, then an equilibrium satisfying the D1 refinement will be fully separating.*

We can show that our game satisfies these conditions by essentially replicating the above proofs.

Proof. We establish (i) and (ii) as condition (iii) is a requirement that $\underline{p}$ is low enough such that I would never choose it.

(i) $\Pi_2^{It}(c_{It}, \kappa_t, p_{It}, c_{Et}) = -\beta g(\kappa_t) \left\{\mathbb{E}_t[V_{t+1}^I | c_{It}, c_{Et}] - \mathbb{E}_t[\phi_{t+1}^I | c_{It}, c_{Et}]\right\}$. This will not be equal to zero if $g(\cdot) > 0$ (which depends on entry costs having sufficient support), and $\left\{\mathbb{E}_t[V_{t+1}^I | c_{It}, c_{Et}] - \mathbb{E}_t[\phi_{t+1}^I | c_{It}, c_{Et}]\right\} > 0$ (expected continuation value as a monopolist greater than as a duopolist). This property was shown above.

(ii) As before, we have

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

Differentiation with respect to c_{It} yields

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

Sufficient conditions for $\frac{\partial \frac{\Pi_3^{It}(c_{It},\kappa_t,p_{It},c_{Et})}{\Pi_2^{It}(c_{It},\kappa_t,p_{It},c_{Et})}}{\partial c_{It}}$ to be < 0 (implying $\frac{\Pi_3^{It}(c_{It},\kappa_t,p_{It},c_{Et})}{\Pi_2^{It}(c_{It},\kappa_t,p_{It},c_{Et})}$ monotonic in c_{It}) are that:

(a) $V_{t+1}^I(c_{It+1}, c_{Et+1}) - \phi_{t+1}^I(c_{It+1}, c_{Et+1}) > 0$ for all (c_{It+1}, c_{Et+1}), implying $\left\{\mathbb{E}_t[V_{t+1}^I | c_{It}, c_{Et}] - \mathbb{E}_t[\phi_{t+1}^I | c_{It}, c_{Et}]\right\} > 0$;

(b) $\frac{\partial\left\{V^I_{t|}(c_{It},c_{Et})-\phi^I_t(c_{It},c_{Et})\right\}}{\partial c_{It}} < 0$ which implies $\frac{\partial\left\{\mathbb{E}V^I_{t|}(c_{It},c_{Et})-\mathbb{E}\phi^I_t(c_{It},c_{Et})\right\}}{\partial c_{It}} < 0$ by Lemma 1[33]; and

(c) $\left[q(p_{It}) + \frac{\partial q^M(p_{It})}{\partial p_{It}}(p_{It} - c_{It})\right] \geq 0$ for all prices below the monopoly price (which will hold given that the static profit function is strictly quasi-concave). These properties were shown above. ■

B Additional Reduced Form Results

This appendix contains additional reduced form results referred to throughout the paper.

Table B.1: Incumbent Responses to the Threat of Entry - Logged 75th Percentile Fare

β Estimates					
Before WN is PE:		WN is PE:		WN is E:	
$t_0 - 8$	-0.053	t_0	-0.135^{***}	t_e	-0.476^{***}
	(0.034)		(0.046)		(0.091)
$t_0 - 7$	-0.063	$t_0 + 1$	-0.170^{***}	$t_e + 1$	-0.597^{***}
	(0.039)		(0.045)		(0.092)
$t_0 - 6$	-0.064	$t_0 + 2$	-0.193^{***}	$t_e + 2$	-0.615^{***}
	(0.041)		(0.046)		(0.098)
$t_0 - 5$	-0.055	$t_0 + 3$	-0.176^{***}	$t_e + 3$	-0.697^{***}
	(0.042)		(0.046)		(0.106)
$t_0 - 4$	-0.042	$t_0 + 4$	-0.194^{***}	$t_e + 4$	-0.707^{***}
	(0.042)		(0.047)		(0.102)
$t_0 - 3$	-0.0333	$t_0 + 5$	-0.190^{***}	$t_e + 5$	-0.655^{***}
	(0.0377)		(0.052)		(0.106)
$t_0 - 2$	-0.105^{***}	$t_0 +$ 6-12	-0.242^{***}	$t_e +$ 6-12	-0.672^{***}
	(0.040)		(0.061)		(0.101)
$t_0 - 1$	-0.111^{***}	$t_0 + 13+$	-0.388^{***}	$t_e + 13+$	-0.636^{***}
	(0.039)		(0.069)		(0.109)
Market-Carrier Fixed Effects:			Yes		
Quarter Fixed Effects:			Yes		
Time-varying Control:			Yes		
N	3904				
adj. R^2	0.742				

Dependent variable is log 75th percentile passenger fare. Standard errors are in parentheses and are clustered by route-carrier. *** denotes significance at the 1% level, ** at 5% and * at 10%.

[33] $$\frac{\partial\mathbb{E}_t[V^I_{t+1}|c_{It},c_{Et}]}{\partial c_{It}} - \frac{\partial\mathbb{E}_t[\phi^I_{t+1}|c_{It},c_{Et}]}{\partial c_{It}} = \int_{\underline{c_I}}^{\overline{c_I}}\int_{\underline{c_E}}^{\overline{c_E}} \left\{V^I_{t+1}(c_{It+1},c_{Et+1}) - \phi^I_{t+1}(c_{It+1},c_{Et+1})\right\} \frac{\partial\psi_I(c_{It+1}|c_{It})}{\partial c_{It}}\psi_E(c_{Et+1}|c_{Et})dc_{It}dc_{Et}$$

Table B.2: Incumbent Responses to the Threat of Entry - Logged Median Fare

β Estimates					
Before WN is PE:		WN is PE:		WN is E:	
$t_0 - 8$	-0.029	t_0	-0.121^{***}	t_e	-0.524^{***}
	(0.034)		(0.039)		(0.090)
$t_0 - 7$	-0.020	$t_0 + 1$	-0.131^{***}	$t_e + 1$	-0.615^{***}
	(0.042)		(0.047)		(0.090)
$t_0 - 6$	-0.023	$t_0 + 2$	-0.129^{***}	$t_e + 2$	-0.650^{***}
	(0.04)		(0.042)		(0.097)
$t_0 - 5$	-0.016	$t_0 + 3$	-0.144^{***}	$t_e + 3$	-0.722^{***}
	(0.039)		(0.042)		(0.104)
$t_0 - 4$	-0.034	$t_0 + 4$	-0.163^{***}	$t_e + 4$	-0.685^{***}
	(0.041)		(0.042)		(0.104)
$t_0 - 3$	-0.024	$t_0 + 5$	-0.175^{***}	$t_e + 5$	-0.628^{***}
	(0.0385)		(0.050)		(0.107)
$t_0 - 2$	-0.107^{***}	$t_0 + 6\text{-}12$	-0.249^{***}	$t_e + 6\text{-}12$	-0.615^{***}
	(0.037)		(0.051)		(0.102)
$t_0 - 1$	-0.097^{**}	$t_0 + 13+$	-0.364^{***}	$t_e + 13+$	-0.612^{***}
	(0.0386)		(0.061)		(0.109)
Market-Carrier Fixed Effects:			Yes		
Quarter Fixed Effects:			Yes		
Time-varying Control:			Yes		
N	3904				
adj. R^2	0.725				

Dependent variable is log median percentile passenger fare. Standard errors are in parentheses and are clustered by route-carrier. *** denotes significance at the 1% level, ** at 5% and * at 10%.

Table B.3: Incumbent Responses to the Threat of Entry - Logged 25th Percentile Fare

β Estimates					
Before WN is PE:		WN is PE:		WN is E:	
$t_0 - 8$	-0.039	t_0	-0.091^{**}	t_e	-0.424^{***}
	(0.031)		(0.037)		(0.074)
$t_0 - 7$	0.002	$t_0 + 1$	-0.105^{**}	$t_e + 1$	-0.455^{***}
	(0.033)		(0.039)		(0.073)
$t_0 - 6$	-0.019	$t_0 + 2$	-0.117^{**}	$t_e + 2$	-0.497^{***}
	(0.037)		(0.041)		(0.076)
$t_0 - 5$	-0.029	$t_0 + 3$	-0.134^{***}	$t_e + 3$	-0.534^{***}
	(0.036)		(0.036)		(0.079)
$t_0 - 4$	0.027	$t_0 + 4$	-0.085	$t_e + 4$	-0.547^{***}
	(0.038)		(0.0404)		(0.081)
$t_0 - 3$	0.005	$t_0 + 5$	-0.099^{*}	$t_e + 5$	-0.523^{***}
	(0.036)		(0.042)		(0.083)
$t_0 - 2$	-0.062^{*}	$t_0 +$ 6-12	-0.170^{***}	$t_e +$ 6-12	-0.502^{***}
	(0.034)		(0.049)		(0.082)
$t_0 - 1$	-0.055^{*}	$t_0 +$ 13+	-0.286^{***}	$t_e +$ 13+	-0.494^{***}
	(0.031)		(0.056)		(0.089)
Market-Carrier Fixed Effects:			Yes		
Quarter Fixed Effects:			Yes		
Time-varying Control:			Yes		
N	3904				
adj. R^2	0.748				

Dependent variable is log 25th percentile passenger fare. Standard errors are in parentheses and are clustered by route-carrier. *** denotes significance at the 1% level, ** at 5% and * at 10%.