An Empirical Model of Dynamic Limit Pricing: The Airline Industry

Chris Gedge∗  James W. Roberts†  Andrew Sweeting‡

July 5, 2012

Abstract

Theoretical models of strategic investment often assume that information is incomplete, creating incentives for firms to signal information to deter entry or encourage exit. However, the very simple one-shot nature of these models has limited the scope for testing whether these models can quantitatively or even qualitatively fit the data. We develop a fully dynamic model with persistent asymmetric information, where an incumbent has incentives to repeatedly signal information about its costs to a potential entrant. The model is well-suited for empirical work in that it has a unique Perfect Bayesian Equilibrium under a standard form of refinement, with strategies that can be computed quite easily. We are in the process of using our model to test whether dynamic limit pricing can explain why a dominant incumbent airline drops its price when Southwest becomes a potential entrant on a route. The current version of the paper uses some existing tests to show that there is strong evidence of some form of strategic pricing behavior on the routes in our sample.

∗Duke University. Contact: cdg20@duke.edu.
†Duke University and NBER. Contact: j.roberts@duke.edu.
‡Duke University and NBER. Contact: atsweet@duke.edu.
We are grateful to Joe Mazur for a help in preparing the data used in this study. All errors are our own.
1 Introduction

In markets where entry costs are significant, a dominant incumbent firm may have an incentive to take actions that deter entry. This possibility has led to a vast array of theoretical models (Belleflamme and Peitz [2009], Tirole [1994]) that are a staple of undergraduate IO courses, but there is very little evidence that these models fit the data quantitatively or even qualitatively, despite the fact that concepts such as limit pricing have attracted IO economists since at least Bain [1949]. This lack of evidence may also be one reason why there have been few attempts by the antitrust authorities to stop pricing or other strategies that may be aimed at limiting or distorting future competition. The lack of evidence is particularly striking for the class of models where strategic behavior results from an asymmetry of information between the incumbent and potential entrants, of which the limit pricing model of Milgrom and Roberts [1982] is the canonical example. One reason is that most of these models have a very simple two-period structure which makes it very unclear what one would expect to see in a realistic setting where the incumbent has to set price repeatedly.

In this paper we propose a simple, tractable model with persistent asymmetric information, which gives an incumbent the incentive to repeatedly signal its costs to a potential entrant using prices in order to affect the entry decision (dynamic limit pricing). The structure of the model is quite simple: there is a single incumbent and a long-lived potential entrant. The potential entrant has a known marginal cost and, each period, it draws a (sunk) entry cost from a distribution. The incumbent has a marginal cost which is serially correlated but evolves from period-to-period, and is not known by the potential entrant prior to entry (post-entry we assume a game of complete information). The potential entrant does know demand. Any incumbent with a cost below the highest possible level has an incentive to signal using price in order to try to deter entry, and there is an incentive to signal every period because costs are not perfectly persistent. The current version of the paper develops the model and shows that it satisfies the conditions required for there to be a unique Perfect Bayesian Equilibrium under a dynamic version of the D1 refinement.
In doing so, we exploit recent generalizations of the theory of signaling games using the properties of supermodularity (Roddie [2012a,b]). It is also relatively easy to characterize and solve for the incumbent’s equilibrium pricing strategy, and to examine the comparative statics of the strategies with respect to parameters such as the marginal cost and the entry cost distribution of the potential entrant.

We will use our model to test whether dynamic limit pricing can explain why incumbent airlines dropped their prices significantly (20%) when faced by the threat of entry by Southwest, a stylized pattern in the data studied by Morrison [2001] and Goolsbee and Syverson [2008], focusing on a subset of markets with a dominant incumbent carrier to match the assumptions of our model. Our strategy is to estimate as many of the parameters of our model as possible using the periods before Southwest became a (realistic) potential entrant and after it became an actual entrant, and then use our calibrated model to test how large the price cuts implied by a dynamic limit pricing strategy would have been in different markets which varied in how attractive entry would have been for Southwest. While we are still in the process of doing this exercise, the current draft contains empirical results which are contributions to the small empirical literature trying to test whether data is qualitatively consistent with strategic behavior. In particular, we follow the strategy of Ellison and Ellison [2011] (Dafny [2005] provides another application) in looking for evidence of a non-monotonicity between the attractiveness of the market for new entry and the level of strategic investment (price cut) by the incumbent. Relative to the existing literature, we find quite strong evidence of a non-monotonicity in our data with larger price cuts in markets of intermediate size, than in smaller markets where entry was unlikely or larger markets where it was very likely. ¹

Our paper also contributes to the literature on dynamic games. Here almost all of the

¹Evidence of strategic behavior does not, of course, prove that our asymmetric information story is correct. Instead, it could be that there is complete information but that a low price locks-in consumers to the incumbent (e.g., frequent flyer programs) and that it is this that deters entry from happening. Our aim in calibrating the limit pricing model to test whether it predicts price declines that are similar to those in the data is not to prove that the asymmetric information story must be right, but to provide the first empirical evidence that this type of model could explain what is going on in the data. Of course, we will try to provide support for the asymmetric information story by compiling additional evidence.
existing literature follows Ericson and Pakes [1995] in assuming that firms have complete information about the current state, or that this is true up to payoff shocks that are iid over time and across players so that there is no incentive for a firm to try to signal the value of these shocks. This is also the approach taken in all of the existing empirical literature. A recent paper by Fershtman and Pakes [2010] considers an infinite-horizon, discrete state, discrete action game with persistent asymmetric information. They argue that in this type of game, it will not be feasible to keep track of the distribution of firms’ beliefs about the types of other firms, so that they propose a computationally-friendly alternative to Perfect Bayesian Equilibrium, which they call Experience Based Equilibrium (EBE). In an EBE beliefs are not specified.

Our ability to use PBE as our equilibrium concept comes two features of the model (the incumbent’s cost is a continuous variable and the incumbent’s price is a continuous action) and from a feature of the equilibrium (full separation, so that there is an invertible one-to-one mapping between cost and price). The equilibrium belief of the entrant about the incumbent’s cost is therefore degenerate, which greatly simplifies the problem. If an incumbent could only choose between discrete actions, or we considered a model where in equilibrium incumbent’s with different costs wanted to choose the same action, we would be faced by the intractable problem discussed by Fershtman and Pakes [2010]. While recognizing that it is these features, which are certainly not general, that allow us to make progress using PBE as a concept, we emphasize that they allows us to study one of the main phenomenon (limit pricing) that motivate interest in models with asymmetric information.

This paper is organized as follows. Section 2 provides a brief discussion of the entry deterrence literature. Section 3 outlines the utility specification and supply side of the model. The data are presented in section 4, with reduced form results in section 5. Section 6 concludes.
2 Related Literature

Prior to Milgrom and Roberts [1982] limit pricing was modeled in a game of complete information. Bain [1949] introduced the idea. His insight was that the current price need play no direct role in the entry decision, as what is of relevance to the entrant is the post-entry price and market share. However, to the extent that the current price is an indicator (or signal) of post-entry profitability it will contain useful information for a potential entrant. An incumbent monopolist with a strategic deterrence incentive could thus price below that of a static profit maximizing monopolist, devoid of the strategic motive. Yet, for this lower price to be optimal it has to be a credible commitment of how post-entry play would be conducted, else it would fall foul of the so-called Chicago School critique (see, e.g. Bork [1978], McGee [1958, 1980]). The intuition is simple: if the lower price was non-credible then the incumbent firm could strictly increase profits through moving its price to that of a static profit maximizing monopolist, i.e. the non-credible lower price is not subgame perfect (Selten [1965, 1978]). In a game of complete information limit pricing was therefore not an equilibrium outcome.

Milgrom and Roberts pointed out that if the incumbent’s marginal cost was private information the optimality of limit pricing can be recovered. In pricing below that of a monopolist the incumbent could signal information about its cost, an unknown probability of post-entry collusion or uncertain elasticity of demand. As in Spence’s [1973] signaling model a separating equilibrium could be supported whereby higher types (lower cost firms) could set low prices so as to deter entry. However, this result is only shown to hold with two types (high and low), for two periods and with type being time invariant\(^2\). In some settings, and in particular in applied work, this may not be appropriate and instead we can think of types as being of continuous support and evolving through time. The evolution of types implies that there may be an incentive for a firm to repeatedly signal its type, rather

\(^2\)Recent work has started to relax these assumptions. Kaya [2009] and Toxvaerd [2010] introduce multiple periods of signaling, but with only two and fixed types, which tends to result in early separation. Elsewhere, Mester [1992] allows for a continuum of imperfectly correlated cost types in a game of repeated signaling between two simultaneous move quantity setting competitors. This leads to a game of learning between incumbents, as opposed to a game containing strategic entry deterrence.
than the once and for all implications of Milgrom and Roberts.

Empirical research in strategic entry deterrence has lagged the theory. The seminal work in this area is by Ellison and Ellison [2011] who investigate entry deterrence in the pharmaceutical industry. Their insight is that, as long as variables are defined appropriately, there is a non-monotonic relationship between market attractiveness and a strategic variable in the presence of strategic entry deterrence, but not otherwise. Entrants into unattractive markets face an unfavorable residual demand curve, acting to shelter incumbents, whereas those in attractive markets face inevitable entry. On the other hand, incumbents in markets of middling attractiveness face entrants that are “on the fence” and it is on these markets that incumbents may therefore attempt to deter entry. In such situations a strategic variable would be expected to be utilized more (or possibly less) than if entry were otherwise unlikely or certain to occur. Using this insight Ellison and Ellison find that medium-sized markets invest less in advertising in the months immediately prior to patent expiration, due to the potential for spillovers of advertising to generic products. Similar effects may well be present in the airline industry. If firms are entering into dynamic limit pricing then the probability of entry can be affected through signaling a low marginal cost, a strategy that will be shown to be incentive compatible, in equilibrium. The incentive to enter into this strategy is thus dependent upon the incumbent being of sufficiently low marginal cost and that the probability of entry is in some medium range. Existence of a non-monotonic relationship of prices and the probability of entry will be a necessary, albeit not sufficient, first indication of firms attempting to deter entry. This insight will be utilized in developing the structural model that follows.

The airline industry has been extensively studied in the Industrial Organization literature, with some suggestion of airlines adopting strategies aimed at deterrence. Closest to the ideas of this paper is Goolsbee and Syverson [2008] who look at the relationship between incumbents’ prices and the presence of Southwest on a route. Interestingly, incumbents cut their prices significantly once Southwest becomes a potential entrant and then again by a similar amount on Southwest’s entry. Goolsbee and Syverson, among other
explanations, rule out the possibility that airlines are attempting to deter entry through capacity adjustments, but they are unable to explain why firms use this price cutting strategy. Similar findings are made elsewhere. Kwoka and Shumilkina [2010] find that removing a competitor, through a merger, can soften price competition by as much as 10 percent. Additionally, removing a potential competitor has a non-trivial effect on lessening price competition (5-6 percent), a finding they attribute to contestability (Baumol et al. [1982]). However, it should be noted that a similar finding would be made if airlines were entering into strategic entry deterrence (or accommodation). Why airlines reduce prices prior to entry of a competitor thus remains an open question.

3 Model

Similar to Ericson and Pakes [1995] we present a model of dynamic strategic interaction between firms. Our model is simpler in that there is a monopolist incumbent on all markets facing one potential entrant, as opposed to having to solve a dynamic oligopoly game for an arbitrary set of $N$ entrants, but it is also more complicated because incumbent firms are signaling their cost type through repeated attempts to deter or accommodate entry. This complication introduces a Bayesian game between the sets of players. Utilizing new results from Roddie [2012b] a Perfect Bayesian Equilibrium can be shown to exist with repeated separation of types.

3.1 Consumer Demand

The demand system is obtained from aggregating over discrete choices of consumers. On each market, to be understood as a non-directional city pair, consumer utility is derived from a vector of individual characteristics, $\epsilon$, and a vector of product characteristics, $(x, \xi, p)$, where $(x, p)$ are observed and $\xi$ are unobserved by the econometrician. A product is a round-trip on market $m$. Consumer $i$’s indirect utility from purchasing a product from airline $j$ on market $m$ is given by,
\[ U(\epsilon_{ijm}, p_{jm}, x_{jm}, \xi_{jm}; \theta) = x_{jm}\beta - \alpha p_{jm} + \xi_{jm} + \epsilon_{ijm} = \delta_{jm} + \epsilon_{ijm} \]

where \( \theta = (\alpha, \beta) \) is the parameters of the system to be estimated. For convenience of notation the subscript \( m \) will be dropped except where its inclusion aids understanding.

As is standard in the literature \( p_j \) is the fare for product \( j \), \( \xi_j \) is a common (to all consumers) vector of unobserved product attributes that acts to vertically differentiate airline-product pairs, e.g. upholstery quality, cabin attendant friendliness, and \( x_j \) will include all observed product attributes, e.g. seat size, number of connections, distance, etc. Consumer \( i \) chooses product \( j \) if and only if,

\[ U(\epsilon_{ij}, p_j, \xi_j, x_j; \theta) \geq U(\epsilon_{ik}, p_k, \xi_k, x_k; \theta) \quad \forall k = 0, 1, \ldots, J \]

where product 0 is the outside option, to be thought of as taking an alternative mode of transport.

Heterogeneity in tastes will enter the model through \( \epsilon \), which is assumed to be independently distributed multivariate extreme value across consumers and products. From equation (1) these \( \epsilon \) define the set of consumers who purchase product \( j \). Formally, this set is given by \( A_j(\delta) = \{ \epsilon_i : \delta_j + \epsilon_{ij} \geq \delta_k + \epsilon_{ik}, \forall k \neq j \} \). The market share of airline \( j \) is given by the probability that \( \epsilon_i \) is contained in \( A_j \),

\[ s_j(\delta(x, p, \xi), x, \theta) = \int_{A_j(\delta)} f(\epsilon, x, \sigma_\epsilon) d\epsilon = \frac{\exp(\delta_j)}{\sum_{k \in J} \exp(\delta_k)} \]

where the second equality follows from the assumptions on the distribution of \( \epsilon \).

The measure of consumers in market \( m \) is given by \( M \). As with elsewhere in the literature (e.g. Borenstein and Rose [1995], Ciliberto and Tamer [2009]) this is taken to be the average of the population in the two endpoints of the route\(^3\). The observed output of

---

\(^3\)The other popular definition (e.g. Berry and Jia [2008], Ciliberto and Williams [2010]) is to use the geometric mean of the endpoints.
firm \( j \) is thus,

\[
q_j = Ms_j(x, \xi, p; \theta)
\]

(3)

with \( q_m = (q_{1m}, q_{2m}, \ldots q_{Jm}) \) denoting the vector of quantities on market \( m \).

3.2 Firm Behavior

Whilst the consumer side of the model is familiar the supply side will require more attention. As an overview, on each independent market there exists a monopolist incumbent and a potential entrant. At time \( t \) the incumbent has a private marginal cost of serving passengers, \( c_{I,t} \), and sets prices so as to maximize the flow of future profits. Importantly, price is used as a strategic variable for two purposes. The first is as a mark-up over marginal costs so as to choose the point on the demand curve that maximizes static profits as in models of complete information. The second is as a mechanism to deter entry, the idea being that the firm can set its price so as to signal its marginal cost. This second objective may well operate in conflict with the first so that price deviates from that of a static profit maximizing monopolist. The intuition is simple: by setting a price below that of a monopolist the entrant may infer that the marginal cost of the incumbent is sufficiently low so as to make entry unattractive. If the signaled cost is insufficient to deter entry then the potential entrant can pay an entry cost \( \kappa_t \). Once the entrant is in the market the firms compete as complete information price setting duopolists for the remainder of the game.

The setup thus far described is similar to that of Milgrom and Roberts [1982]. Where it will differ is that the marginal cost of the incumbent is assumed to be time varying and that it will evolve according to a Markov process defined on continuous support. This generates a repeated incentive to signal (Roddie [2012a,b]). Additionally, the entry cost will be independently time varying and identically distributed. The advantage of this approach is that it can rationalize entry at different periods of the game, in contrast to the all or nothing outcome of the existing literature.
Formally, the model is as follows. There are two players - the incumbent signaler and the potential entrant - who interact over an infinite horizon, where time is discrete. In each period the incumbent’s private marginal cost, $c_{I,t} \in [c_{I,\text{min}}, c_{I,\text{max}}]$ is realized after which the incumbent sets its price, $p_{I,t}$, so as to maximize discounted lifetime profits. The marginal cost of the entrant, $c_E$, is fixed for all periods and is observed by both players. After observing the incumbent’s price the entrant draws a private entry cost, $\kappa_t$, and makes the decision as to whether to enter\(^4\). Entry takes one period to implement with the cost borne in the current period. It is common knowledge that $\kappa_t$ is drawn from distribution $G_\kappa$ each period, independent both of marginal costs and over time. Conditional on entry the marginal cost of the incumbent is public information and the two firms compete as price setting duopolists. For convenience it will be assumed that once the entrant is in the market both firms remain in for all future periods\(^5\) and that both players discount the future at the common discount factor, $\beta$.

Additionally, it is assumed that the incumbent’s marginal cost varies according to the common knowledge Markov process, $\psi : C \rightarrow \Delta C$, for some increasing $\psi$. This is important, but also agrees with intuition. If an incumbent’s marginal cost was iid over time then there would be no link between today’s price signal and tomorrow’s cost thus returning us to the situation where a separating equilibrium could not be supported.

3.2.1 Entrant Strategy Profile

The entrant, which is taken to be Southwest, treats each market as independent when taking its entry decision. After observing the price set by the incumbent in the previous period the entrant is able to form beliefs as to the incumbent’s cost. These beliefs are given by, $\gamma(\tilde{c}_{I,t-1} | p_{I,t-1})$. Utilizing the Markov structure on the incumbent’s cost this implies an expectation of the incumbent’s cost for the current period that will form the entrant’s prior, $\psi(\gamma(\cdot))$.

\(^4\)This approach differs from Milgrom and Roberts who instead assume that the entrant’s marginal cost is private, its entry cost common knowledge. The assumptions taken in this paper are closer to the applied literature on entry games and are chosen for that reason.

\(^5\)This is commonly observed in the data.
Southwest’s problem is fairly straightforward. Upon observing $p_{I,t}$ it updates its beliefs over the incumbent’s cost, $\tilde{c}_{I,t}$, using Bayes rule, and decides whether to pay the realized entry cost, $\kappa_t \in [\kappa_{\text{min}}, \kappa_{\text{max}}]$ or to stay out. As is common in the literature (e.g. Ericson and Pakes [1995], Ryan [2012]), whilst the entry cost is to be paid in the current period the entrant will compete with the incumbent for the first time in the next period. This implies values of $(c_E, \kappa_t)$ and beliefs over the incumbent’s cost for this period, $\tilde{c}_{I,t}$, and for the following period, $\psi(\tilde{c}_I)$, that govern the entry decision.

The entry decision is similar to that of Ryan and Tucker [2011] in that Southwest faces an optimal stopping problem. If the current period realization of $\kappa_t$ is high then Southwest may prefer to forgo next period profits so as to wait for a lower entry cost realization. Suppose that after observing $p_{I,\tau}$ Southwest decides to enter at period $\tau$. The value function associated with this decision is given by,

$$V_E(E_\tau = 1, p_{I,\tau}) = \mathbb{E}\left[\sum_{t > \tau} \beta^{t-\tau} \pi(p_I, p_E)\right] - \kappa_\tau$$

where $E_\tau$ is the entry decision at period $\tau$.

The value function for a potential entrant is thus given by,

$$V_E(E_\tau = 0, p_{I,\tau}) = \max\{\mathbb{E}[V_E(E_\tau = 1, p_{I,\tau}), \beta \mathbb{E}[V_E(E_{\tau+1} = 0, p_{I,\tau+1})]\}$$

where the expectation is over future values of $\kappa$ and of the incumbent’s cost. Equation (5) captures the trade-off facing Southwest. If it enters in the current period it receives the NPV of future profits, less the current period’s entry cost. This is the first term in the braces. If instead it chooses not to enter it can enter in a future period. This latter option is the second term in the braces and constitutes a loss of subsequent period profits, but a potentially lower entry cost, relative to current period entry.

It is assumed that the entry decision will satisfy the following condition:
**Condition 1:** For all beliefs of the incumbent’s marginal cost, the probability of entry, \( P_{\text{entry}} \), satisfies, \( 0 < P_{\text{entry}} < 1 \).

There are two corollaries of Condition 1. The first is that for a given \( c_E \) and low cost beliefs \( \tilde{c}_{I,t} = c_{\text{min}} \), for all subsequent time periods, we can find a \( \kappa_t(c_E, \tilde{c}_{I,\text{min}}) > \kappa_{\text{min}} \) such that,

\[
\frac{\beta}{1 - \beta} (p_E - c_E)M_s(p) - \kappa(c_E, \tilde{c}_{I,\text{min}}) = 0 \tag{6}
\]

In words, for any given marginal cost of the entrant there exists an entry cost low enough that the entrant will enter with positive probability even if beliefs are such that the incumbent will have the lowest possible marginal cost for all future periods. This is given by the set of entry costs, \( \kappa(c_E, \tilde{c}_{I,t}) \in [\kappa_{\text{min}}, \kappa] \). Conversely, we can find a \( \bar{\kappa}(c_E, \tilde{c}_{I,\text{max}}) < \kappa_{\text{max}} \) such that for a given \( c_E \) and beliefs \( \tilde{c}_{I,t} = c_{\text{max}} \) for all future time periods,

\[
\frac{\beta}{1 - \beta} (p_E - c_E)M_s(p) - \bar{\kappa}(c_E, \tilde{c}_{I,\text{max}}) = 0 \tag{7}
\]

i.e. for any \( c_E \) there exists a sufficiently high entry cost such that entry may not be optimal even if it is believed that the incumbent will have the maximal marginal cost for all future periods. This is the set of entry costs given by, \( \kappa(c_E, \tilde{c}_{I,t}) \in [\bar{\kappa}, \kappa_{\text{max}}] \). Graphically these conditions are illustrated in Figure 2.

In the figure the regions of entry are delineated by entry threshold loci that represent equations (6) and (7). The upper locus corresponds to equation (7). For any \( c_E \) we can find a \( \kappa > \bar{\kappa} \) such that entry is not optimal, given beliefs. This is given by the lilac shaded region, labeled “No Entry”. The lower locus corresponds to equation (6), such that for any \( c_E \) we can find a \( \kappa \leq \bar{\kappa} \) whereby entry is optimal, given beliefs. This is the unshaded region in the bottom left, labeled “Entry”. For any other belief not at the maximal or minimal marginal cost there is an equivalent entry threshold that sits in between these two loci.

We can also see that Southwest’s marginal cost cannot be “too high”. Suppose \( c_E \in [c_{E,\text{min}}, c_{E,\text{max}}] \) and the realization is \( c_E = c_{E,\text{max}} \). Then, for the probability of entry to
be non-zero for all beliefs, \( \tilde{c}_I \), we require that \( \kappa \) is sufficiently low to induce entry. In this case, if \( \tilde{c}_I = c_{I,\text{min}} \) for all future periods, entry occurs on the section of the red vertical line below the blue locus. Equivalently, if \( \tilde{c}_I = c_{I,\text{max}} \) and \( c_E = c_{E,\text{min}} \) then entry will still not occur in the region above the black locus on the left hand vertical axis. Thus fixing a distribution for entry costs implies a relationship between the marginal cost of the entrant and the incumbent.

Collecting the above, Southwest’s strategy profile is therefore given by, \( \sigma_E : (\tilde{c}_I, c_E, \kappa) \rightarrow \{\text{Enter}, \text{StayOut}\} \).

3.2.2 Incumbent Strategy Profile

Conditional on entry occurring at period \( \tau \), lifetime profits for the incumbent are given by,
\[ U_I(p_I, p_E, c_I) = \sum_{t \leq \tau} \beta^t (p_{I,t} - c_{I,t}) M s_{I,t}^M(p) + \sum_{t > \tau} \beta^t (p_{I,t} - c_{I,t}) M s_{I,t}^D(p) \] (8)

where \( s_{I,t}^M \) is the market share of the monopolist incumbent at time \( t \) as derived from the consumer optimization problem described above and equivalently \( s_{I,t}^D \) is the duopoly market share. From the previous subsection the entrant comes in if \( \kappa \leq \kappa^* \), which occurs with probability \( G(\kappa^*) \). Given this entry probability and the Markovian setting, with an infinite horizon, discount factor below unity and bounded payoffs the incumbent’s problem can be represented by the value function,

\[ V(c_I, \tilde{c}_I, c_E) = \max_{p_I} \{ \pi_I(p_I, c_I) + \beta[(1 - G(\kappa^*))EV(c_I', \tilde{c}_I', c_E') + G(\kappa^*)\phi_I(p_I(c_I), p_E(c_E))] \} \] (9)

where for notational simplicity the subscript on \( G(\cdot) \) has been dropped.

The first term in equation (9) is the per-period profits prior to entry. The second term is the continuation value given that the entry cost is insufficiently low, \( \kappa > \kappa^* \), and the third term is the post-entry payoffs, which are realized when the entry cost is “low enough”, \( \kappa \leq \kappa^* \). For this third term \( \phi_I \) is the future payoffs in the post-entry complete information game. This can be thought of as equivalent to a scrap value, where in this instance the incumbent is exiting the signaling game as a consequence of the entrant choosing to enter. The state space for the incumbent, \( s = (c_I, \tilde{c}_I, c_E) \), represents the private draw of the current period’s marginal cost, \( c_I \), the entrant’s prior of this cost based on the previous period’s signal, \( \tilde{c}_I \), and the entrant’s marginal cost.

To provide more structure on \( \phi_I \) the following assumption will be made,

**ASSUMPTION 1:** Conditional on entry the marginal cost of the incumbent will be fixed in all subsequent periods at one of three values, \( \forall t \ c_{I,t} \in \{c_{\min}, c_{I,\tau}, c_{\max}\} \), where \( \tau \) is the period of entry. The distribution of this Markovian process will depend on the cost today and is given by,
Table 1: Incumbent’s Post-Entry Cost

| \(c_{I,\tau}\) ∈ \(C_{\text{low}}\) | \(\rho_{LL}\) | \(\rho_{LM}\) | \(\rho_{LH}\) |
| \(c_{I,\tau}\) ∈ \(C_{\text{med}}\) | \(\rho_{ML}\) | \(\rho_{MM}\) | \(\rho_{MH}\) |
| \(c_{I,\tau}\) ∈ \(C_{\text{high}}\) | \(\rho_{HL}\) | \(\rho_{HM}\) | \(\rho_{HH}\) |

with \(\rho_{ij} < \rho_{ii}\ \forall i \neq j\) and where \(C_{\text{low}} \cup C_{\text{med}} \cup C_{\text{high}} = C\).

Under Assumption 1 the realization of the incumbent’s marginal cost in the post-entry game is unknown to both players prior to the entry decision. However, given the signaled cost for the current period both players can form an expectation as to what the cost will be in the post-entry game using the distribution of Table 1. As before, conditional on entry the incumbent’s cost is common knowledge when competing in period \(t > \tau\).

There are two further things to note about Assumption 1. The first is that the incumbent’s cost maintains the Markov property throughout the pre-entry game and into the first period of the post-entry game. The second is that once entry has occurred the incumbent’s cost is fixed at the realization in the first period post-entry, which helps to simplify the analysis compared with the alternative of allowing this cost to evolve continually for all future periods.

Given Assumption 1, we can derive a convenient expression for \(\phi_I\).

\[
\phi_I = \mathbb{E}\left[ \sum_{t>\tau} \beta^t (p_{I,t} - c_{I,t}) Ms_{I,t}(p) \right] = \rho_{iL}\left(\frac{(p_I - c_{\text{min}})Ms_{I,\text{min}}^D(p)}{1 - \delta}\right) \\
+ \rho_{iM}\left(\frac{(p_I - c_{I,\tau})Ms_{I,\tau}^D(p)}{1 - \delta}\right) + \rho_{iH}\left(\frac{(p_I - c_{\text{max}})Ms_{I,\text{max}}^D(p)}{1 - \delta}\right)
\]

(10)

where \(i = \{\text{low}, \text{med}, \text{high}\}\) denotes the current cost set from Table 1. This expression for \(\phi_I\) can then be substituted into the incumbent’s value function above. The post-entry profits for the entrant, denoted \(\phi_E\), are equivalent.
3.3 Equilibrium

The equilibrium concept is Perfect Bayesian Equilibrium, which induces a (unique) Fully Separating Equilibrium (FSE). This will involve each cost type setting a price so as to perfectly signal its private cost. In each time period incumbent firms set prices to solve the value function given by equation (9). This implies strategies, $\sigma_I$, which map from states $(c_I, \tilde{c}_I, c_E)$ into actions,

$$\sigma_I : (c_I, \tilde{c}_I, c_E) \rightarrow p_I$$

which in equilibrium are rational given the entrant’s beliefs, $\gamma(\cdot)$.

A key property of the FSE is that the incumbent’s price is perfectly informative of its marginal cost so that Southwest’s beliefs, $\gamma(\cdot)$, are degenerate for all actions on the equilibrium path. A consequence of this is that we can restrict attention to the signaling payoff space, $\Pi : C \times P \times C \rightarrow \mathbb{R}$ where $\Pi(c_I, p_I, \tilde{c}_I) = \Pi(c_I, p_I, [c_I])$, with $[c_I]$ denoting probability measure one on $c_I$. Beliefs off the equilibrium path and in (possible) non-separating equilibria will be discussed below.

In the FSE Southwest can condition upon the price signal to form Bayesian beliefs, $\gamma : P \rightarrow C$ of the incumbent’s current marginal cost and future marginal cost, $\psi(\gamma(\cdot))$, in making its entry decision. It is optimal to enter once the couple $(\kappa, c_E)$ is sufficiently low, i.e. $\sigma_E^*$ satisfies,

$$\sigma_E^* = \begin{cases} 
\text{Enter} & \text{if } \mathbb{E}[V_E(E_\tau = 1, p_{I,\tau})] > \beta \mathbb{E}[V_E(E_{\tau+1} = 0, p_{I,\tau+1})] \\
\text{Stay Out} & \text{Otherwise}
\end{cases}$$

which is to say that the entrant’s costs are below the entry threshold illustrated in Figure 2.

A FSE for the signaling game requires that each incumbent firm’s strategy profile is optimal given the strategy profile of the potential entrant:

$$V(c_I, c_E, \tilde{c}_I; \sigma_I^*, \sigma_E^*) \geq V(c_I, c_E, \tilde{c}_I; \sigma_I', \sigma_E^*)$$

(13)
subject to satisfying the Single Crossing Condition (SCC), Individual Rationality (IRC) and Incentive Compatibility (ICC) Constraints, for all cost states, beliefs and all possible alternative strategies, $\sigma_I'$.

Of course, there is no guarantee that these strategies are unique, that an equilibrium exists and that this equilibrium will involve separation of types. Roddie [2011] discusses the existence of pure strategies in a repeated signaling game with a continuum of cost types, similar to the one considered here. Uniqueness is obtained through employing the D1 (Cho and Kreps [1987]) equilibrium refinement, selecting the Riley [1979] outcome (approximately least cost signaling). As with all signaling games the essence of Roddie’s proof for existence is that payoffs in the dynamic signaling game have to satisfy a dynamic version of the Single Crossing Condition. This condition and the proof of the following theorem are contained in the Appendix.

**THEOREM:** a unique Fully Separating Equilibrium exists that solves equation (9), with the incumbent adhering to strategy,

$$
\sigma^*_I = \begin{cases} 
  p^*_F(c_{max}) & c = c_{max} \\
  \mathcal{R}(c) & c \in [c_{min}, c_{max})
\end{cases}
$$

(14)

where $\mathcal{R}(c)$ is the Riley outcome and $p^*_F$ is the full information strategy (i.e. static Nash monopoly prices).

*Proof:* See Appendix.

The Riley equilibrium has the intuitive property that it involves the least cost equilibrium actions, so that each type does “just enough” to separate from the type immediately above at each stage of the game. In such an equilibrium of the limit pricing game the value of signaling is that it decreases the probability of entry and hence increases the expected profits in the next period. Thus, lower cost airlines signal their type through low prices that are not optimal for higher cost types to mimic, with the highest cost types instead
setting prices in line with a static complete information monopolist.

The construction of the proof in Roddie [2011] is similar to that of Mailath [1987] except that it is generalized to the case of non-differentiability of the value function. This generalization utilizes supermodularity of the value function to guarantee single crossing, i.e. that low cost firms have a greater incentive to signal than do higher cost firms. The proof of supermodularity of the value function and other necessary conditions for a FSE are provided in the appendix.

At a general level the Riley outcome is the result of utilizing a dynamic version of the D1 refinement. Absent such a refinement there would be multiplicity of equilibria relating to off-path beliefs. A dynamic version of the refinement is called for in the present setting as each period the incumbent is induced to signal its updated cost realization. Hence, whilst the existence of an equilibrium follows from firms satisfying dynamic single crossing and incentive compatibility and rationality constraints, uniqueness is obtained from applying the D1 refinement to the set of equilibria.

3.4 Motivating Examples

3.4.1 Linear Demand

Consider the model above (infinite horizon, monopolist incumbent threatened by entry of Southwest, independent markets). Assume for some market inverse demand for the incumbent is given by, $p_I = \alpha - q_I - \gamma q_E$, where $\gamma$ measures the degree of product substitution, and similarly for the entrant. Inverting the demand system we have,

$$q_I = \frac{1}{1 - \gamma^2}[(1 - \gamma)\alpha - p_I + \gamma p_E]$$

$$q_E = \frac{1}{1 - \gamma^2}[(1 - \gamma)\alpha - p_E + \gamma p_I]$$

For the monopolist $\gamma = 0$. Assuming that $\alpha = 6\frac{2}{3}$ gives $Q(p) = \max\{6\frac{2}{3} - p, 0\}$. Further assume that $c_I \in [2, 4]$ and that $\kappa \sim \text{exp}(\mu)$ where $\text{exp}$ is the exponential distribution with

18
mean $\mu$. On entry the two firms compete as Bertrand full information duopolists with $\gamma = 0.5$. Both firms discount the future using discount factor $\beta = 0.9$ and the population on the market is normalized to $M = 1000$.

A static monopolist would set Nash prices during the pre-entry game, given by $p^{NE} = \frac{62 + c_I}{2} \in [4.33, 5.33]$. The dynamic limit pricing monopolist meanwhile will price so as to satisfy incentive compatibility constraints, subject to an initial condition of the highest cost type playing Nash prices. Satisfying these constraints involves each type pricing so that the type above prefers to signal its own cost and that each type earns a greater payoff from revealing its true type than mimicking the type above. These least cost separating prices are illustrated for this example in Figure 3 for three different values of $\mu$ corresponding to low, medium and high expected entry costs and for three different values of the entrant’s marginal cost, $c_E \in \{2, 3, 4\}$. In each graph the points labeled $DLP(c_E = x)$ represent the optimal dynamic limit pricing policy for the incumbent when facing an entrant with marginal cost $x = \{2, 3, 4\}$.

Figure 2: Motivating Example Linear Demand

For the left-hand figure the mean entry cost is low resulting in a high probability of entry, $p^{entry} E \in [0.57, 0.99]$, increasing in the marginal cost of the incumbent. In the middle graph $p^{entry} E \in [0.25, 0.85]$, and the right graph $p^{entry} E \in [0.18, 0.60]$. The optimal dynamic limit price for the highest cost incumbent ($c_I = 4$) coincides with the static Nash price. This follows from the initial value condition of equation (14). The cost on the horizontal axes is that of the incumbent.

There are several points to take away from Figure 3. The first is that, except where the probability of entry is very low, the higher is the probability of entry the lower is the
incentive to signal. In the limit as the probability of entry tends to one the optimal pricing converges on the static Nash solution, for all values of the entrant’s marginal cost\(^6\). Second, the lower is the incumbent’s cost the more that can be gained from signaling, i.e. the single crossing property holds. Third, the lower is the probability of entry the more curvature there is to the optimal pricing profile indicating that the incentive to signal is stronger when the probability of entry is low. The intuition for this result is that higher cost types have a greater incentive to mimic a lower cost type when the entrant is relatively weak and hence to satisfy incentive compatibility the lower cost incumbent needs to set an even lower price to deter mimicking, as compared to the strong entrant case. The implication is that for those markets of middling attractiveness the incumbent is pricing more aggressively in order to separate from neighboring cost types. We can see this incentive dissipating when the probability of entry is high \((c_E = 2, \kappa = \text{low})\) and when the probability of entry is low \((\kappa = \text{high})\).

Figure 3 also illustrates the main contribution of the paper discussed above. For known distributions of entry costs and the incumbent’s marginal cost and observed prices it can be inferred as to whether the incumbent is practicing dynamic limit pricing through comparing realized prices with the estimated optimal limit pricing policy and in so doing the welfare consequences of the strategy can be calculated. Table 2 contains a simple welfare evaluation for the linear demand example. The per-period prices and quantities are compared with the static Nash equivalents to calculate the deadweight loss that is avoided with the limit pricing strategies. This comparison highlights the welfare consequences of asymmetric information. Through observing the signaled price the entrant can infer the incumbent’s marginal cost, whereas in the perfect information counterpart no signaling is required to obtain the same information. Entry would thus be expected to occur at the same rate and hence post-entry welfare would be equivalent.

It can be seen that, holding fixed the marginal cost of the entrant, increasing the entry

\(^6\) It is also the case that as \(p_{\text{entry}} \to 0\) the optimal policy converges on the Nash outcome. These limiting properties suggest a non-monotonic relationship between probability of entry and attempts at signaling, an insight that will be exploited in the reduced form regressions in section 5.
Table 2: Linear Demand: Welfare Evaluation

<table>
<thead>
<tr>
<th></th>
<th>$c_E = 2$</th>
<th>$c_E = 3$</th>
<th>$c_E = 4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa = low$</td>
<td>14.4</td>
<td>18.6</td>
<td>22.9</td>
</tr>
<tr>
<td>$\kappa = med$</td>
<td>19.5</td>
<td>23.3</td>
<td>25.5</td>
</tr>
<tr>
<td>$\kappa = high$</td>
<td>21.2</td>
<td>26.9</td>
<td>25.8</td>
</tr>
</tbody>
</table>

The welfare amounts in each cell correspond to the difference between consumer surplus under asymmetric information with signaling and the complete information version of the game.

cost tends to increase welfare. The intuition for this result follows from the effect of an increased entry cost on the incentive to cut fares: for low entry cost the entrant is likely to enter and so the incumbent is less inclined to limit price, whereas for middling entry costs the incumbent attempts to deter entry. Although not included in the table, as the entry cost increases to the point where entry is unlikely the welfare benefit begins to decrease for the same reason. Similarly, holding fixed the entry cost, as the marginal cost of the entrant increases so too does welfare, but only up to a point. As with an increase in entry cost, an increase in the entrant’s marginal cost brings with it a decrease in the probability of entry and hence a reduced incentive to signal. Once the marginal cost is sufficiently high so as to imply a low probability of entry the incentive to signal dissipates. We can see this with the cell ($\kappa = high, c_E = 4$) implying a lower welfare gain than the situation with a lower marginal cost ($\kappa = high, c_E = 3$).

3.4.2 Logit Demand

Closer to the model discussed above consider that the utility of consumer $i$ for product $j$ at time $t$ is given by,

$$u_{ijt} = \beta_0 + x_j \beta_x - \alpha p_{jt} + \xi_j + \epsilon_{ijt}$$ (16)

where $x_j$ and $\xi_j$ are, respectively, observed and unobserved time invariant product characteristics, $p_{jt}$ is the price and $\epsilon_{ijt}$ is an idiosyncratic error term assumed to be independent across time and individuals and distributed $T1EV$. The utility of the outside good is given
by $u_{i0t} = \epsilon_{i0t}$, also distributed T1EV.

The exogenous data $x_j, \xi_j$ are created as independent standard normal random variables. The parameter values were chosen to yield moderate variance in market shares and prices, without driving the market shares of the post-entry duopolist to zero or one. The chosen values are $\beta_0 = 0.5$, $\beta_x = 2$, $\alpha = 1$ and $\sigma_\xi = 1$.

Using these parameter values and exogenous data profits can be calculated under the static (Nash) monopolist and post-entry (Nash) duopolist versions of the game for each cost type. With these profit values the dynamic limit pricing strategies are then calculated so that (local) incentive compatibility constraints were satisfied. This involves each type pricing so that the type above does not want to mimic its price and so that each type prefers to signal its true type rather than mimic the type above. The incumbent’s marginal cost was assumed to be distributed uniformly $\in [2,4]$.

Assume there to be one market of size 10,000. The entrant on this market is taken to be one of three possible marginal cost types, with $c_E \in \{2, 3, 4\}$. Each draw of $x_j, \xi_j$ implies a different vector of static prices for the cost types and with it a unique dynamic limit pricing strategy profile for each draw. Figure 4 illustrates these prices for three such draws where the mean entry cost is varied across each plot. Varying the mean of the entry cost distribution the probability of entry, for a given marginal cost of the entrant, will vary across the graphs. Similarly the probability of entry will vary depending on the marginal cost of the entrant within each graph.

In this example the evolution of costs in the post-entry game are given by, $C_{low} = [2,2.67]$, $C_{med} = (2.67,3.33]$ and $C_{high} = (3.33,4]$, with $\rho_{11} = \rho_{22} = \rho_{33} = 0.4$ and $\rho_{ij} = 0.3 \ \forall i \neq j$.

The results for the logit demand specification are similar to those of linear demand. When the mean entry cost is low the incumbent’s incentive to signal is dampened given
As with the linear example above, in the left-hand plot the mean entry cost is low resulting in a high probability of entry. With this distribution the least efficient entrant would be expected to come in one half of the time; the more efficient types to come in more often. In the middle plot the probability of entry is moderate given a medium mean entry cost and in the right-hand plot the mean entry cost is high leading to a low probability of entry. The (marginal) cost on the horizontal axes is that of the incumbent.

the reduced ability to affect the entry decision. This can be seen in the left-hand plot in Figure 4. Similarly, when the probability of entry is low the incumbent chooses to price closer to the Nash level. This is illustrated by the crossing of the optimal pricing profile in the middle and right-hand plots: at high incumbent cost types and medium or high entry cost the incentive to signal when facing a strong opponent is weak due to a high probability of entry. As the incumbent’s type becomes more efficient it prices more aggressively when facing the strong opponent, against whom signaling is now more effective and less aggressively when facing the weak entrant for whom entry is unlikely. Also, as with the linear demand case the single crossing property holds.

3.5 Motivating Example Continuous Types, Logit Demand

TO BE ADDED

4 Data

The data were collected from the U.S. Department of Transportation’s Origin-Destination Survey of Airline Passenger Traffic (also known as DB1A) for the first quarter of 1993
through the final quarter of 2010. The DB1A data represent a 10 percent sample of all domestic tickets in each quarter. Markets are assumed to be non-directional airport pairs, so that itineraries from airport A to airport B are treated identically as those from B to A. The data were cleaned following conventions in the literature (e.g. Borenstein and Rose [2011], Berry and Jia [2008], Berry [1992]). This involves retaining only those routes that satisfied all of the following criteria: maximum of one connection each way; round-trips; travel was within the lower 48 states; and itinerary fare greater than 10 dollars and less than 2,000 dollars. From these itineraries passenger weighted average fares were calculated for each airline-route-quarter. Table 3 contains summary statistics for the dataset.

In the full sample there are 37,175 markets across the 72 quarters with a large amount of dispersion in market size (average population at the two endpoints) and the distance traveled. Southwest operated on 2608 of these markets, entering 2109 during the sample period (i.e. Southwest was already in 499 markets in the first quarter of the sample, Q1 1993). Southwest entered throughout the period (mean entry date was Q25) and often shortly after becoming a potential entrant (mean Q21). Figure 5 plots a histogram of the entry date and the quarter at which Southwest first became a potential entrant, where the dispersion in entry is evident. Also apparent are the masses at quarters 5 and 49 for Southwest as a potential entrant. This is the result of Southwest entering several large airports in these quarters.

Markets tend to be highly concentrated with an average of only 2.1 competitors and approximately one quarter of routes being served by a monopolist in a given quarter, where a monopolist is defined as serving 90 percent of the direct route traffic. There are 1.2 potential entrants that chose not to enter each market, if a potential entrant is defined as operating out of both endpoints. Using the more relaxed definition of serving one endpoint this number increases considerably to 8. This high degree of concentration is surprising. On investigation it is due to a number of markets being small (fewer than 30 DB1A pas-

---

7This differs from the model above which treated markets as non-directional city pairs. Whilst the distinction between cities and airports is important in the full sample, for the subset of markets where the incumbent is a monopolist the difference is likely to be small.
Figure 4: Histogram of Southwest’s behavior.

Quarter of entry is given by the red filled density. Quarter of first appearing as a potential entrant is given by the transparent density. Sample period Q1 1993 - Q4 2010.

sengers in a quarter) and these tending to be served by only one carrier. To correct for this a passenger-weighted average number of competitors was calculated and a variable (Monopolist 30) equal to one if the incumbent was a monopolist and flew more than 30 passengers on the route in each quarter of operation. This produces what seem to be more reasonable statistics, with 6.33 competitors and only 2.9 percent of markets being served by a monopolist.

From these data a subset was taken for those routes where Southwest was active. Here active is taken to be that Southwest was a potential or actual entrant at some point during the panel and where a potential entrant is defined to be operating out of both endpoints of the route, but not flying the route itself. Summary statistics for this subset are reported in the right-hand columns of Table 3.

This subsample has several striking differences to that of the full sample, which are suggestive of selection effects by Southwest. The markets are larger, of greater distance and have more competitors and potential entrants. In this sample Southwest enters 87 percent of all markets. By the end of the period Southwest is a potential entrant on all markets, whereas it is only threatening entry on 19 percent of routes in the first quarter. We can see that the fare is, on average, nine percent lower than in the full sample. This is
Table 3: Summary Statistics

<table>
<thead>
<tr>
<th>Variable</th>
<th>Full Sample</th>
<th></th>
<th>SW Present Sample</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Std. Dev.</td>
<td>Mean</td>
<td>Std. Dev.</td>
</tr>
<tr>
<td>Fare</td>
<td>476.5</td>
<td>213.6</td>
<td>431.17</td>
<td>185.6</td>
</tr>
<tr>
<td>SW Entered</td>
<td>0.07</td>
<td>0.255</td>
<td>0.871</td>
<td>0.335</td>
</tr>
<tr>
<td>SW Q as a PE</td>
<td>21.27</td>
<td>21.11</td>
<td>21.27</td>
<td>21.11</td>
</tr>
<tr>
<td>SW Q Entered</td>
<td>25.27</td>
<td>21.63</td>
<td>25.27</td>
<td>21.63</td>
</tr>
<tr>
<td>Distance (miles)</td>
<td>2,008</td>
<td>1,199</td>
<td>2,382</td>
<td>1,342</td>
</tr>
<tr>
<td>Population (000s)</td>
<td>848.4</td>
<td>1,249.2</td>
<td>2,527</td>
<td>2,131</td>
</tr>
<tr>
<td>Potential Entrants (both)</td>
<td>3.24</td>
<td>2.3</td>
<td>6.79</td>
<td>2.44</td>
</tr>
<tr>
<td>Potential Entrants (one)</td>
<td>10.37</td>
<td>3.43</td>
<td>12.77</td>
<td>2.94</td>
</tr>
<tr>
<td>Competitors</td>
<td>2.09</td>
<td>1.69</td>
<td>4.62</td>
<td>2.36</td>
</tr>
<tr>
<td>WA Competitors</td>
<td>6.33</td>
<td>0.389</td>
<td>6.54</td>
<td>0.45</td>
</tr>
<tr>
<td>Monopolist</td>
<td>0.28</td>
<td>0.45</td>
<td>0.057</td>
<td>0.232</td>
</tr>
<tr>
<td>Monopolist 30</td>
<td>0.029</td>
<td>0.167</td>
<td>0.0315</td>
<td>0.1747</td>
</tr>
<tr>
<td>Number Markets</td>
<td>37,175</td>
<td></td>
<td>2,994</td>
<td></td>
</tr>
</tbody>
</table>

The full sample includes all routes from Q1 1993-Q4 2010. The SW Present Sample is a subset of the full sample and includes only those markets for which Southwest was either a potential or actual entrant at some point during the sample period.

Variable definitions: SW Q as a PE is the first quarter that Southwest became a potential entrant; similarly for SW Q Entered. WA Competitors is a passenger-weighted average number of competitors on a market. Monopolist 30 restricts attention to those routes where the monopolist incumbent flew more than 30 DB1A level passengers in the quarter.

likely a combination of these markets having more competitors and in particular that one of these competitors is Southwest.

Table 4 reports summary statistics for the core sample of the analysis, being those for which the incumbent was a monopolist and Southwest threatened entry. As before a monopolist is taken to be a carrier with direct market share of greater than 90 percent. To be included in the sample the carrier has to satisfy this requirement for the three years prior to Southwest being a potential entrant and up until the time Southwest enters. There are 143 markets that satisfy these criteria. The differences in the summary statistics for this core sample relative to the other two samples are intuitive. The higher fare likely reflects increased market power that outweighs the dampening effect on prices of Southwest’s potential entry. The number of competitors is lower by construction of the sample and for the
same reason there are more monopoly markets*. The population and distance variables are widely, and fairly evenly, dispersed.

*This variable differs from one as a market is included in the sample if the carrier was not a monopolist more than three years prior to Southwest as a potential entrant and/or in the period after Southwest enters, but did serve more than 90 percent of the direct market otherwise.
Table 4: Summary Statistics: Limit Pricing Sample

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>10th Percent.</th>
<th>25th Percent.</th>
<th>75th Percent.</th>
<th>90th Percent.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fare</td>
<td>547.46</td>
<td>172.6</td>
<td>328.07</td>
<td>422.1</td>
<td>653.6</td>
<td>763.1</td>
</tr>
<tr>
<td>SW Entered</td>
<td>0.86</td>
<td>0.345</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>SW Q as a PE</td>
<td>25.5</td>
<td>21.7</td>
<td>5</td>
<td>5</td>
<td>49</td>
<td>49</td>
</tr>
<tr>
<td>SW Q Entered</td>
<td>32.35</td>
<td>23.18</td>
<td>6</td>
<td>8</td>
<td>52</td>
<td>58</td>
</tr>
<tr>
<td>Distance (miles)</td>
<td>2,191</td>
<td>1,262.7</td>
<td>684</td>
<td>1,300</td>
<td>3,008</td>
<td>3,968</td>
</tr>
<tr>
<td>Population (000s)</td>
<td>3,364</td>
<td>2,592</td>
<td>1,119</td>
<td>1,900</td>
<td>3,936</td>
<td>6,412</td>
</tr>
<tr>
<td>Potential Entrants (both)</td>
<td>7.79</td>
<td>1.69</td>
<td>6</td>
<td>7</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>Potential Entrants (one)</td>
<td>14.07</td>
<td>2.59</td>
<td>11</td>
<td>12</td>
<td>16</td>
<td>17</td>
</tr>
<tr>
<td>Competitors</td>
<td>2.82</td>
<td>1.55</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Monopolist</td>
<td>0.829</td>
<td>0.376</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Monopolist 30</td>
<td>0.781</td>
<td>0.413</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Number Markets: 143

For these statistics the data contains only those routes for which the incumbent was a monopolist prior to Southwest entering and for which Southwest was a potential or actual entrant during the period.
The main implication of limit pricing is that to deter entry an incumbent airline sets prices below that of a static profit maximizer so as to signal that entry would be unprofitable (say, due to asymmetric information relating to cost, probability of collusion or demand elasticity). In the panel there are periods in which Southwest was not active, as well as those for which it was a potential entrant and an actual entrant. If incumbent airlines are attempting to deter entry we should therefore observe price decreases once Southwest first becomes a potential entrant. The alternative (that prices only decrease conditional on Southwest’s entry) would imply that either entry deterrence were not feasible or that Southwest had complete information over market and cost characteristics. To explore this idea, Table 5 contains a reduced form regression of logged average fares of a monopolist incumbent on market and entry characteristics. (As before the incumbent was taken to be a monopolist if it carried more than 90 percent of the direct traffic on the route for the three years prior to Southwest becoming a potential entrant and each of the quarters prior to Southwest’s entry, post-potential entry.)

Of the 37,175 routes in the sample there are 143 that feature a monopolist incumbent and are threatened by entry of Southwest. In Table 5 the log of average fare was regressed on entry and potential entry dummies, controlling for time and market effects. This regression is similar to that of Goolsbee and Syverson, where the coefficients are mutually exclusive and are relative to a base period of the logged average fare over the two to three years prior to Southwest becoming a potential entrant and each of the quarters prior to Southwest becoming a potential entrant. In the first quarter that Southwest became a potential entrant, but did not fly the route, denoted $t_0$, prices decreased by 13.2 percent ($\exp(-0.142=0.868)$) relative to the excluded period. Prior to Southwest entering prices drop by an average of 23 percent. Once Southwest enters the route prices fall 23 percent below the control period and then continue to fall to over 32 percent by the end of the sample period. It would therefore appear as if prices are responding strongly to both an entry threat and to actual entry.

9. The results were similar across alternative definitions.

10. For clarity the basic specification is $\log(\text{fare}_{imt}) = \mu_i + \gamma_m + \tau_t + \alpha X_{imt} + \sum_{r=0}^{3} \beta_r (SWPE)_{m,t_0+r} + \sum_{r=0}^{3} \beta_r (SW \text{ on route})_{m,t+r} + \epsilon_{i,m,t}$ for carrier $i$ on market $m$ in quarter $t$ and where $SWPE$ is Southwest as a potential entrant, but not a competitor. It is these $\beta$s that are reported in Table 5.
Table 5: Preliminary Regressions: Incumbent Responses to the Threat of Entry

<table>
<thead>
<tr>
<th></th>
<th>(1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southwest in both airports (no flights)</td>
<td>-0.142***</td>
</tr>
<tr>
<td>$t_0$</td>
<td>(0.05)</td>
</tr>
<tr>
<td>Southwest in both airports (no flights)</td>
<td>-0.137***</td>
</tr>
<tr>
<td>$t_0 + 1$</td>
<td>(0.052)</td>
</tr>
<tr>
<td>Southwest in both airports (no flights)</td>
<td>-0.126**</td>
</tr>
<tr>
<td>$t_0 + 2$</td>
<td>(0.054)</td>
</tr>
<tr>
<td>Southwest in both airports (no flights)</td>
<td>-0.258***</td>
</tr>
<tr>
<td>$t_0 + 3$ to $t_0 + 12$</td>
<td>(0.041)</td>
</tr>
<tr>
<td>Southwest flying route</td>
<td>-0.26***</td>
</tr>
<tr>
<td>$t_e$</td>
<td>(0.054)</td>
</tr>
<tr>
<td>Southwest flying route</td>
<td>-0.308***</td>
</tr>
<tr>
<td>$t_e + 1$</td>
<td>(0.054)</td>
</tr>
<tr>
<td>Southwest flying route</td>
<td>-0.360***</td>
</tr>
<tr>
<td>$t_e + 2$</td>
<td>(0.056)</td>
</tr>
<tr>
<td>Southwest flying route</td>
<td>-0.385***</td>
</tr>
<tr>
<td>$t_e + 3$ to $t_e + 12$</td>
<td>(0.0485)</td>
</tr>
</tbody>
</table>

Market Fixed Effects           | Yes          |
Time Dummies                   | Yes          |

N 2,392                        |
$R^2$ 0.72                     |

The dependent variable is the logged passenger-weighted average fare. The sample includes all routes for which Southwest threatened entry and subsequently entered. Standard errors are in parentheses and are clustered by route-carrier. *** denotes significance at the 1% level.

The threat of entry and actual entry effects are similar to those reported by Goolsbee and Syverson. They find that prices are 17 percent lower at $t_0$ and 29 percent lower at the end of the sample. This may be a little surprising. Goolsbee and Syverson include all carriers in their regressions rather than the subset of markets for which the incumbent was a monopolist. To the extent that an incumbent monopolist has greater market power prices might be expected to decrease less when faced with the threat of entry than in the situation of an oligopoly market. On the other hand, albeit in different market conditions, Bresnahan and Reiss [1991] find that entry stiffens price competition only up until the
third of fourth entrant. It would appear that in the airline industry this latter explanation is in effect.

5 Reduced Form Results

5.1 Ellison and Ellison Style Testing

Empirically identifying strategic investment requires an assessment of the *ex ante* threat of entry and assumptions on the counterfactual that would have been observed in the absence of a strategic incentive. At a general level we might expect incumbent investment to move monotonically with measures of market attractiveness when decisions are devoid of strategic intent. However, when firms internalize their effect on potential entrants it is markets of intermediate attractiveness that are likely to be the most amenable to strategic investment. The source for this intuition is Ellison and Ellison [2011] who point out that in unattractive markets incumbents are sheltered from entry, whereas in highly attractive markets entry is inevitable with the corollary that both these market types are absent of strategic incentives. Ellison and Ellison therefore develop a test, implemented by Dafny [2005], that utilizes this insight. Strategic entry deterrence would reveal itself with a non-monotonic relationship between market attractiveness and incumbent investment, as was hinted at by Figures 1 and 3.

To provide evidence of airlines using limit pricing to deter entry requires that there be a non-monotonic relationship between fares and some measure of market attractiveness. A natural candidate is the average population in the endpoints of the route. Figure 6 plots a histogram of this variable illustrating the dispersion in endpoint population. Table 6 contains probit regressions of an entry indicator variable on the average endpoint population. The entry variable is equal to one if Southwest entered the market at some point during the sample. In column 1 of Table 6 this entry variable is regressed on market characteristics (the average number of competitors, the distance between the endpoints and the average
number of potential entrants\textsuperscript{11}) and the average of the endpoints’ population. In the second column the average population variable is divided into deciles. Both regressions indicate that the larger is the population the more attractive is entry to Southwest, as is intuitive. This suggests that in the absence of strategic effects route fares should be decreasing in population. Conversely, if strategic effects are present the decrease in fares should be more pronounced on intermediate-sized markets.

![Figure 5: Market Attractiveness](image)

To test the prediction of airlines behaving strategically on markets of intermediate attractiveness two regressions were estimated. The first is similar to that of Ellison and Ellison, taking advantage of the panel nature of the dataset,

\begin{equation}
\text{fare}_{it} = \alpha + \beta_1 \text{avgpop}_i + \beta_2 (\text{avgpop}_i - \bar{\text{pop}})^2 + \gamma_1 \text{avgpop}_i \cdot \text{SWPE}_{it} + \\
\gamma_2 (\text{avgpop}_i - \bar{\text{pop}})^2 \cdot \text{SWPE}_{it} + \Gamma X_{it} + \tau_t + \delta_i + \epsilon_{it}
\end{equation}

where $\bar{\text{pop}}$ is the mean of the average population variable, $\delta_i$ is a set of market dummies, $\tau_t$ is a set of quarter dummies, $X_{it}$ is a vector of time varying controls and $\text{SWPE}_{it}$ is an indicator, equal to one if Southwest was a potential entrant for the period. In this equation a finding of $\gamma_1 < 0, \gamma_2 > 0$ constitutes evidence of entry deterrence.

\textsuperscript{11}Here the average is taken for the route over all quarters of the sample. Distance and population are market fixed effects in the data.
Table 7 reports the results for this equation when attention is restricted to the dynamic limit pricing sample using observations prior to Southwest entering. There is some evidence of firms entering into strategic entry deterrence. Upon Southwest becoming a potential entrant fares are decreased more on those markets of middling attractiveness. However, this effect is weak (the coefficient on $\gamma_2$ is not significantly different from zero). As such the following regression, similar to Dafny, was run to attempt to better identify strategic behavior on intermediate markets, again taking advantage of the panel nature of the dataset,

$$
fare_{mt} = \alpha + \Gamma X_{mt} + \tau_t + \delta_m + \sum_{i=1}^{10} \mu_i 1(popdecile_i) + \sum_{i=1}^{10} \rho_i 1(popdecile_i) \ast 1(SWPE_{mt}) + \epsilon_{it} 
$$

where $1(popdecile_i)$ is an indicator function equal to one if the market’s population is in the $i$th decile of the population distribution.

From equation (17) a set of 10 coefficients, one for each decile, is estimated for the effect of Southwest’s entry on fares and how this varies by the measure of market attractiveness. These coefficients, given by $\rho_i$, are reported in Table 8 and plotted against the level of population in Figure 7. There is a clear pattern of non-monotonicity. Incumbent firms tend to decrease prices on those routes of middling attractiveness. On decile 6 the decrease is most pronounced with incumbents reducing fares, on average, by $90. The coefficients on the smallest three deciles and the largest two deciles are not significantly different from zero, as agrees with the intuition of incumbents steering clear of strategic pricing on these routes. The results of an F-test reported in the table indicate that the coefficient on the fifth decile is statistically smaller than both the smallest and largest deciles.

To test the robustness of these results to different divisions of the market attractiveness variable several alternative specifications were run, with similar results. Of particular interest was whether the results from the above regression were being driven by having an equal number of markets in each decile. To address this concern the average population
variable was divided into five categories (very low, low, medium, high and very high). Several different boundaries for the categories were used. Column 2 of Table 7 contains the regression results of the equivalent of equation (17) for the $\rho$ coefficients when the cut-offs points for the boundaries are (in millions) \{1.5, 3, 4.5, 6\}. The u-shaped pattern remains: incumbent monopolists decrease fares by an average $84$ on the medium attractiveness routes. For routes either side of this the change in fare once Southwest becomes a potential entrant is not significantly different from zero.

Whilst the u-shaped pattern of how firms respond when faced with the threat of Southwest’s entry agrees with the intuition of Ellison and Ellison and provides further evidence of strategic entry behavior in the airline industry it is important to point out that in this setting entry deterrence is welfare enhancing: prices are lower than the Nash outcome and sunk entry costs are avoided. The repeated incentive to signal ensures that this auspicious outcome materializes in each period thus appeasing concerns of future price spikes once entry had been deterred.

Figure 6: Market Attractiveness and the Effect on Fares

Each data point in the graph corresponds to a $\hat{\rho}$ coefficient from equation (17), as reported in Table 8. For example $\hat{\rho}_1 = -22.19$ is the left-most point and $\hat{\rho}_6 = -89.93$ is the data point corresponding to population decile six.
5.2 Welfare Implications

The above results are suggestive of firms entering into some form a strategic entry deterrence: on those markets for which entry is more likely to be deterred incumbent firms are reducing fares. For those markets of high or low attractiveness incumbents do not alter their prices once entry is threatened by Southwest. Whilst this latter observation is consistent with a static monopolist, who rather than cutting fares prior to entry will instead wait for entry to occur before altering its price vector, the cutting of prices on markets of middling attractiveness is not an optimal static outcome. There are two questions that follow. First, is this result necessarily the outcome of dynamic limit pricing? Second, what are the welfare implications of these observed strategies?

As noted in the introduction cutting prices prior to the entry of a potential competitor requires a linkage between pre-entry prices and post-entry competition. The maintained hypothesis of this paper is that pre-entry prices act to signal the marginal cost of the incumbent and in so doing indicate to a potential entrant the intensity of post-entry competition. Entry is deterred if the sunk entry cost is too high to cover the expected NPV of future profits, being when the signaled marginal cost of the incumbent is “too low”. Under certain conditions it was shown that using price to signal cost was a subgame perfect strategy of the incumbent and fully informative: low cost types set low prices so as to separate from higher cost types. However, a similar pricing profile could be observed if incumbent firms, when faced with the threat of entry, reduce fares so as to increase consumer switching costs. This “clientèle” effect shrinks the residual demand curve and thus makes entry less auspicious to a potential entrant. As with dynamic limit pricing we would expect the price decrease to only occur on those markets of middling attractiveness and thus the reduced form results above could be explained by both dynamic limit pricing and firms building a clientèle. In the following section the structural estimation technique will be detailed for how these two explanations can be distinguished. The insight is that there is information contained in how incumbent prices change as the rival first appears as a potential entrant and then again on entry and these profiles differ depending on whether incumbent firms
are limit pricing or attempting to increase switching costs.

The welfare implications of entry deterrence through price decreases will depend on what induces the price change. In the case of dynamic limit pricing potential entrants are more often deterred when the incumbent is efficient and the entrant would find entry to be unprofitable. The welfare effects are therefore unambiguously positive: consumers benefit from a reduction in prices and sunk entry costs are avoided. On the other hand, should the price decrease be due to incumbent firms building a clientele the welfare effects are less obvious. Consumers benefit from reduced prices in the current period, but may well be “harvested” in future periods should entry be deterred. Additionally, in this setting it may well be profitable entry that is deterred and thus consumers face less variety than would be present if firms were not allowed to introduce these switching costs. From a policy perspective it is therefore crucial to first identify why incumbent firms reduce prices when faced with the threat of entry before the change in welfare can be calculated.

6 Conclusion

This paper develops a dynamic model of limit pricing where, because of evolving costs and uncertainty about the entry cost draws of a potential entrant, there is an incentive for an incumbent to signal its costs every period using prices in order to try to deter entry. The model is well-suited to empirical work as there is a unique PBE under a standard refinement, and equilibrium strategies are relatively easy to calculate. We aim to test whether our model can explain the stylized fact that incumbent airlines cut prices quite markedly when faced with the possibility of entry by Southwest. Currently, we provide quite strong evidence of strategic pricing behavior on the routes in our sample using the framework proposed by Ellison and Ellison [2011].

While the work presented is preliminary and we hope to generalize the results in several ways, it is worth noting that some features may be difficult to relax. For example, if the entry cost or marginal cost of the potential entrant is serially correlated then the incumbent will also face an inference problem, but it will have to make an inference from a discrete
action. This would require keeping track of belief distributions, so that solving the game would be much more complicated. On the other hand, allowing for richer post-entry cost dynamics seems quite possible as long as appropriate conditions on costs can be developed so that the conditions on pre-entry value functions are satisfied.
Bibliography


S. Borenstein and N.L. Rose. How airline markets work... or do they? regulatory reform in the airline industry, 2011.


Appendix

Proof of Existence and Uniqueness of a FSE

There are five steps to the proof of existence and uniqueness. The first four prove that the signaling payoff in the dynamic limit pricing game is supermodular. The fifth details how this generates a unique fully separating equilibrium in the signaling game.

1. Step 1 - State the assumptions on the signaling payoff.

2. Step 2 - State useful results and definitions.

3. Step 3 - Define dynamic single crossing, incentive compatibility and individual rationality constraints.

4. Step 4 - Prove that the signaling payoff is supermodular in \((c_I, p_I, \tilde{c}_I)\).

5. Step 5 - Describe the equilibrium refinement to select the unique (Riley) equilibrium based on the supermodular payoff.

**STEP 1:** *State the assumptions on the signaling payoff.*

1. The per-period profit of the monopolist, \(\pi(p_I, c_I)\),
   - is continuous; and
   - is strictly quasi-concave in \(p_I\).

2. For some payoffs the highest signal (lowest price) is never optimal, i.e. \(\max_{p_I} \Pi(c_{\text{min}}, p_I, c_{\text{max}}) \geq \Pi(c_{\text{min}}, p_{\text{min}}, c_{\text{min}})\), where \(\Pi(\cdot)\) is the signaling payoff to be discussed below.

The assumptions on the per-period profit function are general properties for guaranteeing existence of an equilibrium (e.g. so that Kakutani’s fixed point theorem can be invoked). They are satisfied in the above game given the Logit demand specification. The assumption on the signaling payoff space ensures that there are costly enough signals for a separating equilibrium to exist.
Also, as a reminder of the assumption in the text, the post-entry game is complete information where both the incumbent’s and the entrant’s marginal cost are fixed at the period of entry.

**STEP 2: Some Useful Results and Definitions.**

**DEFINITION 1 (Increasing differences and supermodularity):** $f(x,y)$ has weakly (strictly) increasing differences if for $x' \geq x$ and $y' \geq y$, $f(x',y') + f(x,y) \geq (> ) f(x',y) + f(x,y')$. $f(x,y)$ is weakly/strictly supermodular if it has weakly/strictly increasing differences in all pairs of variables. See Roddie [2011].

The following results, stated without proof, will be useful,

**RESULT 1** *(Closed under addition):* The sum of supermodular functions is supermodular. See Athey [2001].

**RESULT 2** *(Supermodularity from second derivatives):* if $f$ is twice continuously differentiable then it is supermodular if $\frac{\partial^2 f}{\partial x_i \partial x_j} \geq 0$ for all $i \neq j$. This follows from the definition of increasing differences in Definition 1. See Topkis [1978] for details of the proof.

**RESULT 3** *(Comparative statics):* if $f(a_i, s, a_{-i})$ is supermodular in $(a_i, a_{-i}, s)$ where $s$ is a parameter, then the best response functions $r_i(s)$ are increasing in $s$. See Milgrom and Shannon [1994].

**RESULT 4** *(Single Crossing):* if $f(\theta, a, b)$ has strictly increasing differences in $(\theta, a)$ and weakly increasing differences in $(\theta, b)$ then it satisfies single crossing in $(\theta, a, b)$. See Roddie [2011].

**RESULT 5** *(Supermodularity from the max):* If $u(a^j, a^{-j})$ is supermodular then $\max_{a^j} u(a^j, a^{-j})$ is supermodular in $a^{-j}$. See Topkis [1978].
**STEP 3:** Define dynamic single crossing, incentive compatibility and individual rationality constraints.

A signaling payoff function $\Pi(c_I, p_I, \tilde{c}_I)$ satisfies SCC if lower cost incumbents have a greater incentive to signal their type by setting a lower price than do higher cost incumbents. Formally,

**DEFINITION 2** (Roddie): $\Pi(c_I, p_I, \tilde{c}_I)$ satisfies SCC if whenever $c_{I,1} > c_{I,2}$, $p_{I,2} \leq p_{I,1}$, $\Pi(c_{I,1}, p_{I,1}, \tilde{c}_{I,1}) > \Pi(c_{I,1}, p_{I,2}, \tilde{c}_{I,2})$ and $\tilde{c}_{I,2} \leq \tilde{c}_{I,1}$ $\implies$ $\Pi(c_{I,2}, p_{I,1}, \tilde{c}_{I,1}) > \Pi(c_{I,2}, p_{I,2}, \tilde{c}_{I,2})$.

Likewise for ICC and IRC, a signaling payoff satisfies IRC if revealing type provides a greater payoff than sending any other signal and being perceived as being of the highest cost, whilst for ICC truthful reporting is an optimal strategy, when facing beliefs that are correct given a signal. Formally,

**DEFINITION 3** (Roddie): Given a signaling payoff $\Pi$, a function $\sigma : C \to P$ satisfies IRC if for all $c_I \in C_I$, $\Pi(c, \sigma(c), c) \geq \max_p \Pi(c, p, c_{\max})$ and satisfies ICC if for all $c, c'$, $\Pi(c, \sigma(c), c) \geq \Pi(c, \sigma(c'), c')$.

**STEP 4:** Prove that the signaling payoff for the game is supermodular in $(c_I, p_I, \tilde{c}_I)$.

At any point in the game, prior to entry, the current signaling payoff is given by $\Pi(c_I, p_I, \tilde{c}_I)$. It is this payoff that gives rise to the value function, $V(c_I, \tilde{c}_I, c_E)$ in the text and thus showing supermodularity of $V(\cdot)$ is equivalent to showing supermodularity of $\Pi(\cdot)$. This per-period signaling payoff is comprised of three terms: the instantaneous profit from the current period, $\pi(p_I, c_I)$, the continuation value conditional on the entrant staying out, $(1-G(\kappa^*(\tilde{c}_I, c_E)))V((\psi(c_I), \psi(\tilde{c}_I), c_E))$; and the future profits from the complete information Bertrand game, conditional on entry, $G(\kappa^*(\tilde{c}_I, c_E))\phi_I$. Thus we have,

$$\Pi(c_I, p_I, \tilde{c}_I) = \pi(p_I, c_I) + \delta[G(\kappa^*(\tilde{c}_I, c_E))\phi_I + (1-G(\kappa^*(\tilde{c}_I, c_E)))V((\psi(c_I), \psi(\tilde{c}_I), c_E))] \quad (19)$$
where $\phi_I$ is given an explicit form by Assumption 1.

Following Roddie [2011] and given Result 1 (closed under addition) we need to show that the first term is supermodular in $(p_I, c_I)$ and that the part that relates to future play (inside the brackets) is supermodular in $(c_I,  \hat{c}_I)$. Looking at each term separately and using Result 2 (Supermodularity from second derivatives)$^{12}$,

$$
\frac{\partial^2 \pi(p_I, c_I)}{\partial p_I \partial c_I} = \frac{\partial}{\partial c_I} \left[ \frac{\partial}{\partial p_I} (p_I - c_I) Ms_I(p) \right] = \alpha s_I(1 - s_I) > 0 \quad (20)
$$

Thus the first term is supermodular in $(p_I, c_I)$ as desired.

For the second term we have that,

$$
\phi_I = \rho_{iL} \left( \frac{(p_I - c_{\min}) Ms_{I,\min}(p)}{1 - \delta} \right) + \rho_{iM} \left( \frac{(p_I - c_{I,\tau}) Ms_{I,\tau}(p)}{1 - \delta} \right) + \rho_{iH} \left( \frac{(p_I - c_{\max}) Ms_{I,max}(p)}{1 - \delta} \right) = \frac{\rho_{iL}}{1 - \delta} \pi_L(p_I, p_E) + \frac{\rho_{iM}}{1 - \delta} \pi_M(p_I, p_E) + \frac{\rho_{iH}}{1 - \delta} \pi_H(p_I, p_E) \quad (21)
$$

Hence,

$$
\frac{\partial}{\partial p_I} \left[ G(\kappa^*(\hat{c}_I, c_E)) \phi_I \right] = \frac{G(\kappa^*(\hat{c}_I, c_E))}{1 - \delta} \sum_j \rho_{ij} \frac{\partial \pi_j(p_I, p_E)}{\partial p_I} = \frac{G(\kappa^*(\hat{c}_I, c_E))}{1 - \delta} \left[ \sum_j \rho_{ij} (Ms_j^I(p) - \alpha(p_I - c_j)s_j^I(1 - s_j^I)) \right] \quad (22)
$$

$$
\Rightarrow \frac{\partial^2}{\partial p_I p_E} \left[ G(\kappa^*(\hat{c}_I, c_E)) \phi_I \right] = \frac{G(\kappa^*(\hat{c}_I, c_E))}{1 - \delta} \left[ \sum_j \rho_{ij} (Ms_j^E\alpha \times [s_j^I - \alpha(p_I - c_j)s_j^I(1 - s_j^I) + \alpha(p_I - c_j)s_j^2]) > 0 \right]
$$

We also have that,

$$
\frac{\partial^2}{\partial p_E \partial \hat{c}_I} \left[ G(\kappa^*(\hat{c}_I, c_E)) \phi_I \right] = \frac{g(\kappa^*)}{1 - \delta} \frac{\partial \kappa^*}{\partial \hat{c}_I} M \sum_j \rho_{ij} (p_I - c_j) \alpha s_j^I s_E > 0 \quad (23)
$$

$^{12}$In all the results that follow the specific functional forms of the paper have been implemented, i.e. that demand is of logit form. The results will also generalize to several other demand specifications, e.g. CES, linear, translog.
which follows from the assumption on $\kappa^*$ discussed in Section III, i.e. that the entry threshold is increasing in the belief of the incumbent’s cost, $\tilde{c}_I$.

And, finally, we have that,

$$\frac{\partial^2}{\partial p_I \partial \tilde{c}_I} [G(\kappa^*(\tilde{c}_I, c_E))\phi_I] = \frac{g(\kappa^*)}{1 - \delta} \frac{\partial \kappa^*}{\partial \tilde{c}_I} M \sum_j \rho_{ij} \left( s^*_I - (p_I - c_j) \alpha s^*_j (1 - s^*_j) \right) > 0$$

(24)

where the term in parentheses is marginal revenue for the firm, assumed positive.

Hence the second term is supermodular in $(p_I, p_E, \tilde{c}_I)$. Utilizing Result 5 (Supermodular from the max) we have that for the profit maximizing firm this is therefore supermodular in $(p_E, \tilde{c}_I)$ and as $p_E$ is increasing in $c_I$ that this term is supermodular in $(c_I, \tilde{c}_I)$.

The third term is a continuation value multiplied by the probability of continuing in the signaling game, so that it is comprised of infinite sums of the first and second terms and hence the component $V(\cdot)$ is supermodular given the other two terms are supermodular. Therefore, we need to show that this term multiplied by the probability of continuing in the signaling game is also supermodular.

$$\frac{\partial^2}{\partial c_I \partial \tilde{c}_I} [(1 - G(\kappa^*(\tilde{c}_I, c_E))V((c_I, \tilde{c}_I, c_E))] = (1 - G(\kappa^*(\tilde{c}_I, c_E))) \frac{\partial^2 V(\tilde{c}_I, c_I)}{\partial c_I \partial \tilde{c}_I} - g(\kappa^*(\tilde{c}_I, c_E)) \frac{\partial \kappa^*}{\partial \tilde{c}_I} \frac{\partial V(\tilde{c}_I, c_I)}{\partial c_I}$$

$$= (1 - G(\kappa^*(\tilde{c}_I, c_E))) \frac{\partial^2 V(\tilde{c}_I, c_I)}{\partial c_I \partial \tilde{c}_I} - g(\kappa^*(\tilde{c}_I, c_E)) \frac{\partial \kappa^*}{\partial \tilde{c}_I} \frac{\partial \pi(p_I, c_I)}{\partial c_I} > 0$$

(25)

where the second equality follows from the envelope theorem (Benveniste and Scheinkman [1979]), i.e. that the value of remaining in the signaling game is decreasing in cost, and thus the third term is also supermodular in $(c_I, \tilde{c}_I)$.
Collecting these results we have that the signaling payoff \( \Pi(c_I, p_I, \tilde{c}_I) \), is supermodular in \((c_I, p_I, \tilde{c}_I)\) and thus satisfies single crossing (Result 4 \((\text{Single crossing})\)).

**STEP 5:** *Describe the equilibrium refinement to select the unique (Riley) equilibrium.*

Roddie [2011] discusses the dynamic D1 refinement that selects the Riley equilibrium in each stage of the signaling game. The approach taken is a dynamic version of the argument made by Mailath [1987] and Ramey [1996] to induce a unique equilibrium in signaling games with a continuum of types. Roddie’s contribution is to show that the D1 refinement can be applied recursively.

**DEFINITION \((D1 \text{ Refinement})\):** The D1 refinement specifies that if the set of entrant’s responses that make type \( c_I \) willing to deviate to \( p_I \) is strictly smaller than the set of responses that make type \( c'_I \) willing to deviate then the entrant should believe that type \( c'_I \) is infinitely more likely to deviate to \( p_I \) than is type \( c_I \) [Fudenberg and Tirole, 1991].

Formally, from Roddie [2012a], an equilibrium \( \sigma_I, \gamma \) satisfies D1 if for any \( p_I \in P \) and any \( S \subset C \) with \( \psi(S) > 0 \), \( \cup_{\tilde{c} \in S} \{ \tilde{c}_I : \Pi(c_I, p_I, \tilde{c}_I) > \Pi_{\sigma_I, \gamma}(c_I) \} \subseteq \cap_{c'_I \notin S} \{ c'_I : \Pi(c'_I, p_I, \tilde{c}_I) \geq \Pi_{\sigma_I, \gamma}(c'_I) \} \) implies \( \gamma(p_I)(S) = 1 \).

i.e. after observing \( p_I \) the entrant must place probability one on the incumbent being in the set of types in \( S \).

Similar to Ramey [1996], Roddie [2012b] proves that with a continuum of types the incentive compatibility conditions and D1 refinement induce a unique separating strategy, \( \sigma_I \), once an initial condition is specified. The initial condition is natural, being that the highest cost type plays the complete information outcome, \( p^*_{FI} \), where \( p^*_{FI} = \arg\max_p \Pi(c_I, p_I, c_I) \). Thus our initial condition is given by \( \sigma_I(c_{max}) = p^*_{FI}(c_{max}) \). With this in hand we can utilize Theorem 1 of Roddie [2012b] to prove uniqueness in FSE.
THEOREM 1 (unique FSE): Suppose the signaling payoff \( \Pi \) satisfies: continuous in \((c_I, p_I)\), strictly decreasing in \(c_I\), strictly quasi-concave in \(p_I\) and single crossing; and that \(\sigma_I\) satisfies ICC. Then there exists a unique \(p_I^*\) satisfying \(\Pi(c_{\text{max}}, p_I^*, c_{\text{max}}) = \Pi(c_{\text{max}}, p_I(c_{\text{max}}), c_{\text{max}})\). Then \(\Pi|_{P_I} \in \Phi_{\text{sep}}(P_I)\) and \(\sigma_I = R(\Pi|_{P_I})\) on \([c_{\text{min}}, c_{\text{max}}]\), where \(P_I = [p_{\text{min}}, p_I]\), \(\Phi_{\text{sep}}\) is the set of separating strategies and where \(R\) is the Riley outcome.

The necessary properties for an equilibrium are satisfied in the dynamic limit pricing game.

Proof:

1. Single Crossing - The signaling payoff satisfying single crossing follows from it being supermodular (Result 4 (Single Crossing)).

2. Continuity and strictly quasi-concave - comes from differentiability and Logit demand.

3. Strictly decreasing in \(c_I\) - being perceived to be of lower cost implies a lower probability of entry in the next period and hence greater profits, for any given \(c_I\).

4. \(\sigma_I(c_I)\) satisfies ICC - local incentive compatibility follows from the first order conditions on the value function. Specifically, if the incumbent can send the signal of cost \(c'_I\) when its true cost is \(c_I\), then the first order condition with respect to \(p_I\) is zero when evaluated at the point \(c'_I = c_I\). Combined with single crossing this implies global incentive compatibility (Carroll [2012]).
Table 6: Entry and Population

<table>
<thead>
<tr>
<th></th>
<th>(1)</th>
<th>(2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avgpop</td>
<td>0.02***</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.001)</td>
<td></td>
</tr>
<tr>
<td>Decile 2</td>
<td>0.02***</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.005)</td>
<td></td>
</tr>
<tr>
<td>Decile 3</td>
<td>0.033***</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.007)</td>
<td></td>
</tr>
<tr>
<td>Decile 4</td>
<td>0.047***</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.008)</td>
<td></td>
</tr>
<tr>
<td>Decile 5</td>
<td>0.061***</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.01)</td>
<td></td>
</tr>
<tr>
<td>Decile 6</td>
<td>0.079***</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.0114)</td>
<td></td>
</tr>
<tr>
<td>Decile 7</td>
<td>0.116***</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.014)</td>
<td></td>
</tr>
<tr>
<td>Decile 8</td>
<td>0.137***</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.016)</td>
<td></td>
</tr>
<tr>
<td>Decile 9</td>
<td>0.219***</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.021)</td>
<td></td>
</tr>
<tr>
<td>Decile 10</td>
<td>0.242***</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.023)</td>
<td></td>
</tr>
<tr>
<td>Market Controls</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>N</td>
<td>37,175</td>
<td>37,175</td>
</tr>
<tr>
<td>Pseudo $R^2$</td>
<td>0.50</td>
<td>0.51</td>
</tr>
</tbody>
</table>

Dependent variable is equal to 1 if Southwest entered at some point in the sample period. Coefficients are marginal effects. Robust standard errors are reported in parentheses. *** denotes significance at the 1% level.
Table 7: Entry Deterrence

<table>
<thead>
<tr>
<th></th>
<th>Dependent Variable is $fare_{it}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(1)</td>
</tr>
<tr>
<td>$\gamma_1$</td>
<td>-5.737* (3.42)</td>
</tr>
<tr>
<td>$\gamma_2$</td>
<td>0.694 (0.581)</td>
</tr>
</tbody>
</table>

Market Fixed Effects: Yes  
Time Dummies: Yes

N: 4,072

Robust standard errors are reported in parentheses. * denotes significance at the 10% level. Time varying market controls were also included.
Table 8: Entry Deterrence: Limit Pricing Sample

<table>
<thead>
<tr>
<th></th>
<th>Dependent Variable is $fare_{mt}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>(2)</td>
</tr>
<tr>
<td>$\rho_1$</td>
<td>-22.19 (14.97)</td>
</tr>
<tr>
<td>$\rho_2$</td>
<td>-9.94 (16.44)</td>
</tr>
<tr>
<td>$\rho_3$</td>
<td>16.51 (14.15)</td>
</tr>
<tr>
<td>$\rho_4$</td>
<td>31.68* (17.41)</td>
</tr>
<tr>
<td>$\rho_5$</td>
<td>-43.43** (18.60)</td>
</tr>
<tr>
<td>$\rho_6$</td>
<td>-89.93*** (19.01)</td>
</tr>
<tr>
<td>$\rho_7$</td>
<td>-52.57*** (20.34)</td>
</tr>
<tr>
<td>$\rho_8$</td>
<td>-59.91*** (18.69)</td>
</tr>
<tr>
<td>$\rho_9$</td>
<td>-17.89 (20.79)</td>
</tr>
<tr>
<td>$\rho_{10}$</td>
<td>21.81 (20.82)</td>
</tr>
<tr>
<td>$\delta_1$</td>
<td>-26.08 (29.08)</td>
</tr>
<tr>
<td>$\delta_2$</td>
<td>0.136 (31.73)</td>
</tr>
<tr>
<td>$\delta_3$</td>
<td>-84.19* (42.95)</td>
</tr>
<tr>
<td>$\delta_4$</td>
<td>-29.64 (18.14)</td>
</tr>
<tr>
<td>$\delta_5$</td>
<td>27.59 (18.14)</td>
</tr>
<tr>
<td>$\delta_6$</td>
<td>27.59 (23.77)</td>
</tr>
</tbody>
</table>

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>4,072</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.63</td>
</tr>
<tr>
<td>p-value from $H_0: \rho_5 &lt; \rho_1 \cap \rho_5 &lt; \rho_{10}; H_1: \rho_5 = \rho_1 \cup \rho_5 = \rho_{10}$</td>
<td>0.034</td>
</tr>
<tr>
<td>p-value from $H_0: \delta_3 &lt; \delta_1 \cap \delta_3 &lt; \delta_5; H_1: \delta_3 = \delta_1 \cup \delta_3 = \delta_5$</td>
<td>0.078</td>
</tr>
</tbody>
</table>

*** denotes significance at the 1% level, * at the 10% level. Market and time controls also included. Column (1) contains the post-potential entry coefficients for equation (17) when the population variable is divided into categories of an equal number of markets. Column (2) contains equivalent results for when the population variable is divided into five categories of not necessarily an equal number of markets. The five $\delta$ coefficients thus relate to markets of {very low, low, medium, high and very high} attractiveness, with $\delta_1$ corresponding to very low and $\delta_5$ to very high.