CONGESTION PRICING AND WELFARE: AN ENTRY EXPERIMENT

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Lisa R. Anderson, Charles A. Holt, and David Reiley[•]

Abstract: This paper reports an experiment designed to evaluate the negative externalities associated with entry into a congested activity. In each round, subjects decide whether or not to enter. Payoffs for entry decline with the number of entrants, while the payoff for exit is fixed. Observed entry rates are centered around the level that equates expected payoffs for entry and exit. There is, however, some variability in entry rates from round to round, even after 50 rounds. This entry variance reduces welfare, since higher entry imposes external costs on more people, while savings from lower entry are enjoyed by fewer people. The imposition of an optimal entry fee lowers entry and raises welfare as predicted, but the variability in entry rates continues to be a source of inefficiency. This variability is reduced if participants can observe the number of entrants at any given time prior to making their own decisions. In some sessions, participants were allowed to vote on the level of the entry fee every 10 rounds and to split the fee receipts. This voting process yielded optimal or near-optimal fee levels after a couple of meetings.

[•] Anderson: Department of Economics, College of William and Mary, Williamsburg, VA 23185, lrande@wm.edu, Holt: Department of Economics, University of Virginia, Charlottesville, VA 22904-4182, cah2k@virginia.edu, and Rieley: Department of Economics, University of Arizona, Tucson, AZ 85721, reiley@eller.arizona.edu. We gratefully acknowledge financial support from the National Science Foundation (SBR-0094800) and the Bankard Fund at the University of Virginia. We wish to thank Angela M. Smith for research assistance.

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I. Introduction

One of the most persistent problems facing cities is freeway congestion. With billions of dollars spent every year to add capacity, the number of commuters appears to be growing at a faster rate. In some case, travel on city streets is an attractive alternative. Many commuters face the daily dilemma of taking a predictable, but slower, route or risking hours of gridlock on a potentially faster freeway.

Highway congestion was once just a problem for large cities like Los Angeles and Washington D.C., but it is increasingly affecting smaller metropolitan areas. In addition to the political pressure traffic puts on city planners and other elected officials, congestion imposes huge welfare costs on commuters. Instead of providing innovative solutions to this problem, technological advances have spawned new areas where congestion must be managed, like cell phones and the Internet.[1]

We study the problem of congestion in the context of a binary choice game. Subjects must choose between a "safe" route with a fixed payoff and a "risky" route for which the payoff depends on the number of other users. When subjects must simultaneously choose between the safe and risky options, there is significant congestion, resulting in large welfare losses, even when subjects make the same decision for as many as 60 rounds. We test the effectiveness of a user fee (i.e. a toll) in this environment, and find this effective at reducing congestion. However, the simultaneous nature of the decision still results in a high variance in the number of entrants, which is costly from a welfare perspective. We also test information provision as a policy option and find that it reduces the number of entrants and the variance.

II. Ducks and "Magic"

Yogi Berra's once remarked: "Nobody goes there anymore. It's too crowded." The humorous contradiction in this comment raises the issue of how individuals actually respond to

[1] Experiments motivated by internet congestion issues are reported in Chen and Razzolini (2001) and Friedman and Huberman (2004).

congestion. The solution is suggested by a famous animal foraging experiment, reported by Harper (1982), in which two people stood on opposite banks of a duck pond in the Cambridge University Botanical Garden and began throwing out five-gram bread balls at fixed intervals. The payout rate was twice as high on one bank (every 10 seconds instead of every 20 seconds). The flock of ducks sorted themselves to equalize expected payoffs, as measured in grams per minute. Moreover, a change in the interval times resulted in a new equilibrium within about 90 seconds, which is less time than it would take for most ducks to obtain a single bread ball. As Paul Glimcher (2002) notes, the ducks were in constant motion, with some switching back and forth, even after equilibrium was reached. This stochastic element could offer an evolutionary advantage if it hastens the adjustment to changes in payoff conditions. Entry and congestion problems arise often when choices are decentralized, as in the decisions of individuals concerning whether to congregate in a potentially crowded bar. This latter case is known in the literature as the "El Farol" dilemma, named after a popular bar in Santa Fe (Morgan, Dylan, Bell, and Sethares 1999).

Psychologists and economists have conducted a series of similar binary choice experiments with congestion effects, beginning with Kahenman (1988), who observed the payoff equalization and remarked: “To a psychologist, it looks like magic.” There have been a number of subsequent experiments in which observed behavior tends to equates payoffs, e.g. Ochs (1990). This successful coordination has been explained in terms of adaptation and learning (Meyer, Van Huyck, Battalio, and Saving, 1992; Erev and Rapoport, 1998). However, some experiments have produced too much entry into the more congestion-prone activity. For example, Fischbacher and Thöni (2001) conducted an experiment in each entrant essentially gets a single lottery ticket with an equal chance for winning a money prize, so the expected payoff for entry is a decreasing function of the number of entrants. There was excess entry, which was more severe with large numbers of potential entrants. Camerer and Lovallo (1999) conclude that entry can be affected by overconfidence, since they observe over-entry when post-entry payoffs depend on a skill-based trivia competition, but not otherwise. Goeree and Holt (2005) provide a unified treatment of some (but not all) of these disparate results, using the argument that exogenous random noise in behavior may tend to pull entry rates towards one half, which would result in over entry when the theoretical prediction is less than ½ and under entry otherwise. This systematic (“inverse S”) pattern of over and under entry is reported by Sundali, Rapoport, and Seale (1995).

To summarize, the general result is that the amounts of over entry and under entry are small, and that theoretical predictions are fairly accurate, as long as they are not extreme. The experiment reported in this paper will focus on the welfare consequences of congestion, and on factors that may increase efficiency. In other words, the focus is on how to improve the lives of the ducks.

III. A Stylized Model of Congestion

Consider a group of N commuters who must choose between a slow reliable route and a faster, but potentially congested freeway, bridge or tunnel. Commuting time is fixed on the safe route and is an increasing function of traffic on the risky route. Suppose that the average payoff for an entrant is decreasing in the number of entrants: $A - Bx$, where x is the number of entrants and A and B are positive parameters. The payoff from taking the reliable route is C, which represents the opportunity cost for an entrant. With free entry, average payoffs are equalized if $A - Bx = C$, or equivalently, if $x = (A - C)/B$. This equal-payoff equilibrium outcome is not socially optimal, since entrants do not consider the effects of their own entry decisions on the other entrants. To see this, note that the total payoff with x entrants and $N - x$ non-entrants is: $x(A - Bx) + (N - x)C$, which is maximized when the marginal social value equals the marginal social cost: $A - 2Bx = C$, or when $x = (A - C)/2B$. It follows from these calculations that the optimal rate of entry is half of the equilibrium entry rate in this linear model.

Consider an example in which the payoff for the safe route is \$0.50 and the payoff for the is \$4.50 minus the number of entrants (C = 0.50, A = 4.50, and B = 1). Table 1 shows entry payoffs for the risky route with a total of 12 commuters. Notice that the payoff for the risky route is equal to the payoff for the safe route (at \$0.50) when 2/3 of the commuters enter the risky route. Hence, the free-entry equilibrium prediction is for 8 of the 12 commuters to take the risky route, as can be verified by substituting the payoff parameters into the formula for equilibrium entry derived earlier.

Table 1. **Payoff for the Risky Route**

Number of Entrants	1	2	3	4	5	6	7	8	9	10	11	12
Average Payoff Per Entrant	4.00	3.50	3.00	2.50	2.00	1.50	1.00	0.50	0.00	-0.50	-1.00	-1.50
Total Earnings for All	9.50	12.50	13.50	14.00	13.50	12.00	9.50	6.00	1.50	-4.00	-10.50	-18.00

Figure 1 shows the locations of the free-entry equilibrium and socially optimal entry levels. The marginal (private or social) cost is $0.50, as shown by the horizontal dotted line. This marginal cost is the payoff from taking the safe route, and it equals the individual payoff from entry ("average payoff") when there are 8 entrants, which constitutes an equilibrium. Individual entrants do not consider the cost of entry on other users of the risky route, so to them, the marginal private benefit from entry is just the average payoff, shown by the solid line in the figure. But entry imposes costs on others, so the marginal social benefit of entry (shown by the dashed line) is below the average payoff line. The marginal social benefit line is steeper than the average payoff line because, as the number of entrants increases, each additional entrant causes the value of entry to fall by $0.50 for a larger number of people. The socially optimal number of entrants occurs where marginal social benefit is equal to the marginal private cost, at 4 entrants in this example. Since the marginal private benefit of $2.50 exceeds the marginal social benefit of $0.50 by $2.00 at this point, an entry fee of $2.00 corrects the externality. In the figure, the effect of a $2 fee would be to shift the average payoff line down by $2 in a parallel manner, so that the intersection with the marginal cost line occurs at the optimal entry level of 4. The experiment to be discussed in the next section will evaluate the effects of both exogenous and endogenously determined entry fees.

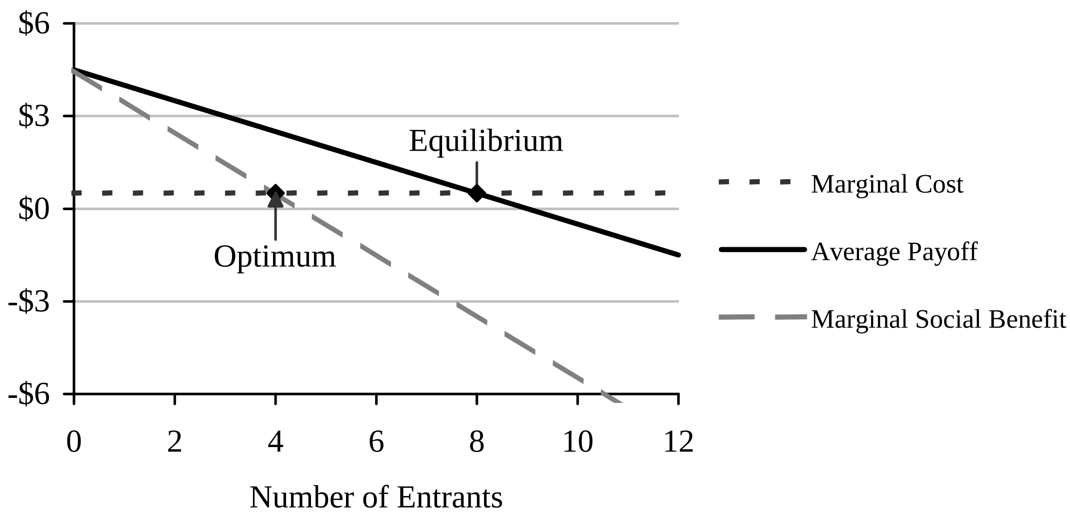

Figure 1. Benefits and Costs of the Risky Route

The equal-average-payoff equilibrium that results from free entry is closely related to the notion of a Nash equilibrium. To see this, note that there is an asymmetric Nash equilibrium in which exactly 8 people enter, since it follows from Table 1 that a ninth entrant would earn 0, which is less than the \$0.50 payoff from staying out. Conversely, with 8 entrants, each earns \$0.50, so none can be better off by taking the safe route. There is however, another Nash equilibrium with 7 entrants, each earning \$1, since a non-entrant who attempts to enter will drive the number of entrants up to 8 and hence will only earn \$0.50. (In the free-entry "competitive" approach, this non-entrant would enter anyway, not realizing that the act of entry will reduce the payoffs from entry.)

Alternatively, consider a symmetric Nash equilibrium in mixed strategies, with the probability of entry denoted by *p*. This probability must be set to ensure that if the other 11 people enter with probability *p*, then the expected entry payoff for the remaining person exactly equals the exit payoff of \$0.50. This person's expected entry payoff can be calculated as a function of *p* using the formula for the density of a binomial distribution with N = 11. It is straightforward to show that the expected entry payoff is \$0.50 when *p* is 7/11, which is approximately 0.64. The difference between this number and the two-thirds entry rate that equalizes expected payoffs is due to the fact that the number of entrants is finite. To see the intuition, think of an individual player who is considering entry or not. To be willing to randomize, the person must have the same expected payoff from entry (*with probability 1*) and exit. The player would be indifferent if exactly 8 entrants are expected (*that person and 7 others*). In order to get 7 entrants out of the 11 others with a binomial distribution, the probability of entry must be 7/11.

Another perspective is to think about why randomizing with probability 2/3 is *not* an equilibrium. If all 12 people randomize with probability 2/3, then it can be shown that each earns \$0.50 on average, which matches the exit payoff. But if one of these people throws the dice and gets a roll that indicates entry, then *at that point* the decision to enter (with probability 1) will increase the expected number of entrants and reduce the expected entry payoff below \$0.50, and the only way to restore indifference is for the entry probability to be reduced from 2/3 to 7/11. It may seem unintuitive, but in the symmetric mixed strategy equilibrium with all 12 players choosing entry with probability 7/11, the expected payoff for an entrant is 68 cents. But this expected payoff is reduced to 50 cents for a person who has already decided to enter, even if that decision was made after seeing the outcome of a random device.

To summarize, a Nash equilibrium in mixed strategies with risk-neutral players is for entry to occur with probability 0.64, and a "free-entry" equilibrium that equates expected payoffs involves an entry rate of 0.67. For large numbers of players, these two approaches would be equivalent, and for the parameters used in the experiment, the predictions are quite close. Therefore, we will use the free entry prediction of 2/3 as the prediction, except as noted below.

IV. A Congestion Experiment

Subjects were recruited from undergraduate classes at the College of William and Mary and at the University of Virginia. There were 12 sessions with 12 participants in each. The experiment was conducted using the Market Entry program on the V*e*conlab website:
(http://veconlab.econ.virginia.edu/admin.htm). In each of round, subjects faced a binary choice to enter the market (i.e., the risky route) or not. As described above, subjects earned a sure \$0.50 payoff in each round they did not enter. The payoff for entry in a given round was determined by the total number of entrants in that round according to the following formula: \$4.50 – 0.50*x, where x denotes the total number of entrants. (The only exception was in the first session where the payoffs were all doubled, since the session involved only 20 rounds.) Sessions lasted about an hour and the average person earned about \$0.50 per round over 30-60 rounds, depending on the treatment, plus a \$6 show-up payment. The treatment parameters for all sessions and the resulting entry rates are listed in the table in the Appendix. The data for all sessions are available at the site: (http://www.people.virginia.edu/~cah2k/data/).

Figure 2 shows results from a session in which subjects made this entry decision for 60 rounds. While the average entry rate is close to the prediction of 2/3, there is significant variation from round to round. Even with 60 rounds of play, the noise does not subside. Although this was the longest session we ran, the amount of variation shown here is typical of the sessions with shorter durations.

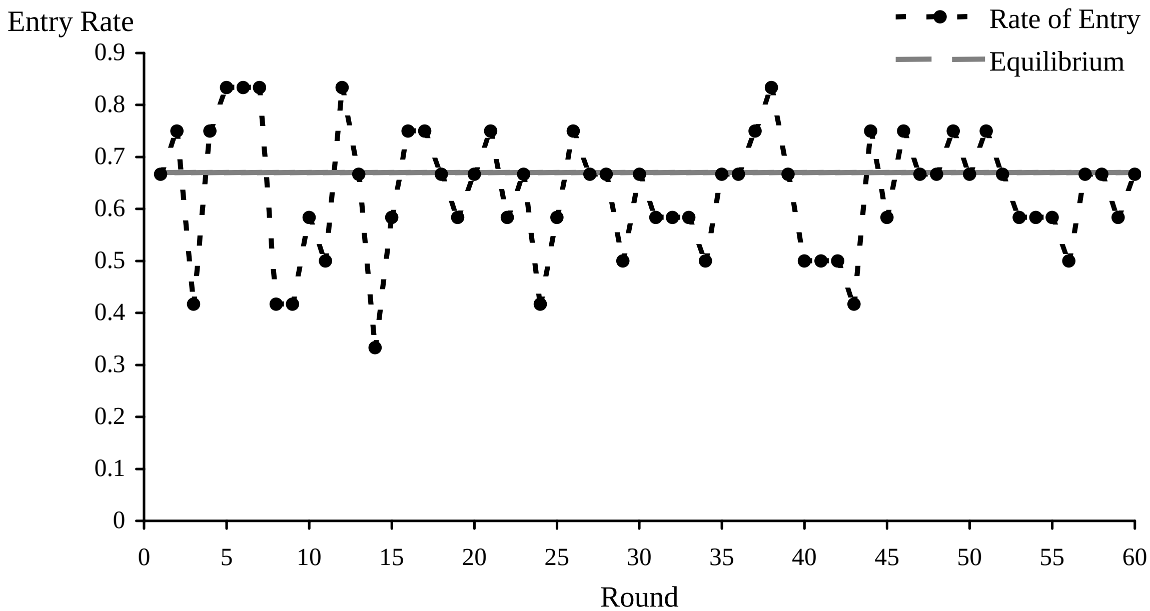

Figure 2. An Entry Game Session with 60 Rounds (me070804)

As mentioned in the previous section, there is a symmetric Nash equilibrium for this game, in which each person enters with a probability of 7/11, or 0.64. Using a binomial distribution (p = 0.54 and N = 12), the probabilities associated with each number of entrants can be calculated, as shown by the gray bars in Figure 3, which show a mode at 8 entrants. The frequencies of the actual numbers of entrants for the 60 round session (in Figure 2) are represented by the black bars in Figure 3, which indicates that outcome variability is about what would be expected.

As noted above, free entry yields inefficient outcomes since entrants do not take the social cost of over entry into account. With a linear average payoff line, the total payoff will be quadratic and concave, and variance will reduce average payoffs. This effect is illustrated in the bottom row of Table 1. At the equilibrium level of 8 entrants, the earnings are $0.50 for each person, whether or not they enter, so total earnings are $6. Now consider how social welfare changes with some variance in the entry rate. If the number of entrants is 7 in one round and 9 in the next, the average entry rate is consistent with the theoretical prediction of 8. However the average total earnings for these two periods is ($9.50 + $1.50)/2 = $5.50. As the variance grows, the welfare loss grows at an increasing rate. For example, with entry at 6 in one period and 10 in the next period, average of the two earning amounts is ($6.00 - $4.00)/2 = $1.

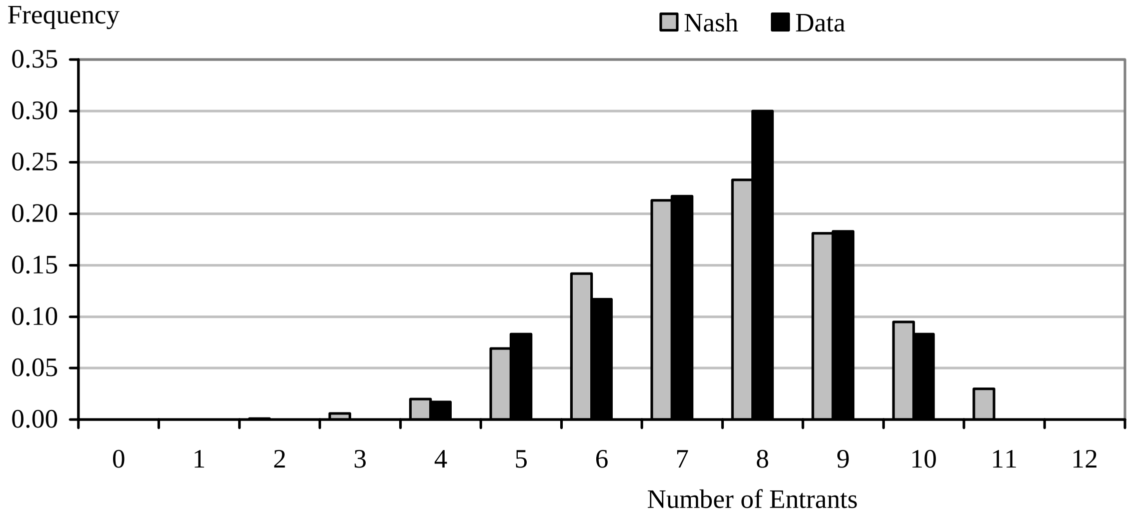

Figure 3. Predicted and Observed Distributions of Entry Outcomes for a Session with 60 Rounds (me070804)

Result 1: There is considerable variation in the entry level, even over longs period of play, which results in large efficiency losses.

V. Congestion Tolls

A common policy approach to congestion is to tax freeway use via a toll. Figure 4 shows results from a session with the optimal user fee of $2 per entrant. Note from Table 1 that the private benefit from entry is $2.50 at the socially optimal entry level of 4. Imposing this $2 cost on entry reduces the private benefit to $0.50, thus moving the free-entry equilibrium prediction to the optimal level. Entry rates quickly fell when the user fee was imposed; the average entry rate was 34% with the fee.

Overall, the optimal entry fee was imposed in parts of six sessions. In two of the sessions, the revenue collected from the fee was split equally between the 12 subjects. In the other four sessions, the entry fee revenue was not rebated to the subjects. The success of the entry fee did not depend on whether or not it was rebated to subjects. In the two sessions with the rebate, the average entry rates were 33% and 38%, and in the sessions without the rebate, the average entry rates were 34%, 35%, 35%, and 35%. Notice that the rebate may reduce the variance around the optimal rate, but there is still considerable noise in the data, and social welfare is not maximized in these sessions. The overall effect of imposing an entry fee, with or without rebate, is substantial and clear; all of the entry rates listed above with the fee are below the rates for the sessions with no-fee treatments: 69%, 65%, 63%, 66%, 68%, 63%, and 62%. There is no overlap in these entry rates by treatment, so the result would be highly significant on the basis of standard non-parametric tests.

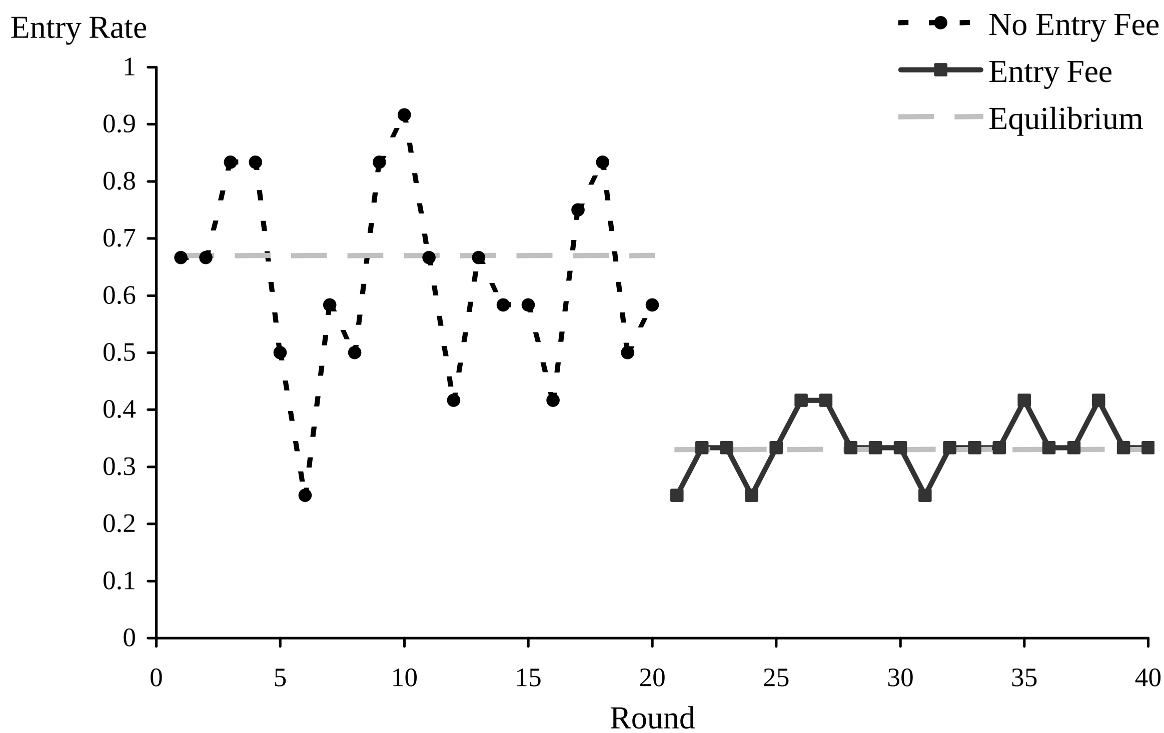

Figure 4: Entry Game with $2 Entry Fee (me062904)

Result 2: With an optimal user fee, entry is reduced to the socially optimal level on average, but there is still noise.

VI. Information and Coordination

Despite the success of user fees at moving usage towards the socially optimal level, the variance in entry still persists in these sessions. If entry decisions are not made simultaneously, then coordination may be facilitated by improved information about current conditions. Much like rush hour traffic reports, we made information about prior entry available to subjects as they were making decisions. Specifically, the number of entrants at any given point in time was displayed on all of the computer screens. People were allowed to enter in any order. Figure 5 shows results from a typical session with endogenous entry order and the provision of prior entry information. The combination of the entry fee and the information in the last half of the session resulted in the socially optimal entry rate in 16 of 20 rounds of play. In most cases, over entry was the result of two players clicking the “enter” button at precisely the same moment.

Even without an entry fee, the provision of prior entry information tended to reduce variance of entry rates. There were five sessions that began with 10 or more rounds of a “No-View” treatment, and seven sessions that began with 10 or more rounds of a “View” treatment that posted the number of prior entrants on each screen update. There was considerable variance in all of the no-view treatments, and the pattern with the View treatment was basically a flat line with an occasional “blip” as seen in Figure 5. The only exception was in Session 9, where only 4 of the first 10 entry rates were at the same level (0.67), but even in this case, the overall variance of entry rates was relatively low.

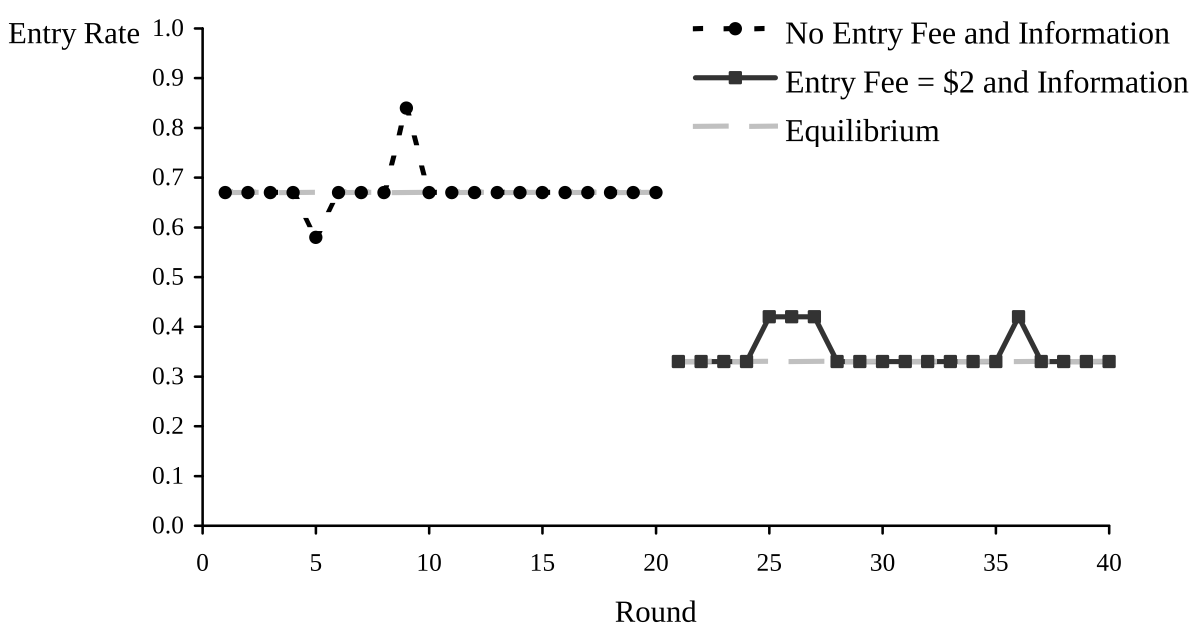

Figure 5. Entry Game with Information about Other Entrants (me071504)

The variances for the first 10 rounds of each of the 12 sessions are shown in Table 2. All of the variances are less than 0.01 for the View treatments, and are greater than 0.01 for the No-View treatments. This difference is significant at the 0.01 level using standard non-parametric tests.

Table 2. Variances of Entry Rates in the First 10 Rounds, by View Treatment

Session	1	2	3	4	5	6	7	8	9	10	11	12
Variance	0.022	0.035	0.042	0.017	0.011	0.031	0.001	0.004	0.006	0.001	0.002	0.046
Treatment	NO	NO	NO	NO	NO	NO	VIEW	VIEW	VIEW	VIEW	VIEW	NO

Result 3: Information about prior entrants reduces noise, which increases welfare. When combined with the optimal user fee, social welfare is maximized in most rounds.

VII. Voting and Endogenous Entry Fees

Consider the effect of an entry fee, F, that is paid by each entrant. One issue is whether the fee setter has an incentive to set an optimal fee. Let the total earnings of entrants, the "surplus," be denoted by $S(x)$, with $S''(x) < 0$. When there are x entrants, the average earnings per entrant are given by $S(x)/x$. (If the surplus is a quadratic concave function, this yields the linear average payoff model considered in section III.) The total earnings of the group as a whole are represented by $S(x) + (N - x)C$, which is maximized by equating marginal surplus to marginal cost: $S'(x) = C$. In contrast, the free-entry equilibrium that equates average payoffs from entry and exit is determined by the equation: $S(x)/x = C + F$. Multiply both sides of this equation by x to obtain an expression for the total entry fee revenue: $xF = S(x) - Cx$, which is maximized when $S'(x) = C$, i.e. when the marginal value of the surplus equals the marginal cost. Thus the revenue-maximizing fee under free entry is the efficient fee that maximizes total earnings for this model. As noted previously, the optimal fee for the parameters used in the experiment is $2, which internalizes the externality at the optimal level of entry. One way to provide subjects in the experiments with the incentive to adopt an optimal entry fee is to split the fee revenues equally, since the fee that maximizes total fee revenue will maximize the $1/N$ share of this revenue.

Figure 6 shows results from a session in which subjects were allowed to vote on an entry fee, with all fee revenue divided equally among participants, whether or not they entered. Voting sessions started with 10 rounds of decision making with no fee. At the end of those 10 rounds, one subject was randomly chosen to be the "chair" and following instructions were read aloud:

> "Now everybody should come to the front of the room, and we will have a meeting to discuss whether or not to require people who enter the market to pay

an entry fee, and if so, how much the fee should be. All fees collected will be totaled and divided equally among the 12 participants, regardless of whether or not they entered. To facilitate this discussion, we will use a random device (throw of a die) to choose a person to chair the meeting. This person will call on people to speak, and then when someone makes a motion that is seconded, the chair will count the votes. The chair may vote to break a tie. Once the fee is selected, it will be entered into the computer and will be in effect for the next 10 rounds, after which we may meet again to decide on a fee for the 10 rounds that follow. You are free to discuss any aspect of the process, except that you cannot talk about who enters and who does not. Let me stress two things: all fees collected get divided up equally among all participants, those who entered and those who did not."

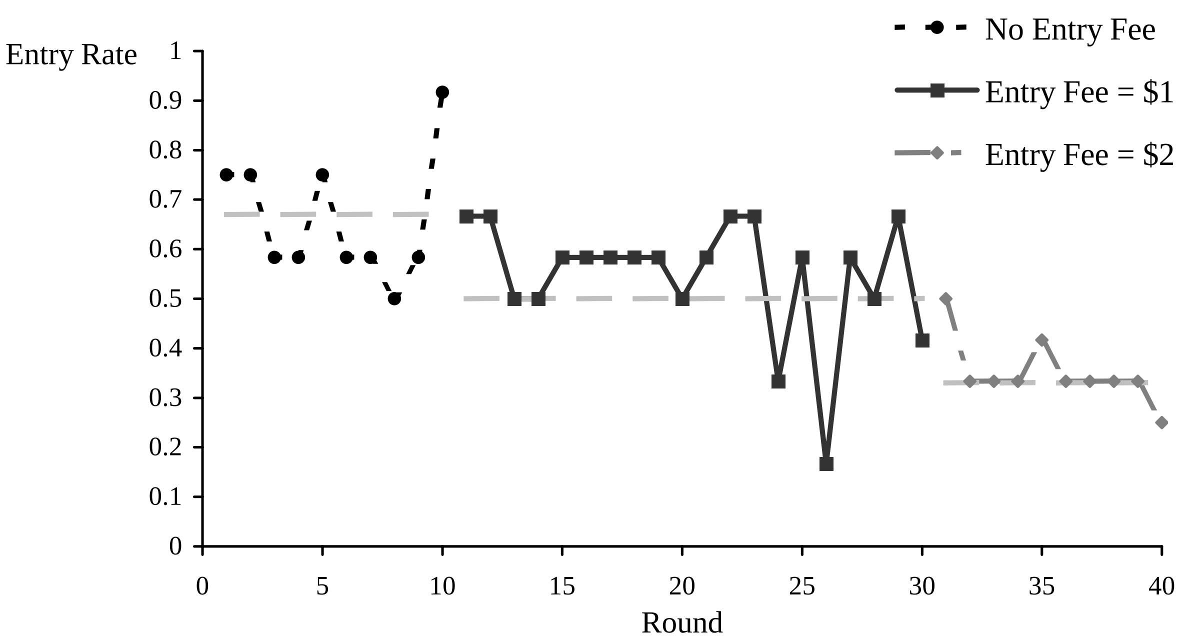

Figure 6. Entry Game with Voting on Entry Fee (me063004)

The chair presided over group discussions of the fee. Anyone could propose a fee and call for a vote. Majority rule determined whether the proposed fee would be enacted for 10 rounds, followed by another vote on an entry fee for the next 10 rounds. In this particular session, an entry fee of $1 was proposed and passed with very little discussion beforehand. In a second meeting following round 20, someone proposed an entry fee of $2, but it only received 4 votes. A proposal of $0.50 also failed to pass, with only 3 votes. A motion to keep the $1 fee passed with a majority of votes. Subsequently fees of $3 and $1.50 were proposed and rejected.

Finally, the $2 was re-proposed and passed with 7 of 12 votes. In another session, the subjects started with a $1 fee and adjusted it to $2 during the second round of voting. However, they lowered it to $1.75 in the third round of voting and to $1.60 in the fourth round of voting. In the last round of voting they increased the fee to $1.80.

Result 4: Subjects have some success at finding the optimal user fee with discussion and voting.

VIII. Summary

We present results from a binary choice experiment based on a stylized model of congestion. On average, entry behavior is approximately at a level that equalizes expected payoffs, but these near-equilibrium entry rates are inefficiently high. Moreover, the variability of entry from round to round introduces another source of inefficiency. By charging the optimal entry fee, outcomes move closer to the socially optimal level but there is still some under and over entry. The combination of the optimal entry fee and information about current entrants moves behavior very close to the socially optimal outcome.

The linear congestion function used in this experiment is, for some purposes, a little too forgiving in the sense that small increases in traffic often have “snowball effects” that increase congestion dramatically. An interesting extension would be to use congestion functions with nonlinear and stochastic elements. This modification would tend to add outcome variability even in settings with many more potential entrants. Also, the information-based and fee-based allocation mechanisms implemented in this experiment would have an additional efficiency-enhancing role if individuals differed in their values for lowered congestion and faster commutes, as shown by Plott (1983).

Appendix. Sessions, Treatments, and Data Averages

	A, B, C N	Rounds	Entry Fee (Share)	View	Voting	Predicted Entry Rate	Average Entry Rate
Session 1 me062304 UVA	9.0, 1.0, 1.0 N = 12	1-10	0.00 (0)	no	No	0.67	0.69
		11-20	4.00 (1/12)	no	No	0.33	0.38
Session 2 me062404 UVA	4.5, .0.5, 0.5 N = 12	1-20	0.00 (0)	no	No	0.67	0.65
		21-40	2.00 (1/12)	no	No	0.33	0.35
Session 3 me062904 UVA	4.5, .0.5, 0.5 N = 12	1-20	0.00 (0)	No	No	0.67	0.63
		21-40	2.00 (0)	No	no	0.33	0.34
Session 4 me063004 UVA	4.5, .0.5, 0.5 N = 12	1-10	0.00 (0)	No	No	0.67	0.66
		11-20	1.00 (1/12)	No	vote	0.50	0.57
		21-30	1.00 (1/12)	no	vote	0.50	0.52
		31-40	2.00 (1/12)	no	vote	0.33	0.35
Session 5 Me070104 UVA	4.5, .0.5, 0.5 N = 12	1-11	0.00 (0)	No	No	0.67	0.68
		12-20	1.00 (1/12)	No	Vote	0.50	0.57
		21-30	2.00 (1/12)	No	Vote	0.33	0.34
		31-40	1.75 (1/12)	No	Vote	0.38	0.37
		41-50	1.60 (1/12)	No	Vote	0.40	0.42
		51-60	1.80 (1/12)	no	vote	0.37	0.38
Session 6 me070804 UVA	4.5, .0.5, 0.5 N = 12	1-60	0.00 (0)	No	no	0.67	0.63
Session 7 me071404 W&M	4.5, .0.5, 0.5 N = 12	1-20	0.00 (0)	view	no	0.67	0.66
Session 8 me071504 W&M	4.5, .0.5, 0.5 N = 12	1-20	0.00 (0)	View	No	0.67	0.67
		21-40	2.00 (1/12)	view	no	0.33	0.35
Session 9 me072104* W&M	4.5, .0.5, 0.5 N = 12	1-20	0.00 (0)	view	no	0.67	0.67
Session 10 me072804 UVA	4.5, .0.5, 0.5 N = 12	1-20	0.00 (0)	view	no	0.67	0.67
		20-40	2.00 (0)	view		0.33	0.35
Session 11 me111004 UVA	4.5, .0.5, 0.5 N = 12	1-15	0.00 (0)	view	no	0.67	0.68
Session 12 me111504 UVA	4.5, .0.5, 0.5 N = 12	1-20	0.00 (0)	no	no	0.67	0.62
		21-40	2.00 (0)	no		0.33	0.35

* The database name for this session was a temporary name, not me072104.

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