The Relevance of Heterogeneity in a Congested Route Network with Tolls: An Analysis of Two Experiments Using Actual Waiting Times and Monetized Time Costs

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Abstract

Heterogeneity is important in some settings. One such instance involves congested networks with tolls, since people trade time for money at different rates. This paper reports results from two experiments that examine these issues. In both experiments, subjects choose between traveling on an indirect route that does not congest and a direct toll route that congests as more subjects travel on it. In the first experiment, values of time are assigned to subjects. Subjects generally sort themselves with high value-of-time subjects choosing the toll route. I also find that as the cost of deviating from the equilibrium prediction increases, subjects are more likely to make choices consistent with equilibrium. In other words, coordination problems diminish as value-of-time heterogeneity increases. The second experiment simulates a boring commute in which subjects must wait after the experimental rounds are finished. Subjects can give up money for reduced waiting time in this experiment by traveling on the toll route. In this experiment, some subjects travel the toll route frequently, giving up some of their payout in order to reduce their waiting time after the experiment. These choices are likely based on individuals' values of time, since aggregate behavior differs by session. There is also evidence that subjects with time constraints travel the toll route more often than other subjects.

Keywords: congestion, Pigou-Knight-Downs paradox, experiment, toll, value of time, externalities, heterogeneity

JEL Classification Numbers: D62, C92, R48

1. Introduction

Experimental economics often uses simplifying assumptions so that subjects understand the scenario being tested. For this reason, homogeneity of some form is often imposed. However, even early experimental work recognized that subject homogeneity does not always produce useful results (see Chamberlain 1948, for an example with heterogeneous profiles). The study of congested environments seems like one such case. Previous congestion experiments only address situations with subject homogeneity. This simplifying assumption leads to situations with coordination problems. Although sometimes relevant, many congestion environments do not suffer from coordination problems, such as when tolls and heterogeneous values of time exist. In these cases, theory predicts that people with high values of time are willing to travel on a toll route in order to reduce travel time. This paper reports the results of two experiments showing that heterogeneity is important in this context.

Both experiments in this paper use the same type of route network. All subjects must travel on one of two routes. One route is a long route that gives a guaranteed travel time. Thus, it does not congest. The other route is a short, but congested route, since travel time depends on the number of people traveling on this route.

In the first experiment, values of time are assigned to subjects. In this case, theory predicts that subjects with high assigned values of time will travel the toll route, while those with low assigned values of time will opt for the longer untolled route. Theory predicts that subjects who travel on the toll route will have a lower travel time than those who travel the other route. Subjects generally act consistently with theory in this respect. The amount of heterogeneity is also important. In cases in which subjects' values of time are close to one another, subjects are not always able to determine their best choice. This leads to lower variance of number of travelers on each route as the amount of heterogeneity increases.

In the second experiment, subjects do not lose money for travel time in each experimental round, but must wait a fraction of their waiting time after the experiment is completed. Since theory predicts a shorter time on the toll route, subjects can lower their waiting time by paying a toll and playing the shorter route. Therefore, each subject has the opportunity to trade money for additional time after the experiment. Some subjects use this opportunity, cutting their waiting time by one-half or more. Some sessions have more frequent play of reducing waiting time than others, implying that some sessions have more subjects with high values of time than others.

Finally, there is some evidence that subjects with time constraints are more likely to reduce waiting time by decreasing their individual payouts.

2. Background and Motivation: Congestion and Experiments

Vickrey (1963, 1969) shows that individuals drive inefficiently large amounts on many unpriced roads and highways because they fail to internalize the congestion time they impose on other drivers. He further shows that differential pricing on roads and highways, similar to practices by the airline and movie industries, can lead to Pareto improvements. In the case of flights and movies, deadweight loss is reduced through price discrimination. On roads and highways, differential pricing is able to divert drivers from more congested routes to less congested routes. In the case of an optimal road or highway pricing mechanism, the marginal benefit of reduced travel time for the last driver equals the marginal external costs due to increasing travel time to the other drivers already on the highway. Section 3 develops this idea more. Further, differential pricing on public roads, in the form of tolls, are not actually costs but rather transfers to the government.[1] The only actual costs generated by tolls are the costs associated with collecting the tolls, costs that have been significantly reduced with transponder technology.[2] As long as the cost of collecting tolls is less than the benefits of decreased travel times, Pareto improvements are possible.

Although Vickrey's ideas are well established in economics, public policy has leaned more towards increased highway capacity than price rationing. This is particularly problematic since such increased capacity often fails to reduce congestion, and in some cases actually worsens it.[3] In a simple case that does not change drivers' outcomes in equilibrium when capacity is increased, congestion remains the same as long as both routes are used.[4] This case, known as the Pigou-Knight-Downs paradox (see Arnott and Small 1994), uses a network with an uncongested route and a shorter congested route.[5] On the uncongested route, travel time is the

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[1] Note, however, that tolls appear to be costs to drivers.
[2] Transponders are small devices that are attached to vehicles. These transponders can be detected by devices on highways without drivers having to slow down.
[3] See Arnott and Small (1994) for cases that predict worse congestion when road capacity is increased.
[4] All analysis of the Pigou-Kinght-Downs paradox in this paper assumes positive traffic flow on both routes.
[5] The travel network used in this paper produces the Pigou-Knight-Downs paradox, which "is often called 'the fundamental law of traffic congestion,'" according to Arnott and Small (1994, p. 451).

same regardless of the number of travelers. On the congested route, the travel time increases for all drivers each time another traveler decides to use the route.

Unlike increasing capacity on the congested route, tolling schemes are capable of reducing congestion in the framework of the Pigou-Knight-Downs paradox, and can therefore lead to Pareto improvements. In equilibrium without tolls, everybody's travel time equals the time on the uncongested route. After the implementation of a toll on the congested route, nobody can be made worse off, because anybody may still travel the uncongested route with the same travel time. Thus, anybody traveling the tolled congested route must be at least as well off as without the toll. Toll revenues are also available to disburse among the population, increase transportation or other funding, or reduce tax burdens.

The problem in the no-toll case is that people fail to internalize the additional costs they impose on others when they use the congestible route. In a no-toll equilibrium, everyone is just as well off in an environment in which both routes exist than in an environment in which only the uncongested route exists.[6] If only the uncongested route exists, adding the congested route without the implementation of tolls adds no social benefit because commuters simply clog the congested route to the point where there is no time gain to traveling the congested route over the uncongested route. Given the negative externalities present on the congested route, a toll here can effectively optimize its use by reducing the travel time of some of the drivers on this route. At the same time, no toll is needed on the uncongested route because there are no externalities, since congestion is never present by definition.

With tolls able to reduce congestion and increase efficiency in a route network, experiments may be a good way to examine people's behavior. However, previous experiments have not used tolls as a mechanism to increase efficiency (see Selten *et al.* (2007), Gabuthy, Neveu, and Denant-Boemont (2006),[7] and Chmura and Pitz (2004a and 2004b)). The experiments analyzed in this paper use tolls to increase efficiency when subjects' values of time are heterogeneous.

[6] The fact that everyone would be as well off in a no-toll equilibrium with or without the bridge is specific to the Pigou-Knight-Downs paradox. Other paradoxes are presented in Arnott and Small (1994) in which travel times are increased when road capacity increases.

[7] Gabuthy, Neveu, and Denant-Boemont (2006) use a toll in their paper. However, their use of tolls does not improve efficiency.

3. A Two-Route Model with Only One Route That Congests

Suppose a group of people need to travel from point A to point B, and that each person has the option to travel on an uncongested but indirect highway, or a more direct but narrow bridge that gets congested (See Figure 1).[8] In other words, highway travel time is independent of the number of travelers, while travel time on the bridge is an increasing function of bridge traffic. Assume that the per-minute travel time cost is independent of route choice. This rules out the possibility that the more scenic route is preferred, all else being equal. Given this framework, under heterogeneous travel time costs, the equilibrium depends on the distribution of the values of time among participants.

3.1. Description of the Route Network

In the modeling used in this paper, I assume that each person's per-minute travel time costs are heterogeneous. For simplicity, I assume that N commuters know the travel time on the bridge (t_B) and the highway (t_H) with certainty. In particular, they know that travel time on the highway is constant and that travel time on the bridge is an increasing linear function of the number of travelers on the bridge (Q) with intercept α and slope β, such that:

(1) $t_B = \alpha + \beta Q$.

For each additional traveler on the bridge, time increases by β minutes. Based on the above information, drivers can determine the marginal private benefit (MPB) of traveling the bridge relative to the highway. If Q drivers travel the bridge, the MPB in minutes of the Q^{th} person traveling the bridge is the difference in travel time between the two routes, or $t_H - (\alpha + \beta Q)$. To convert the travel time into monetary terms, the time saved needs to be multiplied by the individual's value of time:

(2) $MPB_Q = (t_H - (\alpha + \beta Q)) \times V_Q$,

where V_Q represents the value of time for the Q^{th} person to travel the bridge.

3.2. Tolls and Equilibrium in a Heterogeneous Time Cost Setting

In any route network that requires all drivers to travel from point A to point B, the optimal toll minimizes drivers' total travel time costs. In a framework with heterogeneous

[8] This route grid structure is as in Arnott and Small (1994), and some of the theory is similar to Walters (1961).

values of time, the optimal amount of congestion on the bridge can be determined by finding the point where the *MPB* of the last driver on the bridge equals the marginal external cost (*MEC*) imposed on those already traveling the bridge. The *MEC* is positive because an additional driver on the bridge imposes an additional β minutes to each driver already on the bridge. The *MEC* of the Q^{th} driver on the bridge is then:

(3) $$MEC_Q = \sum_{j=1}^{Q} (\beta \times V_j).$$

In any case related to the Pigou-Knight-Downs paradox, there is no need to toll the highway to improve efficiency, since *MEC* is zero by definition. Thus, tolls are only needed on the bridge in order to improve efficiency. With a toll implemented on the bridge, no traveler would prefer the bridge if the travel time on this route exceeds that of the highway. So equilibrium always occurs when travel time on the bridge is less than that on the highway. Recall that the *MPB* of time saved by traveling the bridge is $t_H - (\alpha + \beta Q)$ minutes. With a toll of *C*, the cost per minute of travel time reduction if *Q* people travel the bridge is then

(4) $$\frac{C_Q}{60} = \frac{C}{t_H - (\alpha + \beta Q)},$$

with C_Q denoting the per-hour cost to reduce travel time if *Q* drivers travel on the bridge.[9] Equation (4) translates this into an hourly rate of

(5) $$C_Q = \frac{60C}{t_H - (\alpha + \beta Q)}.$$

Without loss of generality, let each person's value of time be V_Q per hour such that: $V_1 \geq V_2 \geq \ldots \geq V_N$. If $V_1 \leq C_1$, then nobody travels the bridge in any round, since the cost to save $t_H - (\alpha + \beta)$ minutes of travel time is not worth the cost for any single person, even for the person with the highest value of time. Generally, each person travels on the route in which the toll paid, if any, plus travel time cost is lower. Under these conditions, people with the highest values of time travel the bridge because they are able to reduce their travel time costs more than

[9] Since the per-hour cost is C_Q, the per-minute cost is $C_Q/60$.

others due to their high value of time.[10] Specifically, letting C_Q denote the per hour cost in waiting time while Q subjects travel the bridge,

- If $C_Q < V_Q$, the Q^{th} person will travel the bridge.
- If $C_Q = V_Q$, the Q^{th} person will be indifferent between the two routes.
- If $C_Q > V_Q$, the Q^{th} person will not travel the bridge.

I will typically assume that the person that is indifferent travels on the bridge, since this is consistent with the predictions made by Arnott and Small (1994).

<u>A Discrete Example</u>

A simple example incorporating heterogeneous waiting times requires a distribution of waiting time values along with specifying the right hand side parameters for equation (5). For illustrative purposes, column 2 in Table 1 lists a hypothetical set of values of time for the $N = 18$ participants in descending order, while the values for C_Q are determined from $C = \$0.25$, $t_H = 30$, $\alpha = 28.4$, and $\beta = 0.2$. With $\hat{Q} = 8$ in this example, C_Q is undefined when $Q = 8$, and negative when $Q > 8$. In these uninteresting cases, C_Q is listed as N/A in Table 1.

(Table 1 about here)

Here, the person with the highest value of time travels the bridge, due to the \$100 per hour value of time being larger than the \$10.71 per hour cost of exactly one person traveling the bridge. Similarly, the person with the second highest value of time also travels the bridge since \$80 > \$12.50. This continues through the fifth highest value of time, with \$30 > \$25. The sixth highest value of time, with a value of time of \$29 per hour, does not travel the bridge since the additional congestion increases the per-hour cost of traveling the bridge to \$37.50.[11] Thus, five people travel the bridge in equilibrium. Specifically, the five people with the highest values of time travel the bridge.

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[10] There are sometimes exceptions to this when $V_Q \approx V_{Q+1}$, which are examined further in the discrete example below and in Experiment 1.

[11] Note that another equilibrium exists in which the person with $V_Q = 29$ travels the bridge instead of the person with $V_Q = 30$. I generally ignore this type of equilibrium since they are less efficient.

3.3. More on Efficiency

In a discrete case with heterogeneous values of time, there is no simple way to generalize the minimum total time cost concept without knowing the distribution of values of time. For example, assume that 18 people are traveling on the same route grid and the parameters for travel time are the same as in the discrete example from Section 3.2. If the person with the highest value of time has V_1 = $1,000 per hour, while everyone else has a value of time of $10 per hour, the efficient outcome involves only the high-value person on the bridge. This is because the *MEC* from the second person traveling the bridge is higher than the *MPB*.[12]

Formally, an efficient outcome occurs when the following time cost problem is solved:

(6) $$\text{Min} \sum_{i=1}^{18} V_i t_j$$

subject to $t_B = \alpha + \beta Q$,

with $j \in (B,H)$, and t_H, α and β are given. To help solve this problem, note that for a given number of subjects traveling the bridge (as long as the travel time on the bridge is shorter), the lowest total time cost occurs when the subjects with the highest values of time travel the bridge.

Another way of solving Equation (6) is to find the intersection between the *MEC* and *MPB* curves. From Equation (3), the *MEC* generally increases by a smaller amount for each additional driver, while from Equation (2), the *MPB* often flattens as the number of drivers increases. A typical case is seen in Figure 2, with the optimal quantity of travelers denoted as Q^*.[13]

<u>A Discrete Example</u>

To get an efficient outcome, we now know that the people with the highest values of time will travel on the bridge. Using the same example as in Section 3.2 (with values of time seen in Table 1), Table 2 shows the total travel time cost of all drivers as a function of the number of people traveling the bridge, assuming that the people with the highest values of time travel the bridge. The table shows that total travel time cost is the same if either nobody or eight people

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[12] Specifically, if only the person with the highest value of time travels the bridge, her travel time is 28.6 minutes. With the addition of another driver, the high value-of-time driver's time increases by 0.2 minutes, leading to a *MEC* of $3.33 at a rate of $1,000 per hour. The *MPB* of the second driver on the bridge is 1.2 minutes, or $0.20 at a rate of $10 per hour.

[13] Without any controls, an inefficient equilibrium will occur when MPB is zero, when $\hat{Q}$ subjects travel the bridge.

travel the bridge, since everybody's travel time is 30 minutes. This cost is lower when any number of travelers from one to seven travels on the bridge, because the people that travel the bridge require less than 30 minutes to travel the bridge.

In order to see that three people traveling the bridge is optimal, compare the marginal private benefit against the marginal social cost for the third and fourth drivers on the bridge. In the case of the third driver, the time for this driver is reduced by 1.0 minute, from 30 to 29 minutes. The person with the third highest value of time is at $70 per hour, which translates to a MPB of $1.17 if this driver moves from the highway to the bridge. However, external costs are imposed on the two drivers already on the bridge, with an increase in travel time of 0.2 minutes to those already driving on the bridge when the third driver is added. Assuming that the drivers with the highest values of time are already on the bridge, the MEC is 33 cents for the driver with the highest value of time and 27 cents for the second highest. Thus, adding the third driver to the bridge is more efficient, since the MPB of the third driver exceeds the MEC of the two drivers already on the bridge. A similar analysis of adding the fourth driver on the bridge shows that the MPB is less than the total MEC.

4. Experimental Design

The two-route travel grid from the Pigou-Knight-Downs paradox is used in the two experiments described here. Both experiments implement the use of bridge tolls and heterogeneous values of time. In the first experiment, subjects have one of five profiles, implying that subjects have heterogeneous values of time. The second experiment incorporates a waiting time component. In this case, subjects must evaluate a situation in which they have the opportunity to give up money to reduce actual waiting time. This is done by forcing subjects to wait a fraction of their travel time in this experiment after the experimental rounds are complete and before receiving payment. Subjects assess the situation to determine if their own values of time are large enough to travel on the bridge to lower their waiting time. During the waiting time after the experimental rounds are complete, subjects sit in a computer lab and do nothing.[14]

[14] During their waiting time, subjects are not allowed to do any activities, including reading, using a cell phone or computer, listening to music, and talking.

In this case, theory predicts that subjects with high enough values of time will pay the toll to reduce waiting time.

Each experiment has its own advantageous aspect. In the first, knowing each person's value of time is useful to predict the route traveled by each subject in equilibrium. In the second, subjects must incur actual time costs, an idea no other congestion experiment uses. This is important since there is evidence that time costs are treated differently from monetary costs (see Ellingsen and Johanneson 2007). I can also test whether different sessions behave differently in this experiment. If so, then this suggests that the number of subjects with high values of time likely varies by session.

In both experiments, each subject may stay on the same route or change routes from round to round, but no one is permitted to change their choice within a round once their decision is made. At the end of each round, subjects receive information as to how many people traveled on the bridge in that round, along with the total point deduction. Each experiment lasts about one hour in a University of California Santa Barbara computer lab, and subjects earn an average of about $13-15 for participation in one of the experiments.

4.1. Experiment 1

In each experimental session, 15 subjects travel the route network from point A to point B, as shown in Figure 1.[15] Subjects are told that the highway has a guaranteed t_H = 25-minute travel time, while the bridge's travel time is $t_B = (11 + T)$ minutes, or $\alpha = 11$ and $\beta = 1$ using the notation from the previous section.

A toll of 70 points is charged in each round a subject travels the bridge in this experiment. This experiment has two parts (referred to as "segments") with 50 rounds each. Subjects see their individual point deductions on their computer screen after the verbal instructions have been given. There are five sub-groups of three people in each segment of each session. The following three sub-group formats are used:

- (Format I) One sub-group each with a point deduction of 4, 7, 10, 13, and 16 points per minute (high heterogeneity)

[15] Both experiments were programmed and conducted using z-Tree (Fischbacher 2007). Verbal instructions are provided in Appendix A.

- (Format II) One sub-group each with a point deduction of 8, 9, 10, 11, and 12 points per minute (low heterogeneity)
- (Format III) A control group with all sub-groups having point deductions of 10 points per minute (no heterogeneity)

There are three experimental designs:

- (A) Segment 1 uses Format I and Segment 2 uses Format II (Sessions 2 and 5)
- (B) Segment 1 uses Format II and Segment 2 uses Format I (Sessions 1, 4, and 6)
- (C) Both segments use Format III (Session 3)

In this experiment, the number of points that each person starts with is dependent on the point deductions per minute for each of the two segments, and each subject also receives a $5 show-up fee.[16] The point endowment information is displayed in Table 3.[17] Since all costs are monetized in this experiment, subjects do not incur a waiting time at the end of the experiment. After the experiment is complete, subjects receive one dollar per 40 remaining points.

To reach an equilibrium similar to what the previous section predicts, I look most closely at the sub-group with a 10-point-per-minute deduction. Recall from the theory in Section 3.2, when $C_Q = V_Q$, I assume that the Q^{th} person travels on the bridge. With this assumption, all three formats have equilibrium of seven subjects on the bridge. In Formats I and II, the two sub-groups with highest point deductions all travel on the bridge, along with one person with a 10 point deduction per minute. There are other possible Nash equilibria, due to the discrete nature of the experiment, but they are examined minimally in this paper. These equilibria are derived in Appendix B.

In this experiment, there is no symmetric mixed-strategy Nash equilibrium in Formats I and II, since some players have strict preferences in equilibrium. In the control, Format III, a symmetric mixed-strategy Nash equilibrium occurs when the expected number of subjects on the bridge except oneself is 6. This mixed strategy equilibrium occurs when each subject travels on the bridge with probability 3/7, or 0.429.

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16 Subjects receive the show-up fee in both experiments even if all points are used up.

17 Six subjects lost all of their points by the end of the experiment. However, I do not suspect that the results are substantially affected by this, because in all but one case, all subjects had a positive number of points after Round 97 of 100. One subject lost all remaining points in the 91st round. This person has a 4 point per minute deduction in Segment 2, and travels on the highway in each of the final 12 rounds of the experiment.

4.2. Experiment 2

In each experimental session, 18 subjects[18] travel from point A to point B using the congested bridge or the uncongested highway in each round (see Figure 1).[19] In contrast to the previous experiment, the highway guarantees a travel time of $t_H = 20$ minutes. The travel time on the bridge is $t_B = (9 + Q)$ minutes, or $\alpha = 9$ and $\beta = 1$. Before discussing this experiment in detail, it is important to point out that although this experiment includes all three segments described below, this paper focuses on the third segment.

Each of the 10 experimental sessions consists of three segments with 20 rounds (or repetitions), and each subject begins with 8500 points and a $5 show-up fee.[20] Points are deducted for travel time in the first two segments, but not for the third segment. Instead of paying a monetary equivalent for time in Segment 3, subjects are told that more travel time within this segment results in an increased physical waiting time before receiving their payment at the end of the experiment. Finally, tolls are charged (in the form of point deductions) on the bridge in the final two segments of the experiment. After the experiment is finished, the remaining points are converted at a rate of 50 points per dollar.

In Segment 1, subjects are told that each minute of travel time leads to a 10-point deduction, but no tolls are charged. Within this framework, theory predicts an equilibrium with 20 minutes of travel time on both routes in Segment 1. This occurs when $Q = 11$. In Segment 2, subjects continue to pay a 10-point deduction per minute of travel time, but now there is a 60-point-per-round toll charge. At a cost of 10 points per minute, a 60-point toll translates to the equivalent of six minutes of travel time cost. This means that a 14-minute commute on the bridge is now equivalent (in total point deductions per round) to a 20-minute commute on the highway. So the new toll equilibrium results with five people using the bridge in equilibrium. The results for Segments 1 and 2 are reported in Hartman (2007).

In Segment 3, the focus of this paper, subjects can trade money for waiting time. A subject only pays a 6-point toll charge to use the bridge in Segment 3, but no longer faces a point deduction for travel minutes in the experiment. Instead of a point deduction for travel time, a subject's sum of travel minutes for the 20 rounds in this segment (denoted as N) is

[18] Due to lack of full participation, one group had only 17 subjects, but for simplicity all discussion will assume 18 subjects in all sessions unless otherwise noted.
[19] Verbal instructions and questionnaire of personal characteristics are provided in Appendix C.
[20] In no case does any subject lose all points in this experiment.

converted into waiting time at the end of the session. The amount of time that subjects must wait before being paid is $\frac{N-200}{10}$ minutes. Within this set-up, if there are fewer than 11 bridge users in any round, then subjects can literally give up money to gain additional time. Since each session likely has subjects with various values of time, I would generally expect that each subject has a strict preference of routes in equilibrium.

Based on the above conversion factor, each minute of reduced travel time in Segment 3 results in a 0.1-minute reduction of actual waiting time. This means that the actual waiting time saved for each bridge trip (versus traveling the highway) is not $[t_H - (\alpha + \beta Q)]$, but $\frac{[t_H - (\alpha + \beta Q)]}{10}$. Thus, similar to the theory presented in Section 3,

$$(7)\ C_T = 60C \Big/ \left[\frac{t_H - (\alpha + \beta Q)}{10}\right].$$

Since C =\$0.12,[21] $t_H = 20$, $\alpha = 9$, and $\beta = 1$, then

$$(8)\ C_T = \$7.20 \Big/ \left[\frac{11-Q}{10}\right],$$

where $\frac{11-Q}{10}$ is the number of minutes saved on the bridge versus traveling the highway in a particular round. Table 4 shows the relationship between Q, the number of minutes reduced for each round the bridge is traveled in Segment 3 (as a function of Q), and C_Q.

5. Experimental Results and Analysis, Experiment 1

In this section, I show that the results of Experiment 1 are closely matched to theory. This result is important due to the increased efficiency relative to the no-toll equilibrium prediction. Also in this section, it is shown that subjects are more likely to play according to theory if the costs of deviating from equilibrium are high. Experience also leads to increased likelihood of equilibrium play.

[21] Six points at a conversion rate of 50 points per dollar is equivalent to \$0.12.

5.1. Data Summary and Comparison to Pure-Strategy Equilibria

In the equilibrium derived from the theory section, the predicted equilibrium of each of the three formats results in seven subjects on the bridge (including all six subjects with the highest point deductions per minute and one person with a 10-point deduction per minute in the heterogeneous formats) and eight on the highway.[22] However, in each of the formats, there exist possible equilibria such that six subjects are on the bridge (see Appendix B). Table 5 shows the average number of subjects on the bridge by session and segment, along with clusters of sessions with the same design. In each session, the Segment 2 average is lower than the Segment 1 average. This may be due to learning between Segment 1 and Segment 2, especially if some subjects with relatively lower time costs can figure out that they cannot be better off on the bridge with seven or more subjects on the bridge. This may help explain why some of the Segment 2 averages are significantly below 7.[23] Table 5 shows that no statistically significant differences occur in Segment 1. However, the averages in Segment 2 of Sessions 1 and 4 differ from 7. The average for all of the high heterogeneity sessions in Segment 2 collectively, as does the average for all six sessions collectively, also differ from 7. In all of these cases, the averages are lower than 7, which suggest that some sessions may be affected by the equilibrium possibility of 6 subjects on the bridge in Segment 2. For example, in the case of Session 1, the total number of bridge travelers per round alternates between six and seven subjects throughout most of Segment 2. However, in Session 4, the significant difference is due to most of the rounds being at 7 bridge travelers (leading to low variance) combined with more rounds below 7 than above.

5.2. Efficiency

Formats II and III achieve the minimum total travel time cost when seven subjects travel the bridge. In Format I of this experiment, the minimum total travel time cost occurs when six subjects travel the bridge, since a bigger negative externality is imposed on subjects with high values of time when additional subjects travel on the bridge. However, the next best outcome

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[22] This is calculated by the fact that the seventh person on the bridge (with a 10-point-per-minute deduction) can reduce travel time by seven minutes, but must pay a 70-point toll. This trade-off results in this subject being indifferent on either route, given that the six subjects with the highest values of time are already traveling on the bridge.

[23] I also conduct the same tests with the null hypothesis of an average of six drivers on the bridge per round, since this is also a possible pure-strategy equilibrium. In all cases, the null hypothesis is rejected.

occurs when seven subjects travel the bridge. So in all formats, when seven subjects travel the bridge, an outcome occurs that is at or close to the minimum total time cost.

5.3. Analysis

Three important aspects of this route choice experiment are analyzed below. First, when heterogeneity is introduced within the subject pool, most subjects have a strict preference in equilibrium. This means that if subjects are profit maximizing (or minimizing their point deductions), then there should be less variability in the number of bridge travelers from round to round, compared to the homogeneous case. I test to determine if there are differences in variances when comparing two different levels of heterogeneity. Second, since each segment of each session has an equilibrium of seven travelers on the bridge, I run various tests to determine if there are any mean differences. Third, I analyze the relationship between number of points deducted per minute and frequency of travel on the bridge.

5.3.1. Differences in Variance of Number of Travelers on the Bridge, by Format

As heterogeneity increases, the cost of deviating from equilibrium also increases for most people. This may result in subjects learning more quickly what is best for them when there is substantial subject heterogeneity, since the price paid for deviating increases. If this is true, the variance in the number of bridge travelers in sessions with high levels of heterogeneity will be lower. Figure 3 confirms this visually in Segment 1, as the sessions with high levels of heterogeneity have much less variation than the other sessions. This result is stronger if the final 25 rounds are examined in each session. Segment 2 generally has less variation of number of bridge travelers than in Segment 1, implying that experience plays a role in decision making.

(Figure 3 about here)

Table 6 confirms the above learning hypothesis for Segment 1 statistically, with high heterogeneity sessions having substantially less variance than the other sessions. These differences are significant at the 1 percent level. In contrast, the variance for low levels of heterogeneity is not statistically different from the variance with no heterogeneity. Differences in variances decline between Segment 1 and Segment 2, with the only significant difference in Segment 2 being at the 10% level between the high heterogeneity and no heterogeneity formats.

Apparently, the level of heterogeneity does not affect the variance of sessions as much once subjects are experienced with Segment 1.

One final way is used to show that learning occurs more quickly at high heterogeneity levels. Figure 4 shows that the sessions with high heterogeneity in Segment 1 have seven subjects on the bridge in over 45 percent of the rounds, while the other sessions only have this feature about one quarter of the rounds. The high heterogeneity sessions also have fewer rounds with less than six or more than eight on the bridge. By Segment 2, most of this difference is gone, although there are still a higher percentage of rounds in the high heterogeneity case with six to eight subjects on the bridge. This can be seen in Figure 5.

5.3.2. Tests of Differences Between Sessions and Segments

Since the predicted average number of travelers is seven in each segment of each session, it is useful to conduct tests to determine if any differences in means exist. I conduct two types of tests. The first test determines if the segment averages differ from one another, either within a segment or over both segments. The second test compares groups of sessions with the same level of heterogeneity.

The first test asks whether or not segment averages differ from one another. This is done two different ways. First, I test to determine if there are any differences in means of all sessions within the same segment. There are no significant differences in Segment 1, but the differences are marginally significant in Segment 2, with a p-value of 0.057. The second method checks to see if there are any differences in means by segment within the same session. Although the average number of travelers in each session decreases going from Segment 1 to Segment 2, none of these differences is significant.

The second test asks whether or not there are differences by format. More specifically, I look at two of the three different formats at a time ─ with each format having a different amount of heterogeneity ─ and conduct a t-test to determine if there are more travelers in one of the two formats. These tests are displayed in Table 7. The only cases with significantly different averages (at the 10% level) occur in the comparison between high and low levels of heterogeneity. However, the higher average is for Sessions 2 and 5 in both cases. Thus, in Segment 1, the sessions with high heterogeneity have more travelers on the bridge per round. In Session 2, the low-heterogeneity sessions have more bridge travelers per round. This means that the differences are likely dependent on the groups of subjects and not the amount of heterogeneity.

5.3.3. Frequency of Equilibrium Play by Subjects

In Experiment 1, most subjects can only be on one route in equilibrium. From Appendix B, any subject with a per-minute point deduction of 12 or more must be on the bridge in equilibrium, while those with 9 or fewer points deducted per minute of travel time must be on the highway in equilibrium. However, following the assumption that subjects with the highest values of time travel on the bridge, those with 11 points deducted per minute will also travel on the bridge in equilibrium, as will exactly one out of three with 10 points deducted per minute when heterogeneity of point deductions is present.

Table 8 shows the average number of trips on the bridge per subject, by per-minute point deduction and segment. Excluding the control group, the average number of trips is positively correlated with the number of points deducted per minute. However, subjects appear to act more closely to the equilibrium prediction in Segment 2 than in Segment 1 in the low heterogeneity format. This may help to explain the lower variance of number of bridge travelers in Segment 2 of this format.

Although most subjects follow the equilibrium prediction in most rounds when there is a strict preference, there are some that do not. For instance, three of the nine subjects with 9 points deducted in Segment 1 travel on the bridge more than half the time during these 50 rounds. Another subject in Segment 2, with a 9-point deduction per minute, travels the bridge 49 of the 50 rounds. Finally, there are subjects with 12- and 13-point deductions per minute in Segment 2 travel the bridge only five and 11 times, respectively.

For some subjects, they not only make a choice that is not part of equilibrium, but also Pareto dominated. For example, any subject with a 4-point deduction per minute can never be better off on the bridge, since the cost of traveling the highway is always lower. In this case, the time cost is at least 48 points, and the toll is 70 points, leading to a total deduction of at least 118 points. If she travels the highway, her travel time is 25 minutes with no toll, resulting in a point deduction of 100 points.

Despite the fact that any person with a 4-point deduction per minute should always travel the highway in this experimental set-up, there is one person in Segment 2 of this type that travels on the bridge in each of the first 38 rounds.[24] This person, a subject in Session 6, likely caused each of the subjects with 10 points deducted per minute to travel the bridge infrequently in Segment 2. If the irrational play described above is assumed, then the other 14 subjects can reach equilibrium when all other subjects with 10 points or fewer deducted per minute travel the highway. In this session, the three people with 10-point-per-minute deductions travel on the bridge 1, 4, and 19 times each. This compares to the 22.25 trips per subject for counterparts in the segments of other sessions with high heterogeneity. Thus, in Segment 2 of Session 6, subjects with 10 points deducted per minute of travel time seem to become averse to traveling the bridge due to the decision by the person traveling the bridge most of the rounds who has 4 points deducted per minute. This results in a segment that looks like it approaches equilibrium in the aggregate, except for the final 12 rounds in which the most frequent outcome in this part is with six subjects on the bridge.

What also happens sometimes is that two subjects do not act in a way that is consistent with equilibrium. This could make the aggregate appear to look like it is in equilibrium. For example, in Session 2, one person with 9 points deducted per minute travels the highway only once, while a person with 12 points deducted per minute almost never travels the bridge. Although most of the later rounds of this segment are at or around seven bridge travelers per round, these two people should reverse roles in equilibrium. However, by essentially switching roles, the other 13 people can still reach their best outcome with seven subjects on the bridge in total.

5.3.4. Summary

In most of the individual segments of this experiment, the average number of bridge travelers is consistent with the equilibrium of seven bridge travelers per round. Although possible equilibria exist with six bridge travelers per round on the bridge, none of the averages is consistent with this as the sole outcome. However, the existence of possible equilibria with six subjects on the bridge may contribute to some of the averages being different from both 6 and 7.

With heterogeneous profiles, most subjects can only play a pure strategy in equilibrium. This leads to two important points. First, this is the likely cause of lower variation in Segment 1

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[24] Not surprisingly, this subject lost all remaining points in the 41st round of Segment 2. This subject does travel on the highway in the final 12 rounds of the experiment, however.

when there are high levels of heterogeneity, since subjects that deviate from equilibrium pay a high price to do so in this situation. Second, some subjects do not play in a profit-maximizing way when heterogeneity is present. When one person behaves in such a way, there is evidence that others adjust their decisions to attempt to reach their best payout. In another case, two people act in such a way. Here, they essentially trade their route choice decisions, and so the other 13 people can still behave in a way that is consistent with a predicted equilibrium outcome.

6. Experimental Results and Analysis, Experiment 2 (Segment 3)

Experiment 2 examines issues related to subjects' actual values of time. This section shows that about 10 percent of subjects are willing to pay to substantially lower waiting time after the experiment. Furthermore, there is evidence of time-constrained subjects being among those willing to reduce waiting time. There is also evidence that some sessions have more subjects with high values of time. I also compare results of this experiment with other work done on the value of time.

6.1. Data Summary and Comparison to Pure-Strategy Equilibria

As in Experiment 1, tolls persuade some subjects to switch from the congested bridge to the uncongested highway. Specifically, half as many subjects travel the bridge on average than in the inefficient equilibrium without tolls. This toll successfully re-routes traffic to a more efficient equilibrium. Table 9 reports the average number of bridge travelers per round, while Figure 6 shows the round-by-round results of each session.

Subjects' waiting time is based in part on their route choices in the 20 rounds. As can be seen in Table 9, each round has an average of about 5.5 subjects on the bridge per round. This leads to each subject traveling the bridge an average of 6.1 of the 20 rounds, with an average waiting time of 17.0 minutes. The waiting times range from 7.4 to 20 minutes. Tables 10 and 11 report the number of times that each subject travels the bridge and the subjects' waiting times, respectively. Table 10 shows that about a quarter of the subjects travel on the same route in each round, while the rest travel both routes at least once. While the median waiting time is 17.8 minutes, 60 percent of subjects wait 16 minutes or more, implying that they are not willing to give up much money to reduce their waiting time. However, about 9 percent reduce their waiting time to below 12 minutes. The willingness of these subjects to use the bridge in most rounds in order to reduce their waiting time suggests that they have a high value of time.

6.2. Analysis

6.2.1. Efficiency

Although individuals' values of time cannot be directly determined from Experiment 2, average travel times of subjects can be measured. When five or six subjects travel the bridge, the minimum possible total travel time of 330 minutes is achieved.[25] The average individual travel time is 18.49 minutes, or 0.9% higher than the minimum possible total travel time. Further, the total travel time is minimized in 46% of the rounds.

6.2.2. Subject Characteristics and Decision Making

In Experiment 2, route choice is determined by the trade-off between time and money. As such, it is possible that personal characteristics, such as those listed in Table 12, may play an important role in determining the route chosen by each subject. However, the data do not generally support this conjecture. The average number of bridge trips does not differ across self-reported subject characteristics. These data were collected using a pre-experiment written subject survey. In particular, t-tests for many subject characteristics fail to reject the null hypothesis of no difference in the average number of times the bridge is used.[26] Thus, no one characteristic by itself seems to have an effect on the frequency of bridge travel.

One of the most surprising findings is that route selection appears to be independent of wages. As stated above, there is no evidence that subjects who earn $10, $12, or $15 or more per hour[27] are more or less likely to use the bridge. In a similar vein, there is no statistically significant difference in bridge use across employment status. This result seems counter-intuitive since wages are often used to approximate the value of time (see Deacon and Sonstelie (1985), for example). However, since the subjects in this experiment are almost all university

[25] This assumes 18 subjects. In the one session with 17 subjects the minimum total travel time is 310 minutes.

[26] The characteristics tested are whether the subject is a male, a graduate student, a freshman, a sophomore, a junior, a senior, has a grade point average (GPA) of 3.5 or higher, has a GPA below 2.5, has a job of at least five hours per week, has at least one parent with a bachelor's degree, earns $10 per hour or more, earns $12 per hour or more, earns $15 per hour or more, is age 21 or older, and is enrolled in 15 units or more at the time.

[27] The same holds true whether people without jobs are included or excluded from the analysis.

students, job status is usually a secondary consideration behind educational pursuits. While the secondary nature of paid employment may be generally true, the necessity of work for some students, in order to pay for schooling, may lead to substantial time constraints for these individuals. More specifically, students with less educated parents are more likely to face time constraints, since they are more likely to be working in order to afford college.[28] For this reason, it is interesting to compare the route choices of working students with neither parent having an undergraduate degree with those of the other subjects, as it seems reasonable to assume that these students are less likely to work their way through college. Table 13 reports the average number of bridge trips per subject controlling for the possible combinations of whether or not someone has a job of five hours or more per week and at least one parent with a bachelor's degree. Those working and having no parent with a bachelor's degree travel the bridge more often than other subjects. Probit regressions in Table 14 reveal that these subjects are almost 20 percentage points more likely to travel the bridge than other subjects. When a full set of controls is included, this result is significant at just outside the 5% level.[29] A look at the travel patterns without controls also shows that subjects with a job and no parent with a bachelor's degree are more willing to travel the bridge. This group comprises only 9.5% of all subjects, but 41% of subjects that travel the bridge in at least 15 rounds.

6.2.3. Variation in Number of Bridge Travelers by Session

Due to potential heterogeneity in value of time, equilibrium can vary from session to session in Experiment 2 (See Section 3.2). Potential heterogeneity can be tested for by conducting a difference of means test using an F-test. More specifically, the null hypothesis is that the mean number of bridge travelers is the same across sessions. The averages range from 4.20-6.95. These averages are significantly different, with a p-value of less than 0.001. This finding suggests that subject behavior in this experiment is based on individuals' values of time, rather than randomness.

[28] Many studies have examined the educational outcomes of low-income college students. Examples include Kiker and Condon (1981), Ehrenberg and Sherman (1987), Taubman (1989), and Dynarski (2004).

[29] Regressions using ordinary least squares produce similar results, with lower p-values.

6.3. The Value of Time

There is substantial existing work regarding value of time decisions. Becker (1965) assumes constant marginal costs for commuting and makes other assumptions to conclude that commuting time increases when income goes up only when income elasticity of demand for space exceeds one. Deacon and Sonstelie (1985) study waiting times and the decision process for gasoline purchases in 1980. They estimate that the value of time is approximately the after-tax wage rate. Arnott, de Palma, and Lindsey (1994) examine a single commuting route with heterogeneity of costs of being early and late to work. They predict that the time a commuter leaves for work depends on per-minute costs of travel time and arriving early to work. They also examine cases involving multiple starting times for work.

Two recent papers examine the value of time using commuting behavior in southern California. Both papers use commuters with the option to travel on either free or tolled lanes. Brownstone and Small (2005) find the typical estimates of the median value of time of actual morning commute decisions in many studies are in the \$20-\$40 range. Part of these estimates comes from Small, Winston, and Yan (2005). They find a revealed preference[30] median estimate for the value of time of \$21.46 per hour. Commuters participating in this study are also asked to answer what they would do in hypothetical situations. These stated preference estimates for the values of time are considerably lower. Both papers above state that a person's inability to properly estimate time savings may contribute to these differences.

In Experiment 2, subjects are given explicit information that can help them to determine whether or not traveling the bridge in any round is worth the 6-point (or 12-cent) toll. The only uncertainty is that subjects do not know until the round is over how many people travel each route. This means that they do not know how much each person's waiting time is reduced for traveling the bridge until the round is over. The frequency of how often a particular number of subjects travels the bridge is listed in Table 15. Travel time on the bridge is lower in all rounds, except the one round when 11 travelers use the bridge, when the times are equal. The modal and median result occurs when five of 18 subjects travel the bridge, reducing their travel time at a rate of \$12 per hour.

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[30] Revealed preference estimates come from actual commuting behavior.

Although a 95 percent confidence interval can be found for all 10 sessions collectively, Section 6.2.3 reveals that the group averages are significantly different from one another. Thus, I examine the confidence intervals of the number of bridge travelers by group, which are derived from the means, standard deviations, and a sample size of 20 rounds. These intervals are reported in Table 16. Two of the sessions include 4 bridge travelers in the confidence interval, six include 5, three include 6, and three include 7. Although these confidence intervals are not perfectly precise, it is clear that some groups have more people with high values of time than others in this setting.

From Table 16, there does not appear to be any group in which equilibrium is below four bridge travelers per round. Also recall that Table 4 shows the per-hour cost to travel the bridge as a function of number of bridge travelers (C_Q). Since theory predicts that each person on the bridge has a benefit from the time saved that is equal to or greater than the toll cost, this implies at least four subjects in each group have values of time of \$10.29 per hour or more. Table 16 also shows that there is not likely an equilibrium in which there are more than seven bridge travelers per round, implying that at most seven subjects in each group have values of time of \$18 or more. Although these values of time are lower than those reported in Brownstone and Small (2005) and Small, Winston, and Yan (2005), they seem consistent with the earnings power of undergraduates.

7. Conclusion

Although billions of dollars are spent each year on transportation, Americans seem to lose more time due to congestion each year. In many urban areas, the problems are so bad that "building our way out of congestion" is now prohibitively expensive. One of the few viable solutions to this problem involves applying tolls during congested periods on roads and highways. The cost of the technology needed to implement such tolls should now be low enough to ensure that generated toll revenue is sufficient to make substantial Pareto improvements possible.

While theory certainly supports the use of tolls as a mechanism for reducing congestion, there is only limited empirical and experimental evidence examining the functioning of such plans. Perhaps more importantly, until this paper there has been no experimental evidence that allows for commuter heterogeneity. While congestion experiments with homogeneous subjects are able to examine some aspects of behavior, subject heterogeneity is needed to examine how individuals with different values of time trade off time against money. Experiment 1 verifies that people with high values of time are more likely to pay a toll to reduce commuting times than those with low values of time. Experiment 2 shows that some subjects are more willing than others to give up money for reduced waiting time after the experiment. The results in this paper are important because many people in actual traffic environments must make decisions about trading time for money every day. Further, heterogeneity also helps explain why similar traffic networks have different commuting patterns when they serve different populations.[31]

Although the results reported in this paper, and previous experimental congestion papers, answer some important questions about congestion behavior, further research is necessary to address some nagging problems in congestion experiments. First, the existing experimental results do not match perfectly with congestion theory. In Experiment 1, some subjects clearly do not play optimally. In Experiment 2, 20 rounds may not be long enough to reach equilibrium. Second, experiments on congestion have primarily focused on automobile congestion. In recent years, congestion problems have surfaced in other markets as well. The United States electricity market is a good example. Unless forced power outages can be imposed when demand exceeds available supply, entire grids are vulnerable to overloads. While externalities from traffic congestion are usually gradual, those from electricity grid congestion arise quite quickly when demand reaches capacity.

[31] The use of tolls is just one of many variables that could affect different populations of travelers in different ways. Others include the length of the commuting period, the elasticity of demand for travel, employer flexibility of starting and ending of work times, and land use patterns.

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Table 1: V_Q and C_Q for heterogeneous value of time example

Q	V_Q, in dollars	C_Q, in dollars
1	100.00	10.71
2	80.00	12.50
3	70.00	15.00
4	50.00	18.75
5	30.00	25.00
6	29.00	37.50
7	22.00	75.00
8	21.00	N/A
9	20.00	N/A
10	20.00	N/A
11	16.00	N/A
12	15.50	N/A
13	13.00	N/A
14	10.00	N/A
15	9.00	N/A
16	8.00	N/A
17	7.00	N/A
18	2.00	N/A

Table 2: Total travel cost function, using the same information as in Table 1

Number of drivers on bridge	Travel time on bridge, in minutes (t_B)	Total travel time cost of all drivers, in dollars
0	28.4	261.25
1	28.6	258.92
2	28.8	257.65
3	29.0	257.08
4	29.2	257.25
5	29.4	257.95
6	29.6	258.86
7	29.8	259.98
8	30.0	261.25
9	30.2	262.66
10	30.4	264.20
11	30.6	265.83
12	30.8	267.56
13	31.0	269.36
14	31.2	271.18
15	31.4	273.05
16	31.6	274.94
17	31.8	276.87
18	32.0	278.67

Table 3: Point endowments for subjects in Experiment 1

Point deductions per minute, Segment 1	Point deductions per minute, Segment 2	Initial point endowment
4	12	20000
7	11	22850
8	16	28600
9	13	27150
10	10	25700
11	7	22850
12	4	20000
13	9	27150
16	8	28600

Table 4: Cost savings per hour based on the number of bridge travelers, Experiment 2

Number of travelers on the bridge (Q)	Waiting time reduction each round the bridge is traveled	Cost to save one hour of waiting time at this rate (C_Q)
1	1.0	$7.20
2	0.9	$8.00
3	0.8	$9.00
4	0.7	$10.29
5	0.6	$12.00
6	0.5	$14.40
7	0.4	$18.00
8	0.3	$24.00
9	0.2	$36.00
10	0.1	$72.00
11	0.0	Undefined[32]

Table 5: Average number of bridge travelers per round in each segment, by session, Experiment 1

	Segment 1	Segment 2
Session 1	6.84	6.44*
	(1.53)	(0.93)
Session 2	7.10	6.98
	(1.31)	(1.12)
Session 3	7.06	6.74
	(1.71)	(1.19)
Session 4	6.82	6.74*
	(1.53)	(0.66)
Session 5	7.20	7.06
	(1.03)	(1.06)
Session 6	6.84	6.76
	(1.81)	(1.20)
Sessions 1, 4, and 6	6.83	6.65*
	(1.62)	(0.96)
Sessions 2 and 5	7.15	7.02
	(1.18)	(1.08)
All sessions	6.98	6.79*
	(1.50)	(1.05)

Standard deviations are in parentheses.
* denotes significantly different from 7 at the 5% level

[32] Cost of time is undefined here because traveling the bridge does not reduce waiting time any.

Table 6: Tests of differences in variance by format (Experiment 1)

	Segment 1	Segment 2
High heterogeneity versus low heterogeneity	Ratio of variances: 1.899 Significant at the 1% level High heterogeneity has a lower variance	Ratio of variances: 1.262 Not significant
High heterogeneity versus no heterogeneity	Ratio of variances: 2.110 Significant at the 1% level High heterogeneity has a lower variance	Ratio of variances: 1.531 Significant at the 10% level High heterogeneity has a lower variance
Low heterogeneity versus no heterogeneity	Ratio of variances: 1.111 Not significant	Ratio of variances: 1.213 Not significant

Table 7: Tests of differences in means by format (Experiment 1)

	Segment 1	Segment 2
High heterogeneity versus low heterogeneity	$\|t\|$ = *1.79* Significant at the 10% level High heterogeneity has a higher average	$\|t\|$ = 2.86 Significant at the 1% level Low heterogeneity has a higher average
High heterogeneity versus no heterogeneity	$\|t\|$ = *0.34* Not significant	$\|t\|$ = 0.56 Not significant
Low heterogeneity versus no heterogeneity	$\|t\|$ = 0.85 Not significant	$\|t\|$ = 1.44 Not significant

Notes: The results of Table 6 determine the test used as follows: Italicized t values are determined from an unpaired t-test with the assumption that variances of both samples are unequal (also known as Welch's test). The remaining t values are determined from an unpaired t-test with the assumption that variances of both samples are equal. The choice of test does not change significance at the 1%, 5%, or 10% level in any case above.

Table 8: Average number of trips per subject on the bridge, by sub-group and segment (Experiment 1)

	Segment 1	Segment 2
4 points per minute	3.83	6.00
	(4.02)	(12.05)
7 points per minute	4.33	2.11
	(3.01)	(1.69)
8 points per minute	12.44	6.50
	(9.46)	(6.02)
9 points per minute	19.44	13.83
	(13.34)	(17.59)
10 points per minute	18.67	18.80
(excluding format III)	(12.19)	(19.69)
11 points per minute	25.44	37.33
	(20.56)	(17.49)
12 points per minute	41.44	36.83
	(5.43)	(15.92)
13 points per minute	44.83	41.78
	(2.71)	(12.11)
16 points per minute	42.17	44.56
	(6.88)	(5.90)
10 points per minute	23.53	22.47
(format III only)	(12.11)	(21.08)

Standard deviations are in parentheses.

Table 9: Average number of bridge travelers per round, by session, Experiment 2, Segment 3.

Session 1	6.35 (1.69)
Session 2	5.00 (1.56)
Session 3	6.50 (1.36)
Session 4	6.95 (1.90)
Session 5	5.00 (1.59)
Session 6	5.30 (1.49)
Session 7	5.90 (1.71)
Session 8	5.00 (1.30)
Session 9*	4.20 (1.79)
Session 10	4.70 (1.63)
All sessions	5.49 (1.79)

Standard deviations are in parentheses.
* Only 17 subjects participated in this session.

Table 10: Distribution of number of bridge trips by subject, Segment 3, Experiment 2

Number of bridge trips	Fraction of subject pool (out of 179 subjects)
0	19.6%
1-4	27.9%
5-9	27.9%
10-14	11.7%
15-19	8.9%
20	3.9%

Table 11: Distribution of waiting times, Experiment 2

Waiting time, in minutes	Fraction of subject pool (out of 179 subjects)
6-7.9	0.6%
8-9.9	2.2%
10-11.9	6.1%
12-13.9	7.8%
14-15.9	13.4%
16-17.9	21.2%
18-19.9	29.1%
20	19.6%

Table 12: Summary statistics of personal characteristics, Experiment 2

Characteristic	Mean (standard deviation)
Male	0.44 (0.50)
Age	20.68 (3.03)
Subject is a student at UCSB	0.98 (0.13)
Number of units enrolled in (conditional on being a student)	14.86 (2.79)
Freshman	0.27 (0.45)
Sophomore	0.19 (0.39)
Junior	0.27 (0.45)
Senior	0.18 (0.39)
Graduate student	0.09 (0.29)
Grade point average 3.5 or higher[33]	0.33 (0.47)
Grade point average below 2.5	0.04 (0.20)
Works at least five hours per week	0.36 (0.48)
Earns $10 per hour or more	0.17 (0.37)
Earns $12 per hour or more	0.11 (0.32)
Earns $15 per hour or more	0.08 (0.28)
At least one parent has a bachelor's degree	0.71 (0.46)

[33] Grade point average information is missing from two students.

Table 13: Average number of trips on the bridge in Experiment 2, based on job and parental education status

Characteristics of subject	Works at least five hours per week	Does not work at least five hours per week
Has at least one parent with a bachelor's degree	5.65 (5.24) [48]	5.78 (5.41) [79]
Has neither parent with at least a bachelor's degree	9.71 (7.87) [17]	5.86 (5.82) [35]

Notes: Standard deviations are in parentheses. Number of subjects in the category is in brackets.

Table 14: Probit regressions based on job and parental education status

Variable	(1)	(2)	(3)	(4)
Job, No PD	0.197	0.204	0.185	0.198
	(0.095)	(0.102)	(0.100)	(0.106)
	[0.030]	[0.037]	[0.054]	[0.051]
No Job, PD		0.007		0.010
		(0.050)		(0.048)
		[0.886]		[0.835]
No Job, No PD		0.011		0.031
		(0.064)		(0.065)
		[0.863]		[0.634]
Controls	No	No	Yes	Yes

Notes: Dependent variable is a dummy for traveling the bridge. Sample size is 179 subjects, 3580 observations. Each marginal effect is calculated as a discrete change of the dummy variable from 0 to 1, at the mean values of the other covariates. Clustered standard errors (by subject) are in parentheses, and p-values are in brackets. PD stands for at least one parent with a bachelor's degree. Job means working at least five hours per week. The excluded PD/Job category is Job, PD. Columns (3) and (4) also include gender, age, number of units currently taken, graduate student, GPA above 3.5, and GPA below 2.5.

Table 15: Number of travelers on the bridge, by round, in Segment 3, Experiment 2

Number of travelers on the bridge	Frequency, out of 200 rounds
1	1
2	10
3	18
4	23
5	50
6	42
7	31
8	16
9	7
10	1
11	1

Table 16: Means and confidence intervals for number of bridge travelers per round in Segment 3 of Experiment 2, by session

	Mean	Low end of 95% confidence interval	High end of 95% confidence interval
Session 1	6.35	5.56	7.14
Session 2	5.00	4.27	5.73
Session 3	6.50	5.86	7.14
Session 4	6.95	6.06	7.84
Session 5	5.00	4.26	5.74
Session 6	5.30	4.60	6.00[34]
Session 7	5.90	5.10	6.70
Session 8	5.00	4.39	5.61
Session 9	4.20	3.36	5.04
Session 10	4.70	3.94	5.46

[34] This value is rounded from about 5.997, which means that 6 is not quite in this 95% confidence interval.

Figure 1: A visual of the scenario that subjects see for their travel situation

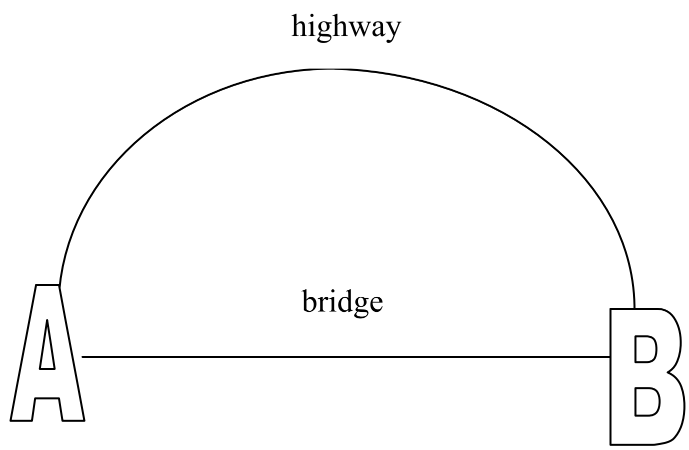


Figure 2: MEC, MPB, efficiency (Q^*), and equilibrium without tolls ($\hat{Q}$) in a heterogeneous value of time case

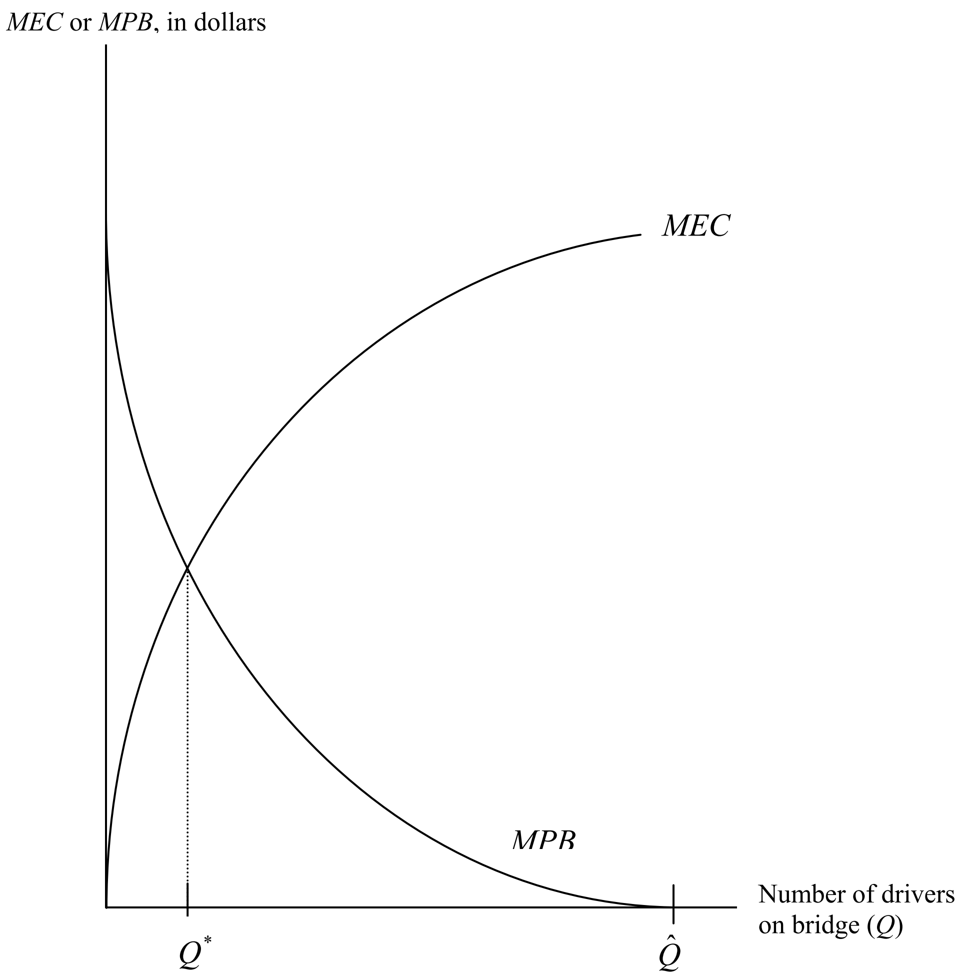
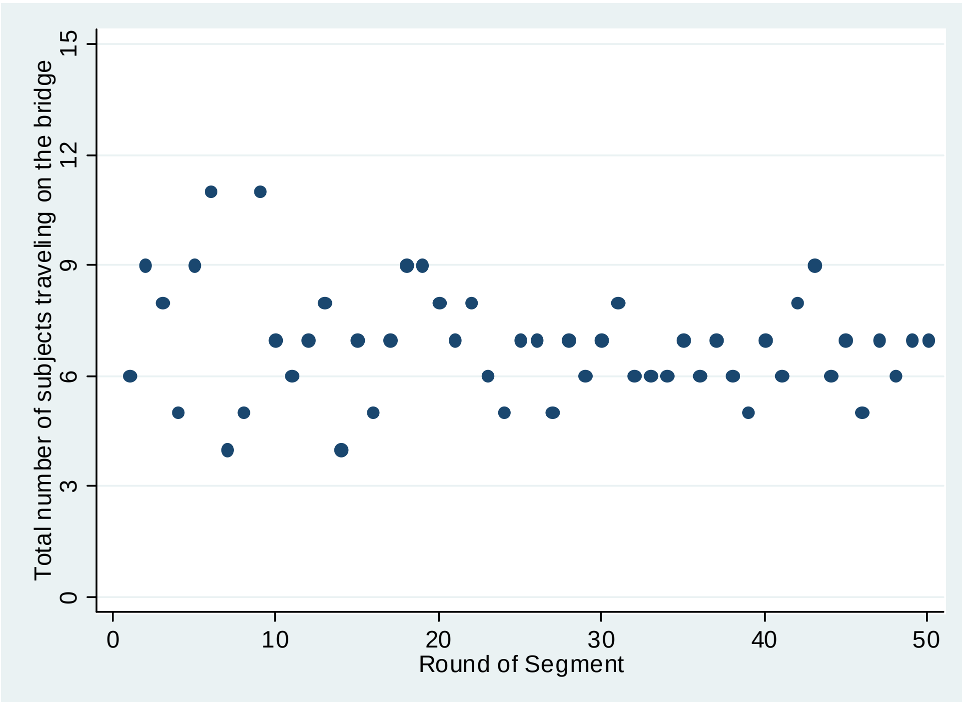
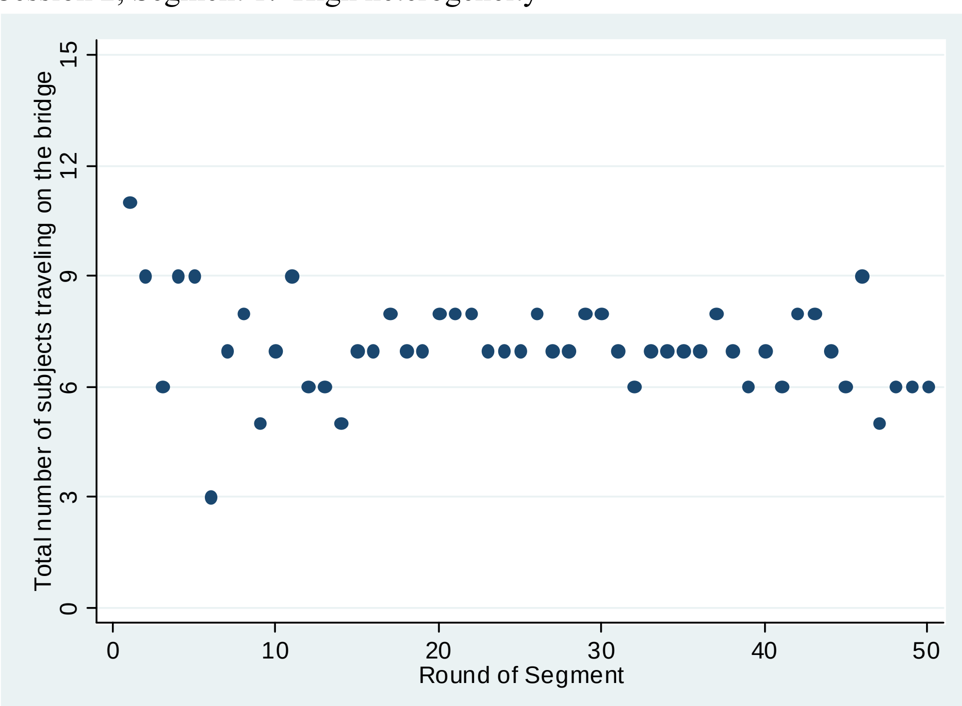


Figure 3: Round-by-round results of number of travelers on the bridge for each session and segment, Experiment 1

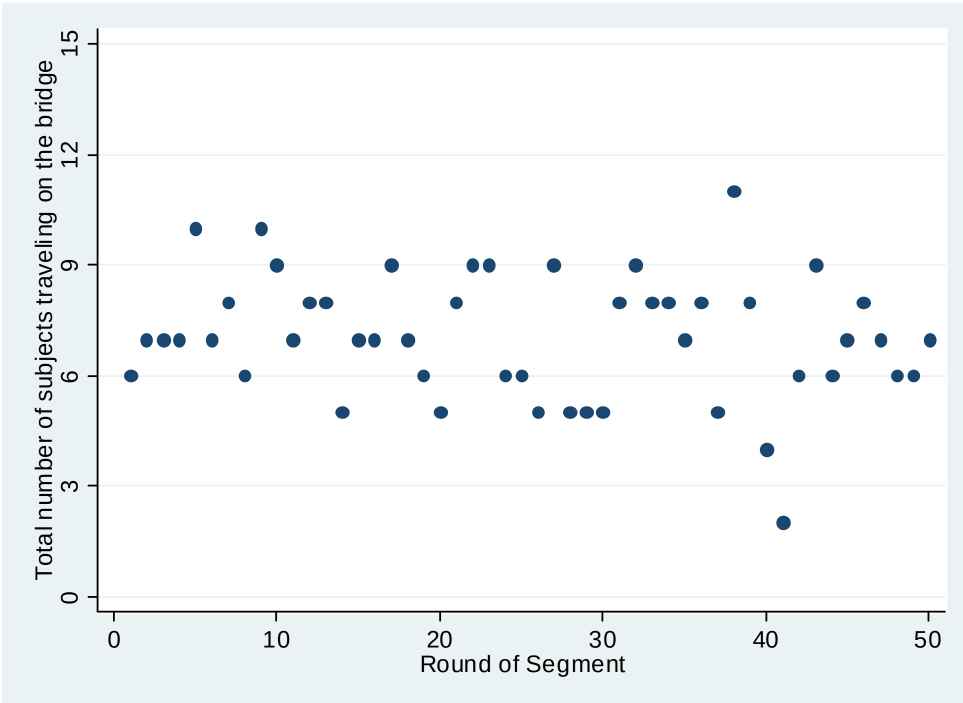
Session 1, Segment 1: Low heterogeneity



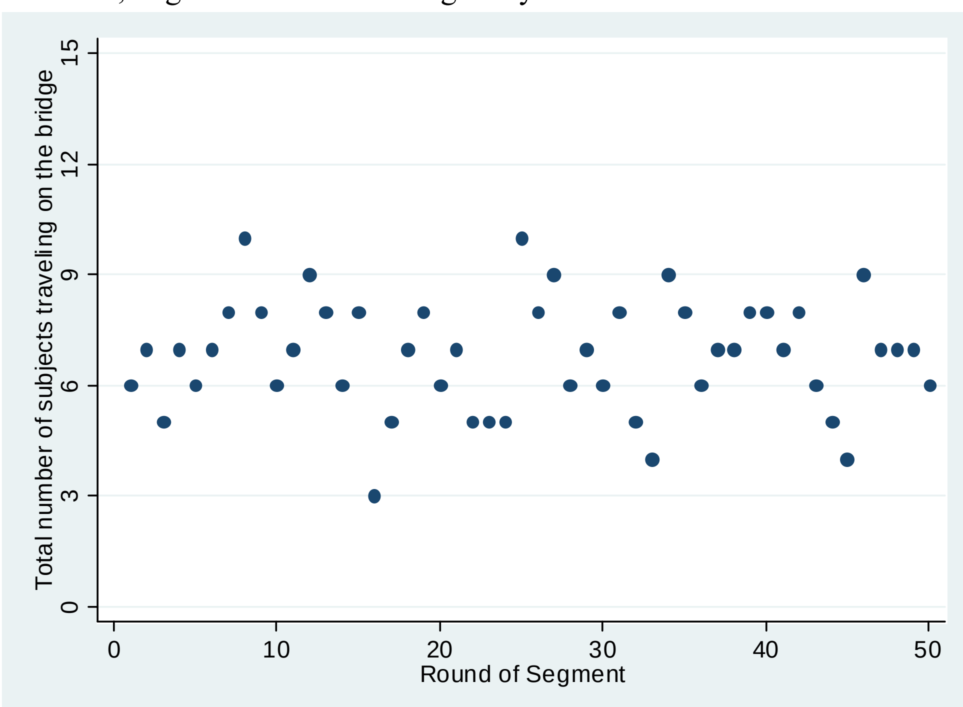
Session 2, Segment 1: High heterogeneity



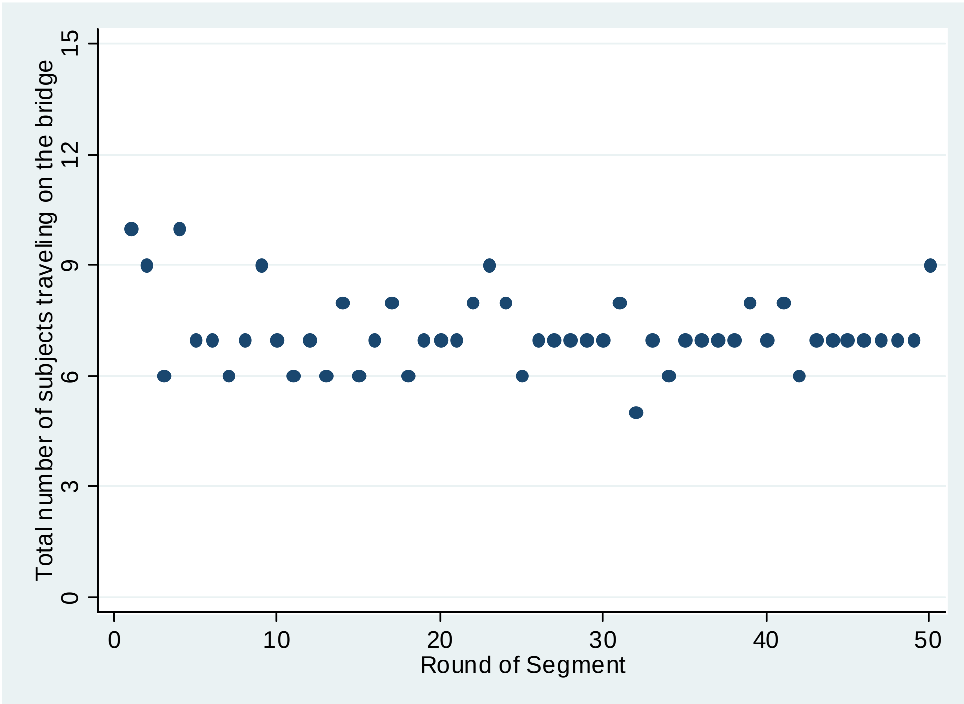
Session 3, Segment 1: No heterogeneity



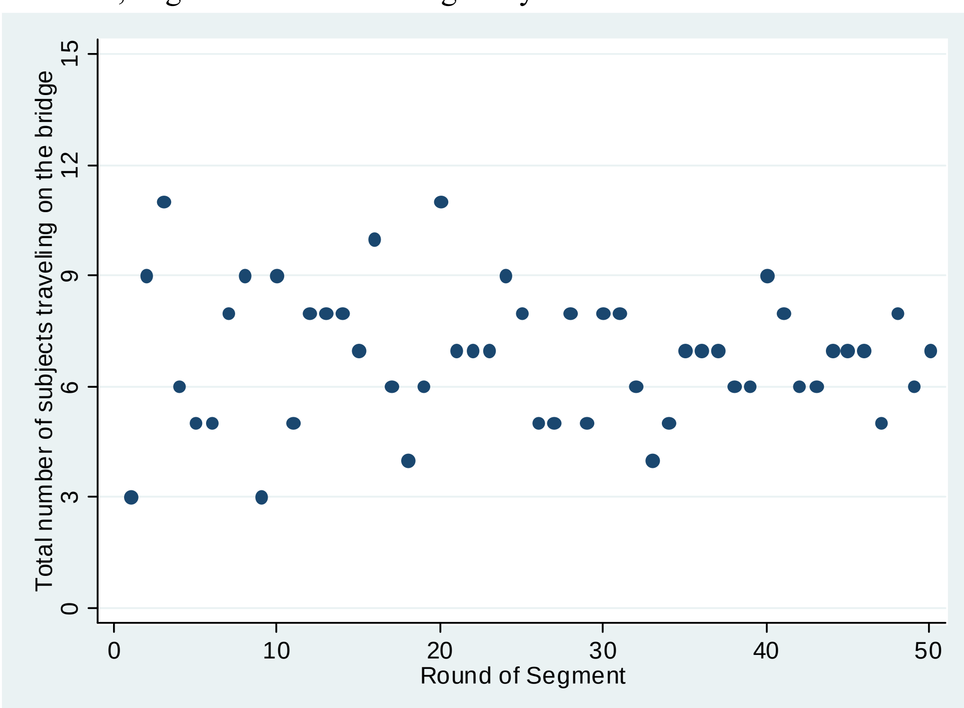
Session 4, Segment 1: Low heterogeneity



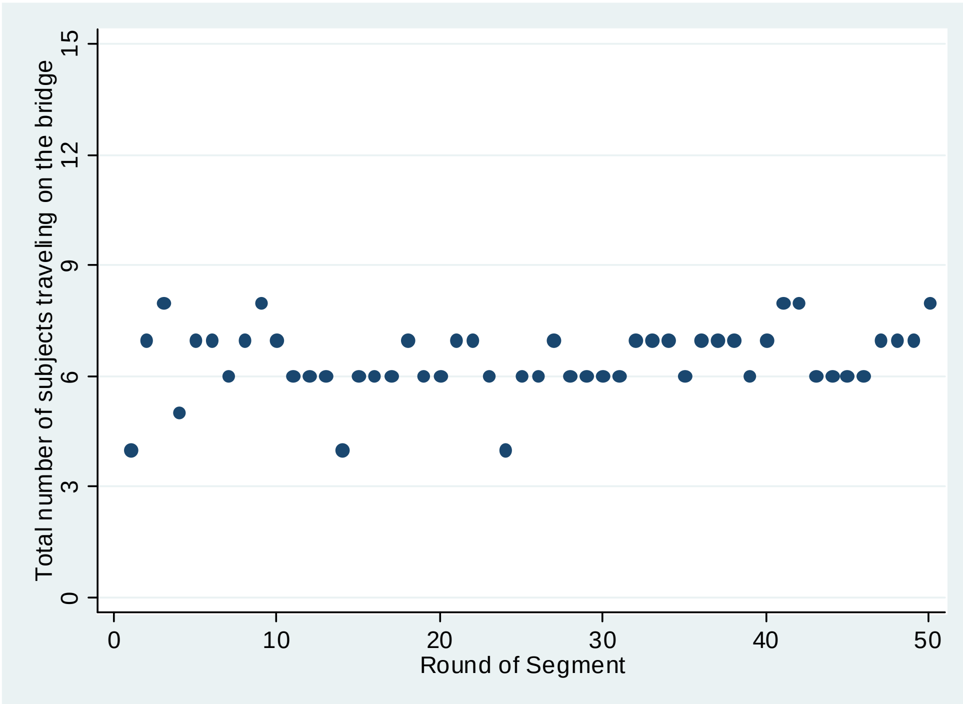
Session 5, Segment 1: High heterogeneity



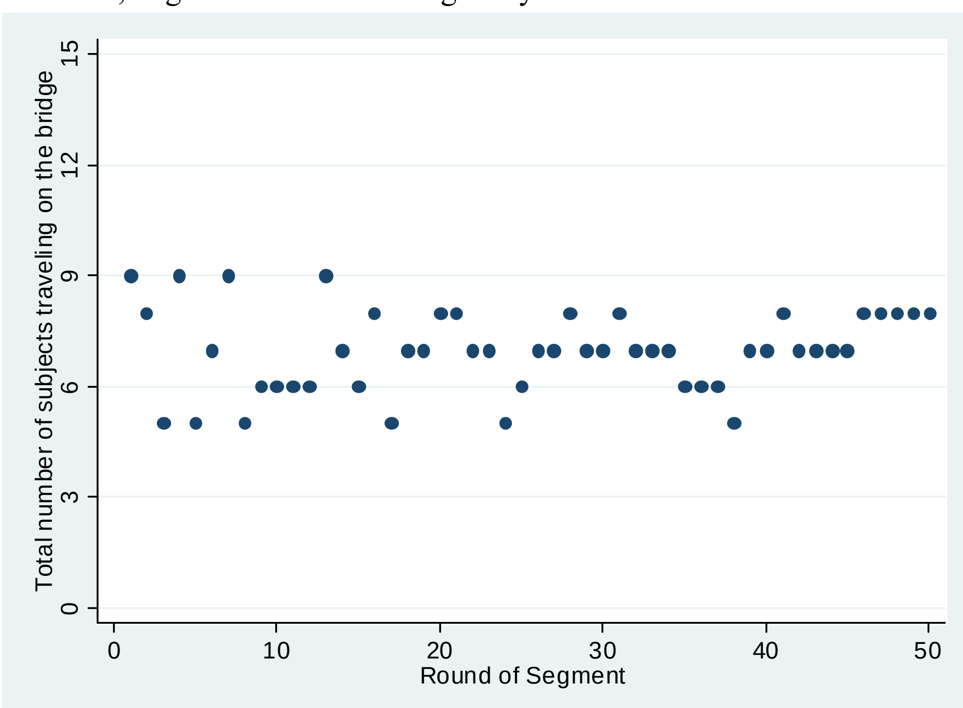
Session 6, Segment 1: Low heterogeneity



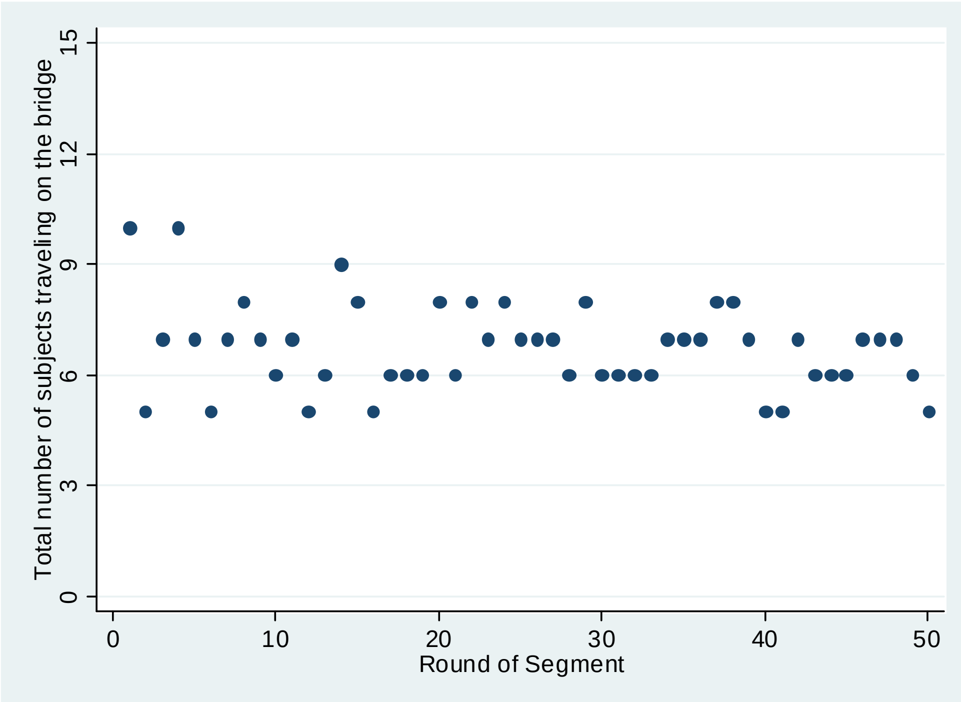
Session 1, Segment 2: High heterogeneity



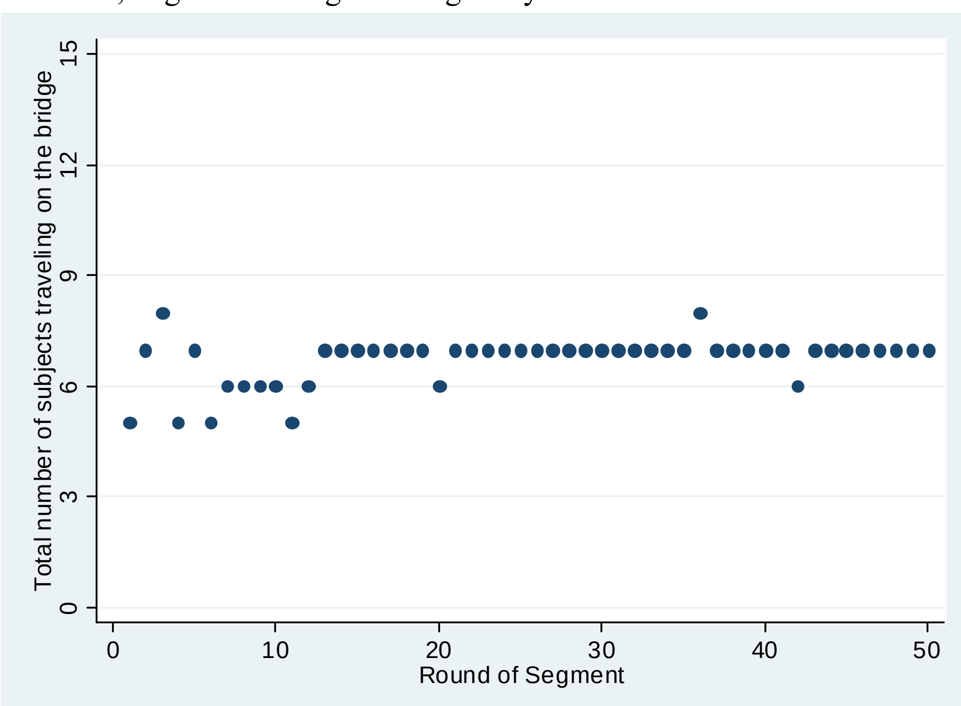
Session 2, Segment 2: Low heterogeneity



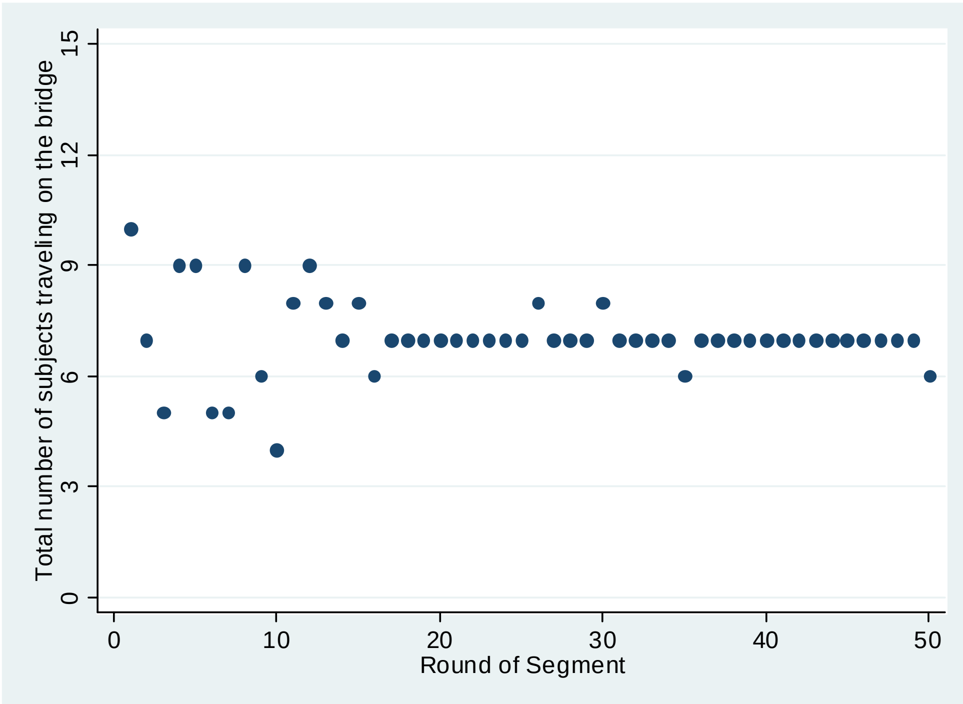
Session 3, Segment 2: No heterogeneity



Session 4, Segment 2: High heterogeneity



Session 5, Segment 2: Low heterogeneity



Session 6, Segment 2: High heterogeneity

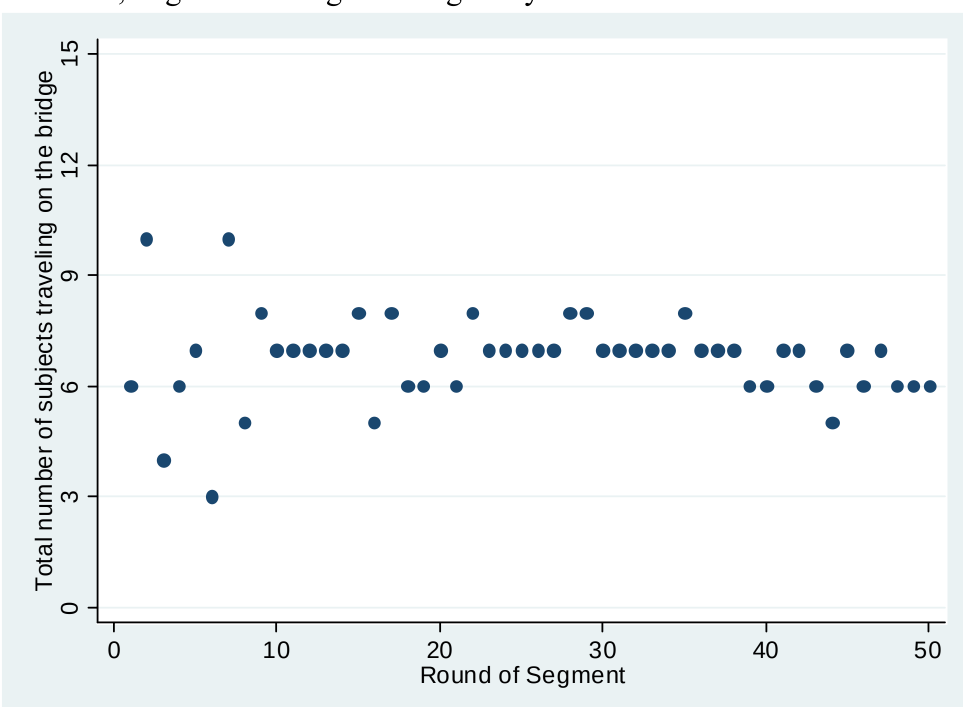


Figure 4: Distribution of number of bridge travelers in Segment 1 of Experiment 1

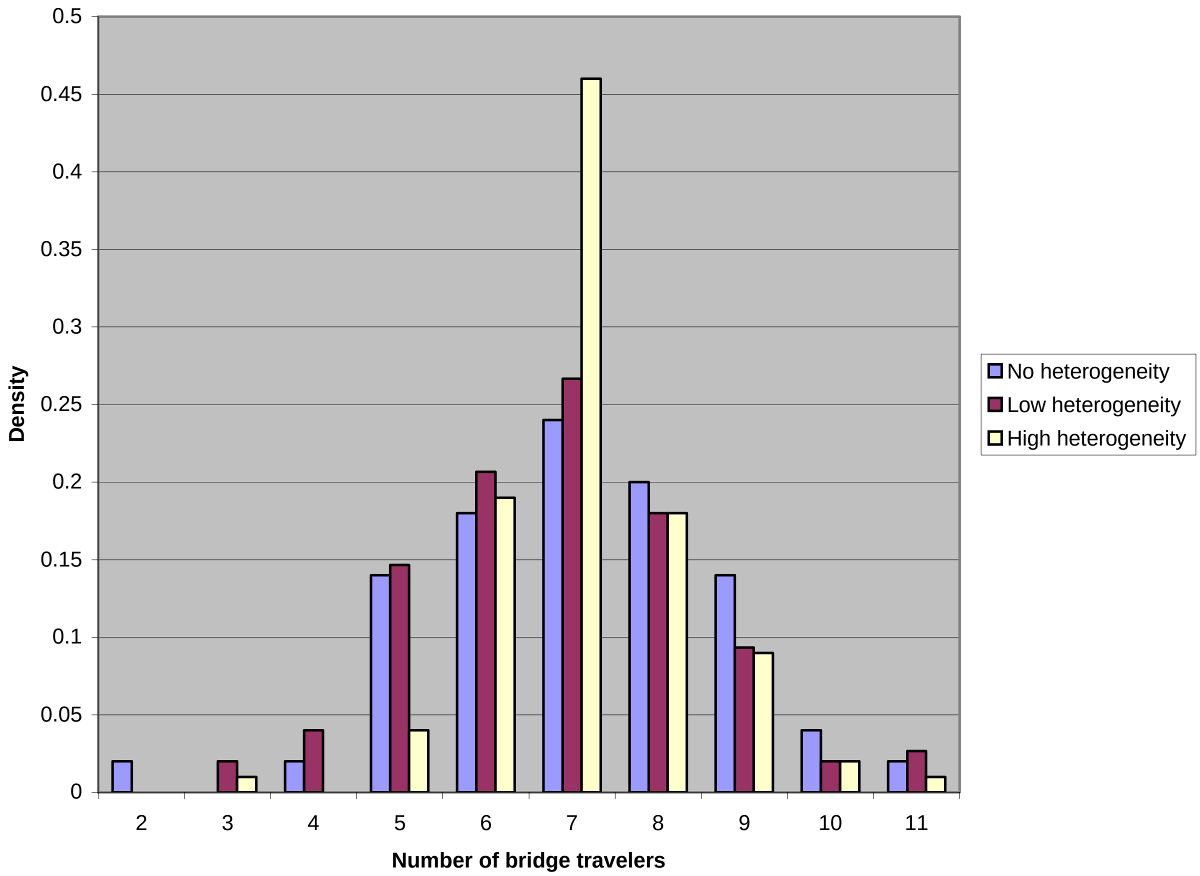


Figure 5: Distribution of number of bridge travelers in Segment 2 of Experiment 1

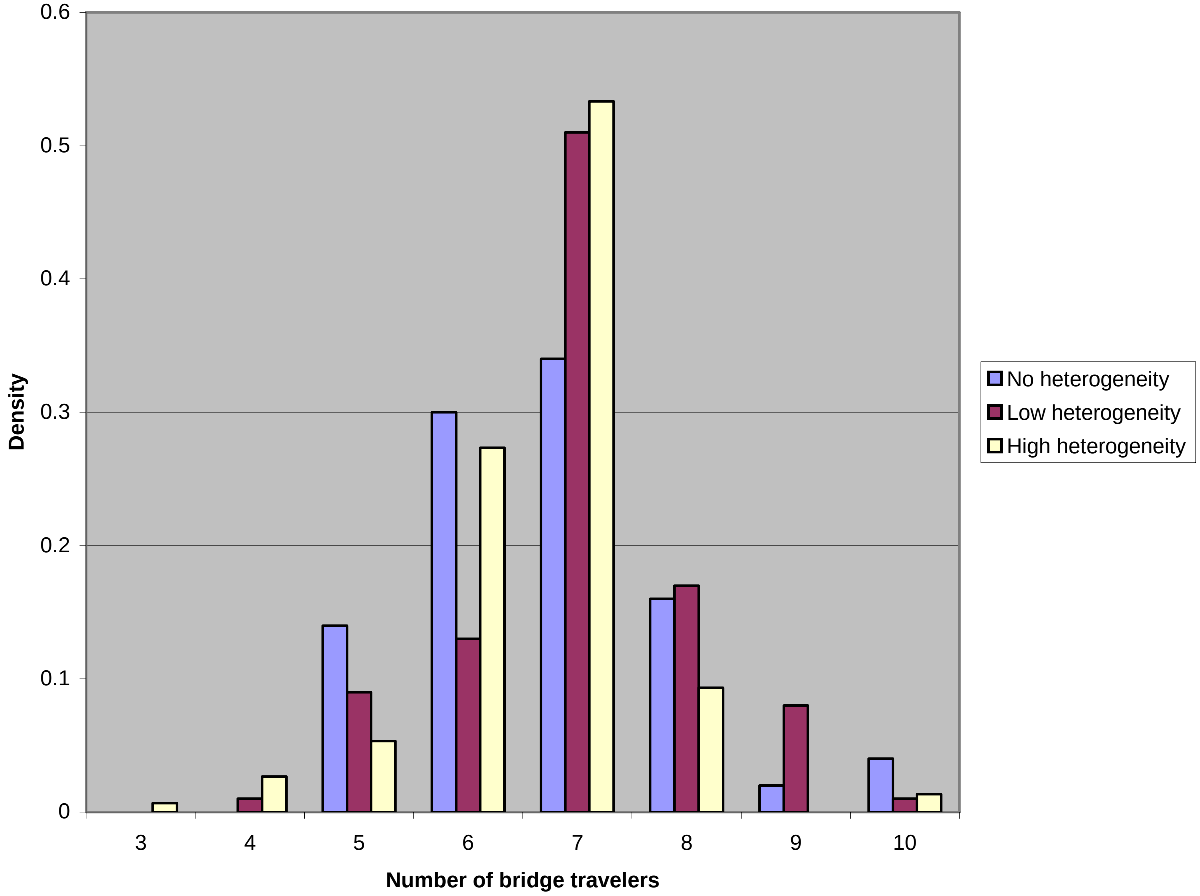
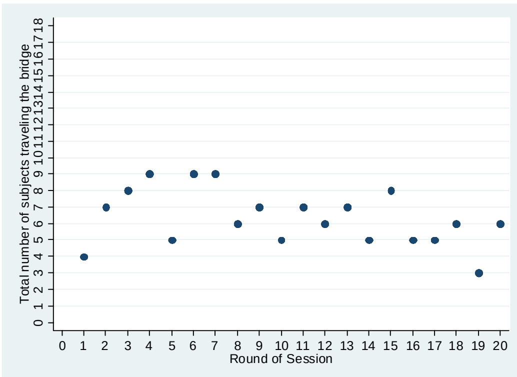
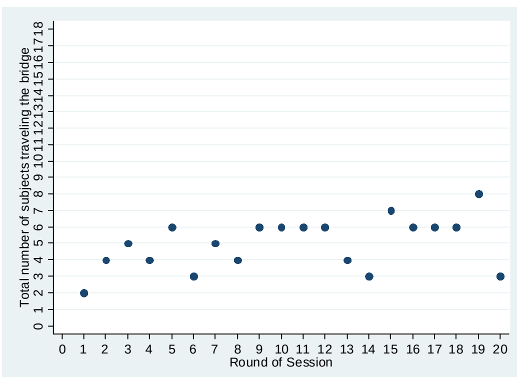


Figure 6: Round-by-round results of number of travelers on the bridge for each session and segment, Experiment 2, Segment 3

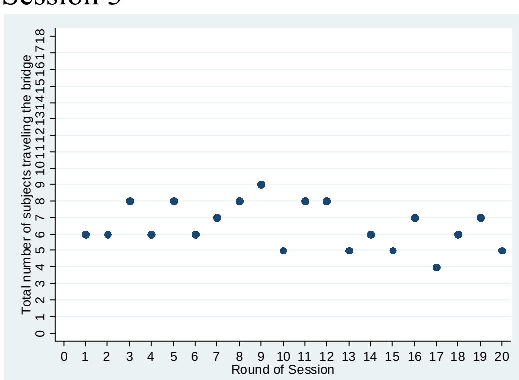
Session 1



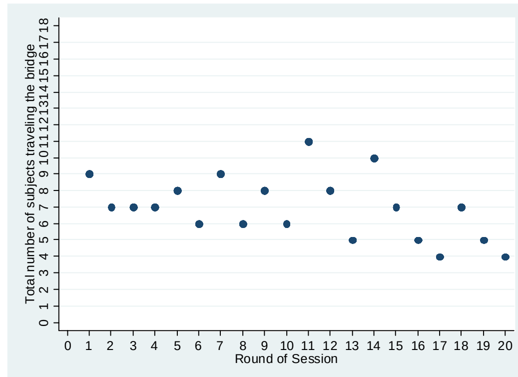
Session 2



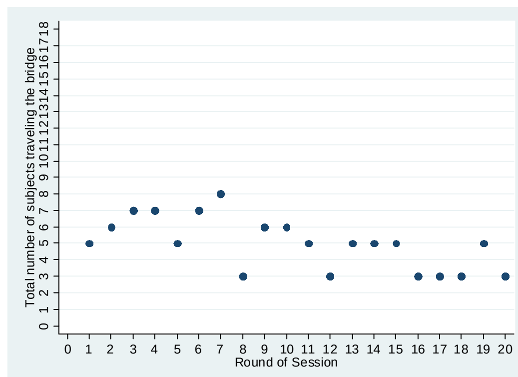
Session 3



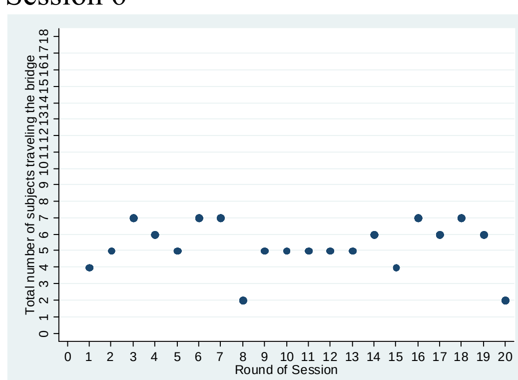
Session 4



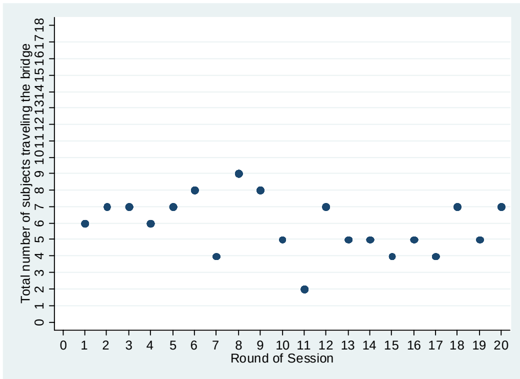
Session 5



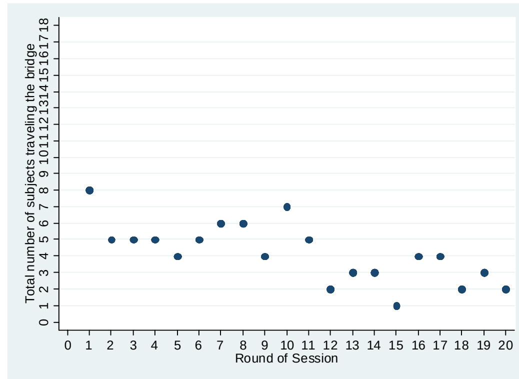
Session 6



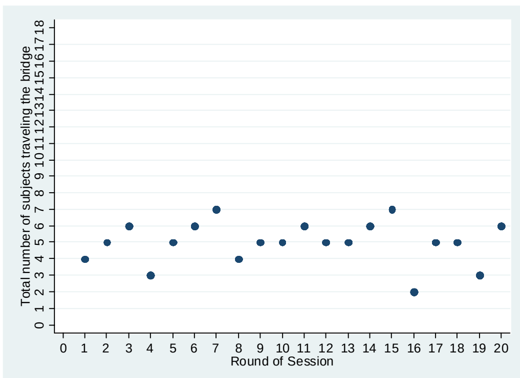
Session 7



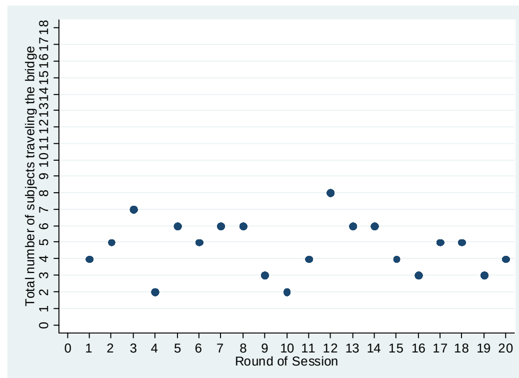
Session 9



Session 8



Session 10



Appendix A

Verbal instructions used in Experiment 1

(Note that "segment" in the paper is equivalent to "part" in these instructions.)

General information

First, please sign the consent form provided if you agree to the conditions. Once you agree to participate in the experiment, please completely fill out the questionnaire.

In this experiment, you will make many choices. The experiment will be split into two parts. Your choices in both parts will help in determining your payout after the experiment. The total time for the entire experiment will probably be about one hour. Each part of the experiment will give you a travel situation, and you must make a single choice for the 50 rounds of each part. You will also receive two forms of payment:

- A $5 payment for showing up.
- You will receive a number of points at the beginning of the experiment. However, points will also be deducted throughout the experiment based on route choices and tolls paid. Any remaining points will have monetary value at an exchange rate of 40 points = $1 if and only if you complete both parts of the experiment. Note that you are not allowed to disclose the number of points per minute that you are deducted to anyone. The one exception to this is if you ask me privately without exposing this information to other participants of the experiment.

From now until you receive payment, you are not to communicate with any other person except me. Also until you receive payment, you are not to look at any other person's decisions, nor are you to use the computer in front of you for anything other than this experiment.

Are there any questions before we begin?

Part 1

Before we begin Part 1, you will begin with a number of points as shown on your computer screen. Remember that once points are deducted for your travel decisions in both parts, you will receive $1 cash for every 40 remaining points.

In Part 1, you will need to travel from point A to point B that you can see in the diagram (*A diagram will be provided showing the following scenario.)*. You will have a choice of traveling one of two routes in each round. One route is an uncongested highway. On this route, you are guaranteed a 25-minute trip. The other route is a bridge. If you are the only traveler on this route, your travel time is 12 minutes. However, since this bridge is narrow, for each additional traveler on the bridge, all travelers will be subject to an increase of one minute in travel time. So if there are two drivers on the bridge, the travel time of both travelers is 13 minutes; three drivers, 14 minutes, etc. Each person will also pay a toll of 70 points in each round that the bridge is traveled.

This part will consist of 50 rounds. Each round will consist of you choosing your trip from point A to point B using either the highway or the bridge. Each person may change route choice from round to round, but once you commit to a choice in any round, it cannot be changed.

Finally, for each minute of travel time you incur, you will be deducted the number of points as shown on your computer screen. Note that points will also be deducted in the second part of the experiment.
Are there any questions before we begin with Part 1?

Part 2

In Part 2, you will have the same choice of decisions as you did in Part 1. However, you may have a different deduction of points per minute of travel time. Please look carefully at your computer screen to determine if your per-minute point deduction has changed. The toll per trip on the bridge continues at 70 points.

Are there any questions before we begin with Part 2?

After Part 2 is complete

Now that the experimental rounds are complete, please be patient as I calculate each person's payment. Before the experiment, I decided at random to pay participants in this order: ________________ (explain order here).

Appendix B

In this appendix, I show the set of possible pure strategy Nash equilibria in formats with heterogeneity. Recall that in each format described, there are three people of each type. The two experimental designs are point deductions of 8, 9, 10, 11, and 12 (low heterogeneity), and 4, 7, 10, 13, and 16 (high heterogeneity).

In the low-heterogeneity framework, suppose that 5 or fewer subjects on the bridge constitutes an equilibrium. Then there must be at least one person with an 11 or 12 point per minute deduction on the highway. If an 11 is on the highway, her point deduction for traveling this route is 25×11, or 275. She could switch routes to the bridge and have a point deduction no higher than $70 + 17 \times 11$, or 257. Since the bridge is strictly the better choice when 5 or fewer other subjects are on the bridge, each 11 is better off by traveling the bridge. Similarly for 12's, the choices are 25×12, or 300, and $70 + 17 \times 12$, or 274, respectively. Again, each 12 is better off on the bridge. This leads to a contradiction, since all 11's and 12's cannot be on the bridge when there are 5 or fewer on this route. So no equilibrium is possible such that 5 or fewer on the bridge.

Next, suppose that an equilibrium exists such that 8 or more subjects travel the bridge. This means that at least one 8, 9, or 10 must be traveling on the bridge. Then if an 8 is on the bridge, his point deduction on this route is at least $70 + 19 \times 8$, or 222. He could switch to the highway for a point deduction of 25×8, or 200. Thus, each 8 is better off on the highway in this situation. Similarly for 9's, the choices are $70 + 19 \times 9$, or 241, and 25×9, or 225, respectively. For the 10's, the choices are $70 + 19 \times 10$, or 260, and 25×10, or 250, respectively. Both the 9's and 10's are better off on the highway. This leads to a contradiction, since all 8's, 9's, and 10's cannot be on the highway if there are 8 or more subjects on the bridge.

Next suppose that an equilibrium exists such that exactly 6 subjects are on the bridge:

- Suppose there is an 8 on the bridge. Then her point deduction on this route is $70 + 17 \times 8$, or 206. She could switch to the highway for a point deduction of 25×8, or 200. She is better off on the highway, and thus any 8 must be on the highway whenever there is an equilibrium with exactly 6 subjects on the bridge.

- Suppose there is a 9 on the bridge. Then his point deduction on this route is $70+17\times 9$, or 223. He could switch to the highway for a point deduction of 25×9, or 225. So there could be a 9 on the bridge since switching to the highway is not a better option.
- Suppose there is a 9 on the highway. Then his point deduction on this route is 25×9, or 225. He could switch to the bridge for a point deduction of $70+18\times 9$, or 232. So there could be a 9 on the highway, since switching to the bridge is not a better option.
- Suppose there is a 10 on the bridge. Then her point deduction on this route is $70+17\times 10$, or 240. She could switch to the highway for a point deduction of 25×10, or 250. So there could be a 10 on the bridge since switching to the highway is not a better option.
- Suppose there is a 10 on the highway. Then her point deduction on this route is 25×10, or 250. She could switch to the bridge for a point deduction of $70+18\times 10$, or 250. So there could be a 10 on the highway since switching to the bridge is not a better option.
- Suppose there is an 11 on the highway. Then his point deduction on this route is 25×11, or 275. He could switch to the bridge for a point deduction of $70+18\times 11$, or 268. So he is better off on the bridge, and thus any 11 must be on the bridge whenever there is an equilibrium with exactly 6 subjects on the bridge.
- Suppose there is a 12 on the highway. Then her point deduction on this route is 25×12, or 300. She could switch to the bridge for a point deduction of $70+18\times 12$, or 286. So she is better off on the bridge, and thus any 12 must be on the bridge whenever there is an equilibrium with exactly 6 subjects on the bridge.
- In summary: All 11's and 12's must be on the bridge, the 9's and 10's could be on either route, and all 8's must be on the highway for any equilibrium with exactly 6 subjects on the bridge. From these criteria, the only equilibrium possible under these conditions is if all 11's and 12's are on the bridge, and all others are on the highway.

Next suppose that an equilibrium exists such that exactly 7 subjects are on the bridge:

- Suppose there is an 8 on the bridge. Then his point deduction on this route is $70+18\times 8$, or 214. He could switch to the highway for a point deduction of 25×8, or 200. He is better off on the highway, and thus any 8 must be on the highway whenever there is an equilibrium with exactly 7 subjects on the bridge.
- Suppose there is a 9 on the bridge. Then her point deduction on this route is $70+18\times 9$, or 232. She could switch to the highway for a point deduction of 25×9, or 225. She is better off on the highway, and thus any 9 must be on the highway whenever there is an equilibrium with exactly 7 subjects on the bridge.
- Suppose there is a 10 on the bridge. Then his point deduction on this route is $70+18\times 10$, or 250. He could switch to the highway for a point deduction of 25×10, or 250. So there could be a 10 on the bridge since switching to the highway is not a better option.
- Suppose there is a 10 on the highway. Then his point deduction on this route is 25×10, or 250. He could switch to the bridge for a point deduction of $70+19\times 10$, or 260. So there could be a 10 on the highway since switching to the bridge is not a better option.
- Suppose there is an 11 on the bridge. Then her point deduction on this route is $70+18\times 11$, or 268. She could switch to the highway for a point deduction of 25×11, or 275. So there could be an 11 on the bridge since switching to the highway is not a better option.
- Suppose there is an 11 on the highway. Then her point deduction on this route is 25×11, or 275. She could switch to the bridge for a point deduction of $70+19\times 11$, or 279. So there could be an 11 on the highway since switching to the bridge is not a better option.
- Suppose there is a 12 on the highway. Then his point deduction on this route is 25×12, or 300. He could switch to the bridge for a point deduction of $70+19\times 12$, or 298. He is better off on the bridge, and thus any 12 must be on the bridge whenever there is an equilibrium with exactly 7 on the bridge.

- In summary: All 12's must be on the bridge, the 10's and 11's could be on either route, and all 8's and 9's must be on the highway for any equilibrium with exactly 6 subjects on the bridge. From these criteria, the only equilibrium possible under these conditions is if a total of 4 10's and 11's are on the bridge and the other 2 are on the highway.

In the high-heterogeneity framework, most of the results are similar. There is no equilibrium with 5 or fewer on the bridge, nor are there any equilibria with 8 or more on the bridge. In any equilibrium with exactly 6 on the bridge, all 13's and 16's must be on the bridge. This means that all 4's, 7's, and 10's must be on the highway. In any equilibrium with 7 on the bridge, all 13's and 16's must be on the bridge and all 4's and 7's must be on the highway. Then any equilibrium with 7 on the bridge must have exactly 1 10 on the bridge and the other 2 on the highway.

Appendix C

<u>Verbal instructions used in Experiment 2</u>

(Note that "segment" in the paper is equivalent to "session" in these instructions.)

If you do not see the consent form, please ask to look at a paper copy. Once you agree to participate in the experiment, please completely fill out the questionnaire.

In this experiment, you will make many choices. Your choices will be split into three sessions. Your choices in all three sessions will help in determining your payout after the experiment. In the third session, your choices will determine the amount of time you will have to wait after this session and before receiving payment. The total time for the entire experiment will probably be about one hour.

The active portion of the experiment will consist of three sessions. Each session will give you a travel situation, and you must make a single choice in 20 rounds of each session. You will also receive two forms of payment:

- A $5 payment for showing up.
- You will receive a number of points at the beginning of the experiment. However, points will also be deducted throughout the experiment based on route choices and tolls paid. Any remaining points will have monetary value at an exchange rate of 50 points = $1 if and only if you complete the three sessions and your individual waiting time.

From now until you receive payment, you are not to communicate with any other person except me. Also until you receive payment, you are not to look at any other person's decisions, nor are you to use the computer in front of you for anything other than this experiment.

Are there any questions before we begin?

<u>Session 1</u>

Before we begin Session 1, you will begin with 8,500 points. Remember that once points are deducted for your travel decisions in all three rounds, you will receive $1 cash for every 50 remaining points.

In Session 1, you will need to travel from point A to point B that you can see in the diagram (*A diagram will be provided showing this scenario.)*. You will have a choice of traveling one of two routes in each round. One route is an uncongested highway. On this route, you are guaranteed a 20-minute trip. The other route is a bridge. If you are the only traveler on this route, your travel time is 10 minutes. However, since this bridge is narrow, for each additional traveler on the bridge, all travelers will be subject to an increase of one minute in travel time. So if there are two drivers on the bridge, the travel time of both travelers is 11 minutes; three drivers, 12 minutes, etc.

This session will consist of 20 rounds. Each round will consist of you choosing your trip from point A to point B using either the highway or the bridge. Each person may change route choice from round to round, but once you commit to a choice in any round, it cannot be changed.

Finally, for each minute of travel time you incur, you will be deducted 10 points from your initial allotment of 8,500 points. Note that points will also be deducted in Session 2 and may be deducted in Session 3 from your initial allotment.

Are there any questions before we begin with Session 1?

Session 2

In Session 2, you will make the same decisions as you did in Session 1. However, if you decide to travel on the bridge in any round of Session 2, you will be charged a toll of 60 points for that round. Note that you will continue to be deducted 10 points for each minute of travel time in each round. Everything else is the same as in Session 1.

Are there any questions before we begin with Session 2?

Session 3

In Session 3, you will continue to make the route choice decisions as you did in Sessions 1 & 2. However, fewer points will be deducted and your performance in this part of the experiment will determine an amount of time that you will need to wait before receiving payment. During this wait time, you will be sitting and not be able to perform any activities, including talking to other people in this room, using a cell phone, using the computer in front of you, and reading. As in the previous sessions, Session 3 will have 20 rounds.

In this session, you will ***NOT*** be deducted any points for minutes of travel time. However, the more minutes of travel time in Session 3, the longer you will have to wait before receiving payment. Also in Session 3, if you decide to travel the bridge, your toll will be 6 points, which is less than what was deducted in Session 2. To travel the bridge in any round of Session 3, you will need to have at least 6 points available before the round begins. To determine your wait time after Session 3, the following formula will apply:

- The travel time of the 20 rounds will be totaled.
- From this total, subtract 200.
- Finally, divide by 10. The result of this formula will dictate the number of minutes you must wait after Session 3 before receiving payment.

Here is some information that may help you in making you decisions for Session 3:

- Remember that your points will be converted at 50 points per dollar when you get paid. So each time you travel the bridge in Session 3, your payout will be reduced by 6 points, or 12 cents. Thus, if you traveled the bridge in every round of Session 3, your payment will be $2.40 less than if you traveled the highway in each round of this session. After Session 3, your wait time by traveling the bridge could be lower.
- If your travel time is 12 minutes in each round of Session 3, your wait time after Session 3 will be 4 minutes. A 16-minute travel time in each round of Session 3 yields a wait time of 12 minutes. 20 minutes of travel time per round of Session 3 yields a wait time of 20 minutes.

Are there any questions before we begin with Session 3?

Some instructions before your waiting time begins

Now that we have concluded Session 3, your waiting time has been determined. When your number is called, you may collect your money, at which point you will need to leave this room until all subjects have been paid. Until then, you are to quietly remain seated. You may not talk with other people, use your cell phone, use the computer in front of you, read, or perform any other activity.

If you do not follow these directions, I will add to your waiting time. The amount of time added will be equal to the amount of time that you do not follow these directions. If repeated requests to follow these directions are not followed, you will be asked to leave.

Are there any questions before your time begins?

Questionnaire used in Experiment 2

I would like to ask you a few questions regarding some of your characteristics. Please remember that your information will not be linked to you. Your characteristics will be linked to the choices that you make in this experiment in order to help answer important research questions. Thank you.

1. What is your gender? Male__________ Female__________

2. How old are you? _____________

3. Are you currently a student at UCSB? Yes__________ No__________

4. If you are a UCSB student, how many units are you currently taking?__________

   What is your year in school (Fresh., Soph., Jr., Sr., Grad.)?__________________
   If you are not a UCSB student, please explain if you are a student elsewhere and how many units/classes you are taking.

   ____

5. What is your major? If you have not declared a major, please put "undeclared."

   ____

6. If you are a student at UCSB, what is your overall grade point average?

   3.5 to 4.0_____ 3.0 to 3.49_____ 2.5 to 2.99_____
   2.0 to 2.49_____ 1.5 to 1.99_____ less than 1.5_____ N/A________

7. Are you currently working in a paid job for at least five hours per week?

Yes__________ No__________

8. If you are working, are you wages at least $10 per hour?

Yes__________ No__________

9. At least $12 per hour? Yes__________ No__________

10. At least $15 per hour? Yes__________ No__________

11. Do you have at least one parent with a bachelor's degree?

Yes__________ No__________