The Relative Efficacy of Price Announcements and Express Communication for Collusion: Experimental Findings*

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Abstract: Collusion is when firms coordinate on suppressing competition, and coordination typically requires that firms communicate in some manner. This study conducts experiments to determine what modes of communications are able to produce and sustain collusion and how the efficacy of communication depends on firm heterogeneity and the number of firms. We consider two different communication treatments: non-binding price announcements and unrestricted written communication. Our main findings are that price announcements allow subjects to coordinate on a high price but only under duopoly and when firms are symmetric. While price announcements do result in higher prices when subjects are asymmetric, there is little evidence that they are coordinating their behavior. When subjects are allowed to engage in unrestricted communication, coordination on high prices occurs whether they are symmetric or asymmetric. We find that the incremental value to express communication (compared to price announcements) is greater when firms are asymmetric and there are more firms.

1 Introduction

For firms to successfully collude, they must coordinate their behavior, and coordination requires some form of communication. In practice, this communication can involve tacking on a few digits to a multi-million dollar bid (FCC spectrum auction) or announcing future intended prices (airlines) or unilaterally announcing a pricing strategy (truck rental) or sitting in a hotel room and talking about prices and sales quotas (lysine). While the last mode of communication is presumably the most effective, it is also the most clearly unlawful. Firms interested in jointly raising prices then face a tension in that communication which is more likely to result in coordination may also be more likely to result in prosecution. Hence, they may choose to more indirectly communicate when it is sufficient to produce at least some collusion.

This trade-off raises two questions that we will examine here. First, what are the various forms of communication that can produce coordinated collusive outcomes? In particular, how indirect can communication be and still be reasonably effective? This question is central to antitrust and competition law and, in spite of a legion of legal cases that speak to what practices are and are not lawful, there remains a large gray area where legality is unclear. Second, how does the answer to the first question depend on the structure of the market?

These questions are notoriously difficult to examine theoretically because the equilibrium framework cannot speak to the issue of how firms coordinate in moving from one equilibrium to another which is exactly what is at issue here: What forms of communication will result in firms coordinating a move from a static equilibrium with competitive prices to a dynamic equilibrium with supracompetitive prices? Experimental methods offer a comparative advantage in that subjects engage in exactly the dynamic process of coordination that we are trying to understand. While the subjects are college students and not managers - and thus extrapolating from experiments to market behavior is always a precarious leap - experimental methods have more promise than other methods for shedding light on the effectiveness of various communication practices in producing collusion.

The specific form of those two questions are addressed here are as follows. In practice, two commonly observed methods of communication for coordinating firm behavior are advance price announcements (as arose in the ATPCO airlines cases) and unrestricted communication using natural language (as practiced by all hard core cartels; for example, lysine, vitamins, and fine arts auction houses). To assess the relative efficacy of different modes of communication, the research plan is to compare outcomes when sellers can make price announcements with when they cannot, and to compare unrestricted communication (through online chat) with price announcements. When are price announcements effective at producing collusion? When is unrestricted communication particularly effective in producing collusion relative to price announcements? Answers to these questions will shed light on when we can expect firms to engage in the most egregious form of collusion - involving unrestricted communication - and when they will instead choose less express methods. In considering the relative efficacy of these different forms of communication, the primary variation in market structure is the extent of firm heterogeneity though the number of sellers is also examined. While unrestricted communication is surely expected to be more effective than price announcements, less clear is how the incremental value of unrestricted communication depends on firm heterogeneity.

Our main findings are that firms are able to coordinate on a high price with price announcements but only for duopoly and when firms are symmetric. While price announcements do result in higher prices for an asymmetric duopoly, there is only weak evidence that they are coordinating their behavior. When firms engage in unrestricted communication, coordination on high prices occurs whether firms are symmetric or asymmetric and regardless of the number of firms. We also investigate how they are coordinating with unrestricted communication which helps explain why collusion with price announcements is relatively ineffective when firms are different.

Section 2 provides a brief summary of experimental work pertinent to the current study. Section 3 describes the theoretical model underlying the experiment and derives equilibrium predictions, while the experimental design is provided in Section 4. The results from the experiments are described and discussed in Section 5.

2 Literature Review

Pertinent to this paper are past studies that experimentally examine how the frequency and extent of supracompetitive outcomes depend on: 1) the method of communication between firms about price or quantity intentions; and 2) firm heterogeneity. There is a voluminous literature addressing the first issue, while the set of experiments addressing the second issue is relatively sparse. There are no experiments that address the interaction of communication and firm heterogeneity, which is the primary focus of the current study. We provide here a brief summary of results from previous experiments, and an extensive review is available in our working paper (Harrington, Hernan-Gonzalez, and Kujal, 2013). Previous surveys of the experimental literature on communication of intentions in an oligopoly include Cason (2008), Normann (2008), Haan, Schoonbeek, and Winkel (2009), and Potters (2009).

The communication protocols used in past oligopoly experiments can be partitioned into four categories. In all of these cases, the announcements made by subjects are non-binding. A Simple Price Announcement protocol involves one or more subjects announcing a price and possibly subjects responding to an announcement by affirming or rejecting it. An Iterative Price Announcement protocol has multiple stages where price announcements made in an earlier stage restrict the announcements that can be made in the current stage. A Strategy Announcement protocol has subjects announce not a price but a strategy for the game or, more generally, some set of contingency plans. Finally, a Chat protocol allows for either oral or written communication using natural language with minimal restrictions though typically prohibiting a subject from revealing his or her identity.

The following results are distilled from the experimental literature using those communication protocols (and when no communication is allowed). We have noted papers that tested for the hypothesized behavior though not every paper finds evidence supportive of the noted regularity.

1. Without communication, prices above static Nash equilibrium levels commonly occur when there are two sellers but very rarely occur with more than two sellers. (Huck, Normann, and Oechssler, 2004; Engel, 2007; Friedman, Huck, Oprea, and Weidenholzer, 2012; Rojas, 2012)

2. Compared to prices when sellers do not communicate, allowing sellers to announce prices results in initially higher prices but then prices decline to levels mildly above or close to levels when communication is prohibited. (Holt and Davis, 1990; Cason, 1995; Cason and Davis, 1995; Harstad, Martin, and Normann 1998; Hinloopen and Soetevent, 2008; Bigoni et al, 2012)

3. Making communication costly tends to raise price. (Andersson and Wengström (2007) assume a cost per message, while Hinloopen and Soetevent (2008) and Bigoni et al (2012) assume probabilistic penalties from all firms agreeing to communicate.)

4. Compared to prices when sellers do not communicate, chat produces significantly higher prices which persist over time. (Friedman, 1967; Issac and Plott, 1981; Issac, Ramey, and Williams, 1984; Davis and Holt, 1998; Cooper and Kühn, 2011; Dijkstra, Haan, and Schoonbeek, 2011; Fonseca and Normann, 2012)

5. Compared to when firms are symmetric, asymmetric costs result in lower prices. (Mason, Phillips, and Newell, 1992; Mason and Phillips, 1997; Fonseca and Normann, 2008; Dugar and Mitra, 2009; Argenton and Müller, 2012)

Pertinent to the current study, the literature has not addressed the following questions:

- What is the effect of firm heterogeneity on the efficacy of communication?

- What is the effect of firm heterogeneity on the efficacy of unrestricted communication compared to price announcements?

- Do price announcements allow firms (whether symmetric or asymmetric) to effectively collude when there are more than two firms?

3 Experimental Design

The experimental setting is based on a modified Bertrand price game. Sellers offer homogeneous products but may have different cost functions. In each period, a seller chooses price and an upper bound on how much it produces and sells (this choice variable will allow sellers to allocate demand). The horizon is indefinite horizon and the history is common knowledge. Section 3.1 provides a detailed description of the setting. A summary of the equilibrium properties for the game are provided in Section 3.2. The various treatments to be run are described in Section 3.3, and the procedures deployed in conducting the experiments are summarized in Section 3.4.

3.1 Environment

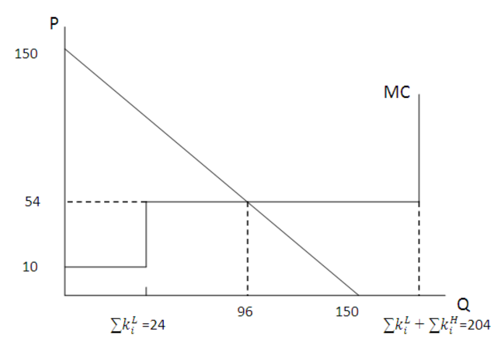
The experiment consists of a multi-period posted offer market with fixed matching. If the market has n sellers then n participants are matched and the match is kept fixed throughout the session. Participants are told that the experiment will last for at least 40 periods after which there is an 80% chance in each period of the experiment continuing to the subsequent period.[1] Sellers offer identical products and face market demand $D(P) = 150 - P$, and are informed that the buyers are simulated.[2]

Each seller's cost function is a step-function with the low cost step equalling 10 and the high cost step equalling 54. Seller i is assigned k_i^L low cost units and k_i^H high cost units so the cost function is

$$C_i(q) = \begin{cases} 10q & \text{if } q \in \{0, 1, ..., k_i^L\} \\ 10k_i^L + 54\left(q - k_i^L\right) & \text{if } q \in \{k_i^L + 1, ..., k_i^L + k_i^H\} \end{cases}$$

In all treatments, industry capacity is fixed at 24 units of low cost capacity and 180 units of high cost capacity, while the allocation of those units varies across treatments (and will be described later). Thus, market demand and the industry cost curve are as depicted in Figure 4.1

Figure 4.1: Industry Cost and Demand



[1] The shortest experiment ran for 40 periods while the longest lasted for 53 periods.

[2] There are then 150 computerized buyers with one buyer with a valuation of 150, one with a valuation of 149, and so forth.

In each period, subjects simultaneously choose a price and a maximal quantity (to be sold). A subject's total number of units produced and sold equals the minimum of its demand and the maximal quantity it selected. Subjects are told that low cost units will be sold first, and any excess demand will not be carried over to the next period. Sellers only incur costs for the units sold. Subjects have 60 seconds to select a price and a maximal quantity, and there is only one price-maximal quantity offer posted by a subject in each period. If a subject chose not to post an offer then s/he earns zero profits for that period. Once subjects post their price-maximal quantity offers, the market clears using computerized buyers. Buyers first purchase from the low price seller until demand or the low price seller's maximal quantity is reached. If there is any residual demand, the process is repeated for the next lowest price seller. This process continues until all demand is met at the prevailing prices or maximal quantities are achieved. Buyers only purchase units if the price is below their valuation for those units. In case of a tie, the system alternates between sellers buying a single unit from each seller (with identical prices) until all available units are exhausted. Subjects are informed about the tie-breaking rule and that the buyers are computerized.

At the end of each period, each subject learns the price-maximal quantity offers of all subjects as well as all subjects' results in terms of units sold and profit earned. They can also review the entire history at any point in time. The environment that subjects face is common knowledge; in particular, they all know market demand, the number of sellers, and each seller's cost function. Subjects are provided with a profit calculator where they can input price-maximal quantity offers for all sellers and learn the resulting profits. They are told: "The profit calculator allows you to estimate your (and others') profits. To do so you can input your price and quantity and make guesses for the other sellers." The calculator allows them to try various combinations of offers and learn the effect on profits.

In all of the treatments, each firm's low cost capacity is sufficiently small so that all units are used up at the joint profit maximum (as well as at a static Nash equilibrium). Hence, the joint maximizing price is 102. Though firms may differ in terms of their low cost capacity, they have the same ordering over a common price. The cost asymmetry is then very mild. As described in the next sub-section, an attractive feature of this mild cost asymmetry is that static Nash equilibria are symmetric but dynamic (collusive) equilibria could either entail symmetric or asymmetric outcomes.

3.2 Theory

In the static game for the experiment, a pure strategy is of the form (p, r) where p is a firm's price and r is a firm's maximal quantity. In characterizing equilibria for the static game, we will allow for mixed strategies. Let $r_i(p)$ denote the maximal quantity associated with firm i choosing price p (whether as part of a pure or mixed strategy). Note that when $p > 54$ (which, recall, is the cost of high cost capacity units), $r_i(p)$

is part of an optimal strategy as long as it is as least as large as residual demand. In addition, setting the maximal quantity at least as large as market demand $D(p)$ weakly dominates setting it below market demand. We will focus on Nash equilibria in which $r_i(p) \geq D(p)$ when $p \geq 54$.

The following theorem holds for the parametric assumptions in the experiment.[3]

Theorem 1 *Consider a mixed strategy Nash equilibrium in which* $r_i(p) \geq D(p)$ $\forall p \geq 54$ *in the support of firm i's strategy,* $\forall i$*. Each firm's strategy assigns probability one to prices in* $\{54, 55\}$*.*

The set of Nash equilibria underlying Theorem 1 is composed of all firms pricing at 54, all firms pricing at 55, and firms randomizing over 54 and 55. Thus, the "competitive price" is 54-55.[4]

Turning to the indefinite horizon repeated game, there are obviously many subgame perfect equilibria. Our objective here is to characterize some of them in order to acquire some insight regarding what to expect in the experiments. For this purpose, let us think of the n firms acting collectively - as a cartel - to generate payoffs that exceed static equilibrium payoffs. Imagine the cartel choosing an outcome path that maximizes a cartel welfare function subject to the path being implemented by a subgame perfect equilibrium. The question is: For various specifications of the cartel welfare function (that is, preferences) and the subset of equilibrium outcome paths from which the cartel can choose (that is, the choice set), how do the resulting outcome paths depend on firms' low cost capacities? In particular, do firms equally share market demand? Or do firms with more low cost capacity have more or less market share?

Suppose the cartel welfare function is the objective from the Nash Bargaining Solution and the choice set is composed of all stationary outcome paths implementable using the grim punishment.[5] Let us further limit our attention to firms choosing a common price but possibly setting maximal quantities in order to unequally allocate market demand. In this case, it can be shown that firm heterogeneity does not matter in that the resulting outcome is symmetric.

Theorem 2 *The Nash Bargaining Solution for the set of outcomes sustainable by grim subgame perfect equilibria is symmetric.*

[3] All results in this section are proven and discussed more extensively in Harrington, Hernan-Gonzalez, and Kujal (2013) and are available in an online appendix.

[4] An advantage of having the step-wise marginal cost function is that, contrary to when marginal cost is constant, the static Nash equilibrium price is not weakly dominated. For example, if there are two symmetric firms and both price at 55 (and set the maximal quantity at least as high as 95) then each earns expected profit of 575.5, while profit is zero by pricing above 55 (as residual demand is zero) and profit is only 528 by pricing at 54 (and is even lower by pricing below 54).

[5] This specification was used in Harrington (1991) for the duopoly case when $k_1^L = 0$ and $k_2^L = \infty$ (that is, constant marginal cost that differs between firms). Also see Thal (2011) where optimal punishments are considered.

While firms' traits then need not affect collusive behavior, this was shown for just one possible specification of collusion. There are two general ways in which asymmetry in firms' traits could possibly translate into asymmetry in the collusive outcome. First, firms may care about relative profits and not just absolute profits. In particular, a firm may not agree to an outcome that has it earn a significantly lower level of profit than other firms. Given that a firm's profit is increasing in the amount of its low cost capacity, this would result in an inverse relationship between a firm's collusive market share and its low cost capacity share. Second, asymmetry could be induced by the equilibrium constraints. If an equilibrium has all firms producing at least as much as its low cost capacity (for all histories) then the equilibrium conditions are independent of the amount of low cost capacity. However, consider a strategy profile in which the punishment has the deviator produce zero for some number of periods and, after doing so, there is a return to the collusive outcome. Now equilibrium conditions depend on a firm's low cost capacity because a firm with more low cost capacity foregoes more profit when it produces zero. By affecting the set of equilibrium outcomes from which the cartel selects, firms' traits may then result in an asymmetric outcome.

To pursue this latter point, consider the following strategy profile where the collusive outcome has all firms set a common price and firm i's share of market demand is s_i. If a firm deviates from the outcome path suppose that the punishment has the deviator choose $(p, r) = (55, D(55))$ and the non-deviators choose $(p, r) = (54, D(54))$ for one period - so the deviator sells zero and the non-deviators share market demand at a price of 54 - and then there is a return to the collusive outcome. This punishment applies whether a firm deviates from the original collusive path or the punishment path. Considering this strategy profile at the joint profit maximizing price 102 and assuming capacities for the asymmetric duopoly treatment - $\left(k_1^L, k_2^L\right) = (18, 6)$ - it can be shown that all equilibrium conditions are satisfied if and only if $s_1 \geq .403$ and $s_2 \geq .504$. Thus, equal market shares is not sustainable because the high cost firm requires a higher market share. While any amount between .504 and .597 for the high cost firm will work, if relative profits are a consideration in the selection of an outcome then the market share may need to exceed the minimum .504 that will ensure stability.

The conclusions of our analysis of dynamic equilibria are imprecise but perhaps informative nevertheless. First, there is a wide class of scenarios whereby the collusive outcome is symmetric even when firms have different cost functions (at least as heterogeneity is modelled here). If firms focus on equilibria in which they always produce at least as much as their low cost capacity (such as with symmetric equilibria constructed on the grim punishment) and the selection of an outcome does not depend on relative profits then the prediction is that the collusive outcome will involve equal market shares. Second, scenarios have been identified whereby the collusive outcome has the firm with fewer units of low cost capacity assigned a higher market share. If the selection of an outcome considers relative profits then the higher cost firm may receive a higher market share in order to reduce the difference in profits. If the punishment used in equilibrium has the deviator produce zero (for some length of time), it is the higher cost firm's equilibrium condition that is most stringent which means it will need to have more market share. There could, of course, exist punishments whereby it is instead the lower cost firm's equilibrium condition that is more stringent, but thus far they have not been found.

3.3 Treatments

There are three sources of treatments - number of firms, seller cost heterogeneity, and information. The number of firms varied between 2, 3, and 4. In the symmetric treatment, all sellers have the same number of low cost and high cost units. The asymmetric treatment - which was run only for the case of a duopoly - assumes that both firms have total capacity of 102 units with firm 1 having 18 units of low cost capacity and firm 2 having 6 units of low cost capacity. The market structure treatment allows the number of sellers to vary between two, three, and four. The various market structure and cost treatments are shown in Table 4.1.

Table 4.1: Market Structure and Cost Treatments

Symmetric			Asymmetric
$n = 2$	$n = 3$	$n = 4$	$n = 2$
$\left(k_i^L, k_i^H\right) = (12, 90)$	$\left(k_i^L, k_i^H\right) = (8, 60)$	$\left(k_i^L, k_i^H\right) = (6, 45)$	$\left(k_1^L, k_1^H\right) = (18, 84)$ $\left(k_2^L, k_2^H\right) = (6, 96)$

There are three informational treatments.

- **No Communication**: All information is common and sellers have access to the entire history; specifically, sellers can observe all past price-maximal quantity offers, transaction prices, quantities sold, and profits. Sellers cannot communicate in any form with their rivals. Sellers simultaneously choose price-maximal quantity offers and have a maximum of 60 seconds to make a decision. If offers are made earlier, the system goes directly to determining the market outcome (that is, allocating demand according to the price-maximal quantity offers selected and calculating profit) and informing sellers of the outcome. Sellers also have the option of not posting an offer by clicking on the "Do not send an offer" button.

- **Price Announcement**: Sellers are informed that each period of the experiment consists of two stages. In the first stage (Price Announcement), sellers simultaneously choose (or not) to make a single non-binding price announcement regarding the price they will select in the market competition stage. Thus, communication between sellers is exclusively numeric and no additional information can be transmitted. If any sellers choose to announce a price, the announcements are simultaneously released to the other sellers. All sellers know that all price announcements are non-binding, and that they can choose not to make an announcement. The first stage can last for up to 60 seconds, however, it moves to the second stage if all announcements are made before the time limit. As in the No Communication treatment, the second stage has them simultaneously make price-maximal quantity offers. All information is common and sellers have access to the entire history, including all subjects' announcements.

- **Chat**: Sellers are informed that each period of the experiment consists of two stages. In the first stage, they can participate in an online chat room where they can communicate with the other seller(s) for 60 seconds. The communication protocol is explicitly explained to the participants: "You are free to discuss any aspects of the experiment, with the following exceptions: you may not reveal your name, discuss side payments outside the laboratory, or engage in inappropriate language (including such shorthand as 'WTF'). If you do, you will be excused and you will not be paid." After the first stage chat session, they simultaneously make price-maximal quantity offers. All information is common and sellers have access to the entire history.

The No Communication treatment describes the usual environment in which firms can only coordinate by signaling through their actual transaction prices. The Price Announcement treatment captures a feature of some markets in which firms make non-binding announcements about future prices. For example, advance price announcements have been deployed and argued to have produced coordinated supracompetitive prices in steel (Scherer, 1980), airlines (Borenstein, 2004), and diesel and petrol fuel in Taiwan (Fair Trade Commission, 2004). In our experiments, price announcements can only affect seller behavior because buyers are simulated and, even if buyers were live, they would be irrelevant to buyer behavior. It is then best to think of the Price Announcement treatment as relevant to markets in which these announcements are not received by buyers (for example, they occur through a trade association) or where such information is of little value to buyers. The Price Announcement treatment is designed to give firms an instrument by which to coordinate that is short of express communication. The issue is whether price announcements are sufficiently informative to induce coordinated behavior.[6] Finally, the Chat treatment models explicit collusion in that firms can engage in unrestricted communication in order to coordinate on a collusive outcome and engage in an exchange of assurances. The primary objectives of this study is to assess how effective are price announcements (relative to no communication) for producing supracompetitive outcomes, how effective is chat (relative to price announcements) for producing supracompetitive outcomes, and how the incremental value of communication depends on firm heterogeneity.

[6]We intentionally did not allow firms to also announce maximal quantities because such quantity announcements are very uncommon though have occurred in the automobile industry (Doyle and Snyder, 1999).

There are three sources of variation in treatments: market structure (that is, number of sellers), firm heterogeneity (that is, symmetric vs. asymmetric cost functions), and communication protocol. Table 4.2 summarizes the different combination of treatments used in the experiments along with the notation we will use when referring to the treatment. In [   ] is the number of experiments run with that treatment. Given the large number of possible combinations, the market structure-firm heterogeneity treatments were chosen to make the best use of our budget by avoiding treatments that were unlikely to provide new information. For example, if n firms for a treatment yielded competitive results then we did not run the treatment with more than n firms as it is likely to produce competitive results.

Table 4.2: Experimental Treatments

Communication Protocol	Symmetric			Asymmetric
	$n = 2$	$n = 3$	$n = 4$	$n = 2$
No Communication	SNC2 [12]	SNC3 [8]		ANC2 [13]
Price Announcements	SAN2 [12]	SAN3 [8]	SAN4 [6]	AAN2 [12]
Chat	SCH2 [12]		SCH4 [6]	ACH2 [12]

3.4 Procedures

Our subject pool consisted of students from a major American university with a diverse population. Participants were recruited by email from a pool of more than 2,000 students who had signed up to participate in experiments. Emails were sent to a randomly selected subset of the pool of students. Subjects were recruited for a total of two hours. The experiments took place in May 2011. In total, 242 students participated in 73 duopoly, 16 triopoly and 12 quadropoly experiments.

The instructions were displayed on subjects' computer screens and they were told that all screens displayed the same set of instructions. They had exactly 20 minutes to read the instructions (see Appendix). A 20-minute timer was shown on the laboratory screen. Three minutes before the end of the instructions period, a monitor entered into the room announcing the time remaining and handing out a printed copy of the summary of the instructions. None of the participants asked for extra time to read the instructions. At the end of the 20-minute instruction round, the experimenter closed the instructions file from the server, and subjects typed their names to start the experiment. The interaction between the experimenter and the participants was negligible.

Average payoffs (including the show-up fee) varied from a low of $18.85 (which was for triopoly with the No Communication treatment) to a high of $34.35 (which was for duopoly with the Chat treatment).

4 Results

In this environment, a seller is trying to determine both the optimal price given the other sellers' anticipated prices, and what prices it should anticipate being set by the other sellers. There appears to be a fair amount of learning of the first kind as revealed in the experimental output and the messages from the Chat treatment. In the Chat treatment, even when sellers communicated their intent to maximize joint profit, there was a lot of discussion about what price would actually achieve that objective. Presumably, when there is no chat, an individual seller is also trying to "figure out" the best price, given beliefs as to the other sellers' prices. What this suggests is that the experimental output in the early periods is a confluence of learning, competition, and cooperation, while the output in later periods is more representative of what we are interested in which is competition and cooperation. Therefore, results will be reported for periods 1-20, 21-40, and 1-40 (recall that the length of the horizon is 40 periods for sure and is then stochastically terminated).

4.1 Baseline: No Communication

For the No Communication (NC) protocol, Table 5.1 reports the average market price for the symmetric duopoly (SNC2), symmetric triopoly (SNC3), and asymmetric duopoly (ANC2).[7] In examining these prices, recall that the competitive (static Nash equilibrium) price is 54-55 and the monopoly price is 102. As reported in Table 5.1, average market price is at least 55 in all treatments so the transaction price is at least as high as the static Nash equilibrium price. With a symmetric duopoly, average market price is 66.7 over periods 1-40 and 69.5 for periods 21-40; while it is 61.5 and 63, respectively, for when firms are asymmetric. With a symmetric triopoly, average market price is 58.5 over periods 1-40 and 56.3 for periods 21-40 which is very close to the competitive level. Conducting a t-test for the hypothesis that average market price exceeds a price of 56, it is soundly rejected for a triopoly and soundly accepted for both symmetric and asymmetric duopolies.[8] Examining the histograms in Figure 5.1 for market price, the price distribution has a peak around 55 for symmetric triopoly and asymmetric duopoly, while the peak is closer to 60 for symmetric duopoly. As we move from symmetric triopoly to asymmetric duopoly to symmetric duopoly, there is a shifting of mass to higher prices.

Consistent with previous findings in the experimental literature, supracompetitive prices occur with two sellers but not with three sellers. We also find for the case of a duopoly that prices are higher when firms' cost functions are identical though it is only barely statistically significant (which is not surprising given only 12 observations). For

[7] The market price is the sum of firms' prices weighted by the firm's market share. The average market price for a group is the market price averaged across all periods and is the unit of observation for calculating the average, median, and standard deviation in Table 5.1.

[8] In conducing this test, one group (that is, a matched set of subjects interacting for 40+ periods) is an observation so there are 12 data points.

periods 1-40, prices are higher under symmetry by 8.5% (= (66.7 - 61.5)/61.5) with a p-value of .103 (see Table 5.4), and are higher for periods 21-40 by 10.3% (with a p-value of .128).[9]

Property 1: For the case of no communication, average market price exceeds the competitive level in duopoly (symmetric and asymmetric) but not in triopoly (symmetric).

Property 2: For the case of duopoly and no communication, average market price is higher when firms have identical cost functions than when they have different cost functions.

4.2 Signaling: Price Announcements

Now we turn to the central part of the analysis which is assessing the effect of the communication protocol on behavior and how the communication's effect depends on market structure. It is important to emphasize that our interest lies in determining whether firms collude, and collusion is more than high prices; it is a mutual understanding among firms to suppress competition. Prices could be high, and yet subjects are not colluding. For example, firms may periodically raise price with the intent of coordinating on some supracompetitive outcome but never succeed in doing so. High average prices are then the product of failed attempts to collude. Or sellers may engage in randomized pricing that periodically results in high prices - thus producing high average prices - but again there is not the coordination that we would associate with collusion.[10]

In the ensuing analysis, sellers are said to be colluding when they achieve high and stable prices. This could mean they consistently set identical prices, and equally share demand. Or firms could set different prices with the firm with the lower (but still high) price restricting its supply so that the firm with the higher price has residual demand. Or firms could alternate over time with one firm selling to the market and the other firm pricing itself out of the market or not participating. Recognizing the different forms that supracompetitive outcomes can take, various measures will be used in our analysis.

As an initial step let us focus on collusion that takes the form of firms setting identical supracompetitive prices. To identify the extent to which price announcements make such collusion more common, we will report average market price and two measures of coordination: the number of periods for which sellers set the same price (*Same*) and the longest number of consecutive periods for which sellers set identical

[9] Keep in mind that the degree of asymmetry is rather mild in that firms only differ in the number of low cost capacity units and, at any relevant symmetric outcome, firms are producing well beyond their low cost capacities in which case they face the same marginal cost.

[10] While such randomizing pricing is not predicted by the theory, it appears to fit the pricing of some groups.

prices (*Duration*). If sellers achieve a high average price and high measures of Same and Duration, this is compelling evidence that they are colluding. If sellers achieve a high average price and low measures of coordination than it could either be that firms are not colluding or are colluding in a different manner.[11]

In going from the No Communication to the Price Announcement treatment, Table 5.2 reports that the average market price under duopoly substantially increases, whether firms are symmetric or asymmetric. Over periods 1-40, price rises from 66.7 to 76.2 under symmetry (though the p-value is .133, see Table 5.4) and from 61.5 to 67.5 under asymmetry (p-value = .004). For periods 21-40, price rises from 69.5 to 79.5 under symmetry (p-value = .273) and from 63.0 to 70.6 under asymmetry (p-value = .017). While the increase in average price is actually larger when firms are identical - compare 9.9 (or 14.2%) for symmetric firms with 7.6 (or 12.1%) for asymmetric firms - the standard deviation is much larger under symmetry which is why the difference is statistically significant only for the asymmetric duopoly case. We will return to this point later.

Having the ability to make price announcements proves insufficient to produce collusion when there are more than two firms. For symmetric triopolies, average price is 57.7 (periods 21-40) which is close to average price without announcements (56.3) and to the competitive price (54-55). Similar results were found in six sessions conducted with four symmetric firms. In sum, price announcements matter when there are two sellers - whether symmetric or asymmetric - but not when there are more than two sellers. The general finding in the literature - collusion in the absence of communication is unlikely when there are more than two sellers - is robust to allowing sellers to communicate by announcing prices.

While price announcements are producing distinctly higher average prices for duopolies, is this collusion? Examining the coordination measures, the evidence is compelling that symmetric duopolies are colluding, but that is not the case with asymmetric duopolies. As shown in Table 5.3, there is almost a doubling in the number of periods in which firms in a symmetric duopoly set identical prices; it increases from 8.3 to 16.1. It is even more impressive if we focus on periods 21-40 where the frequency of identical prices rises from under 25% of periods (4.6 out of 20 periods) to more than 50% (10.3 out of 20 periods). The Duration measure tells the same story; the average maximal number of consecutive periods for which firms set the same price goes from 2-3 to 8-10 periods. In contrast, price announcements do not produce any change in the coordination measures when firms are asymmetric. Though, given the small number of observations, the differences for symmetric firms are not statistically significant by the usual standards (see Tables 5.5 and 5.6), the evidence is suggestive that price announcements are producing more coordination.[12]

[11] Of course, a low average price and high coordination is consistent with competition.

[12] In identifying the presence of collusion, this finding highlights the importance of including measures of coordination as well as price levels. For example, Fonseca and Normann (2012) find reasonably supracompetitive prices with duopoly without communication but an examination of the

Of course, the lack of evidence for increased coordination in asymmetric duopolies may just reflect the inadequacy of our measures. Same and Duration are designed to detect coordination on identical prices. Perhaps, due to cost differences, asymmetric duopolies collude with different prices and choose maximal quantities so as to allocate market demand, or instead alternate in supplying the entire market. If firms have settled down to such supracompetitive outcomes then this will be reflected in high and stable industry profit.

Figures 5.2 and 5.3 report the mean and standard deviation of industry profit over periods 21-40 for asymmetric and symmetric duopolies, respectively, and for both the No Communication and Price Announcement treatments.[13] Collusion is associated with the northwest quadrant where industry profit is high with low volatility. Examining Figure 5.2, price announcements raise average industry profit for asymmetric duopolies but there are no observations of high and stable profit (relative to when firms are not permitted to make price announcements). Instead, price announcements are causing higher and *more* variable profit. In contrast, price announcements result in higher and *less* variable profit for symmetric duopolies. More specifically, there are four groups in Figure 5.3 in which profit is high and the standard deviation is lower than in any of the 12 groups in the No Communication treatment. In sum, we find clear evidence that price announcements are significantly increasing the extent of collusion for symmetric duopoly but little evidence that it is doing so for asymmetric duopoly.

Property 3: When firms can make price announcements then - compared to no communication - firms in a duopoly set higher prices whether they are symmetric or asymmetric, but firms coordinate more only when they are symmetric. When there are more than two firms, price announcements do not result in supracompetitive prices.[14]

There is a rather natural explanation for why price announcements are more effective in producing collusion when firms are symmetric. When sellers have identical cost

price series (made available to us by the authors) shows that there is very little coordination. There is something going on but it is not a straightforward story of tacit collusion.

[13] Note that the monopoly profit is 3360, and when all firms set a price of 54 the industry profit is 1056.

[14] Let us make two comments regarding our measures of coordination. First, these measures look at the mean and standard deviation for periods 21-40. A duopoly could succeed in colluding late in the horizon and thereby fail to have a high stable profit in this 20 period window. Inspection of the time series for all of the groups reveals only two such cases: one symmetric duopoly (SAN2 group 4) and one asymmetric duopoly (AAN2 group 9). They are both examined below. Second, sellers could be coordinating on an industry outcome with periodicity exceeding one period. For example, firms could cycle between both setting the monopoly price and both setting the competitive price which would produce reasonably high industry profit but with a high standard deviation. Besides the fact that a multi-period cycle would be both more difficult to coordinate upon and sustain and probably less profitable, an inspection of prices, quantities, and profits shows no evidence of such a pattern.

functions, a symmetric supracompetitive outcome is focal, and can be implemented by coordinating on identical prices. However, when sellers have different cost functions, a symmetric outcome is no longer focal. An asymmetric division of industry profit could be produced in a variety of ways but arguably the most straightforward is for sellers to set identical prices and unequally allocate market demand, which is what has been done with many cartels (see Harrington, 2006). For example, if sellers wanted to support the joint profit maximum and have the high cost seller receive 60% of market demand, both sellers could charge the monopoly price of 102, which yields market demand of 48, and have the low cost seller set its maximal quantity equal to 19, which will result in the high cost seller supplying the residual demand of 29. However, this collusive outcome requires coordination of prices *and* quantities. The difficulty in coordinating on equal prices and unequal quantities in the Price Announcement treatment is that sellers are only allowed to announce prices. Of course, just because an asymmetric outcome may be the first-best collusive outcome for an asymmetric duopoly, it does not imply that firms would try to coordinate on it. If it is perceived to be too difficult then they may decide to go for a second-best solution of coordinating on identical prices and equally sharing market demand; some collusion is better than competition. However, that is not what we are finding. Under asymmetric duopoly, sellers are not coordinating on a common price and, with one exception to be analyzed below, they are not coordinating on different prices either.

It is worth pointing out that, in contrast to other experiments that have allowed sellers to make non-binding price announcements, the effect of producing more coordinated behavior persists over time.[15] Indeed, the results are stronger for periods 21-40 than for periods 1-20. More informative to this point are the price series from the 12 symmetric duopolies in Figure 5.4. In five out of the 12 groups, sellers eventually had identical prices well above competitive levels. In four out of those five groups (groups 3, 7, 8, 12), sellers set the same price for the last 20 or so periods with price at or near the monopoly level for three of them (it was around 75 for group 7). (Group 9 is also a candidate for inclusion in that set.) In the other run (group 4), sellers' prices were common but steadily rising in the last 15 periods as they climbed from the competitive level to the monopoly level. Only in one group did sellers achieve reasonably stable, common, and supracompetitive prices to then experience an unravelling whereby prices retreated back to competitive levels (group 2). Thus, our results show that price announcements can be effective in producing persistent collusive pricing.

Let us now return to the issue of the high standard deviation for average price for a symmetric duopoly under the Price Announcement treatment (see Table 5.2). The price paths in Figure 5.4 reveal that, generally, either sellers set high identical prices (groups 3, 4, 8, 9, 12) or set prices near competitive levels with some unsuccessful

[15] From the survey of Cason (2008): "Although price signaling often increases transaction prices, this increase is very often temporary. [Steady-state] behavior may be unaffected by non-binding price signaling in many environments."

forays into supracompetitive territory (groups 1, 5, 6, 10, 11). (Group 2 does not fall into either of those two bins, and group 7 would fall into the first bin except that price is only 75.) This pattern can also be seen in the market price histograms in Figure 5.5. For the symmetric duopoly, the distribution has a mode near the competitive price and one near the monopoly price (both for periods 1-40 and 21-40). In comparison, there is not this stark dichotomy when firms are asymmetric. The distribution in Figure 5.5 for asymmetric duopoly is unimodal for periods 1-40 and far less bimodal for periods 21-40 than under symmetry.

It is this dichotomy in outcomes for the symmetric duopoly which is producing a relatively high standard deviation; either firms have great success in colluding or very little success. Figure 5.6 nicely depicts this distinction between symmetric and asymmetric duopolies. An observation here is a group's average market price and the number of periods for which firms set the same price. When firms are symmetric, the observations form two clumps which are circled; one with low price and low coordination, and the other with high price and high coordination (with the exception of group 2 which has high price and low coordination). Note that the lowest average price for the groups in the "high Same" clump exceeds the highest average price for the groups in the "low Same" clump. When firms are asymmetric, there is no apparent relationship between average price and the frequency with which firms set the same price.

Having found that collusion in symmetric duopolies is more common when sellers can make price announcements, it is useful to examine the pattern of announcements and prices in order to gain some insight into the underlying mechanism responsible for this finding. It was with this objective in mind that we performed a statistical analysis of announcements. However, it proved uninformative which is not too surprising given that announcements are cheap talk. (Even if announcements do serve to coordinate behavior in some instances, any regularity could easily be lost if many announcements are meaningless.) Instead, let us engage in some post hoc analysis of seller behavior in a few groups, which is suggestive but speculative.

To frame our thinking, consider two hypotheses regarding how announcements could produce collusion. The first hypothesis is that a seller believes there is mutual understanding of a desire to collude and the only challenge is to coordinate on a particular price. In that case, one might expect to observe a seller announce a high price and, in anticipation that the announced price coordinates expectations, sellers then price at the announced level. A second hypothesis is that a seller is uncertain that there is mutual understanding regarding collusion and, therefore, acts cautiously by announcing a high price but not pricing at that level until the other seller has made the same announcement. If both sellers are thinking that way then we ought to observe high prices only when both of them have announced high prices.[16]

[16]This latter scenario corresponds with the ATPCO case whereby American Airlines would announce a future price increase and enact that price increase if and only if the other airlines also announced a future price increase; otherwise, the proposed price increase would be retracted.

Illustrative of the first hypothesis is group 12 from the symmetric duopoly treatment (see Figure 5.7). After some initial failed attempts at coordinating through announcements, success occurred in period 24 when firm 1 announced a price of 102 and both firms priced at 102. Thereafter, they priced at that level and, with the exception of one period, firm 1 preceded it with the same announcement.

Perhaps illustrative of the second hypothesis is group 9 from the symmetric duopoly treatment. In period 13, firm 2 announced a price of 100 but firm 1 did not make an announcement, and neither set a high price. Again in period 17, firm 2 announced 100. Though firms did not raise prices, firm 1 did respond in periods 18 and 19 with an announcement of 95 though again there was no effect on prices. In period 20, firm 2 priced at 90 even though it made no announcement. Finally, in period 21, both firms announced high prices - firm 1 with 90 and firm 2 with 95 - and firms coordinated on the lower announcement by pricing at 90. From that point onward, announcements and prices steadily rose. What differs from the second hypothesis is that firm 1 raised price in period 20 prior to the simultaneous announcements in period 21. Thus, coordination of expectations could be due to the price increase in period 20 and/or the price announcements in period 21.

Another symmetric duopoly, group 4, is interesting. During the first third of the experiment, announcements were rarely used and, subject to some initially high prices, prices settled down at competitive levels. Then, in period 15, there was an attempt to coordinate on higher prices which ultimately failed. A second attempt to coordinate began in period 25 which proved successful. Firm 1 announced 55 and priced at that level. Though 55 is the competitive price, firm 1's purpose may have been to signal to firm 2 that its announcement is an accurate predictor of its price. Firm 1 gradually raised its announcement while always pricing at its announcement, as did firm 2. From period 25 to 38, price gradually rose to 102. Every now and then, firm 2 would make a different announcement but prices always followed firm 1's announcement. Clearly, firm 1 emerged as the market leader.

Turning to an asymmetric duopoly, group 9 initially had a lack of success in coordinating - in spite of firms using announcements - but eventually one firm took charge and collusion ensued. In period 21, firm 2 (high cost firm) announced 100 and priced at 62 but firm 1 priced at 54 and sold all units. In period 22, firm 2 continued to announce 100 but dropped price to 56. While firm 1 priced at 55, it limited its supply to 18 units which left residual demand for firm 2; firm 1's profit was 810 and firm 2's was 416. Starting with period 23, firm 1 began announcing. It announced and priced at 57 and again limited its supply to 18 units, while firm 2 announced 100 but priced at 58. Firm 1's profit was 864 and firm 2's profit was 560. From that point onward, firm 1 gradually raised its announcement, always priced at its announcement, and always limited its quantity to 18. While firm 2 was pricing above firm 1's price, firm 2 always had residual demand due to the limited supply of firm 1; in fact, firm 2 (who had higher cost) made higher profit along this path. The steady-state was reached in period 33 and it was characterized by firm 1 announcing and pricing at 99, firm 2 announcing and pricing at 100, and firms sharing market demand with firm 1 selling 18 units and firm 2 selling 32 units. The steady-state profit was 1602 for firm 1 and 1736 for firm 2. This group clearly colluded and was able to coordinate on different prices and quantities.

Summarizing this section, the ability to make non-binding price announcements produces more collusion - as reflected in stable supracompetitive outcomes - only for symmetric duopolies. In contrast to previous experiments, collusion persists until the end of the experiment. For symmetric duopolies, if price announcements are able to produce collusion then the collusion is typically considerable in that sellers consistently set identical near-monopoly prices. While price announcements do raise average prices for asymmetric duopolies, there is little evidence that sellers are coordinating; they do not set common prices, and an examination of profit does not support coordination on an asymmetric outcome (with the exception of one group).

4.3 Express Communication: Chat

Turning to the Chat treatment, collusion is rampant; sellers set high and identical prices most of the time and in almost all groups. From Table 5.2 for the symmetric case, average price is 91.2 over periods 1-40 (which is 77% of the gap between the competitive and monopoly prices) and is 98.9 over periods 21-40 (93% of the gap). Even more impressive, the median price is the monopoly price of 102 (periods 21-40). Prices are just as high when the duopoly has asymmetric firms: an average price of 91.2 for periods 1-40 and an average price of 99.5 for periods 21-40. From Table 5.4, the difference in price between the Price Announcement and Chat treatments is highly statistically significant with p-values of .022 under symmetry and .000 under asymmetry (periods 21-40).

We have already noted that, when sellers are symmetric, coordination is higher with price announcements compared to when there is no communication, and they are yet higher when sellers can chat. From Table 5.3, when sellers are symmetric, the percentage of periods for which sellers set the same price (during periods 21-40) is less than 25% with no communication, is more than 50% with price announcements, and is more than 90% with chat; these differences are statistically significant. When sellers are asymmetric, the percentage of periods for which sellers set the same price (during periods 21-40) is 20-25% with either no communication or price announcements and jumps to almost 60% with chat. For the case of asymmetric duopolies, the extent of coordination that emerges with chat is even higher than what those numbers suggest. As we describe below, some groups successfully coordinate on asymmetric collusive outcomes. The power of chat for producing collusion is consistent with earlier work.[17]

[17] We also ran the Chat treatment with four symmetric firms and found it very effective at producing coordinated supracompetitive prices. For five out of six groups, sellers eventually settled on and persisted with identical high prices of 79, 102 (three groups), and 110.

Property 4: When sellers can engage in chat then - compared to either no communication or price announcements - sellers set higher prices and coordinate more, whether they are symmetric or asymmetric. With chat, prices are often at or near monopoly levels.

An examination of the messages conveyed during chat for asymmetric duopolies shows, for some groups, a goal of equal profits which has sellers selling different amounts by constraining demand through maximal quantities; prices may be the same or different. To exemplify this point, here are some communications from three of the 12 asymmetric duopolies.

In ACH2 Group 7, sellers initially seek to equate profit with different prices. In period 5, the low cost firm is supposed to set a price of 61 and the high cost firm a price of 72. The low cost firm would then have demand of 89 but it sets its maximal quantity at 35 and thereby leaves residual demand for the high cost seller. Again in period 10 they are proposing to set different prices while supplying the same amount. Later in the horizon (period 28), they are proposing to set the same price of 98 and set maximal quantities so that the high cost firm's market share is 65%.

- ACH2 Group 7
  - Period 5
    - Low cost firm 1: "I got it. you sell 100 units for 72. I sell 35 for 61."
    - High cost firm 2: "okay"
    - Low cost firm 1: "so for it looks like i'll get 1037 and then you get 1038"
  - Period 10
    - Low cost firm 1: "sell 33 for 83 and i do 33 for 67. we both get 1221. i'll look for a higher even. nice"
  - Period 28
    - Low cost firm 1: "You sell 37/98. And i sell 20/98. we both get 1672."

In the next group, sellers eventually reached a point at which they are setting identical prices and allocating 60% of the market to the high cost firm.

- ACH2 Group 12 - Period 36
  - High cost firm 2: "you sell 18 at 103 and i sell 28 at 103. itd be 1674 and 1636 respectively"
  - Low cost firm 1: "okay cool"
  - High cost firm 2: "its a little less for you and a little more for me"

The final case is especially interesting in that sellers persisted with different prices and quantities with the stated objective of equating their profits. The low cost firm is to price at 90 and the high cost firm at 82 and limits its supply to 42 so that the low cost firm has residual demand of 18. As they correctly calculated, each earns 1,440. Figure 5.8 reports the price and maximal quantities (when they are binding) and shows that this collusive outcome was sustained for the last 21 periods of the session.

- ACH2 Group 6
  - Period 19 - Low cost firm 1: "do 42 and 82. ill do 18 and 90. we both win"
  - Period 20 - Low cost firm 1: "We will both get 1440 until the end of the experiment if you follow my advice. Check it out on the calculator."

For the case of asymmetric duopoly, seven of the 12 Chat groups have sellers eventually set identical prices equal to or very close to the monopoly price, and there are three additional groups which coordinated on a supracompetitive outcome with different prices. In the just examined ACH2 Group 6, sellers coordinated on unequal supracompetitive prices and implemented unequal sales quotas. In two other groups, sellers took turns being the exclusive supplier. In one case, they alternated between being the low and high priced sellers; in the other, they rotated setting a price of 102 and not being in the market (that is, not posting an offer).[18] Thus, 10 out of the 12 Chat groups with an asymmetric duopoly eventually colluded. When firms are symmetric, collusion occurred in 11 out of 12 groups.

We observe for the Chat treatment that subjects in our experiment exhibit a desire to equalize payoffs. As has been shown in other experiments, such concerns may arise when there is an absence of entitlements (see, for example, Hoffman et al 1994; and Engel, 2011). In our setting, cost is randomly assigned (rather than, in some sense, earned) in which case subjects may have no reason to believe that lower cost comes with it a right to higher profit. This lack of entitlements may then allow the equal sharing of profit to emerge as a focal point under asymmetric costs. Of course, the relevance of payoff equalization to real world markets is an open question. A firm with higher cost could promote profit equalization as a bargaining strategy, and managers may be concerned with relative performance in light of incentive contracts. In any case, the presence, source, and implications of subjects pursuing payoff equalization in asymmetric oligopoly experiments is a matter that warrants further investigation.

[18] A policy of taking turns as the lone supplier does not maximize joint profit because it results in some low cost capacity not being used in each period.

4.4 Regression Analysis

As a final analysis of the data, panel data regressions were conducted to measure the effect on market price of the communication protocols and cost structures. The empirical model is:

$$p_{i,t} = \mu_o + \beta X'_{i,t} + e_{i,t}$$

where $p_{i,t}$ is the market price in group i in period t and $X'_{i,t}$ are dummy variables for each treatment. Similar to previous studies, we allow for serial autocorrelation of the disturbance.[19] The model was estimated for duopolies and for periods 1-20, 21-40, and 1-40

Let us begin by assessing the effect of allowing price announcements relative to the case of no communication. In Table 5.7, DAnn is a dummy variable that takes the value 1 for the Price Announcement treatment (and value 0 for the No Communication treatment), DAsym is a dummy variable that takes the value 1 for the asymmetric cost treatment, and we also have an interaction term for the two treatments.

All estimated coefficients are highly significant. Confirming Property 2, the coefficient on DAsym is negative indicating that, when communication is prohibited, prices are lower when firms are asymmetric. Permitting firms to make price announcements raises price by 10 for symmetric duopolies and 7.64 for asymmetric duopolies (using the estimated coefficients for periods 21-40). Of course, as previously argued, coordination is higher only with symmetric firms. The negative coefficient on the interaction term DAnn x DAsym supports the claim that indirect communication through price announcements is a more effective collusive device when firms are symmetric.

Table 5.8 reports estimates that allow us to compare the efficacy of communicating through chat with non-binding price announcements. Express communication significantly raises price. When firms are symmetric, price is higher by 19.43 and, when firms are asymmetric, the price increase is 28.71 (using the estimated coefficients for periods 21-40). The positive coefficient for the interaction term supports the claim that direct communication through chat is a more effective collusive device when firms are asymmetric, compared to price announcements. Thus, the incremental value to directly, as opposed to indirectly, communicating, is greater when firms have different cost functions.

Property 5: Price announcements are more effective in producing collusion when firms are symmetric compared to when they are asymmetric. Relative to price announcements, chat is more effective in producing collusion when firms are asymmetric compared to when they are symmetric.

[19] See Mason, Phillips and Nowell (1992), Mason and Phillips (1997), and Argenton and Müller (2012).

5 Concluding Remarks

The objectives of this project are to investigate: 1) the efficacy of non-binding price announcements in producing collusion; 2) the efficacy of unrestricted communication relative to price announcements in producing collusion, and 3) how the answers to those first two questions depend on market structure in terms of firm asymmetries and the number of firms. One main finding is that price announcements clearly increase the frequency of collusion for a symmetric duopoly but do not facilitate collusion when firms are asymmetric or there are more than two firms. Though price announcements do raise average price with asymmetric duopolies, there is little evidence that they are able to generate stable supracompetitive outcomes. Regarding the efficacy of unrestricted communication, it is highly effective in producing collusion whether firms are the same or different and regardless of the number of firms. For all cases, prices and profits are significantly higher when sellers can engage in express communication compared to when only price announcements are available. The incremental gain of direct communication (through chat) compared to indirect communication (through price announcements) is large for all market structures but especially when firms are asymmetric and when there are more than two firms.

Our experimental evidence is consistent with the following two hypotheses. First, indirect communication through price announcements is sufficient for producing collusion in symmetric duopolies. Second, reasonably direct communication is required to produce collusion when firms are asymmetric and/or there are more than two firms. The evidence for that hypothesis is that collusion was widely observed when firms engage in online chat, while price announcements rarely resulted in collusion when there were more than two firms or firms had different cost functions. Of course, there are other forms of indirect communication and they may be able to succeed where price announcements have failed. Also, while price announcements produced little collusion for asymmetric duopolies, higher prices were observed which may indicate failed attempts at colluding. Perhaps the addition of quantity announcements would be sufficient to result in collusion in that case, or allowing firms to announce strategies. At the same time, the asymmetry in our experiment is very mild so it is rather striking that price announcements are insufficient for coordination. In actual markets, firms are asymmetric, yet it seems that price announcements have worked; for example, in the airlines industry. There is then a gap between what is being found experimentally and what has occurred in actual markets.

In terms of future research, there is more to be done in terms of allowing for different firm asymmetries and communication protocols. The cost asymmetry could be more extensive by assuming it applies to all units. Other forms of asymmetry to consider are capacity and product differentiation. It is especially important to investigate other types of non-express means of communication such as the announcement by a seller of a strategy. Such messages were the basis for at least two Section 5 "invitation to collude" cases pursued by the U.S. Federal Trade Commission in recent years. Finally, some experiments have allowed for probabilistic penalties in response to sellers choosing to engage in online chat, in order to simulate the penalties imposed by antitrust and competition law. Our design could be modified to make online chat an option. Sellers could then seek to "legally" collude through price announcements or "illegally" collude through online chat. This design would serve to identify the types of market structures for which sellers opt for express communication.[20]

6 Appendix: Instruction Summary (Asymmetric Firms and Price Announcement)

Complete instructions are available at *sites.google.com/site/collusionexperiments/home.* Here we provide an overview of the instructions for the treatment with asymmetric duopoly and price announcements.

- You will be matched with the same person during the length of the experiment. There are two sellers in each market.
- Today's experiment will consist of a number of trading days.
- In the first stage, you will make an announcement regarding the price you propose to offer. This announcement is not binding.
- In the second stage, you will choose a price and quantity offer in the subsequent stage. Both the quantity and price can be changed in the following trading days.
- In today's experiment one seller will have a Unit Cost of 10 and 54 for the first 18 and 84 units. The other seller, meanwhile, will have a Unit Cost of 10 and 54 for the first 6 and 96 units. Unit Costs are the same in all trading days.
- You will be paid 1 U.S. dollar for every 2500 "experimental units (dollars)" you earn in the market. Your total earnings for today's experiment will be the sum of your earnings in the experiment, plus your appearance fee.
- The experiment will continue at least till period 40. After period 40, and in every subsequent period, the continuation of the experiment will be determined with the draw of a number between 0 and 100. If a number lower than 20 is chosen the experiment ends.
- The trading day proceeds as follows: 1) Each seller first makes a price announcement. 2) After the announcement, each seller offers to sell certain units (or none) at a certain price on any trading day. While choosing the quantity you should keep in mind that,
- Your Earnings = Revenues - Total Cost. You earn profits only by selling units at a price above Unit Cost. If you sell at a price below cost you will lose money. You earn zero if you sell nothing.
- Your demand in the experiment is: Q=150-P. The low price seller gets to sell first.
- Your unit cost for the first 12 units is 10 cents, and is 54 cents for the remaining 90 units.

[20] We would like to thank Massimo Motta for suggesting this idea.

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TABLE 5.1: Average Market Price (No Communication)

Periods	Treatment	Average	Median	Standard Deviation	t-test (T>56) (p-values)
1-40	SNC2	66.7	63.4	11.8	**0.005**
	SNC3	58.5	56.8	8.1	0.206
	ANC2	61.5	57.8	10.9	**0.047**
1-20	SNC2	64.0	61.3	11.7	**0.018**
	SNC3	60.7	56.0	15.9	0.216
	ANC2	60.0	56.6	12.4	0.135
21-40	SNC2	69.5	64.1	17.1	**0.010**
	SNC3	56.3	55.6	2.2	0.352
	ANC2	63.0	56.9	14.3	**0.052**

SNC2 – Symmetric, No Communication, Duopoly

SNC3 – Symmetric, No Communication, Triopoly

ANC2 – Asymmetric, No Communication, Duopoly

Table 5.2: Average Market Price

Average (Median) [Std. Dev] Market Price

	No communication		Announcements			Chat		
Periods	Sym2	Asym2	Sym2	Asym2	Sym3	Sym2	Asym2	Sym4
1-40	66.7 (63.4) [11.8]	61.5 (57.8) [10.9]	76.2 (72.6) [17.6]	67.5 (65.7) [5.9]	58.0 (55.7) [21.5]	91.2 (92.7) [12.5]	91.2 (90.4) [17.6]	89.6 (94.7) [17.1]
1-20	64.0 (61.3) [11.7]	60.0 (56.6) [12.4]	72.9 (64.5) [18.1]	64.4 (64.3) [7.3]	58.3 (56.1) [5.3]	83.5 (83.8) [18.4]	82.7 (83.5) [20.2]	85.7 (87.2) [16.8]
21-40	69.5 (64.1) [17.1]	63.0 (56.9) [14.3]	79.5 (76.5) [20.2]	70.6 (72.8) [9.4]	57.7 (55.8) [4.3]	98.9 (102.0) [8.6]	99.5 (99.8) [17.2]	93.4 (102.0) [18.5]

Sym2 – Symmetric Duopoly

Asym2 – Asymmetric Duopoly

Sym3 – Symmetric Triopoly

Sym4 – Symmetric Quadropoly

Table 5.3: Coordination Measures (Duopoly)

		No Communication		Price Announcements		Chat	
	Periods	Sym	Asym	Sym	Asym	Sym	Asym
Number of periods with equal price	1-40	8.3	8.3	16.1	7.5	31.7	20.4
	1-20	3.7	3.9	5.8	3.4	13.1	8.6
	21-40	4.6	4.4	10.3	4.1	18.6	11.8
Duration of Price coordination	1-40	2.8	2.9	10.5	2.5	27.1	14.0
	1-20	1.4	1.6	3.6	1.5	10.2	6.4
	21-40	2.5	2.2	8.3	1.9	17.9	10.4

Table 5.4: Average Market Price – Mann-Whitney-Wilcoxon (MWW) Tests

p-values for the test that average market price is the same across two treatments, periods 1-40 (1-20) [21-40]

	SNC2	**SAN2**	**SCH2**	**SNC3**	**SAN3**	**SAN4**	**SCH4**	**ANC2**	**AAN2**
SAN2	.133 (.184) [.273]								
SCH2	**.001** **(.008)** **[.001]**	**.057** (.184) **[.022]**							
SNC3	**.045** (.488) **[.009]**	**.004** **(.007)** **[.002]**	**.000** **(.017)** **[.000]**						
SAN3	**.037** (.355) **[.025]**	**.009** **(.031)** **[.006]**	**.001** **(.004)** **[.000]**	.916 (.674) [.529]					
SAN4	**.349** (0.999) **[.092]**	**.039** (.454) **[.011]**	**.003** **(.019)** **[.001]**	.302 (.245) [.699]	.699 (.366) [0.999]				
SCH4	**.015** **(.019)** **[.031]**	.134 (.134) **[.092]**	.925 (0.999) [.758]	**.005** **(.014)** **[.002]**	**.005** **(.007)** **[.005]**	**.016** **(.025)** **[.006]**			
ANC2	.103 (.828) [.128]	**.008** **(.030)** **[.019]**	**.000** **(.002)** **[.000]**	.311 (.562) [.426]	.515 (.612) [.612]	.793 (.599) [.726]	**.003** **(.005)** **[.007]**		
AAN2	.326 (.564) [.248]	.525 (.453) [.419]	**.001** **(.004)** **[.000]**	**.004** **(.037)** **[.001]**	**.003** **(.064)** **[.003]**	**.039** (0.999) **[.011]**	**.025** **(.011)** **[.019]**	**.004** (.211) **[.017]**	
ACH2	**.001** **(.006)** **[.001]**	**.074** (.225) **[.065]**	.564 (.817) [.231]	**.000** **(.009)** **[.000]**	**.000** **(.002)** **[.000]**	**.002** **(.019)** **[.001]**	.708 (.454) [.638]	**.000** **(.002)** **[.000]**	**.000** **(.008)** **[.000]**

SNC2 – Symmetric, No Communication, Duopoly

SNC3 – Symmetric, No Communication, Triopoly

SAN2 – Symmetric, Price Announcement, Duopoly

SAN3 – Symmetric, Price Announcement, Triopoly

SCH2 – Symmetric, Chat, Duopoly

SCH4 - Symmetric, Chat, Quadropoly

ANC2 – Asymmetric, No Communication, Duopoly

AAN2 – Asymmetric, Price Announcement, Duopoly

ACH2 – Asymmetric, Chat, Duopoly

<u>Table 5.5: Same (Coordination) Measure - MWW Tests</u>

p-values for the test that the number of periods with firms setting the same price is the same across two treatments, for periods 1-40 (1-20) [21-40]

	SNC2	SAN2	SCH2	SNC3	SAN3	SAN4	SCH4	ANC2	AAN2
SAN2	.269 (.883) [.128]								
SCH2	**.000** **(.002)** **[.000]**	**.008** **(.020)** **[.003]**							
SNC3	.877 (.726) [.877]	.131 (.459) [.141]	**.001** **(.004)** **[.000]**						
SAN3	**.015** **(.021)** [.239]	**.005** **(.017)** **[.016]**	**.000** **(.001)** **[.000]**	.289 (.146) [.315]					
SAN4	.239 **(.005)** [.887]	**.048** **(.002)** [.219]	**.002** **(.001)** **[.001]**	.745 **(.043)** [.897]	.744 (.161) [.512]				
SCH4	**.024** **(.021)** **[.021]**	.146 (.144) [.128]	.672 (.851) [.372]	**.033** **(.027)** **[.051]**	**.033** **(.022)** **[.027]**	**.036** **(.020)** **[.035]**			
ANC2	.681 (.847) [.783]	.199 (.869) **[.074]**	**.000** **(.002)** **[.000]**	.772 (.532) [.799]	**.035** **(.001)** [.306]	.252 **(.001)** [.894]	**.022** **(.030)** **[.017]**		
AAN2	.663 (.657) [.862]	.111 (.929) **[.037]**	**.000** **(.002)** **[.000]**	.969 (.576) [.641]	**.040** **(.001)** [.508]	.451 **(.001)** [.814]	**.024** **(.021)** **[.019]**	.891 (.843) [.848]	
ACH2	**.040** **(.071)** **[.022]**	.370 (.210) [.352]	**.053** (.118) [.013]	**.053** **(.074)** **[.095]**	**.011** **(.003)** **[.013]**	**.024** **(.001)** **[.042]**	.301 (.324) [.252]	**.041** **(.074)** **[.016]**	**.032** **(.069)** **[.017]**

Table 5.6: Duration (Coordination) Measure - MWW Tests

p-values for the test that the maximum number of consecutive periods for which firms set the same price is the same across two treatments, for periods 1-40 (1-20) [21-40]

	SNC2	SAN2	SCH2	SNC3	SAN3	SAN4	SCH4	ANC2	AAN2
SAN2	.170								
	(.344)								
	[.155]								
SCH2	**.000**	**.004**							
	(.002)	**(.016)**							
	[.000]	**[.002]**							
SNC3	.936	.269	**.001**						
	(.870)	(.342)	**(.005)**						
	[.968]	[.182]	**[.000]**						
SAN3	.408	**.089**	**.000**	.703					
	(.024)	**(.008)**	**(.001)**	(.189)					
	[.775]	[.123]	**[.000]**	[.745]					
SAN4	.626	.142	**.001**	.743	.895				
	(.010)	**(.004)**	**(.001)**	**(.073)**	(.298)				
	[.922]	[.181]	**[.001]**	[.895]	[.947]				
SCH4	**.024**	.157	.481	**.044**	**.031**	**.036**			
	(.019)	**(.074)**	(.814)	**(.027)**	**(.019)**	**(.020)**			
	[.024]	[.165]	[.343]	**[.042]**	**[.026]**	**[.035]**			
ANC2	.637	.113	**.000**	.849	.669	.749	**.025**		
	(.852)	(.326)	**(.001)**	(.747)	**(.011)**	**(.003)**	**(.018)**		
	[.622]	**[.056]**	**[.000]**	[.701]	[.970]	[.892]	**[.016]**		
AAN2	.879	.171	**.000**	1.000	.467	.773	**.023**	.602	
	(.446)	(.150)	**(.001)**	(.964)	**(.019)**	**(.004)**	**(.016)**	(.466)	
	[.928]	[.115]	**[.000]**	[.905]	[.781]	[.886]	**[.018]**	[.691]	
ACH2	**.038**	.334	**.026**	**.078**	**.023**	**.030**	.259	**.025**	**.025**
	(.021)	(.177)	(.200)	**(.071)**	**(.001)**	**(.002)**	(.347)	**(.013)**	**(.005)**
	[.025]	[.428]	**[.008]**	**[.066]**	**[.026]**	**[.043]**	[.275]	**[.010]**	**[.018]**

Table 5.7: Duopoly Market Price - No communication vs. Price Announcements

	Regression 1	Regression 2	Regression 3
Periods:	1-20	21-40	1-40
Constant	64.00***	69.47***	66.74***
	(3.05)	(1.03)	(1.98)
DAnn	8.93***	10.00***	9.46***
	(2.86)	(1.66)	(1.92)
DAsym	-4.04***	-6.46***	-5.25***
	(1.06)	(0.78)	(0.75)
DAnn x DAsym	-4.48***	-2.36*	-3.42***
	(1.52)	(1.35)	(1.07)
N	980	980	1960

*p -value<.10, ** p-value<.05, and *** p-value<.01.
Driscoll-Kraay standard errors in parentheses.

Table 5.8: Duopoly Market Price - Price Announcements vs. Chat

	Regression 1	Regression 2	Regression 3
Periods:	1-20	21-40	1-40
Constant	72.93***	79.47***	76.2***
	(1.48)	(0.71)	(1.27)
DChat	10.38*	19.43***	14.97***
	(5.59)	(0.64)	(3.32)
DAsym	-8.51***	-8.83***	-8.67***
	(1.25)	(1.54)	(1.06)
DChat x DAsym	7.85***	9.28***	8.53***
	(2.16)	(1.59)	(1.37)
N	953	959	1912

*p -value<.10, ** p-value<.05, and *** p-value<.01.
Driscoll-Kraay standard errors in parentheses.

Figure 5.1: Market Price Histogram (No Communication)

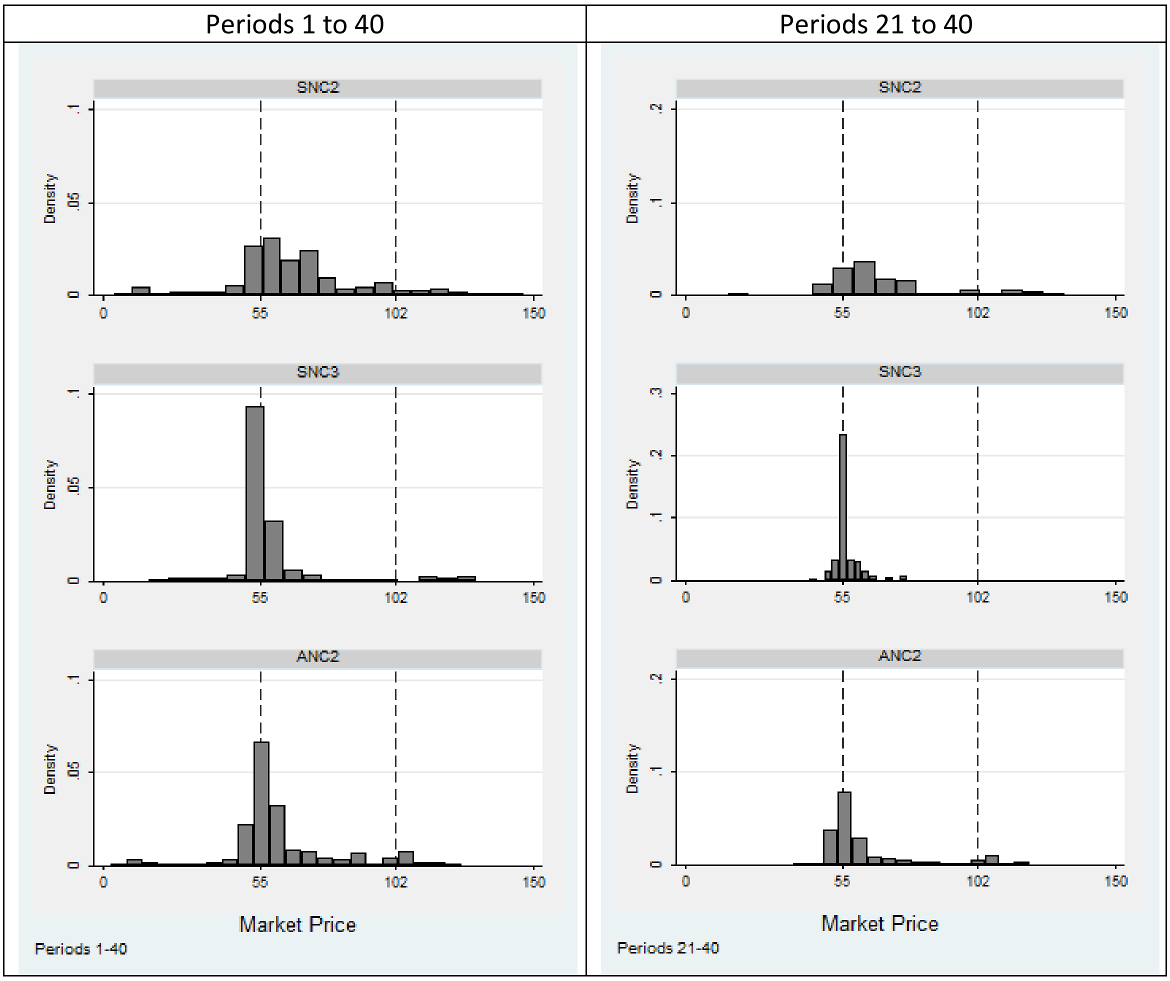


Figure 5.2: Mean and Standard Deviation of Profit - Asymmetric Duopoly

(No Communication and Price Announcement Treatments)

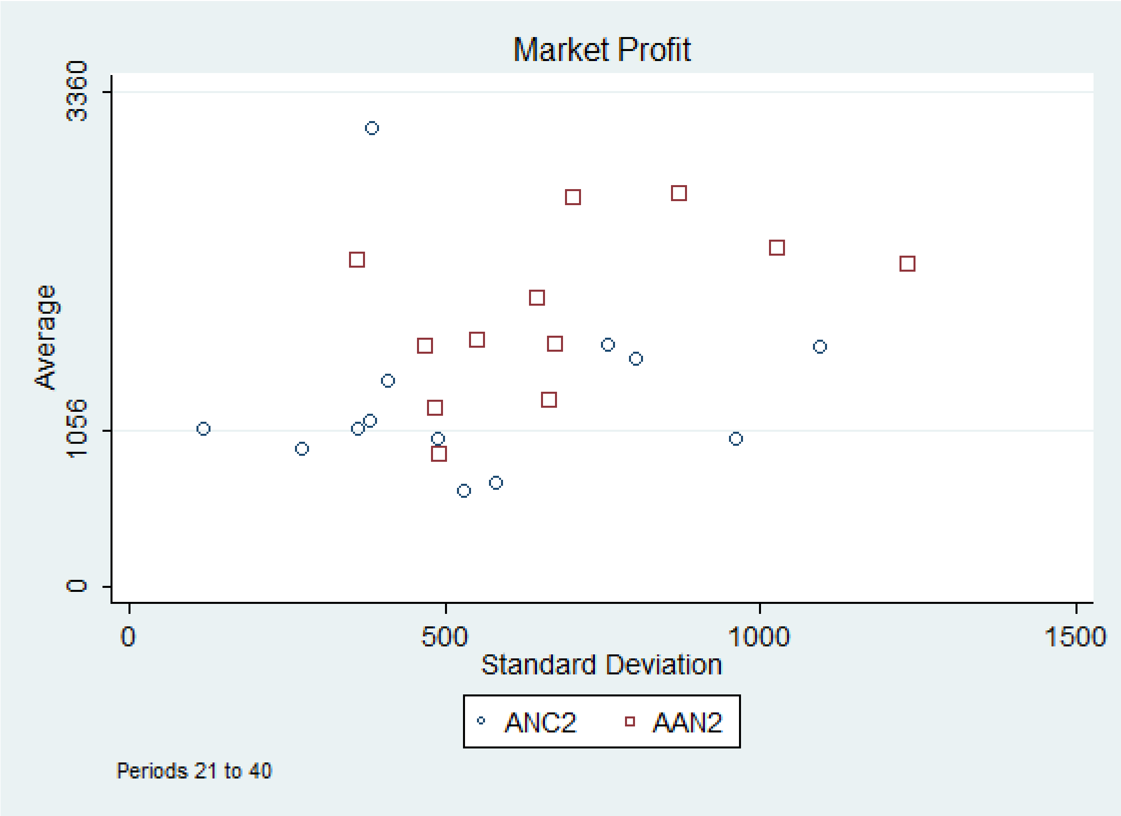


Figure 5.3: Mean and Standard Deviation of Profit - Symmetric Duopoly

(No Communication and Price Announcement Treatments)

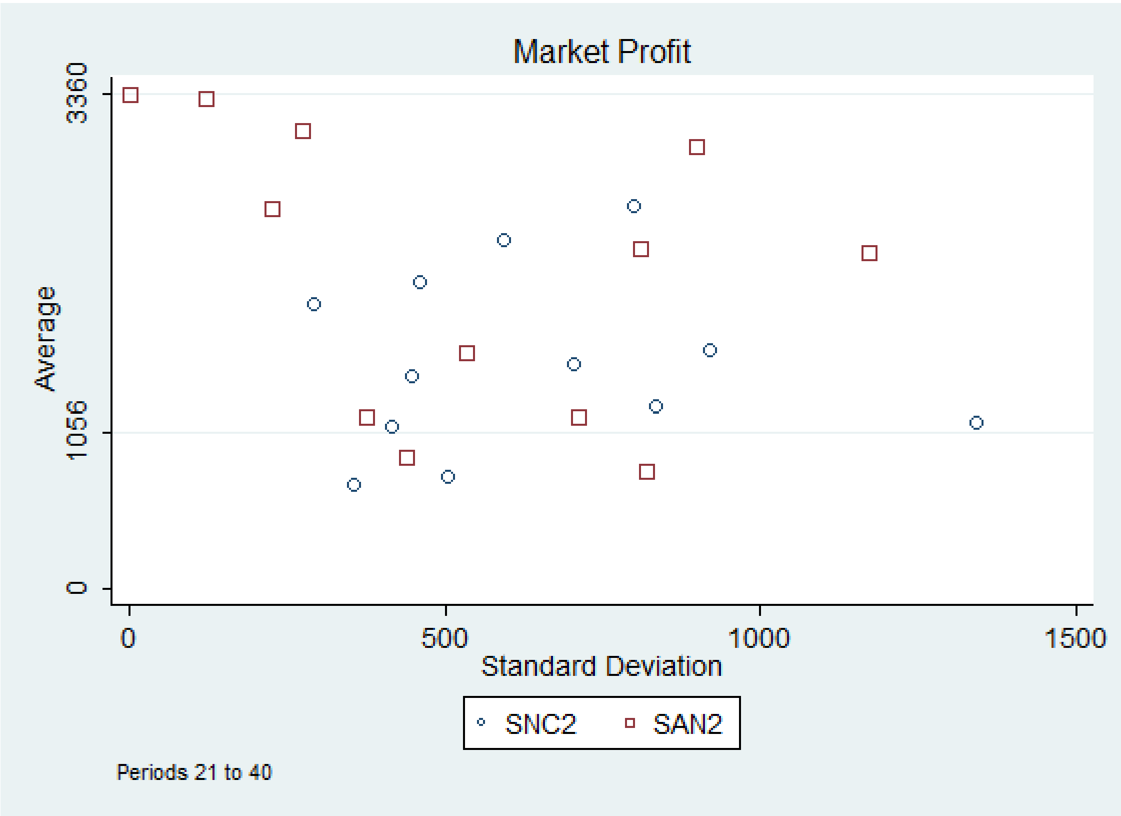


Figure 5.4: Price Series for Symmetric Duopoly with Price Announcements

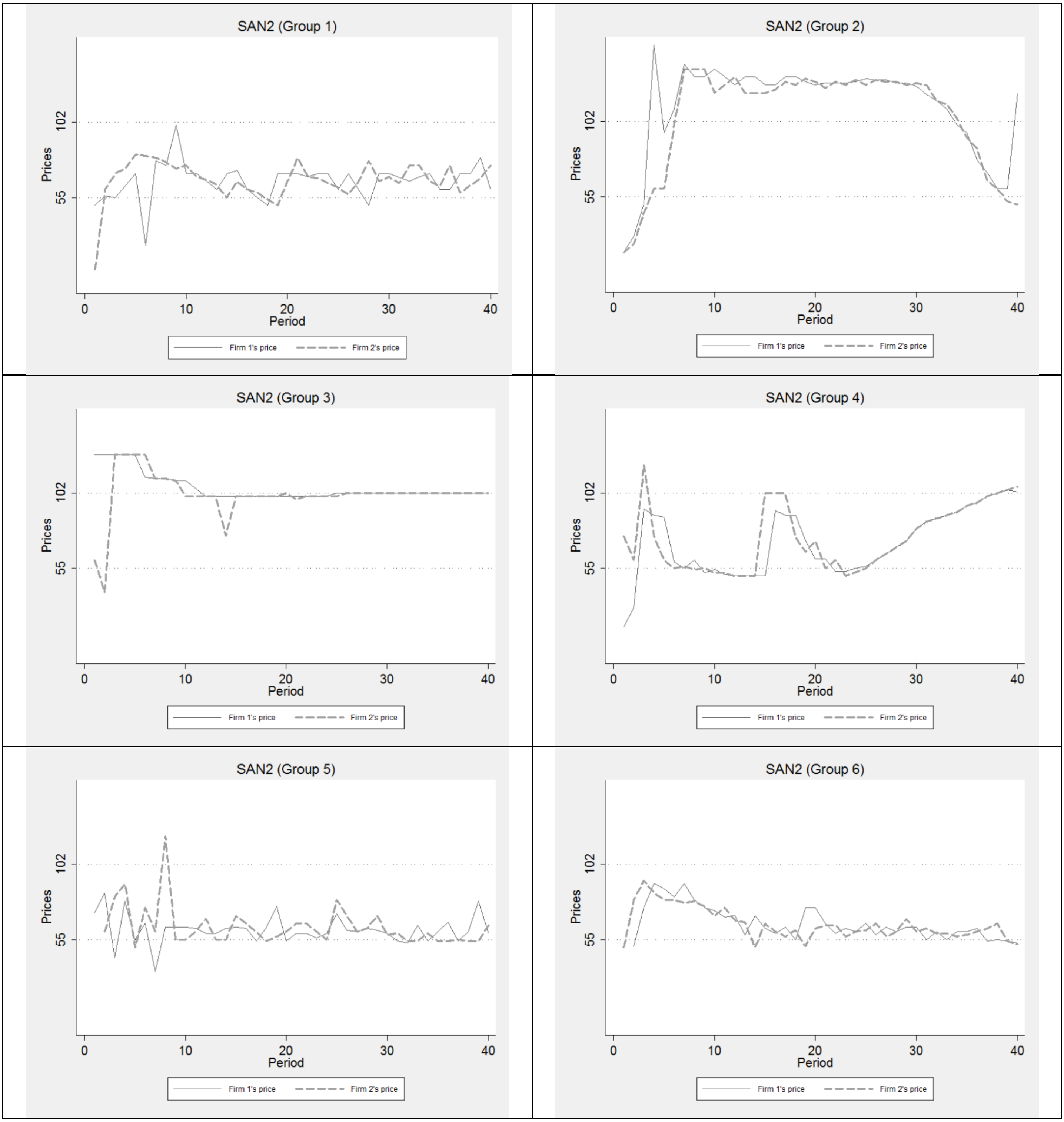


Figure 5.4: Price Series for Symmetric Duopoly with Price Announcements (continued)

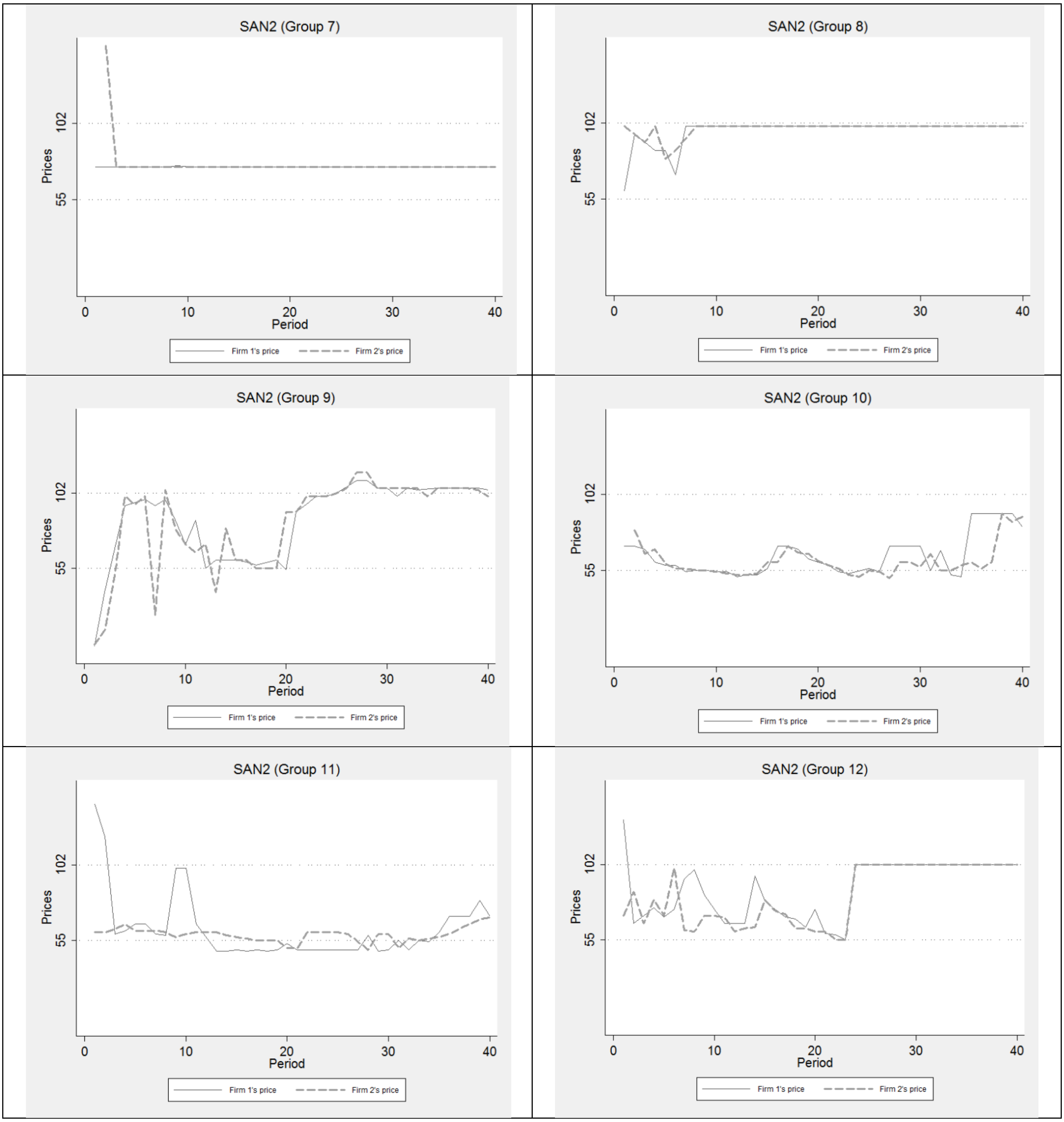


Figure 5.5: Market Price Histograms

Periods 1 to 40

Periods 21 to 40

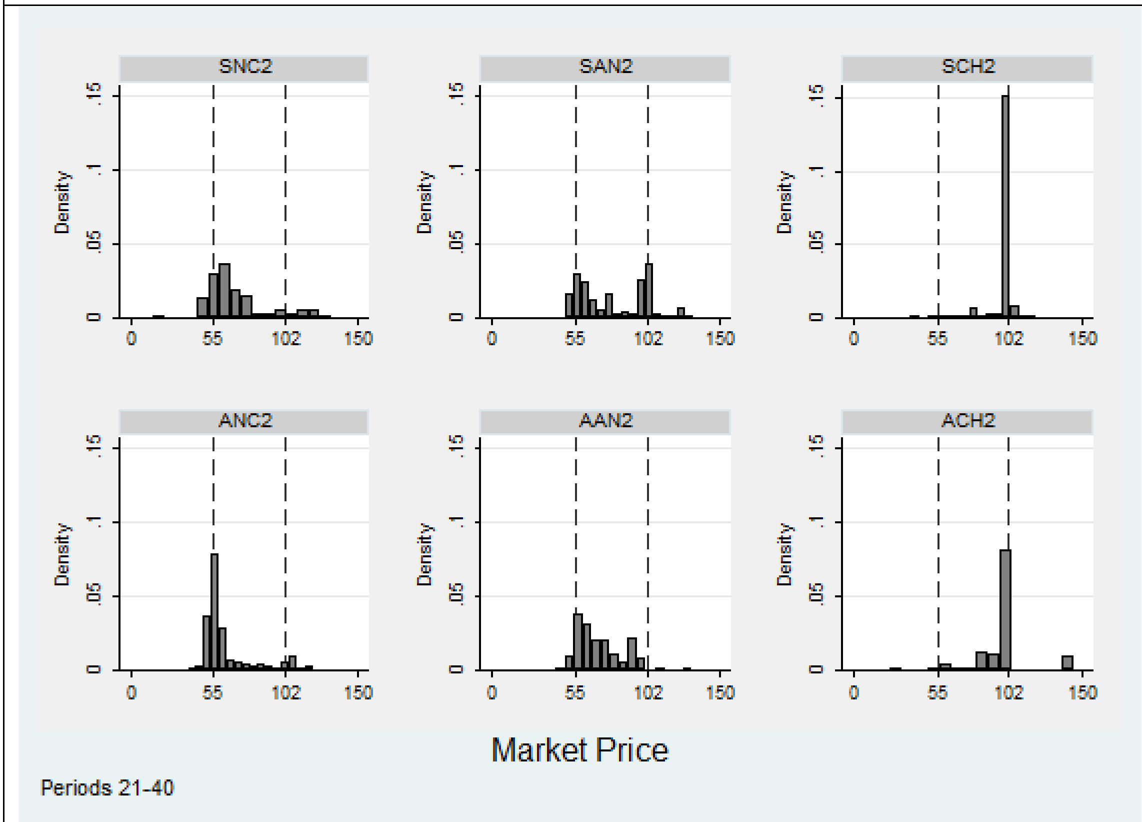


Figure 5.6: Average Market Price and Coordination (Same)

Price Announcement: Symmetric and Asymmetric Duopolies

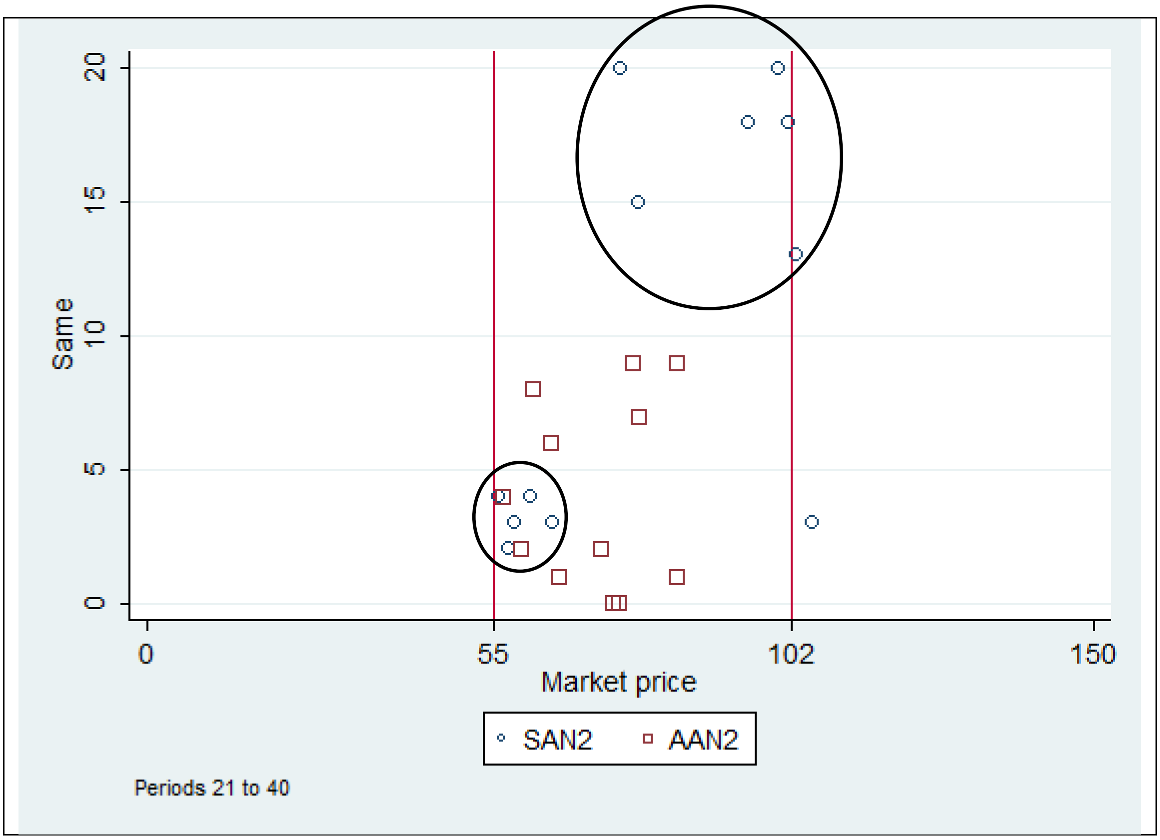
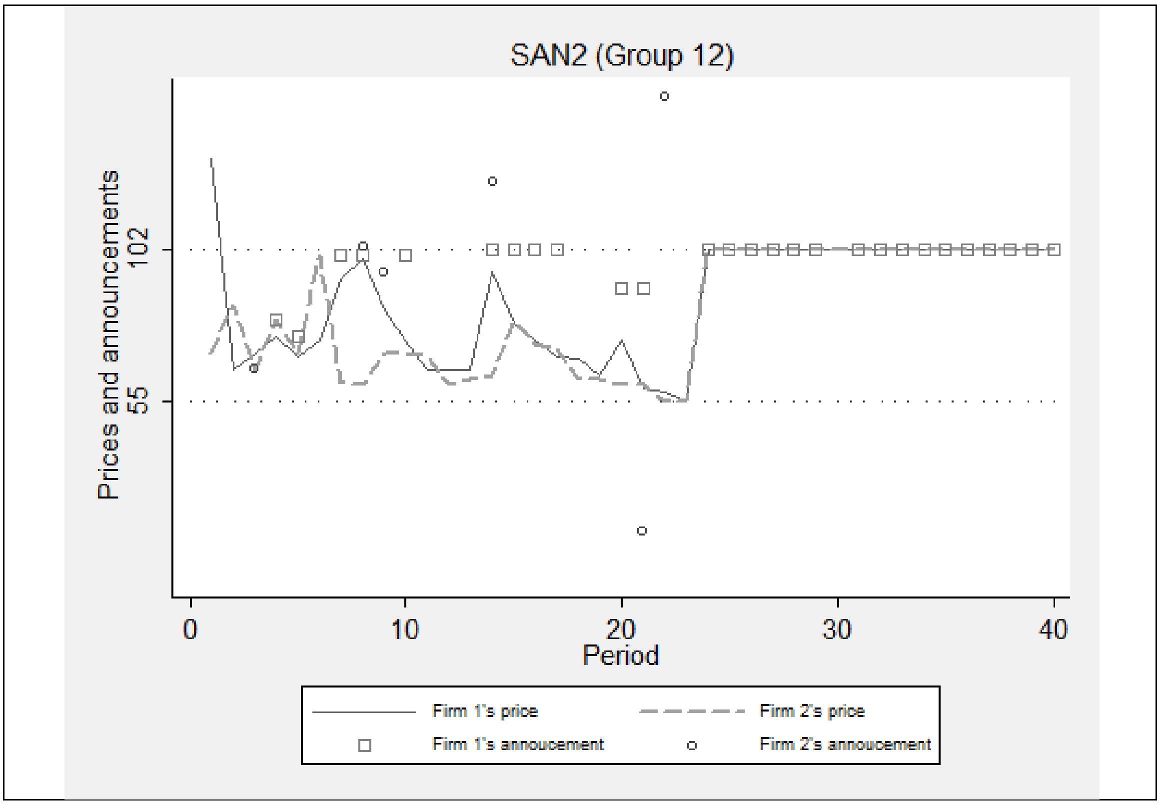


Figure 5.7: Some Price and Announcement Series for Duopoly



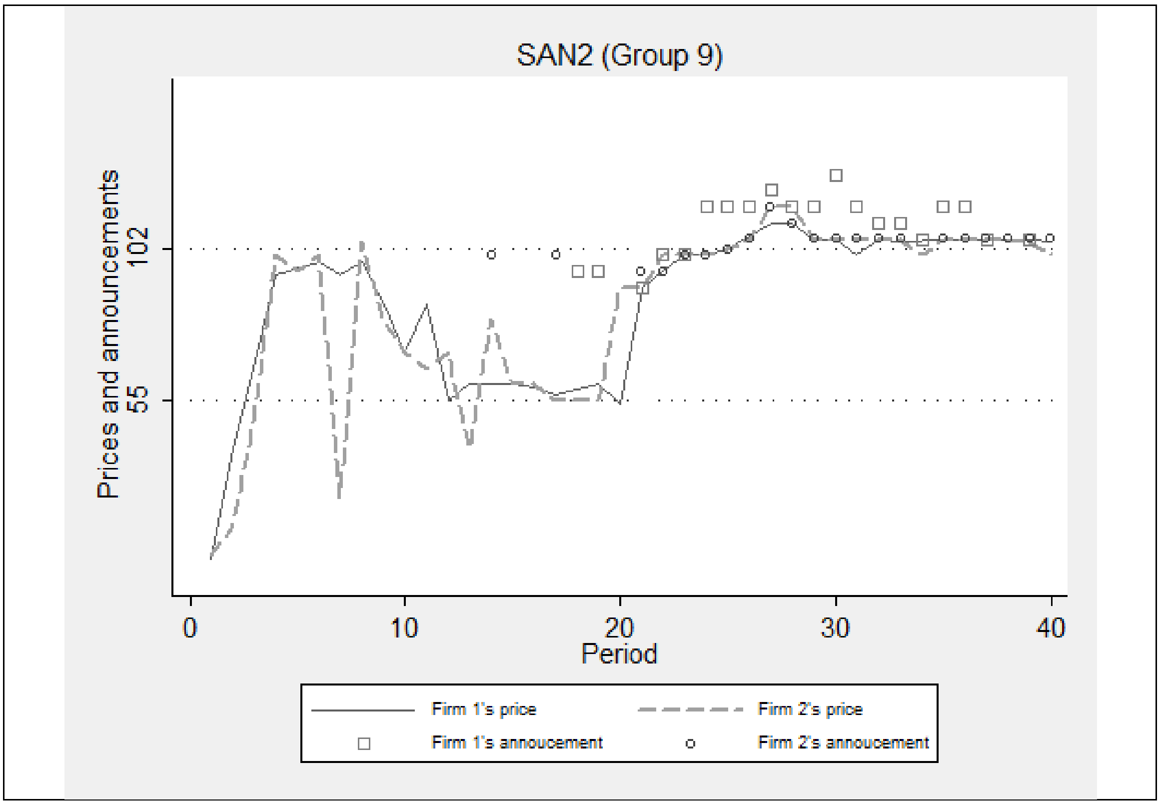
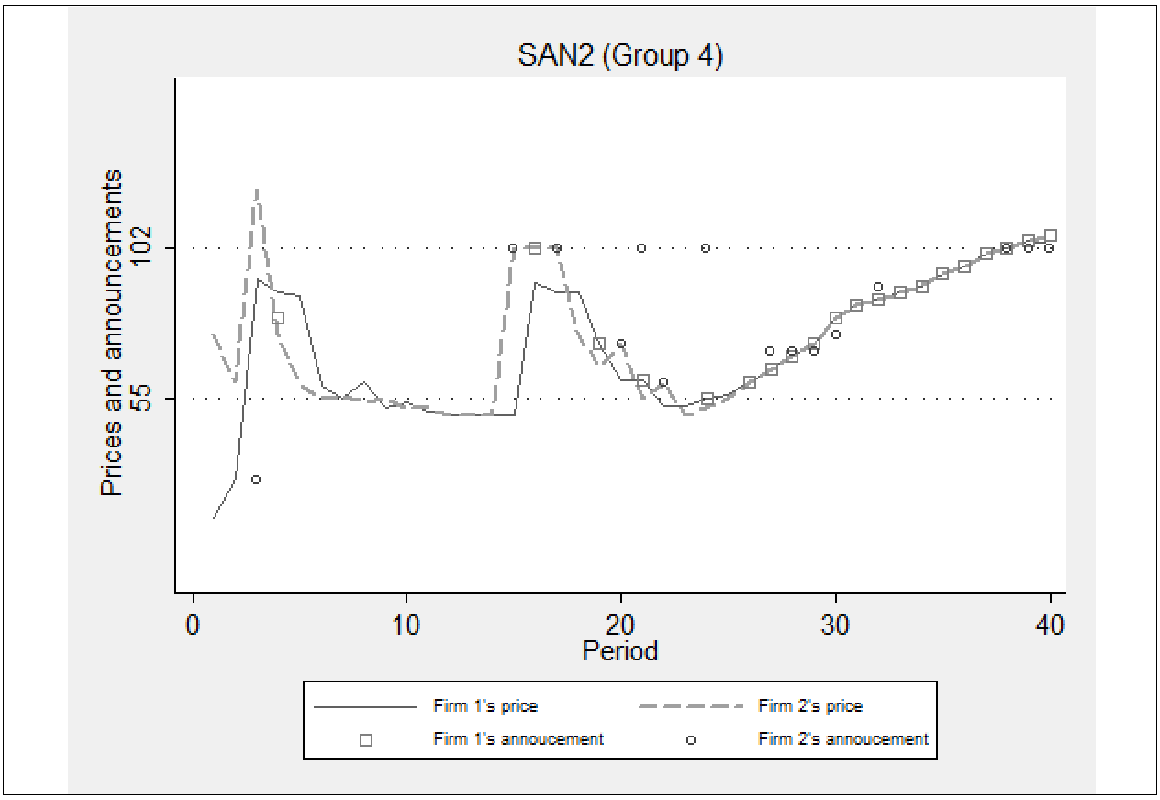


Figure 5.7: Some Price and Announcement Series for Duopoly (continued)



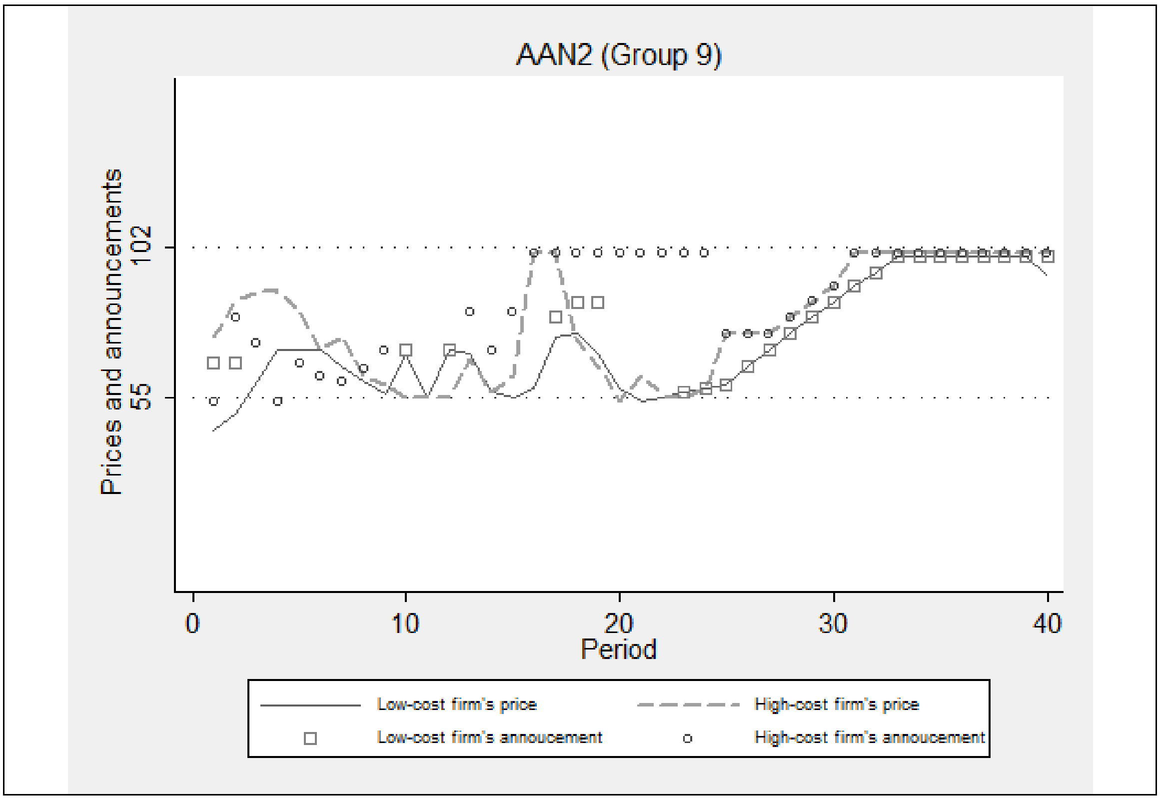


Figure 5.8: Asymmetric Duopoly with Chat:

Collusive Outcome with Different Prices and Quantities