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Optimal collusion with private information

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We analyze collusion in an infinitely repeated Bertrand game, where prices are publicly observed and each firm receives a privately observed, i.i.d. cost shock in each period. Productive efficiency is possible only if high-cost firms relinquish market share. In the most profitable collusive schemes, firms implement productive efficiency, and high-cost firms are favored with higher expected market share in future periods. If types are discrete, there exists a discount factor strictly less than one above which first-best profits can be attained using history-dependent reallocation of market share between equally efficient firms. We also analyze the role of communication and side-payments.

1. Introduction

■ Antitrust law and enforcement vary widely over time, across countries and between industries. For example, as Stocking and Watkins (1946) detail, U.S. antitrust policy was relatively permissive in the first part of the 20th century, and industry associations in which firms shared information and records, allocated market shares and fixed prices, and exchanged side-payments were commonly observed.¹ The recent U.S. policy, by contrast, is considerably more antagonistic. Started in 1993, the U.S. Antitrust Division's Revised Amnesty Program provides incentives for firms to self-report collusive conduct, and this has led to the prosecution of a number of "hard-core" cartels, often operating in international markets and characterized by "price fixing, bid-rigging,

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¹ Sophisticated cartels of this kind were found in the steel, aluminum, incandescent electric lamp, sugar (Genesove and Mullin (1999, 2001)), and shipping (Deltas, Serfes, and Sicotte (1999)) industries.

and market- and customer-allocation agreements” (Griffin (2000)).² Levinsohn (1996) describes the significant variation in antitrust law and enforcement that is found across countries. And significant variation also occurs within countries and between industries; for example, in many countries (including the United States), the legal stance toward cartels is more tolerant in export industries.

The different manifestations of antitrust policies naturally affect the organizational structure of collusive activity. If the antitrust environment is permissive, then firms may set up a formal organization, in which they set prices and allocate sales, communicate about current circumstances, keep records of past experiences, and exchange side-payments. On the other hand, when the antitrust policy is antagonistic, the organization of collusive activity may be more secretive and less formal. Firms may avoid direct meetings altogether. Or they may communicate surreptitiously, in “smoke-filled rooms.” And firms might also refrain from direct side-payments, which leave a “paper trail.”

The implications of antitrust policies for collusive conduct are more subtle. In its perfected form, collusion enables a group of firms to conduct themselves as would a single firm: prices are set and market shares are allocated in a manner that maximizes joint profits. In practice, however, the road to perfection contains obstacles. One important obstacle is impatience: high prices can be enjoyed only if firms are sufficiently patient that they resist the temptation to undercut. A further obstacle is that firms naturally possess private information as to their respective circumstances. At a given time, some firms may have high costs while others enjoy low costs, due to variations in local conditions, labor relations, inventory management, and so on. The market-share allocation that achieves productive efficiency then may be feasible only if firms communicate cost information, and truthful communication may be possible only if higher-cost firms are assured of side-payments or some future benefit. In broad terms, antitrust policy affects collusive conduct by influencing the “instruments” that firms may use when encountering such obstacles.

This perspective suggests three questions concerning the optimal collusion of impatient firms. First, how does the presence of private information among firms affect collusive profits? In particular, is it possible for privately informed firms to construct a self-enforcing collusive scheme in which they act as would a single firm and thereby achieve first-best profits? Second, how does the presence of private information affect collusive conduct? In particular, when privately informed firms collude, what are the implications for market prices and shares? Finally, how do antitrust policies affect collusive profits and conduct? In particular, what are the consequences of restrictions on communication and side-payments for collusive profits and conduct?

These are basic questions whose resolution might offer practical insights. For example, a theory that answers these questions might provide a lens through which to interpret observed (historic or current) collusive conduct in terms of the surrounding antitrust environment. And it also might provide a framework with which to better predict the consequences of a change in antitrust policies for collusive conduct. Nevertheless, in the literature on self-enforcing collusion, these questions are as yet unanswered. Indeed, as we explain below, even the most basic issues—e.g., how might communication among firms facilitate collusion?—are poorly understood.

Motivated by these considerations, we develop here a theory of optimal collusion among privately informed and impatient firms, and we examine how the level and conduct of collusion varies with the antitrust environment. The modelling framework is easily described. We consider an infinitely repeated Bertrand game, in which prices are publicly observed and each firm receives a privately observed, i.i.d. cost shock in each period. We assume further that demand is inelastic, there are two firms, and each firm’s unit-cost realization is either “high” or “low.” These assumptions simplify our presentation. Our main findings would emerge as well in a model with finite numbers of firms and cost types.

To understand our findings, it is helpful to recall the theory of the legalized cartel, in which side-payments can be enforced by binding contracts. As Roberts (1985), Cramton and Palfrey

² Prominent examples include the lysine, vitamin, graphite electrode, and citric-acid cartels.

(1990), and Kihlstrom and Vives (1992) have shown, the central tradeoffs are then well captured in a static mechanism design model. An important consideration for the cartel is that production is allocated efficiently over cartel members, but when firms are privately informed as to their respective costs of production, this requires communication and transfers. Communication enables firms to establish before production the identity of the lowest-cost firm, while transfers (from this firm to the other cartel members) ensure that firms have the incentive to communicate truthfully.

Outside of a legalized cartel, however, the collusive relationship must be self-enforcing, and antitrust policies may restrict the manner in which firms interact. Thus, we characterize optimal collusive conduct among privately informed firms that interact repeatedly in environments that are distinguished on the basis of restrictions on the instruments available to the firms. In our base model, we make the following assumptions: (i) firms can communicate with regard to current cost conditions, and (ii) firms cannot make side-payments (use “bribes”). We show that optimal collusion involves extensive use of “market-share favors,” whereby individual firms are treated asymmetrically as a reward or punishment for past behavior. After studying this model in some detail, we then analyze the way in which optimal collusion changes as each of the two assumptions is relaxed.

Our modelling approach is to recast our repeated private-information game as a static mechanism, similar to that analyzed in the legalized-cartel literature. To this end, we follow Abreu, Pearce, and Stacchetti (1990) and Fudenberg, Levine, and Maskin (1994) and observe that perfect public equilibrium (PPE) payoffs for the firms can be factored into two components: current-period payoffs and (discounted) continuation values. This suggests that PPE continuation values can play a role like that of side-payments in the legalized-cartel literature, although transfers are now drawn from a restricted set (namely, the set of PPE continuation values). In this way, we argue that firms prohibited from making side-payments can still implement a self-enforcing scheme, in which communication has potential value, where in place of a side-payment from one firm to another, the collusive mechanism specifies that one firm is favored over another in future play.³

While this analogy is instructive, the two approaches have important differences. Suppose that firm 1 draws a low-cost type while firm 2 draws a high-cost type. In the legalized-cartel model, firm 2 would reveal its cost type and not produce, anticipating that it would then receive a transfer. In our base model, firm 2 would likewise report its high-cost type, expecting to receive its “transfer” in the form of a more favorable continuation value. In turn, this value can be delivered, if firm 2 receives future market-share favors, corresponding to future cost states in which firm 2’s market share is increased. But here key differences appear. First, if the required transfer is too large, there may not exist a PPE that yields the necessary continuation value for firm 2. Second, even if the corresponding PPE value does exist, when the transfer is achieved through an adjustment in future play, the transfer may involve an inefficiency: the strategies that achieve this transfer may involve firm 2 enjoying positive market share in some future state in which it alone has high costs.

This second difference directs attention to an interesting feature of our base model. Future play is burdened with two roles: in a given future period, production must simultaneously (i) serve a transfer role, rewarding firms for past revelations of high costs, and (ii) serve an efficiency role, allocating production as efficiently as possible in the future period itself. These roles may conflict. We show, however, that no conflict emerges, so long as firms are sufficiently patient. In particular, our first general finding is as follows: For the base model, and for a wide range of parameter values, there exists a critical discount factor that is strictly less than one and above which the cartel can achieve first-best profits in every period. Intuitively, firms disentangle the two roles for future play, if they limit transfer activities to future “ties,” in which both firms are equally efficient. If the discount factor is sufficiently high, the transfers so achieved are sufficient to ensure truth-telling.

³ An interesting case study is offered by McMillan (1991), who describes collusion among firms in the Japanese construction industry. Consistent with our formal analysis, McMillan reports that firms use future market-share favors as a means of providing incentive for honest communication so that greater productive efficiency can be achieved.

This finding is of broader interest. It generalizes a related finding by Fudenberg, Levine, and Maskin (1994), who consider a family of repeated private-information games and show that first-best payoffs can be reached in the limit as the discount factor goes to unity. By contrast, making use of our assumption of a finite number of types, we show that first-best payoffs can be achieved exactly, by firms that are not infinitely patient, and we offer an explicit construction of the efficient PPE. To our knowledge, this is the first construction of a first-best PPE in a repeated private-information game, when players are impatient.⁴

In addition, this finding raises an important qualification for a common inference that is drawn in empirical studies of market-share stability. In many studies, such as those offered by Caves and Porter (1978), Eckard (1987), and Telser (1964), an inference of greater collusive (competitive) conduct accompanies an observation of greater market-share stability (instability). Our analysis suggests that this inference may be invalid when colluding firms have private information. Indeed, when firms achieve first-best profits, a firm's future market share tends to be negatively correlated with its current market share.⁵

We consider next the possibility that firms are less patient. When the firms attempt to reward firm 2's honest report of high costs with favored treatment in future ties, a problem now arises: firm 1 may be unwilling to give up enough market share in the event of ties. More generally, if the disadvantaged firm's assigned market share is too low in a particular cost state, then it may undercut the collusive price and capture the entire market. When firms are less patient, therefore, productive efficiency today necessitates some inefficiency in the future. The firms, however, can choose the form that this inefficiency takes. For example, the collusive scheme may call for pricing inefficiency: the firms may lower prices when market-share favors are exchanged, to diminish the gain from undercutting. Or the scheme may require productive inefficiency: the disadvantaged firm may provide some of the transfer by giving up some market share in the state in which it is most efficient. Finally, in view of these future inefficiencies, less patient firms may decide to implement less productive efficiency today (e.g., firm 2 may have positive market share today, even when it alone has high costs), thus reducing the future transfer burden. Among these possibilities, we argue that pricing inefficiency is often the least appealing. Our second general finding is the following: when firms are less patient, for a wide range of parameter values, they give up productive efficiency (today or in the future) before lowering prices.

We next evaluate our two assumptions about the antitrust environment. We begin with the role of communication. Our third general finding is that communication introduces potential benefits and costs to colluding firms. The benefit of communication is that it allows firms to smoothly divide the market on a state-contingent basis. Without communication, firms can only allocate market share with prices, and this decentralized approach limits the range of market-sharing plans available. The cost of communication in our Bertrand model is subtle. Intuitively, when firms do not communicate, a given firm does not know its opponent's cost type when it chooses its price. Accordingly, if the opponent's price varies with cost, then the firm also does not know the exact price that its opponent will choose. This in turn diminishes a firm's incentive to undercut its prescribed price. Put differently, when firms communicate, the temptation to undercut may be exacerbated. Building off this general cost-benefit tradeoff, we establish a number of specific results. We show that in the absence of communication, there again exists a discount factor strictly less than one above which first-best profits still can be achieved. For firms of moderate patience, however, restrictions on communication may diminish collusive profits. In addition, firms may choose not to communicate in periods with significant market-share favors, as the absence of communication then serves to diminish the disadvantaged firm's incentive to undercut. More generally, impatient firms may choose to avoid communication in some but not all periods.

⁴ In related contexts, Athey, Bagwell, and Sanchirico (1998) and Aoyagi (1998) characterize particular asymmetric PPE, and Athey, Bagwell, and Sanchirico characterize optimal symmetric PPE. The present article, by contrast, characterizes optimal PPE.

⁵ Such negative correlation may have characterized the citric-acid cartel (*Business Week*, July 27, 1998, p. 50), in which (in a creative implementation of market-share favors) any firm that sold beyond its budget in a given year purchased from "under-budget" firms in the following year.

To our knowledge, we are the first to identify benefits and costs from communication for colluding firms.⁶ Communication offers no benefit in the standard (complete-information, perfect-monitoring) or public-monitoring (e.g., Green and Porter (1984)) collusion models. A potential benefit from communication is suggested in the emerging private-monitoring literature, wherein firms observe private and imperfect signals of past play. As Compte (1998) and Kandori and Matsushima (1998) explain, communication can then generate a public history on the basis of which subsequent collusion may be coordinated. But, as these authors acknowledge, they are unable to characterize optimal collusive conduct when communication is absent, and so they cannot determine when, or even whether, communication benefits colluding firms. In comparison, we assume that private information concerns current circumstances and past play is publicly observable. A public history is thus generated whether firms communicate or not, and we may examine both cases.

Finally, we consider antitrust environments in which firms may entertain the exchange of bribes, though these must be self-enforcing and may incur inefficiencies, as through a risk of detection. Firms can potentially substitute current-period bribes for future market-share favors. In practice, bribes may be direct, with one firm paying other firms for the right to produce, or they may be associated with sophisticated and indirect processes, such as “knockout auctions,”⁷ “common funds,”⁸ or other schemes.⁹ Our fourth general finding is as follows: When detection by antitrust officials is a concern, so that bribes are not fully efficient, bribes never fully replace future market-share favors as a means of transferring utility. Put differently, unless bribes are perfectly efficient, firms strictly prefer to keep track of history, using nonstationary equilibria that specify a future advantage to firms that admit high costs.

Our findings suggest that antitrust policy can have perverse consequences. A recurring theme is that successfully colluding firms tolerate productive inefficiency before lowering prices. An antagonistic antitrust policy, which limits firms’ ability to communicate or exchange bribes, may thus limit productive efficiency without affecting prices. Such policies increase consumer welfare, though, if firms are sufficiently impatient that removing these instruments destroys their ability to collude at high prices. Overall, our findings provide some formal support for those (Bork (1965, 1966) and Sproul (1993)) who are attentive to the efficiency gains that restraints of trade may afford.

2. The model

■ We focus on a stylized model with two firms and two cost types, where firms 1 and 2 produce perfect substitutes and sell to a unit mass of customers with valuation r . Each firm has possible costs θ_L and θ_H , where $r > \theta_H > \theta_L$, and privately observes its realized costs prior to any pricing decisions. Thus, the state space in any period is denoted $\Omega = \{L, H\} \times \{L, H\}$, and we index these states as $(j, k) \in \Omega$, where the costs of firms 1 and 2 are given by $\theta^1 = \theta_j$ and $\theta^2 = \theta_k$ in state (j, k) . The probability of the cost draw $j \in \{L, H\}$ in any period is denoted $\Pr(\theta^i = \theta_j) = \eta_j$, where $\eta_j > 0$ and $\eta_L + \eta_H = 1$; this is independent over time and across firms. To simplify the exposition of a few of the results, we assume $\eta_L > 1/2$.

⁶ A role for communication also arises in Shapiro (1986) and Vives (1984), where firms can commit to share information before the play of a static oligopoly game. As Ziv (1993) shows, without this commitment, truth-telling incentives can be provided if firms exchange transfers. See Kühn and Vives (1994) for a survey.

⁷ Colluding suppliers may hold a “knockout” auction (among themselves) that determines the firm that is to win the procurement contract, and then rig the actual bids to ensure that this firm wins with a low bid (see, e.g., McAfee and McMillan (1992)).

⁸ A firm that exceeds its production quota may contribute to a “common fund,” while a firm that falls below its quota is permitted to withdraw from the fund. Common-fund arrangements appeared in the steel, aluminum, and incandescent electric lamp cartels of the early 1900’s (Stocking and Watkins, 1946). A similar arrangement was also found in the recent Garment Box case (FTC Docket 4777).

⁹ For example, an “over-budget” firm may compensate an “under-budget” firm by purchasing the latter’s output at the end of the budget period. Griffin (2000) reports that “compensation schemes” are common among international cartels (e.g., the lysine cartel).

The Nash equilibrium to the one-shot pricing game (without communication or transfer possibilities) is a symmetric mixed-strategy equilibrium.¹⁰ For each firm, the high type charges price equal to cost ($p = \theta_H$), while the low type mixes, receiving profit equal to $(\theta_H - \theta_L)\eta_H$, the expected profit from just undercutting the price charged by the high-cost type. Thus, *ex ante* expected profit to each firm in this equilibrium is equal to $\pi^{NE} \equiv (\theta_H - \theta_L)\eta_H\eta_L$. This payoff can be contrasted with the first-best level of profit to each firm, $\pi^{FB} \equiv (1/2)(r - E[\min(\theta^1, \theta^2)])$.

In our basic repeated-game model, firms can meet and communicate their types but cannot make side-payments. Formally, the firms play the following stage game in each period: (i) each firm i observes its type θ^i , (ii) each firm i makes an announcement $a^i \in A \equiv \{L, H, N\}$, (iii) each firm i then selects a price p^i and makes a market-share proposal q^i , and (iv) for $\mathbf{p} \equiv (p^1, p^2)$ and $\mathbf{q} \equiv (q^1, q^2)$, market shares $m^i(\mathbf{p}, \mathbf{q})$ are allocated as follows: if $p^i > r$, then $m^i(\mathbf{p}, \mathbf{q}) = 0$; if $p^i < p^j \leq r$, then $m^i(\mathbf{p}, \mathbf{q}) = 1$; and if $p^i = p^j \leq r$, then $m^i(\mathbf{p}, \mathbf{q}) = 1/2$ if $a_i = N, a_j = N$, or $q^i + q^j \neq 1$, while otherwise $m^i(\mathbf{p}, \mathbf{q}) = q^i$.

We interpret this stage game as describing an environment in which firms meet, make announcements about their respective cost types, and then select prices and make market-share proposals. We allow each firm three possible announcements: a firm may announce that it has low (L) or high (H) costs, or it may choose to say nothing (N). We include the latter option because although we allow firms to meet and communicate, they are under no obligation to do so. Our formalization of market-share proposals permits firms to jointly determine their respective market shares when they set the same price. Since the market-share proposals follow the firms' announced cost positions, this formalization allows equally priced firms to allocate market share in a state-dependent fashion. But we do not permit both firms to produce positive quantities at different prices.¹¹ Beyond this restriction, the model grants firms considerable flexibility, and in principle they may mimic a centralized "mechanism" that gathers cost reports and determines prices and market shares. Our decentralized representation of interaction among firms, however, must incorporate further constraints that dissuade firms from deviations (e.g., undercutting the collusive price) that real-world firms might consider but that would not be possible under the assumption that a mechanism sets prices.

We now define firm strategies for the stage game. Letting $\Omega^i \equiv \{L, H\}$, the space of policies from which a firm might choose is given by

$$S^i = \{\alpha^i \mid \alpha^i : \Omega^i \rightarrow A\} \times \{\rho^i \mid \rho^i : \Omega^i \times A \rightarrow \mathfrak{R}\} \times \{\varphi^i \mid \varphi^i : \Omega^i \times A \rightarrow \mathfrak{R}\}.$$

A typical policy for firm i , given θ^i and firm j 's announcement a^j , is denoted $s^i(\theta^i, a^j) = (\alpha^i(\theta^i), \rho^i(\theta^i, a^j), \varphi^i(\theta^i, a^j))$, where α^i is the announcement function, ρ^i is the pricing function, and φ^i is the market-share proposal function. Further, letting $\theta = (\theta^1, \theta^2)$ and $\mathbf{a} = (a^1, a^2)$, we define the following vectors:

$$\begin{aligned} \alpha(\theta) &\equiv (\alpha^1(\theta^1), \alpha^2(\theta^2)); \\ \rho(\theta, \mathbf{a}) &\equiv (\rho^1(\theta^1, a^2), \rho^2(\theta^2, a^1)); \\ \varphi(\theta, \mathbf{a}) &\equiv (\varphi^1(\theta^1, a^2), \varphi^2(\theta^2, a^1)); \\ \mathbf{s}(\theta) &\equiv (s^1(\theta^1, \alpha^2(\theta^2)), s^2(\theta^2, \alpha^1(\theta^1))). \end{aligned}$$

A policy vector $\mathbf{s}(\theta)$ determines announcements as well as the price and market-share proposal responses to these announcements. A policy vector thus determines a path through the stage game,

¹⁰ We consider pure-strategy equilibria in the repeated game. This creates little tension, since we emphasize Pareto-optimal equilibria, and in the characterizations we highlight these are pure.

¹¹ We thus rule out the possibility that the firms divide the market (e.g., geographically) and charge different prices in each segment. While the stage game is somewhat ad hoc, it does offer a simple framework (e.g., all transactions occur at the same price, so a rationing rule is not needed) within which to allow that firms may communicate and allocate market share in a state-contingent fashion.

and we may write stage-game payoffs conditional on a realization of cost types as $\pi^i(\mathbf{s}(\theta), \theta^i)$, with expected stage-game payoffs then given as $\bar{\pi}^i(\mathbf{s}) \equiv E_\theta[\pi^i(\mathbf{s}(\theta), \theta^i)]$.

Consider now the repeated game. The firms meet each period to play the stage game described above, where each firm has the objective of maximizing its expected discounted stream of profit, given the common discount factor δ . Upon entering a period of play, a firm observes only the history of (i) its own cost draws and policy functions and (ii) realized announcements, prices, and market-share proposals. Thus, a firm does not observe rival types or rival policy functions. Following Fudenberg, Levine, and Maskin (1994), we restrict attention to those sequential equilibria in which firms condition only on the history of realized announcements, prices, and market-share proposals and not on their own private history of types and policy schedules. Such strategies are called *public strategies* and such sequential equilibria are called *perfect public equilibria (PPE)*.

Formally, let $h_t = \{\mathbf{a}_t, \mathbf{p}_t, \mathbf{q}_t\}$ be the history of realized announcements, prices, and market-share proposals up to date t . Let H_t be the set of potential histories at period t . A strategy for firm i in period t is denoted $\sigma_t^i : H_t \rightarrow S^i$. Let σ_t be a strategy profile in period t , and let σ represent a sequence of such strategy profiles, $t = 1, \dots, \infty$. Then, given a history h_t , the expected per-period payoff in period t for firm i is $\bar{\pi}^i(\sigma_t(h_t))$. Each strategy induces a probability distribution over play in each period, resulting in an expected payoff for firm i of $E[\sum_{t=1}^{\infty} \delta^{t-1} \bar{\pi}^i(\sigma_t(h_t))]$, where h_1 is the null history.

We assume that after every period, firms can observe the realization of some public randomization device and select continuation equilibria on this basis. This is a common assumption in the literature, and it convexifies the set of equilibrium continuation values.¹² We do not introduce explicit notation for the randomization process.

Following Abreu, Pearce, and Stacchetti (1986, 1990), we can now define an operator $T(V)$ that yields the set of PPE values, V^* , as the largest invariant, or “self-generating,” set. Letting $S = S^1 \times S^2$ and $\mathbf{v} = (v^1, v^2)$, the operator is defined as follows:

$$T(V) \equiv \{(u^1, u^2) : \exists \mathbf{s} \in S \text{ and } \mathbf{v} : A^2 \times \mathbb{R}^4 \rightarrow co(V) \text{ such that} \\ \text{for } i = 1, 2, u^i = \bar{\pi}^i(\mathbf{s}) + \delta E v^i(\mathbf{s}(\theta)) \\ \text{and, for each } i \text{ and } \tilde{s}^i \in S^i, u^i \geq \bar{\pi}^i(\tilde{s}^i, s^j) + \delta E v^i[(\tilde{s}^i, s^j)(\theta)]\} \cup \mathbf{u}^{NE},$$

where $\mathbf{u}^{NE} \equiv (\pi^{NE}/(1 - \delta), \pi^{NE}/(1 - \delta))$ denotes the repeated-Nash payoffs, which derive from mixed strategies and may be used as an off-the-equilibrium-path punishment. This operator effectively decomposes equilibrium play into two components: current-period strategies $\mathbf{s} \in S$ and continuation values \mathbf{v} drawn from the convex hull of the set V .

Below, we establish that T maps compact sets to compact sets (see Lemma 1). This property of T is the critical one for applying the methodology of Abreu, Pearce, and Stacchetti (1990). In particular, let V_0 be compact and contain all feasible, individually rational payoffs (e.g., $V_0 = [0, r/(1 - \delta)] \times [0, r/(1 - \delta)]$), and define $V_{n+1} = T(V_n)$, $n \geq 0$. Then the definition of T implies that $T(V_n) \subseteq V_n$. Using this and the fact that V_n is nonempty for each n (since $\pi^{NE}/(1 - \delta)$ is in every V_n), $V^* = \lim_{n \rightarrow \infty} V_n$ is a nonempty, compact set. Following the arguments in Abreu, Pearce, and Stacchetti (1990), V^* is the largest invariant set of T , and thus it is equal to the set of equilibrium values of this game.

To present our findings, we distinguish between two kinds of equilibria. In an *informative PPE*, firms employ equilibrium strategies in which they always share their cost information with one another: for all $i \in \{1, 2\}$ and $j \in \{L, H\}$, if $\theta^i = \theta_j$, then $\alpha^i(\theta^i) = j$. By contrast, in an *uninformative PPE*, firms are unwilling (or unable) to communicate, and we capture this by focusing upon equilibria in which firms never share cost information: for all $i \in \{1, 2\}$ and $j \in \{L, H\}$, $\alpha^i(\theta_j) = N$. We use the operators $T^I(V)$ and $T^U(V)$, respectively, to capture these

¹² While we believe that this assumption is fairly innocuous, convexity of the set of continuation values plays an important role in parts of our analysis. In Section 4, we discuss conditions under which convexity obtains without resorting to randomization.

additional restrictions on \mathbf{s} . Informative and uninformative PPE are of independent interest, and the juxtaposition of these two classes of PPE highlights the benefits and costs of informative communication for colluding firms. The characterization of such equilibria also contributes to our understanding of the full PPE set, V^* , since optimal equilibria of the unrestricted PPE class may involve informative communication following some histories and not others.

3. The mechanism design approach

■ In this section we consider the class of informative PPE and show that the search for the optimal informative PPE can be recast in terms of a static mechanism design program. In addition, we establish the solution to this program in two benchmark cases.

□ **Mechanism notation and incentive constraints.** The set of informative PPE values, V^I , is the largest invariant set of the operator T^I ; therefore, every utility vector $\mathbf{u} \in V^I$ can be generated by associated current-period strategies and continuation-value functions, \mathbf{s} and \mathbf{v} . When following these strategies, firms report their cost types truthfully and receive the corresponding prices and market-share allocations. Our approach in this section is to introduce notation for such state-contingent prices, market-share allocations, and continuation values, and then formalize the corresponding incentive constraints that these must satisfy to be implementable as equilibrium play.¹³

We begin with a general description of the incentive constraints. In an equilibrium of the repeated game, there are two kinds of deviations. First, a firm with cost type θ^i may adopt the policy that the equilibrium specifies when its cost type is instead $\theta^{i'} \neq \theta^i$. Such an “on-schedule” deviation is not observable, as a deviation, to the rival firm. The equilibrium prices, market shares, and continuation values therefore must be incentive compatible. Second, a firm also must not have the incentive to choose a price and market share that is not assigned to any cost type. Such an “off-schedule” deviation is observable to the rival firm as a deviation, and a sufficiently patient firm is deterred from a deviation of this kind if the collusive scheme then calls for a harsh “off-the-equilibrium-path” punishment. The on-schedule incentive constraints are reminiscent of truth-telling constraints in standard mechanism design theory, with continuation values playing the role of transfers. The off-schedule constraints are analogous to type-dependent participation constraints.

To make these analogies precise, we first define state-contingent prices, market shares, and continuation values. In state (j, k) , firm i serves q_{jk}^i customers at price p_{jk} .¹⁴ The continuation value assigned to firm i in state (j, k) is denoted v_{jk}^i . Let \mathbf{p} , \mathbf{q} , and \mathbf{v} denote the associated vectors, and let $\mathbf{z} = (\mathbf{p}, \mathbf{q}, \mathbf{v})$ be the “policy vector.” Finally, we use $\mathcal{Z}(V)$ to denote the set of such vectors that are feasible and consistent with the extensive-form game when continuation values are drawn from the set V :

$$\mathcal{Z}(V) = \{ \mathbf{z} = (\mathbf{p}, \mathbf{q}, \mathbf{v}) : \text{For all } i = 1, 2, (j, k) \in \Omega, (v_{jk}^1, v_{jk}^2) \in co(V), \\ p_{jk} \leq r; q_{jk}^i \in [0, 1] \text{ and } q_{jk}^1 + q_{jk}^2 = 1 \}.$$

Next, we denote expected market shares and continuation values for each firm, given a cost realization, by

$$\bar{q}_j^1 = \sum_{k \in \{L, H\}} \eta_k \cdot q_{jk}^1; \quad \bar{v}_j^1 = \sum_{k \in \{L, H\}} \eta_k \cdot v_{jk}^1;$$

¹³ This is analogous to the revelation principle. However, communication is an explicit part of the extensive-form game, unlike the typical case where the idea that firms “report” their costs to a mechanism is an abstraction. In our model, the incentive constraints protect against deviations at each stage. See Myerson (1986) for more discussion of multistage communication games.

¹⁴ Our Bertrand model ensures that in any state (j, k) a single transaction price p_{jk} prevails. Firm i therefore sets this price if it makes positive sales (i.e., if $q_{jk}^i > 0$). If firm i makes no sales in state (j, k) , then firm i 's price may differ from p_{jk} , but it cannot be lower.

and likewise for firm 2. Consider now each firm’s interim current-period payoff as a function of its announcement, assuming that the opponent announces truthfully and both firms adhere to the schedule. When firm 1 announces cost type \hat{j} when the true cost type is j , interim current-period profits are given by

$$\Pi^1(\hat{j}, j; \mathbf{z}) = \sum_{k \in \{L, H\}} \eta_k \cdot q_{jk}^1 \cdot (p_{jk} - \theta_j).$$

Adding on continuation values, we write interim and *ex ante* utilities as

$$U^1(\hat{j}, j; \mathbf{z}) = \Pi^1(\hat{j}, j; \mathbf{z}) + \delta \bar{v}_j^1; \quad \bar{U}^1(\mathbf{z}) = \sum_{j \in \{L, H\}} \eta_j \cdot U^1(j, j; \mathbf{z}).$$

These functions are defined analogously for firm 2.

Using this notation, the on-schedule incentive constraints can be easily related. We distinguish “upward” from “downward” incentive constraints, since typically only the downward constraints are binding:

$$U^i(H, H; \mathbf{z}) \geq U^i(L, H; \mathbf{z}) \tag{IC-On i $_D$ }$$

$$U^i(L, L; \mathbf{z}) \geq U^i(H, L; \mathbf{z}). \tag{IC-On i $_U$ }$$

Our next task is to represent the off-schedule incentive constraints. In an informative PPE, there are two kinds of off-schedule constraints. The first concerns the incentive of a firm to deviate from the assigned price after communication takes place. If both firms are assigned a price less than firm 1’s cost, firm 1 might like to price slightly above firm 2, to avoid producing in that state; alternatively, at higher prices, firm 1 might wish to slightly undercut firm 2’s price and capture the entire market.¹⁵ If the following constraint is satisfied, neither of these deviations is profitable:

$$\delta(v_{jk}^1 - \underline{v}^1) \geq \max(q_{jk}^2(p_{jk} - \theta_j), q_{jk}^1(\theta_j - p_{jk})), \tag{IC-Off1 $_j^I$ }$$

where $\underline{v}^i = \underline{v}^i(V) \equiv \inf\{v^i : v \in V\}$.¹⁶ As \underline{v}^i is reached only off of the equilibrium path, we can essentially treat it as a parameter in the analysis. IC-Off2 $_j^I$ is defined analogously.

The second kind of off-schedule deviation is an *interim* deviation. Suppose that the collusive scheme assigns a lower price in state (L, L) or (L, H) than in (H, H) or (H, L) . If firm 1 draws a low cost, firm 1 might be tempted to report a high cost in order to induce firm 2 to price high, so that firm 1 might then undercut firm 2’s high price. Firm 1 might wish to learn the realization of firm 2’s type before making a final decision to undercut. Deviations of this kind are dissuaded if

$$U^1(L, L; \mathbf{z}) \geq \sum_{k \in \{L, H\}} \eta_k \cdot \max((p_{Hk} - \theta_L) + \delta \underline{v}^1, q_{Hk}^1(p_{Hk} - \theta_L) + \delta v_{Hk}^1), \tag{IC-Off-M1}$$

where the M is mnemonic for “misrepresentation.” The constraint for firm 2 is defined analogously. Since a firm gains most from a market-share increase when its costs are low, it can be verified that if the other on- and off-schedule incentive constraints are satisfied, then the high type never has the incentive to engage in this type of misrepresentation. Further, if prices are the same in each state (as in many of our characterizations below), then the other off-schedule constraints render IC-Off-M1 redundant.

¹⁵ Given that unit costs are constant in output, a firm best deviates by claiming or relinquishing all market share. In either event, a small change in price serves the purpose. We therefore need not consider the possibility that a firm deviates by maintaining the price and adjusting its proposed market share.

¹⁶ We write \underline{v}^i rather than $\underline{v}^i(V)$ to conserve notation, and we take the off-schedule constraints relative to the set of values under consideration in a particular context.

□ **The repeated game as a mechanism.** We introduce notation for the feasible set of policy vectors when firms use informative communication, given an arbitrary set of continuation values V :

$$\mathcal{F}^I(V) = \{z = (\mathbf{p}, \mathbf{q}, \mathbf{v}) \in \mathcal{Z}(V) : \text{For all } i = 1, 2, \text{ IC-Oni}_D, \text{ IC-Oni}_U, \text{ IC-Offi}_{jk}^I \text{ and IC-Off-Mi hold}\}.$$

With this notation in place, we present the following lemma.

Lemma 1. Given a set $V \subset \mathbb{R}^2$, let

$$\tilde{T}^I(V) = \{(u^1, u^2) : \exists z = (\mathbf{p}, \mathbf{q}, \mathbf{v}) \in \mathcal{F}^I(V) \text{ such that for } i = 1, 2, u^i = \bar{U}^i(z)\} \cup \mathbf{u}^{NE}.$$

Then: (i) $\tilde{T}^I(V) = T^I(V)$, and (ii) \tilde{T}^I maps compact sets to compact sets.

Part (i) follows by a comparison of constraints (see Athey and Bagwell (1999) for further discussion). Part (ii) follows because the constraints entail weak inequalities, the feasible set is compact, and utility and constraint functions are real-valued, continuous, and bounded.

For the class of informative PPE, Lemma 1 formalizes the relationship between the repeated game and the mechanism-design problem we have just defined. It states that we can characterize the operator T^I as generating the set of all utilities that satisfy the constraints of a fairly standard mechanism-design problem, with the addition of the unusual restriction $(v_{jk}^1, v_{jk}^2) \in V$. An important consequence of this result is that for any informative PPE utility vector \mathbf{u} , there exists a policy vector $(\mathbf{p}, \mathbf{q}, \mathbf{v})$ that “implements” \mathbf{u} , in the sense that it satisfies the conditions in the definition of $\tilde{T}^I(V)$.

□ **Benchmark cases.** In this subsection, we characterize the Pareto frontier of $\tilde{T}^I(V)$ for two examples of sets V . These examples are motivated by the static mechanism-design literature where V is the set of available monetary transfers. In the first example, V is a line of slope -1 ; this represents “budget-balanced” transfers of utility that incur no efficiency loss. In the second example, we consider sets of the form $V = \{(v^1, v^2) : v^1, v^2 \leq K\}$; for such sets, all continuation values except (K, K) are Pareto inefficient. The cases are illustrated in Figure 1. These benchmarks allow us to develop some basic intuition, on which we build when we later consider sets V with more general shapes, such as the convex set illustrated in Figure 2.

To draw most clearly the analogy to the static mechanism-design literature, we ignore the off-schedule incentive constraints in this section. We then refer to the set of constraints excluding off-schedule incentive constraints as $\mathcal{F}_{On}^I(V)$, and we define

$$\tilde{T}_{On}^I(V) = \{(u^1, u^2) : \exists z = (\mathbf{p}, \mathbf{q}, \mathbf{v}) \in \mathcal{F}_{On}^I(V) \text{ such that for } i = 1, 2, u^i = \bar{U}^i(z)\}.$$

In discussing schemes, we say that a scheme uses *productive efficiency* if $q_{LH}^1 = q_{HL}^2 = 1$. We say that a scheme uses *efficient pricing* if $p_{jk} = r$ for all $(j, k) \in \Omega$. Similarly, the scheme is characterized by *Pareto-efficient continuation values* if for every (j, k) , there does not exist a continuation value pair $(\tilde{v}^1, \tilde{v}^2) \in V$ that Pareto-dominates (v_{jk}^1, v_{jk}^2) .

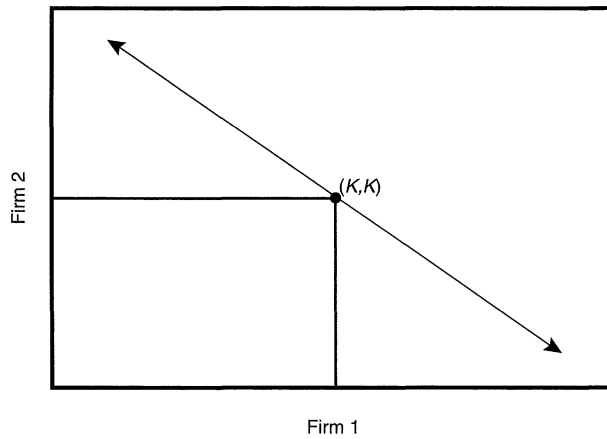
To begin, we record the following standard lemma:

Lemma 2. Any z satisfying IC-Oni_D and IC-Oni_U also satisfies $\bar{q}_H^i \leq \bar{q}_L^i$. If IC-Oni_D binds, then

$$U^i(H, H; z) = U^i(L, H; z) = U^i(L, L; z) - \bar{q}_L^i(\theta_H - \theta_L). \tag{1}$$

Market-share monotonicity follows since our model satisfies a single-crossing property: the low-cost type has a higher marginal return to market share. The representation of the relationship between the interim utilities follows directly and says that the low-cost type earns an “efficiency rent” of $\bar{q}_L^i(\theta_H - \theta_L)$ over the high-cost type.

FIGURE 1
SETS OF FEASIBLE CONTINUATION VALUES FOR BENCHMARK CASES

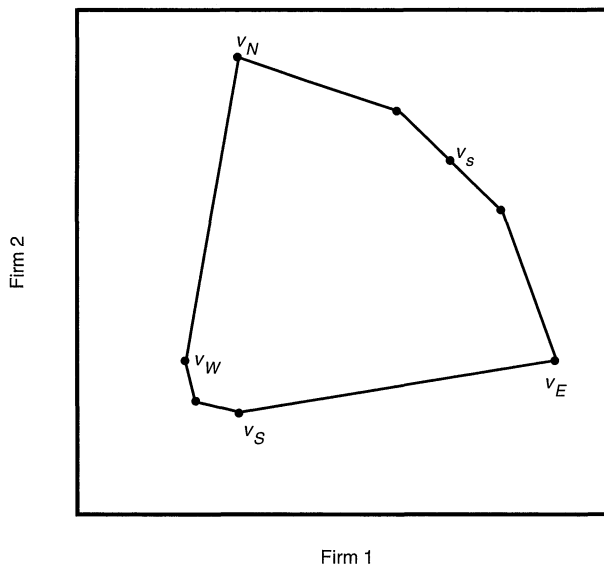


By Lemma 2, when IC-Oni_D binds for each firm, the *ex ante* utility for firm *i* is

$$\bar{U}^i(\mathbf{z}) = U^i(H, H; \mathbf{z}) + \eta_L \bar{q}_L^i(\theta_H - \theta_L) = \Pi^i(H, H; \mathbf{z}) + \delta \bar{v}_H^i + \eta_L \bar{q}_L^i(\theta_H - \theta_L). \quad (2)$$

Among the set of allocation rules where IC-Oni_D binds, firm *i* is indifferent between providing incentives with low prices or low continuation values for its low-cost type. Intuitively, in contrast to market share, neither the price nor the continuation value interacts directly with the firm's type in the firm's objective function; thus, the cartel has a preference over low-cost prices and continuation values for which a firm's on-schedule constraint binds, only insofar as these instruments generate utility losses or gains for the other firm. Lowering price decreases the utility of the other firm. In contrast, when cross-firm transfers of utility are available, lowering one firm's continuation value may allow an increase in that of the other firm. Continuation values are then a superior instrument.

FIGURE 2
A CONVEX SET OF CONTINUATION VALUES



To better highlight some of these themes, we turn now to two special cases. First, we suppose that the set of feasible continuation values is a line of slope -1 .¹⁷

Lemma 3. For $K \in \mathfrak{R}$, suppose that $V(K) = \{(v^1, v^2) : v^1 + v^2 = 2K\}$. Then, the Pareto frontier of $\tilde{T}_{On}^I(V(K))$ is $\{(u^1, u^2) : u^1 + u^2 = 2\pi^{FB} + \delta 2K\}$, and this frontier can be implemented with a policy vector $(\mathbf{p}, \mathbf{q}, \mathbf{v})$ that satisfies the following properties: productive efficiency, pricing efficiency, and Pareto-efficient continuation values; $v_{HL}^1 - v_{LH}^1 = (r - \theta^H)/\delta$; IC-Oni_D binds for each i ; and $v_{LH}^1 < v_{jj}^1 < v_{HL}^1$ for $j \in \{L, H\}$.

As expected, first best is attained. The downward on-schedule constraints bind, since it is the low-cost type who has the higher market share, and market share is desirable for both firms. Thus, the relevant consideration is to dissuade the high-cost type from mimicking the low-cost type; as lower-cost types have a higher marginal benefit to high market share, if the high-cost type is just indifferent between the high and low announcement, the low-cost type strictly prefers the low-cost announcement. The optimal mechanism requires transfers through continuation values that reward a firm for announcing high costs.

Next, we consider a second special case, wherein the firms receive continuation values from a rectangular set in which each firm receives at most K . The continuation-value Pareto frontier is then a single point, and efficient continuation-value transfers across firms are thus unavailable. To state the result, we refer to the following condition:

$$\kappa \equiv (r - \theta_H)/(\theta_H - \theta_L) > \eta_H. \tag{3}$$

Lemma 4. For any $K \in \mathfrak{R}$, suppose that $V(K) = \{(v^1, v^2) : v^1, v^2 \leq K\}$. (i) Suppose that (3) holds. Then the Pareto frontier of $\tilde{T}_{On}^I(V(K))$ is

$$\{(u^1, u^2) : u^1 + u^2 = r - E[\theta] + \delta 2K, u^i \geq 0\},$$

and this frontier can be implemented with a policy vector $(\mathbf{p}, \mathbf{q}, \mathbf{v})$ that satisfies the following properties: pricing efficiency, Pareto-efficient continuation values, and productive inefficiency with $\bar{q}_H^i = \bar{q}_L^i$ for $i = 1, 2$. (ii) Suppose that (3) fails. Then the Pareto frontier of $\tilde{T}_{On}^I(V(K))$ is given by

$$\{(u^1, u^2) : u^1 + u^2 = \eta_H(r - \theta_H) + \eta_L(1 + \eta_H)(\theta_H - \theta_L) + \delta 2K, u^i \geq 0\}.$$

This can be implemented with a policy vector $(\mathbf{p}, \mathbf{q}, \mathbf{v})$ that satisfies the following properties: productive efficiency, Pareto-efficient continuation values, pricing efficiency in state (H, H) ($p_{HH} = r$), and a price of $[\eta_H/(1 + \eta_H)](r - \theta_H) + \theta_H$ in other states.

Lemma 4 refers to an environment in which the only instruments available (reduced continuation values, low prices) with which to achieve productive efficiency are wasteful. When (3) holds, so that the profit to the high-cost type is large relative to the efficiency advantage of the low-cost type, Lemma 4 establishes that the Pareto frontier entails productive inefficiency: the loss in profit from either Pareto-inefficient continuation values or inefficient pricing overwhelms any potential productive efficiency gain.

To see the role of (3), consider raising productive efficiency by increasing q_{HL}^2 (and therefore decreasing q_{HL}^1). The subtle aspect of the intuition entails understanding the effects of this change when prices and continuation values must adjust to maintain the on-schedule constraints. The change decreases firm 1's *ex ante* utility by $\eta_L(r - \theta_H)$, since firm 1's high type bears the cost

¹⁷ For the public-goods problem, d'Aspremont and Gérard-Varet (1979) show that the first best can be attained using budget-balanced transfers, when participation constraints are ignored. McAfee and McMillan (1992) specialize this to first-price auctions, showing that participation constraints can be satisfied. The following result is a two-type specialization, where continuation values may sum to a nonzero constant.

directly and firm 1's low type must now charge a lower price or receive a lower continuation value to avoid violating IC-On1_D. The change increases firm 2's *ex ante* utility by $\eta_L \eta_H (\theta_H - \theta_L)$, the higher "efficiency rent" ($\theta_H - \theta_L$) available to firm 2's low-cost type in state (H, L). Then (3) guarantees that the cost to firm 1, incurred across both states (H, L) and (L, L), outweighs the efficiency benefit to firm 2 in state (H, L). This result introduces a theme that will recur throughout our analysis. There is a "tax" on productive efficiency: improving productive efficiency tightens on-schedule constraints, leading to further distortions. If instead (3) fails, with a rectangular continuation value set, it is always possible to achieve the optimal collusive payoffs using the highest available continuation values and low prices for the low-cost types.¹⁸

Whether firms choose to produce efficiently or not, cartel profit is not improved by moving from $V = \{(K, K)\}$ to $V = \{(v^1, v^2) : v^1, v^2 \leq K\}$. Wasteful continuation values are not useful for providing incentives. With this observation, Lemma 4 may be related to other findings for continuum-type models. In their (static) analysis of "weak" bidding cartels, McAfee and McMillan (1992) show that when transfers are prohibited ($V = \{(0, 0)\}$) and the distribution over types, $F(\theta)$, is log-concave, the optimal cartel uses identical bidding at the seller's reservation value. This is the bidding cartel analog of pricing efficiency and productive inefficiency. Athey, Bagwell, and Sanchirico (1998) consider collusion among sellers where $V = \{(v^1, v^2) : v^1 = v^2\}$. In a repeated game, this corresponds to symmetric PPE. They find that wasteful continuation values ("price wars") are not used, while pricing efficiency and productive inefficiency obtain when $F(\theta)$ is log-concave.¹⁹

4. Characterization of informative PPE

■ We next characterize the set of informative PPE values. Our analysis builds on the insights developed in the benchmark cases of Section 3. We develop analytically some key findings, and we then illustrate additional subtleties with computational examples.

Before beginning the formal analysis, we outline the central tradeoffs. Suppose the firms attempt to implement first-best profits. In the first period of the game, a first-best scheme must implement productive efficiency and pricing efficiency; thus, from the perspective of current-period profits, high-cost firms are tempted to misreport their costs in order to achieve greater market share. To ensure truthful reporting, the agreement therefore must provide that firm 2 receives future market-share favors from firm 1 following a realization of the state (L, H). Suppose then that (L, H) is realized in the first period, and consider the scheme in the second period. In a first-best collusive scheme, productive efficiency is again required; consequently, if state (L, H) is once more realized, then firm 2 must again receive zero market share. On the other hand, if the firms experience the same costs in the second period, then the collusive arrangement may favor firm 2 while simultaneously delivering first-best profits. This is achieved by giving firm 2 more than half of the market in the second period when the (L, L) and (H, H) states are realized. If these market shares are appropriately chosen, both firms still have the incentive to report truthfully. What might prevent such a scheme from succeeding? The firms must be sufficiently patient so that firm 1 is dissuaded from undertaking an off-schedule deviation following a realization of (L, L), when its assigned market share is low. What if this cannot be accomplished? Then, asymmetric treatment introduces new inefficiencies. In particular, the scheme may require low prices, or it may call upon firm 1 to relinquish some market share in period 2 in the (L, H) state, even though it is most efficient, as its temptation to undertake an off-schedule deviation is low when its assigned market share is high.

¹⁸ Notice that the pricing scheme outlined in Lemma 4 can be implemented decentrally: each firm charges a price of r when its own cost is high, and it selects a lower price \hat{p} when its own cost is low. This allocates market share efficiently and achieves the price of \hat{p} in all states except (H, H).

¹⁹ The continuum- and two-type models may be further related using an N -type model. Let η_n be the probability of cost type n . Then, the following conditions replace (3): $(r - \theta_N)\eta_m - \eta_N(\theta_{m+1} - \theta_m) \sum_{n=1}^m \eta_n > 0$ for all $m < N$; and $(\theta_{m+1} - \theta_m) \sum_{n=1}^m \eta_n / \eta_m$ is nondecreasing in m . The first expression is the analog of (3); the second condition is the analog of log-concavity of $F(\theta)$. If $r > \theta_N$, the first expression is satisfied in the continuum-type limit, when the η_n 's go to zero at a common order.

Pulling these themes together, we may summarize the central tradeoffs as follows. If in a given period, the firms seek productive efficiency “today,” then asymmetric treatment is required “tomorrow.” Productive and pricing efficiency tomorrow, however, can then be maintained only if the asymmetric treatment is implemented through asymmetric market-share assignments among equally efficient firms pricing at the reservation value. In turn, this is possible only if tomorrow the disadvantaged firm is sufficiently patient to endure its assigned low market share; if not, some inefficiency may be required. In view of these tradeoffs, a cartel composed of moderately patient firms may assign market shares today without achieving full productive efficiency, in order to lessen the future transfer burden and thus reduce future inefficiency.

In the next subsection, we derive conditions on the discount factor under which firms are able to implement a given level of efficiency (such as first best) in every period of the game. Subsequently, we explore in greater depth the optimal resolution of the tradeoffs between current and future efficiency faced by firms of moderate patience.

□ **A linear informative PPE set with first-best profits.** In this subsection, we identify a discount factor strictly less than one above which the cartel can achieve first-best profits in every period. We first develop the theory, and then present examples of the corresponding equilibria for particular parameter values.

Recall that in Section 3 we analyze Pareto-optimal schemes for an exogenous set of continuation values. We now confront the endogenous nature of the continuation-value set. Our goal is to establish the existence of a set of informative PPE values, where (i) each utility pair yields first-best profits to the cartel, and (ii) when implementing any point in the set, only other elements of the set are used as continuation values on the equilibrium path. A “self-generating” set of values supporting first-best profits must be a line segment with slope -1 , together with the “punishment” values that serve as threats to deter off-schedule deviations.

We attempt to construct such a line segment of equilibrium values, where the endpoints are denoted (x, y) and (y, x) . We focus on finding a policy vector \mathbf{z} that implements the endpoint (x, y) using pricing and productive efficiency and continuation values taken only from the line segment $[(x, y), (y, x)]$, while satisfying all feasibility and incentive constraints. If this can be accomplished, then there exists a \mathbf{z}' that exchanges the roles of the two players and implements (y, x) . Any convex combination of (x, y) and (y, x) can be attained using a convex combination of \mathbf{z} and \mathbf{z}' .

We proceed in two steps. First, we consider the implementation of the endpoint (x, y) when off-schedule constraints are ignored. This step can be challenging. If monopoly profit for a high-cost firm, $r - \theta_H$, is too large, it may be difficult to achieve the desired level of profit for firm 1, $\bar{U}^1(\mathbf{z}) = x$, while maintaining $v_{jk}^1 \geq x$. Intuitively, firm 1’s average profit today then must be worse than its per-period profits derived from each of its continuation values: $E[\Pi^1(j, j; \mathbf{z})] \leq v_{jk}^1(1 - \delta)$ for each (j, k) . Further, firm 1 has an incentive to reveal a high-cost type only if the future looks *relatively* better after a realization of (H, L) : following the logic of Lemma 3, the on-schedule constraints can be satisfied only if $v_{HL}^1 - v_{LH}^1 \geq (r - \theta_H)/\delta$. This requirement places additional downward pressure on today’s expected profit. But productive and pricing efficiency impose a lower bound on today’s profit. Similarly, if the efficiency-rent term $\theta_H - \theta_L$ is too small, it can be difficult to implement $\bar{U}^2(\mathbf{z}) = y$ while maintaining $v_{jk}^2 \leq y$. Intuitively, firm 2’s average profit today then must be greater than its per-period profits derived from each of its continuation values. Recalling (2), this is more easily achieved when the efficiency rent $\theta_H - \theta_L$ is large.

This discussion suggests a restriction under which $\kappa \equiv (r - \theta_H)/(\theta_H - \theta_L)$ is not too large. Recalling our assumption $\eta_L > 1/2$, we consider the following restriction:²⁰

$$\eta_L^2 > \kappa(2\eta_L - 1). \tag{4}$$

²⁰ Our assumption that $\eta_L > 1/2$ determines which continuation value, v_{HH}^1 or v_{LL}^1 , is lower and thus more likely to drop below x when we try to implement $\bar{U}^1 = x$ with $v_{LH}^1 = x$ and $v_{HL}^1 \leq y$. For $\eta_L < 1/2$, it can be shown that a different but analogous condition must hold.

We may verify that (4) is satisfied if $\kappa < 1$; more generally, it holds if η_L is sufficiently close to $1/2$.²¹ Under (4), and in the absence of off-schedule constraints, we show in the Appendix that the implementation of (x, y) is feasible if δ exceeds a critical value, δ^{Fon} , which is less than unity and defined as follows:

$$\delta^{Fon} = \frac{\kappa}{\eta_L^2 + 2\kappa(1 - \eta_L)}.$$

The second step is to assume (4) and consider restrictions implied by the off-schedule constraints. Of course, if firms are sufficiently patient, then an off-schedule deviation is unattractive. But the associated critical discount factor is difficult to compute, since the exact value depends on the worst punishment available. Fortunately, our qualitative results do not depend on a closed-form calculation. Instead, we proceed as follows.

First, for any given δ , we let $\underline{v}_1(\delta)$ denote the worst equilibrium value for firm 1. From the folk theorem of Fudenberg, Levine, and Maskin (1994), we know that $\underline{v}_1(\delta)$ approaches zero as δ approaches one; furthermore, since the repeated play of the static Nash equilibrium is a feasible punishment, we also know that $\underline{v}_1(\delta) \leq \pi^{NE}/(1 - \delta)$. We thus may define $\lambda^I(\delta) \in [0, 1]$ by $\underline{v}_1(\delta) \equiv \lambda^I(\delta)\pi^{NE}/(1 - \delta)$, so that $\lambda^I(\delta)$ gives the fraction of the static Nash profits that can be sustained, on average, in the worst equilibrium for firm 1. The function $\lambda^I(\delta)$ is nonincreasing and satisfies $\lambda^I(0) = 1 > 0 = \lambda^I(1)$. Second, for any given λ and associated punishment value $\lambda\pi^{NE}/(1 - \delta)$, we solve for the critical discount factor for supporting first-best profits, denoted $d^F(\lambda)$. The function $d^F(\lambda)$ is nondecreasing, where $d^F(0) < 1$ and $d^F(1)$ are the critical discount factors for implementing first-best profits when the punishment entails zero and repeated-Nash profits, respectively. The critical discount factor is thus determined as the fixed point of the equation $\delta = d^F(\lambda^I(\delta))$, and it must lie in $(d^F(0), d^F(1))$.

Consider now the derivation of $d^F(\lambda)$. We seek the smallest δ such that the values (x, y) can be sustained as an equilibrium, using only values on $[(x, y), (y, x)]$ on the equilibrium path and $\lambda\pi^{NE}/(1 - \delta)$ as the off-schedule punishment. The program is formalized in the Appendix. In describing its solution, a subtlety arises: for different parameter values, different constraints bind, and so the formula for $d^F(\lambda)$ changes. Rather than enumerating all possible cases, we derive an upper bound for $d^F(\lambda)$ that applies for all parameter values. As we discuss further in the Appendix, to construct this upper bound, we impose that IC-Off_{1LL} is binding, and we set the punishment at its “softest” level with repeated-Nash play (i.e., $\lambda = 1$). With this, we may report a (conservative) upper bound for the critical discount factor that suffices for an informative PPE that achieves first-best profits:

$$\delta^{FB} = \max \left(\delta^{Fon}, \frac{\eta_L + \kappa(1 - \eta_L)}{\eta_L + \kappa(1 - \eta_L) + \eta_L^2\kappa} \right).$$

Observe that $\delta^{FB} < 1$ when (4) is satisfied.

Proposition 1. Assume (4). Then, for all $\delta \in (\delta^{FB}, 1]$, there exist values $y > x > 0$ such that $x + y = 2\pi^{FB}/(1 - \delta)$, and the set $[(x, y), (y, x)] \cup \mathbf{u}^{NE}$ is a self-generating set of informative PPE values.

Proposition 1 can be thought of as a generalization of Fudenberg, Levine, and Maskin’s (1994) folk theorem. Instead of resorting to taking the limit as $\delta \rightarrow 1$, we compute a discount factor strictly less than one where first best is achieved. Our result further provides an explicit characterization of the behavior associated with this first-best arrangement. The following specific example illustrates how this is accomplished.

²¹ If (4) fails, firms may be unable to implement first-best profits. But self-generating sets composed of three connected line segments can be constructed, where all points on the interior segment are implemented using productive efficiency. As firms become more patient, the width of the interior segment grows, and first best is approximated as δ approaches one.

□ **Example: achieving first-best collusion.** To understand how first-best collusion unfolds over time, consider a particular example, where $r = 2.5$, $\theta_H = 2$, $\theta_L = 1$, and $\eta_L = .6$, so that $\pi^{FB} = .67$.

Consider first the critical discount factors. For these parameter values, we find that $\delta^{Fon} = .66$ and $\delta^{FB} = .816$. As described above, these bounds are, in general, conservative. Given specific parameter values, however, the program defined in the Appendix for $d^F(\lambda)$ can be readily solved. In the present example, for all $\lambda \in [0, 1]$, $d^F(\lambda)$ is achieved using a policy vector whereby the following constraints bind: $p_{jk} \leq r$ for all $(j, k) \in \Omega$, $q_{LH}^1 \leq 1$, $q_{HL}^1 \geq 0$, $q_{HH}^1 \geq 0$, $v_{HH}^1 \geq x$, $v_{LH}^1 \geq x$, $v_{HL}^1 \leq y$, IC-On1_D, IC-On2_D, and IC-Off1_{LL}. We find that $d^F(\lambda) = 12.5[(1087 - 216\lambda)^{1/2} - 3]/(108\lambda - 539)$, which yields $d^F(1) = .769$ and $d^F(0) = .695$. That is, when the firms use repeated-Nash play as the off-schedule punishment, first-best profits can be sustained if and only if $\delta \geq .769$.

Now consider the collusive strategies that support these payoffs. We take $\delta = .769$ and $\lambda = 1$, so that the equilibrium we describe is sure to exist; for lower levels of λ , the qualitative description of play is similar. In implementing a first-best equilibrium, the history of past play can always be summarized by one of five states, numbered 1 to 5, where state 1 is best for firm 1 and state 5 is best for firm 2; this is illustrated in Figure 3. Table 1 summarizes the policy vectors that implement each state (recalling that prices always equal r).

After the null history, play begins in state 3. In that state, firms are treated symmetrically. The firms implement productive efficiency and share the market otherwise. Following a realization of (L, H) , the firms proceed to state 5, while following a realization of (H, L) they proceed to state 1. Otherwise, they return to state 3.

Suppose now that the cost types are (L, H) in the first period. The firms proceed to state 5, where payoffs are asymmetric but productive efficiency is still achieved. The asymmetries are most pronounced in state (H, H) : $q_{HH}^1 = 0$, and if (H, H) is realized, the firms return to state 5 in the next period. The constraint IC-Off1_{LL} binds, so to mitigate the incentive to cheat, $q_{LL}^1 = .152$; after the realization of state (L, L) , the firms proceed to a better state for firm 1, state 4. Firm 1 is induced to admit when it draws a high cost, by the prospect of a future reward: if the cost realizations are (H, L) , firm 1 receives no market share, but in the next period the firms proceed to state 1.

Observe that the firms never make use of “review” strategies, where they try to infer the likelihood of a sequence of reported cost draws.²² Because the collusive scheme gives firms the incentives to report truthfully in each period, the firms are not concerned with the possibility of past misrepresentations. Even after a history where (L, H) is realized 10 periods in a row, firms start period 11 by following the strategies specified in state 5, without worrying about how long they have been there.

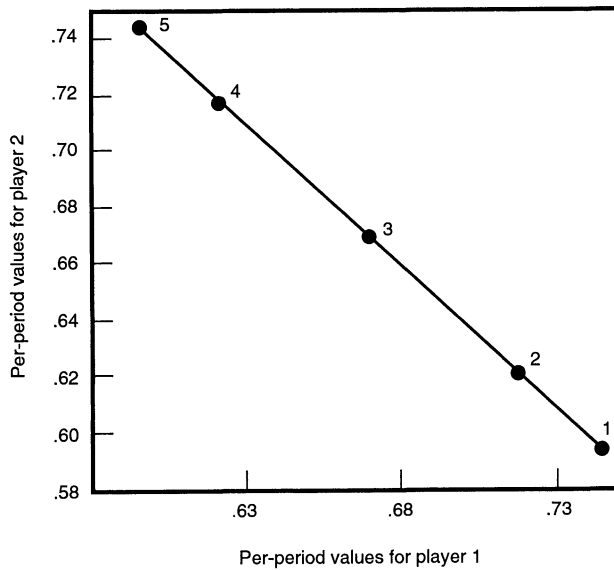
□ **Example: obstacles to first-best collusion.** Suppose now that firms are less patient and consider the factors that limit their ability to sustain first-best profits. In the example above, the limiting factor is that IC-Off1_{LL} binds when implementing state 5. When firms are less patient, therefore, firm 1 would undercut the collusive price, charging $r - \varepsilon$, in state 5 when it draws a low cost.

What is to be done when δ is too small to support first-best profits? One possibility is to reduce productive efficiency in all states. This would yield a line segment of equilibrium values, where the total profit is less than first-best. But such a solution may be too drastic. A more profitable equilibrium can be attained if firms are treated symmetrically and use productive efficiency in the first period, but then use productive inefficiency in the subsequent asymmetric states.

To be more precise, we return to the parameter values of the last subsection, except we now take $\delta = .768$. Again, we set $\lambda = 1$, noting that the qualitative features of the solution are

²² See Radner (1981) for a first-best result for infinitely patient firms that use review strategies in a “hidden-action” game. Our firms achieve first-best profits but are not infinitely patient. Also, when firms are less patient, inefficiencies may be required to provide incentives, and we characterize below the optimal manner in which to provide such incentives.

FIGURE 3
A SELF-GENERATING EQUILIBRIUM SET THAT ACHIEVES FIRST-BEST PROFITS



maintained under more severe punishments. First, consider constructing an equilibrium set that is a line segment with reduced productive efficiency. To this end, we may impose the binding constraints described in the last subsection, while setting $\delta = .768$ and now allowing q_{LH}^1 and q_{HL}^1 to vary. It is straightforward to calculate that the best equilibrium with these features has $q_{LH}^1 = .992$ and $q_{HL}^1 = 0$ when implementing the endpoint (x, y) , and it yields per-period *ex ante* expected profits of .66903 for each firm.

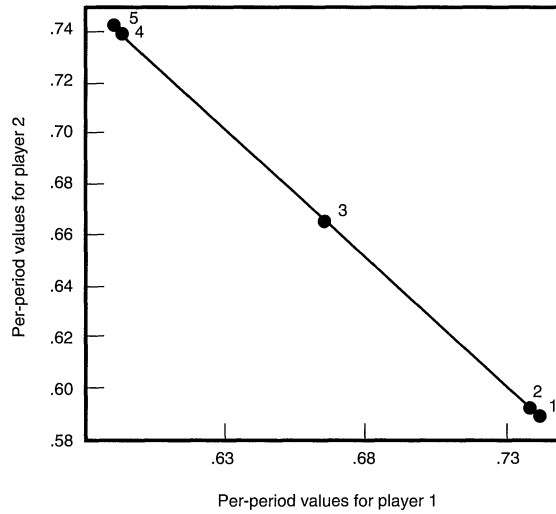
Now consider a more sophisticated equilibrium, illustrated in Figure 4 and Table 2. To simplify the description of the equilibrium, we allow the firms to randomize among continuation equilibria, although it is possible to achieve the same payoffs without such randomization by introducing new states, where q_{LL}^1 and q_{HH}^1 are chosen appropriately. To denote the continuation play where the firms proceed to state 2 with probability .83 and to state 4 with probability .17, we write “(2,4), (.83, .17).”

In this equilibrium, productive efficiency is used in states 2, 3, and 4, while productive inefficiency is used in states 1 and 5. The firms use productive efficiency in state 3, but then productive inefficiency is used in implementing rewards and punishments following realizations of either (L, H) or (H, L) . Subsequently, productive inefficiency is used in some periods but not others, depending on history. The sum of firm profits in states 1 and 5 is strictly less (by .004)

TABLE 1

State	Values	Transitions (States)				Player 1 Market Shares			
		(L, L)	(L, H)	(H, L)	(H, H)	(L, L)	(L, H)	(H, L)	(H, H)
1	(.745, .595)	2	5	1	1	.848	1.000	.000	1.000
2	(.718, .622)	2	5	1	1	.679	1.000	.000	.733
3	(.670, .670)	3	5	1	3	.500	1.000	.000	.500
4	(.622, .718)	4	5	1	5	.321	1.000	.000	.267
5	(.595, .745)	4	5	1	5	.152	1.000	.000	.000

FIGURE 4
A SELF-GENERATING EQUILIBRIUM SET THAT ACHIEVES CLOSE TO FIRST-BEST PROFITS



than the sum of profits in states 2, 3 and 4. *Ex ante* expected firm profits in this equilibrium are .66964, higher than those in the simpler equilibrium described above. This illustrates a theme that we will return to below in our theoretical characterizations: colluding firms of moderate patience use greater productive efficiency to implement fairly symmetric equilibrium values, and they use reduced productive efficiency when implementing highly asymmetric equilibrium values.

What would happen if, instead of reducing productive efficiency in states 1 and 5, the firms were to lower p_{LL}^1 ? Reducing p_{LL}^1 allows the firms to further reduce q_{LL}^1 without violating the off-schedule constraint, and it relaxes the on-schedule constraints, since the low-cost type gets lower profits. Continuing with our parametric example, if firms follow an equilibrium with the same structure as Figure 4, except they always use productive efficiency, but reduce prices and q_{LL}^1 in state 5 (and symmetrically in state 1), the highest *ex ante* expected profits per period for each firm that can be supported are .66930,²³ lower than the equilibrium of Figure 4. Intuitively, lowering q_{LH}^1 increases profits for firm 2, while lowering p_{LL}^1 makes both firms worse off.

TABLE 2

State	Values	Transitions (States, Probabilities)				Player 1 Market Shares			
		(L, L)	(L, H)	(H, L)	(H, H)	(L, L)	(L, H)	(H, L)	(H, H)
1	(.742, .590)	(2, 4) (.83, .17)	(2, 4) (.02, .98)	1	2	.838	.984	.000	1.000
2	(.741, .592)	(2, 4) (.82, .18)	4	1	2	.841	1.000	.000	1.000
3	(.667, .667)	3	(4, 5) (.5, .5)	(1, 2) (.5, .5)	3	.500	1.000	.000	.500
4	(.592, .741)	(2, 4) (.18, .82)	5	1	4	.159	1.000	.000	.000
5	(.590, .742)	(2, 4) (.17, .83)	5	(2, 4) (.98, .02)	4	.162	1.000	.016	.000

²³ These profits are computed by solving a system of equations. Letting the profits in state 5 be (x, y) and those in state 4 be (t, w) , the system imposes productive efficiency in all states, and pricing efficiency except in states 1 and 5. When implementing states 4 and 5, the following conditions hold: $q_{HH}^1 = 0, v_{HH}^1 = t, v_{LH}^1 = x, v_{HL}^1 = w, IC-On1_D, IC-On2_D, \text{ and } IC-Off1_{LL}$.

□ **The shape of the Pareto frontier.** The examples above demonstrate some of the tradeoffs that firms face when they are too impatient to implement the first best. We now provide more general characterizations of the informative PPE utility set. We begin by characterizing the shape of the Pareto frontier of the informative PPE utility set. As discussed at the start of this section, when firms attempt to implement highly asymmetric equilibrium values, the off-schedule constraints bind and some inefficiency may be required. We thus anticipate that total cartel profits fall as values become more asymmetric, indicating that the frontier is typically nonlinear. Here we shall establish conditions under which a *subset* of the Pareto frontier of the set of informative PPE values is a line with slope equal to -1 . In addition, we characterize the manner in which the off-schedule constraints determine the boundaries of this linear subset (as well as the boundaries of the frontier itself).

To begin, recall our assumption that firms can randomize between continuation equilibria, which ensures that firms have available a convex set of continuation values at any point in time. Figure 2 illustrates the general shape of a symmetric, convex set of continuation values. The set has four “corners,” labelled as North, South, East, and West, or $v_N, v_S, v_E,$ and v_W , where $v_N = (v_N^1, v_N^2)$ and likewise for the other corners. Between two corners, the boundary of the set is monotone. The part of the boundary between v_N and v_E is of particular interest to us, since it represents the set of Pareto-efficient continuation values.

When describing the Pareto frontier of the set of feasible continuation values given a set V , we use the notation

$$f(v_{jk}^1) = \begin{cases} \max\{v_{jk}^2 : (v_{jk}^1, v_{jk}^2) \in co(V)\} & \text{if } v_{jk}^1 \in [v_N^1, v_E^1] \\ v_N^2 & \text{if } v_{jk}^1 < v_N^1 \\ -C \cdot (v_{jk}^1 - v_E^1) & \text{if } v_{jk}^1 > v_E^1 \end{cases}$$

for some large constant C . Of course, convexity of the set V implies concavity of the frontier f . We define the function f outside the domain of the Pareto frontier in order to simplify the statement of some of our results about the slope of the frontier.

Given our assumption that firms are symmetric, $f(v) + v$ is maximized at $v^1 = v_s^1$, where $f(v_s^1) = v_s^1$. We may thus say that a scheme is characterized by *future inefficiency* if $v_{jk}^1 + f(v_{jk}^1) < 2v_s^1$ for some (j, k) , so that under some state the continuation values fail to maximize total cartel future profits. As mentioned above, future inefficiencies are associated with highly asymmetric values, and they represent an efficiency cost that is incurred when firms attempt to provide incentives with such values. Thus, it is important to identify conditions under which a subset of the Pareto frontier has a slope of -1 , so that the firms may make some use of future market-share favors without efficiency loss.

For the informative PPE set V^I , let v_s^I be the point on the Pareto frontier of V^I that provides equal utility to both firms. Consider a policy vector that implements v_s^I , and assume that the off-schedule constraints do not bind in states (L, L) and (H, H) . Suppose for simplicity that pricing efficiency is used. By lowering firm 1’s market share in state (L, L) by ε/η_L and (H, H) by ε/η_H , it is possible to transfer market share from firm 1 to firm 2 without upsetting any of the on-schedule constraints. This new scheme is also feasible. Although firm 1’s profit is lower, total cartel profit is unchanged, so the Pareto frontier has an interval with slope equal to -1 .

How can we ensure that the off-schedule constraints do not bind in states (L, L) and (H, H) ? Without loss of generality, when implementing v_s^I , we may specify that $q_{jj}^I = 1/2$ and $v_{jj} = v_s^I$ for $j \in \{L, H\}$. With this specification in place, and observing that the most demanding circumstance from the perspective of off-schedule constraints arises in state (L, L) when $p_{LL} = r$, we see that it suffices to check the following condition:

$$(r - \theta_L)/2 < \delta(v_s^{1I} - \underline{v}^1). \tag{5}$$

Of course, v_s^{1I} is endogenously determined. To establish that (5) holds based on exogenous parameters, we present the following lemma, which describes a self-generating set of equilibrium values that exists for a wide range of discount factors.

Lemma 5. There exists a $\delta^{lin} < 1$ such that, for all $\delta > \delta^{lin}$:

(i) There exist values $y > x > 0$ such that the set $[(x, y), (y, x)] \cup \mathbf{u}^{NE}$ is a self-generating set of informative PPE values. Each utility pair \mathbf{u} on the segment can be implemented using a policy vector $(\mathbf{p}, \mathbf{q}, \mathbf{v})$ such that for each (j, k) , $p_{jk} = r$ and $v_{jk} \in [(x, y), (y, x)]$, and $q_{LH}^1 + q_{HL}^2 = 1 + \delta(\kappa + \eta_L) / [\delta(\kappa + \eta_L) + \kappa + \delta\eta_L^2]$.

(ii) (5) holds.

This result establishes a lower bound for v_s^{1I} : since the set $[(x, y), (y, x)]$ described in the lemma must be contained in V^I , v_s^{1I} must be greater than $(x + y)/2$. Further, IC-Off $_{LL}^I$ will be slack when implementing $((x + y)/2, (x + y)/2)$, implying that (5) holds for $\delta > \delta^{lin}$. For the parameter values used in our examples ($r = 2.5, \theta_H = 2, \theta_L = 1$ and $\eta_L = .6$), $\delta^{lin} \approx .7$, and at that discount factor $q_{LH}^1 + q_{HL}^2 \approx 1.5$, less than the first-best value of 2.

When (5) holds, we have an initial characterization of the Pareto frontier:

Proposition 2. Assume (5).

(i) The Pareto frontier of V^I has an open interval with slope equal to -1 .

(ii) Let (x, y) and (y, x) denote the endpoints of this open interval, and let $(\mathbf{p}, \mathbf{q}, \mathbf{v})$ implement (x, y) . Then at least one of the following holds: (a) for some $j \in \{L, H\}$, IC-Off $_{jj}^I$ binds; (b) $v_{jj}^1 \leq x$ for some $j \in \{L, H\}$, and either $p_{jj} \leq \theta_j$ or $q_{jj}^1 = 0$ for some $j \in \{L, H\}$.

Part (i) confirms the existence of a subset of the Pareto frontier with slope -1 . Part (ii) then identifies the factors that limit this subset. When implementing an endpoint of this subset, either an off-schedule constraint binds, or else the firms run out of market-share favors and the ability to shift continuation values in the event of ties. In either case, the firms cannot implement any further transfer of utility away from firm 1 and toward firm 2 without a loss of efficiency. For firms of moderate patience ($\delta < \delta^{FB}$), the off-schedule constraints typically bind first.

Next, we observe that the off-schedule constraints also determine the endpoints of the entire Pareto frontier and that they force the firms to bear inefficiency when implementing those endpoints.

Proposition 3. Suppose that $(\mathbf{p}, \mathbf{q}, \mathbf{v})$ implements v_N^I . (i) If IC-Oni $_U$ is slack for each i , then there is either pricing inefficiency, productive inefficiency, or both. (ii) If $\bar{q}_L^i > \bar{q}_H^i$ for each firm i , at least one of the following holds: (a) for some $j \in \{L, H\}$, IC-Off $_{jj}^I$ binds; (b) $v_{jj}^1 \leq v_N^I$ for some $j \in \{L, H\}$, and either $p_{jj} \leq \theta_j$ or $q_{jj}^1 = 0$ for some $j \in \{L, H\}$.

To understand part (i), suppose that the firms implement some equilibrium value while using productive and pricing efficiency. Firm 1's off-schedule constraints are then slack in state (L, H) ; therefore, so long as the upward on-schedule incentive constraints are slack,²⁴ firm 1 could give up some market share in state (L, H) without violating any incentive constraints. The feasibility of this utility transfer indicates that the firms originally could not have been implementing the corner, v_N^I . Part (ii) is similar to Proposition 2 (ii).

Finally, we consider whether the set of equilibrium values is itself convex. Since payoffs and constraints are nonlinear in market shares and prices (they depend on $q_{jk}^1, q_{jk}^1 \cdot p_{jk}$, and $(1 - q_{jk}^1) \cdot p_{jk}$), $\mathcal{F}^I(V)$ is not generally convex, and V^I may not be convex either. When prices are the same in two distinct equilibria, however, the nonlinearity does not pose a problem, and the convex combination of two equilibrium values can be implemented using a convex combination of the two associated policy vectors. In the next subsection we analyze conditions under which prices are always equal to the reservation value r when implementing values on the Pareto frontier of the equilibrium set.

□ **Pricing and continuation value efficiency.** We now consider the implementation of Pareto-efficient informative PPE values, and we establish important circumstances under which the

²⁴ We observe also that if IC-Oni $_D$ binds for firm i , then IC-Oni $_U$ can bind only if $\bar{q}_L^i = \bar{q}_H^i$, indicating productive inefficiency. We discuss below conditions under which IC-Oni $_D$ binds.

implementation of such values requires that pricing and continuation-value Pareto efficiency are used. These results indicate that even if firms are only moderately patient, when they collude optimally, they often maintain pricing and continuation-value Pareto efficiency. We explain as well that these properties imply that the downward on-schedule constraints are typically binding.

To begin, we consider the implementation of any Pareto-efficient equilibrium value such that (i) the off-schedule constraints are slack and (ii) the Pareto frontier is sufficiently wide, and the equilibrium value is sufficiently far from the corners of the Pareto frontier, v_N^I and v_E^I , that the firms implement the equilibrium value using continuation values strictly between v_N^I and v_E^I . As Proposition 1 indicates, these properties hold when implementing values in the neighborhood of v_s^I for discount factors that exceed δ^{FB} . However, conditions (i) and (ii) apply in a wider set of circumstances. In particular, for a range of moderate discount factors, there is a set of equilibrium values on the interior of the Pareto frontier that can be implemented with slack off-schedule constraints (though these constraints bind in subsequent periods, when implementing values that are sufficiently asymmetric).

Proposition 4. Let $(\mathbf{p}, \mathbf{q}, \mathbf{v})$ implement a Pareto-efficient utility pair in V^I . Suppose that the off-schedule constraints hold with slack, and $v_N^I < v_{jk}^I < v_E^I$ for all (j, k) . Then (i) continuation values are Pareto efficient and (ii) prices are efficient.

Part (i) is proved by showing that it is possible to adjust continuation values in pairs (moving them closer together, farther apart, or increasing both) in ways that do not affect the incentive constraints but move the values closer to the Pareto frontier. Part (ii) follows because it is always possible to raise prices and lower continuation values to keep the firms indifferent, and we establish in part (i) that continuation values below the frontier can be strictly improved upon.

We next establish conditions under which pricing and continuation-value Pareto efficiency are necessary, even when we relax the constraint that the continuation values lie strictly between the corners of the Pareto frontier.

Proposition 5. Suppose that (3) holds. Suppose that $(\mathbf{p}, \mathbf{q}, \mathbf{v})$ implements a Pareto-efficient utility pair in V^I , the off-schedule constraints hold with slack, and further either (a) both v_{HH} and v_{LL} are on the interior of the line segment on the Pareto frontier of $co(V)$ with slope equal to -1 , or (b) $0 < q_{jj}^I < 1$ for $j \in \{L, H\}$. Then (i) continuation values are Pareto efficient and (ii) prices are efficient.

This result generalizes Proposition 4, under additional restrictions. To understand the restrictions, recall Lemma 5, which establishes that when (3) holds and the valuation set is rectangular, firms increase cartel profit by decreasing productive efficiency and increasing the efficiency of prices and continuation values.²⁵ As an extension of Lemma 4, this result implies that when the continuation value frontier is narrow and firms maximize cartel profit, they choose productive inefficiency over inefficient prices and continuation values.²⁶ It further implies that under (5), continuation-value Pareto efficiency and pricing efficiency hold at the start of the game, when implementing v_s^I .

So far, we have considered only the on-schedule constraints. We now make two observations about the effects of off-schedule constraints on pricing and continuation-value Pareto efficiency. First, off-schedule constraints place downward pressure on the prices of low-cost firms, to reduce their incentive to undercut the equilibrium price; however, we argue below that in some circumstances firms choose to give up productive efficiency before lowering price. Second, in establishing continuation-value Pareto efficiency, we employ arguments in which firms shift profits

²⁵ When (3) fails, cartel profits are maximized using productive efficiency, even at the expense of inefficient prices and continuation values. When firms implement asymmetric utility vectors, we expect that they then may use both pricing and continuation-value inefficiency, but we do not pursue this case further here.

²⁶ As Proposition 5 allows, when other transfer instruments are exhausted, an optimal cartel conceivably might implement a utility transfer with an inefficient continuation value, particularly in the (L, L) state, so as to draw utility from a firm while relaxing that firm's downward on-schedule constraint. This possibility does not arise in our computational examples, however.

across states of the world. When off-schedule constraints bind, the profit of a firm in a particular state of the world may be constrained, and our characterizations are more limited.

Finally, in Athey and Bagwell (1999), we consider the implications of pricing and continuation-value Pareto efficiency. Returning to the case in which the off-schedule constraints are slack, we find that if a Pareto-efficient utility pair $\mathbf{u} \in V^I$ can be implemented by some policy vector for which pricing and continuation-value Pareto efficiency holds, then there must exist a policy vector that implements \mathbf{u} for which each firm's downward on-schedule constraint binds.²⁷ Intuitively, given that the frontier is concave, asymmetric continuation values are associated with future inefficiency; therefore, unless behavior is constrained by off-schedule considerations, if asymmetric continuation values are used to provide incentives for greater productive efficiency, then they should be used to the minimal extent possible. More generally, this finding confirms that the relevant on-schedule concern is indeed the incentive of high-cost firms to mimic low-cost firms.

□ **Productive efficiency.** We establish above conditions under which firms use pricing and continuation-value Pareto efficiency when implementing Pareto-efficient utilities. We argue now that the case for productive efficiency is then weaker. The key reason is that when the efficiency frontier is concave, a tradeoff arises between productive efficiency today and inefficiency in the future.

To begin, we establish sufficient conditions under which productive efficiency is used. Our result applies to all points on the Pareto frontier, with no additional restrictions. In particular, off-schedule constraints may or may not bind.²⁸ The result generalizes Lemma 3 beyond budget-balanced transfers: since low-cost firms find high market share relatively more attractive, firms will use asymmetric continuation values to provide incentives for productive efficiency, if the future inefficiency is not too great.

Proposition 6. Choose any Pareto-efficient utility pair in V^I and let $(\mathbf{p}, \mathbf{q}, \mathbf{v})$ be the policy vector that implements this pair. Then productive efficiency holds in state (L, H) (i.e., $q_{LH}^1 = 1$) if $p_{LH} > \theta_H$ and if there exists $\varepsilon > 0$ such that

$$1 + \Delta_\varepsilon^- f(v_{LH}^1) \equiv 1 + [f(v_{LH}^1) - f(v_{LH}^1 - \varepsilon)]/\varepsilon < (\theta_H - \theta_L)/(p_{LH} - \theta_L). \tag{6}$$

Productive efficiency holds in state (H, L) (i.e., $q_{HL}^1 = 0$) if $p_{HL} > \theta_H$ and if there exists $\varepsilon > 0$ such that

$$1 + \Delta_\varepsilon^+ f(v_{HL}^1) \equiv 1 + [f(v_{HL}^1 + \varepsilon) - f(v_{HL}^1)]/\varepsilon > -(\theta_H - \theta_L)/(p_{HL} - \theta_L). \tag{7}$$

As suggested, productive efficiency is used when implementing Pareto-efficient utilities, if the continuation values in the (L, H) and (H, L) states are drawn from regions of the frontier at which the frontier slope does not depart too greatly from -1 . Since (5) implies that the frontier has a linear portion, it then follows that some productive efficiency is used at the start of the game, when implementing v_s^I .²⁹

Proposition 6 provides sufficient but not necessary conditions for productive efficiency. We now tighten the characterization under the assumptions that the off-schedule constraints are slack,

²⁷ This statement allows that firms might be indifferent among a range of equally desirable implementation schemes (as might occur if continuation values lie on a linear segment of the frontier).

²⁸ We do, however, maintain the assumption that points on the Pareto frontier are implemented using pure strategies. Given that the static Nash equilibrium is described by mixed strategies, this implies that the discount factor exceeds some minimal level.

²⁹ Under (5) a symmetric scheme may be implemented, with $q_{jk}^i = 1/2$, $p_{jk} = r$, and $v_{jk} = v_s^I$ for all (j, k) . This is a best scheme with no productive efficiency. Propositions 2 and 6 then imply that this scheme is Pareto-dominated by an alternative scheme with at least some productive efficiency, implemented using v_{LH} and v_{HL} (at least weakly) outside the interval of the Pareto frontier with slope -1 .

the upward on-schedule constraints are slack, and utility is transferrable without efficiency loss (as in conditions (a) and (b) of Proposition 5). For example, under (3), these assumptions imply pricing and continuation-value Pareto efficiency (by Proposition 5); yet, as we now confirm, the case for productive efficiency is then weaker.

Proposition 7. Suppose that $(\mathbf{p}, \mathbf{q}, \mathbf{v})$ implements an equilibrium value \mathbf{u} on the Pareto frontier of V^I and either assumption (a) or (b) of Proposition 5 is satisfied. Further, suppose that the off-schedule constraints and IC-Oni_{*U*} are slack for each *i*. Finally, select an implementation such that $p_{LH} = p_{HL} > \theta_H$, $q_{LH}^1 = q_{HL}^2$, $v_{LH}^1 = v_{HL}^2$, and no other such policy vector implements \mathbf{u} using a larger q_{LH}^1 .³⁰ Then $q_{LH}^1 \in (1/2, 1)$ and $q_{HL}^1 \in (0, 1/2)$ if and only if for all $\varepsilon > 0$,

$$1 + \Delta_\varepsilon^+ f(v_{LH}^1) \leq \frac{\theta_H - \theta_L}{p_{LH} - \theta_H + \eta_L(\theta_H - \theta_L)} < 1 + \Delta_\varepsilon^- f(v_{LH}^1). \tag{8}$$

Further, $q_{LH}^1 = 1/2$ and $q_{HL}^1 = 1/2$ if and only if the second inequality holds at $v_{HL}^1 = v_{LH}^1 = v_s^{I1}$, while $q_{LH}^1 = 1$ and $q_{HL}^1 = 0$ if and only if the second inequality fails.

One implication of this result is that if $v_E^{II} - v_N^{II} < (r - \theta_H)/\delta$ (the minimum width required to implement productive efficiency using pricing and continuation-value Pareto efficiency), there is productive inefficiency even in the first period of play, when implementing v_s^I , so long as the off-schedule constraints do not bind. Further, we see that if future inefficiency is extreme, so that $\Delta_\varepsilon^- f(v_s^{I1}) = 0$, the second inequality in (8) holds when $p_{LH} = r$ if and only if (3) holds. Thus, we can interpret Proposition 7 as a generalization of Lemma 4. In general, firms implement some productive efficiency; however, they stop short of full productive efficiency if the slope of the frontier gets too steep or too flat and, in particular, if the frontier is too narrow.^{31,32}

Let us now summarize our characterizations of Pareto-efficient collusive schemes for firms of moderate patience. First, we find that firms are willing to bear a moderate future inefficiency to gain productive efficiency in the present. Second, when off-schedule constraints do not bind, and either the Pareto frontier is wide enough or (3) holds, the firms maintain pricing and continuation-value Pareto efficiency, even at the possible expense of productive efficiency. Finally, the firms may sacrifice even pricing and continuation-value Pareto efficiency when they attempt to implement asymmetric equilibrium values, if the off-schedule incentive constraints prevent the use of future market-share favors in the event of ties. Thus, for firms of moderate patience, we expect to start the game using fairly efficient schemes (at worst, there is some productive inefficiency), but the schemes may incorporate additional inefficiencies following a series of one or more cost realizations whereby one firm has lower cost than another.

□ **Computational examples.** In this subsection we develop a computational example to illustrate some of the tradeoffs and themes developed above. We begin by offering some remarks about our computational approach. Motivated by Abreu, Pearce, and Stacchetti (1990), we specify a set V^0 and then compute $V^t = \tilde{T}^I(V^{t-1})$ for $t = 1, \dots$, iterating until the distance between the sets becomes lower than a given tolerance level (.0001 in our computations). To operationalize this algorithm, a natural method is to divide each set V^t into a grid and then check that members of this grid survive to become members of V^{t+1} . This approach is slow, however. Following Wang

³⁰ Multiple policy vectors may implement the same equilibrium value. Then, we consider schemes that are symmetric in that $p_{jk} = p_{kj}$, $v_{jk}^1 = v_{kj}^2$ and $q_{jk}^1 = q_{kj}^2$ for $j \neq k$, and select the policy vector with the highest level of productive efficiency. The equilibrium value can be implemented in this way, as long as utility is transferrable.

³¹ Additional characterizations can be provided. For example, if the upward on-schedule constraints are slack, then for ε sufficiently small, if $\Delta_\varepsilon^- f(v_{HH}^1) < -1$, then $q_{HH}^1 = 1$, and if $\Delta_\varepsilon^+ f(v_{HH}^1) > -1$, then $q_{HH}^1 = 0$. In other words, the firms take the market shares to the extreme before incurring future inefficiency in state (H, H) .

³² It also may be shown that, if off-schedule constraints are slack, f is differentiable and all continuation values are interior, then Pareto-efficient points require $f'(v_{LH}^1) \cdot f'(v_{HL}^1) = f'(v_{LL}^1) \cdot f'(v_{HH}^1)$. Intuitively, the continuation values are chosen to balance the inefficiencies incurred in each state of the world.

(1995), we use a trick that speeds up the computations.³³ At the start of the algorithm, we divide the set $[0, r/(1-\delta)]$ into a fixed grid. The grid represents the set of feasible continuation values for firm 2, and these are the only values ever permitted for firm 2. On each iteration of the algorithm, we compute the set of continuation values for firm 1 that can be sustained for each utility level for firm 2 on this grid.

To further ease the computational burden, we impose two restrictions. First, we assume that firms punish off-schedule deviations by reverting to the static Nash equilibrium. This restriction does not directly affect the qualitative characterization of the efficiency frontier, since in the computations firms only leave the efficiency frontier off the equilibrium path. Repeating the computations using lower punishments affects only the level of the discount factor at which different types of equilibria can be supported. Second, we consider only equilibria where firms use pricing efficiency on the equilibrium path. This restriction certainly matters for impatient firms, but without it the computation becomes much more complex. Given the restrictions we have imposed, the equilibrium sets we construct should be interpreted as lower bounds on the Pareto frontier of equilibria.

In Figure 5 and Table 3, and in Figure 6 and Table 4, we illustrate equilibrium sets for particular parameter values.^{34,35} Consider Figure 5 in relation to Proposition 4. Neither the off-schedule constraints nor the constraints on the width of the Pareto frontier are binding for the policy vectors that implement states 9 to 22, and thus our characterizations from Proposition 4 apply for those states. Continuation-value Pareto efficiency indeed holds: in every state, after every realization of cost types, the firms move to another state on the Pareto frontier. Given that, the diagram only labels and represents the Pareto frontier. Similar results hold in Figure 6, where the conditions of Proposition 5 are satisfied when implementing states 9 to 17. Observe that the Pareto frontier is narrow, and the implementation of Pareto-efficient utilities is achieved with continuation values that fall on the corners (following the (L, H) and (H, L) states). Nevertheless, as Proposition 5 requires, the continuation values are always Pareto efficient.

Now consider productive efficiency in Figure 5 and Table 3. Notice that for a wide range of states (9 to 22), productive efficiency is (approximately) implemented, as predicted by Proposition 6: at the extreme continuation values (in states (L, H) and (H, L)) associated with these states, the slope of the frontier is always within the bounds specified in (6) and (7). Further, states 9 to 21 use the same extreme continuation values ($v_{LH} = 24$ and $v_{HL} = 3$); due to concavity of the frontier, increasing or decreasing both continuation values would reduce total utility across the two firms. Notice also that the firms use productive inefficiency when implementing the asymmetric values of the Pareto frontier. In particular, states 3 and 24 use productive inefficiency; since these states (or less efficient ones) are reached with positive probability from every starting point, even the most profitable points on the Pareto frontier yield less than the first-best profits. This is consistent with Proposition 6: when implementing state 24, $v_{LH} = 26$, the corner of the Pareto frontier, and so (6) fails, indicating that productive efficiency is not necessarily optimal.

Now consider Figure 6 and Table 4. Across all but the most extreme states, the overall level of productive efficiency is approximately the same, with $q_{LH}^1 + q_{HL}^2$ approximately equal to 1.57, and incentives for truth-telling are provided in a similar fashion, with the firms going to state 1 following a realization of (H, L) and to state 20 following a realization of (L, H) . These states correspond to the corners of the frontier, and so the fact that firms achieve only partial productive efficiency is consistent with Proposition 6. However, consistent with Proposition 5, the firms do

³³ Wang's approach builds on Phelan and Townsend (1991). Recently, Judd, Yeltekin, and Conklin (2000) have developed approaches to computation that, if extended to this model, could be more efficient. As our aim is only to illustrate the theoretical results, we do not pursue this here.

³⁴ Observe that the computations yield slightly asymmetric continuation values across the two firms; this arises as a result of the computational algorithm, which treats one firm's profit as discrete and the other's as continuous.

³⁵ On the region where the continuation-value frontier is approximately linear, there are often many ways to implement a given value; but, due to the discretization of the frontier, the firms may have a strict preference among alternative collusive schemes giving approximately the same utility. Thus, behavior sometimes "jumps" among nearby states.

FIGURE 5
A SELF-GENERATING EQUILIBRIUM SET FOR FIRMS OF MODERATE PATIENCE

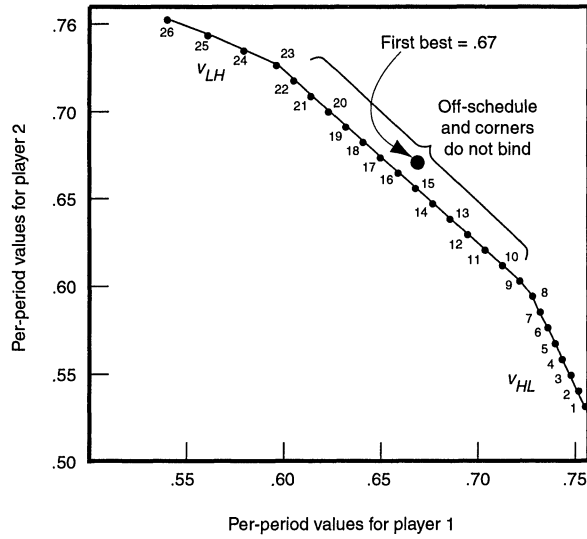
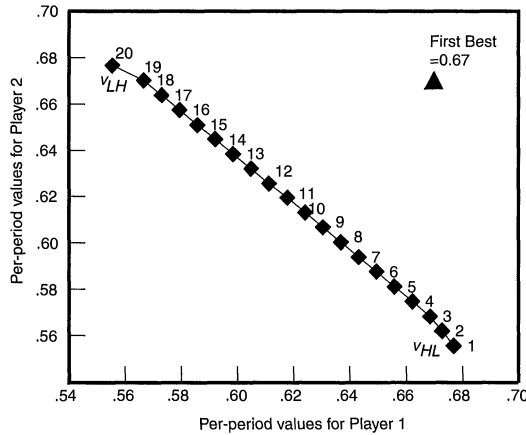


TABLE 3

State/Realization	Transitions				Player 1 Market Shares			
	(L, L)	(L, H)	(H, L)	(H, H)	(L, L)	(L, H)	(H, L)	(H, H)
1	7	12	2	13	.649	.983	.556	1.000
2	10	14	3	15	.700	.998	.529	1.000
3	9	15	1	13	.675	.994	.407	1.000
4	7	17	3	11	.648	.994	.345	1.000
5	7	18	1	10	.641	.966	.231	1.000
6	8	20	2	10	.659	1.000	.184	1.000
7	10	21	1	11	.691	.995	.104	1.000
8	8	23	1	8	.660	.999	.003	1.000
9	12	24	3	12	.733	.989	.000	.995
10	13	24	3	13	.704	.989	.000	.926
11	13	24	3	13	.652	.989	.000	.847
12	13	24	3	13	.600	.989	.000	.769
13	13	24	3	13	.548	.989	.000	.691
14	13	24	3	13	.495	.989	.000	.612
15	13	24	3	13	.443	.989	.000	.534
16	13	24	3	13	.391	.989	.000	.456
17	13	24	3	13	.339	.989	.000	.377
18	13	24	3	13	.286	.989	.000	.299
19	13	24	3	13	.234	.989	.000	.221
20	13	24	3	13	.182	.989	.000	.142
21	18	24	3	18	.246	.989	.000	.110
22	20	25	5	20	.271	.998	.000	.057
23	21	26	8	21	.288	.971	.000	.022
24	22	26	11	21	.305	.825	.000	.037
25	23	26	14	20	.323	.672	.000	.012
26	21	26	18	18	.286	.468	.000	.110

FIGURE 6
A SELF-GENERATING EQUILIBRIUM SET



not use continuation-value inefficiency to implement higher levels of productive efficiency. Finally (and similar to Figure 4), to implement the extreme states, somewhat greater productive inefficiency is required. Thus, colluding firms capture some productive efficiency in the first period of the game, but at the cost of greater inefficiency in the future. The result is a concave Pareto frontier.

TABLE 4

State/Realization	Transitions				Player 1 Market Shares			
	(L, L)	(L, H)	(H, L)	(H, H)	(L, L)	(L, H)	(H, L)	(H, H)
1	3	18	1	18	.529	.996	.485	1.000
2	3	19	1	18	.518	.994	.453	1.000
3	3	20	1	18	.511	.992	.414	1.000
4	3	20	1	16	.527	.918	.340	1.000
5	3	20	1	16	.516	.885	.307	1.000
6	6	20	1	18	.553	.843	.265	1.000
7	3	20	1	14	.521	.778	.201	1.000
8	3	20	1	13	.524	.725	.147	1.000
9	5	20	1	14	.550	.679	.101	1.000
10	5	20	1	14	.539	.646	.068	1.000
11	5	20	1	14	.528	.613	.035	1.000
12	5	20	1	9	.518	.577	.000	.850
13	5	20	1	9	.485	.577	.000	.800
14	15	20	1	12	.592	.577	.000	.591
15	5	20	1	9	.420	.577	.000	.701
16	5	20	1	9	.387	.577	.000	.652
17	5	20	1	9	.354	.577	.000	.603
18	10	20	1	12	.391	.577	.000	.520
19	16	20	1	12	.442	.577	.000	.319
20	19	20	4	10	.479	.497	.000	.202

5. Informative versus uninformative communication

■ We now consider the role of communication. We begin by contrasting the case of informative communication with the opposite possibility, where firms are unable or unwilling to communicate. Building on this analysis, we then discuss the qualitative features of the set of unrestricted PPE, where firms choose whether to use informative communication in any period as a function of the history of play.

Recall the extensive-form game defined in Section 2. Any communication occurs first and then firms make pricing decisions and market-share proposals, where the market-share proposals affect outcomes only when prices are equal. In this game, to capture a situation in which firms are unable or unwilling to communicate, we simply specify that firms use the uninformative announcement $\alpha^i(\theta^i) = N$ in all states of the world. Following this announcement, if firms charge the same price, they must share the market.³⁶

In this context, how are the firms affected by requiring announcements to be uninformative? This requirement has both a cost and a benefit. The cost is easily understood: in the absence of informative communication, the set of market-sharing arrangements that can be implemented is restricted, since state-contingent arrangements are then feasible only when they are compatible with decentralized decision making. But how severe is this restriction?

In our Bertrand setting, the restriction is less severe than one might expect. For example, a simple no-communication scheme sets $\rho^2(\theta_H) = \rho^1(\theta_H) = r$ and $\rho^2(\theta_L) = \rho^1(\theta_L) = r - \Delta$. This yields productive efficiency, equal market shares in ties, and approximate pricing efficiency (for $\Delta > 0$ and small). Similarly, by setting $\rho^2(\theta_H) = r$, $\rho^1(\theta_H) = r - \Delta$, $\rho^2(\theta_L) = r - 2\Delta$, and $\rho^1(\theta_L) = r - 3\Delta$, the firms may continue to achieve productive and approximate pricing efficiency, but now firm 1 wins all ties.

Despite these examples, the restriction is real. First, in our Bertrand setting, many market-sharing arrangements are infeasible without informative communication. For example, any arrangement with $q_{jk}^i \notin \{0, .5, 1\}$ requires informative communication. Second, our Bertrand model understates the actual cost of decentralized behavior, as it abstracts from a variety of benefits to communication and “advanced planning” that naturally arise in other models. In the Bertrand model, firms bear the cost only for realized market share, and it is costless to be “prepared” to serve those consumers. Other models, such as Cournot, would entail much greater costs to decentralization.³⁷ To capture costs of this kind, we define $\Delta \geq 0$ as the minimum price difference that can be perceived by consumers (e.g., pennies or dollars), so that $\Delta > 0$ provides a crude means of representing the cost of allocating market shares decentrally, through price differences. We interpret $\Delta = 0$ as an approximation for the case where Δ can be arbitrarily small.

The absence of informative communication also has a benefit, once the off-schedule constraints are considered. When informative communication is absent, each firm must be dissuaded from deviating after observing its own type, but before knowing the type of the other firm. In other words, the off-schedule incentive constraints bind at the interim stage. For example, suppose that an equilibrium specifies $q_{LL}^1 = 1/2$, $q_{LH}^1 = 1$, $q_{HL}^1 = 0$, and $q_{HH}^1 = 1/2$. This market-share allocation can be achieved without informative communication. If the firms communicate, IC-Off 1_{LL}^1 might bind, because after communication, firm 1 knows that the state is (L, L) and is tempted to cut price slightly and pick up the remaining half of the market. By contrast, if the firms do not communicate, a low-cost firm 1 is unaware of firm 2’s cost type, so that its expected market share is $\eta_H + (1 - \eta_H)(1/2) > 1/2$, leaving less to gain from a deviation. The absence of informative communication can thus promote cooperation, by preserving uncertainty about opponent play and softening the off-schedule incentive constraint. Notably, uninformative

³⁶ As we show in Athey and Bagwell (1999), if firms were allowed to withhold quantity in a decentralized way, the range of outcomes would expand somewhat, but the qualitative results of this section would not change.

³⁷ In a Cournot model, without communication, colluding firms typically suffer large inefficiencies: a high-cost firm produces, just in case the opponent is high cost, but this is wasteful if the opponent is low cost. In contrast, when the firms can communicate, they can pick one firm to produce, who selects its monopoly output given its cost type.

communication relieves some of the pressure to give up productive efficiency that is present in an informative PPE, since it becomes easier to maintain $q_{LH}^1 = 1$ and lower q_{LL}^1 without violating the off-schedule constraints.

To formally represent the incentive constraints under uninformative communication, let $p_{jk} = \min\{\rho^1(\theta_j), \rho^2(\theta_k)\}$ be the transaction price for state (j, k) . The market share received by firm 1, q_{jk}^1 , is determined as described in Section 2. Finally, let v_{jk}^1 represent the continuation value for firm 1 that is induced by the price selections $\rho^1(\theta_j)$ and $\rho^2(\theta_k)$. The on-schedule constraints are again represented by IC-Oni_D and IC-Oni_U. To define the off-schedule constraints, it is somewhat easier to refer directly to the decentralized pricing strategies. For $j \in \{L, H\}$, and for Δ sufficiently small, IC-Off1_j^U is defined as

$$\sum_{k \in \{L, H\}} \eta_k [q_{jk}^1 (p_{jk} - \theta_j) + \delta v_{jk}^1] \geq \max((\rho^2(\theta_L) - \Delta - \theta_j), \eta_H(\rho^2(\theta_H) - \Delta - \theta_j), 0) + \delta \underline{v}^1,$$

while the corresponding constraint for firm 2, IC-Off2_k^U, is defined analogously.

For a given continuation-value set V , we now define a function $C(\mathbf{p}, \mathbf{q}, \mathbf{v})$, where $C : \mathfrak{R}_+^4 \times [0, 1]^4 \times V^4 \rightarrow \{0, 1\}$. We let $C(\mathbf{p}, \mathbf{q}, \mathbf{v}) = 0$ if there exist decentralized pricing strategies $(\rho^1(\cdot), \rho^2(\cdot))$ that can induce the specified prices, market shares, and continuation values, while $C(\mathbf{p}, \mathbf{q}, \mathbf{v}) = 1$ if informative communication is necessary.³⁸ When $C(\mathbf{p}, \mathbf{q}, \mathbf{v}) = 1$, the off-schedule constraints defined previously, IC-Offi^I and IC-Off-Mi, are appropriate, while the IC-Offi^U constraints are appropriate if $C(\mathbf{p}, \mathbf{q}, \mathbf{v}) = 0$. The feasible set when firms use uninformative communication is written

$$\mathcal{F}^U(V) = \{\mathbf{z} = (\mathbf{p}, \mathbf{q}, \mathbf{v}) \in \mathcal{Z}(V) : C(\mathbf{p}, \mathbf{q}, \mathbf{v}) = 0; \text{ for all } i = 1, 2, j \in \{L, H\}, \\ \text{IC-Oni}_D, \text{IC-Oni}_U \text{ and IC-Offi}_j^U \text{ hold}\}.$$

As the off-schedule constraints are different from the case of informative PPE, neither $\mathcal{F}^U(V)$ nor $\mathcal{F}^I(V)$ is a subset of the other. Following our earlier arguments, the set of uninformative PPE, V^U , can then be characterized as the largest invariant set of the following operator:

$$\tilde{T}^U(V) = \{(u^1, u^2) : \exists \mathbf{z} = (\mathbf{p}, \mathbf{q}, \mathbf{v}) \in \mathcal{F}^U(V) \text{ such that for } i = 1, 2, u^i = \bar{U}^i(\mathbf{z})\} \cup \mathbf{u}^{NE}.$$

An initial observation is that in an uninformative PPE, even if firms collude at the reservation price and the off-schedule constraints are slack, the set of feasible policy vectors $\mathcal{F}^U(V)$ is not convex. Thus, the set of equilibrium values may not be convex, so that we rely more heavily on our assumption that firms can randomize among continuation equilibria.

We now discuss circumstances under which restricting communication might hurt firms if the off-schedule constraints do not bind. Consider the choice of q_{LH}^1 . In regions where the continuation-value frontier is too steep or too flat, or if it is too narrow, Propositions 6 and 7 establish that the firms implement productive inefficiency. In such cases, intermediate values of q_{LH}^1 are optimal, so that the restriction to uninformative communication may be costly. More formally, observe that the tradeoff between productive efficiency and future inefficiency can be characterized in a manner analogous to Proposition 6. A scheme $(\mathbf{p}, \mathbf{q}, \mathbf{v})$ where $q_{LH}^1 = 1/2$ can be improved upon by a scheme where $\tilde{q}_{LH}^1 = 1$ and \tilde{v}_{LH}^1 is chosen to satisfy IC-On1_D (holding the rest of the scheme fixed), if

$$1 + [f(v_{LH}^1) - f(\tilde{v}_{LH}^1)] / (v_{LH}^1 - \tilde{v}_{LH}^1) < (\theta_H - \theta_L) / (p_{LH} - \theta_L).$$

However, if the frontier is too narrow, or if it eventually becomes too steep, firms sacrifice

³⁸ Notice that, when $C(\mathbf{p}, \mathbf{q}, \mathbf{v}) = 0$, continuation values can only be state-contingent to the extent that the state of the world is revealed by the prices.

productive efficiency even if (6) holds so that, were it available, a *small* increase in q_{LH}^1 (holding the market shares in other states fixed) would increase profits. Thus, restricting communication may lead to greater productive inefficiency.

Circumstances may exist, therefore, under which cartel profits are reduced when firms are prohibited from informative communication. But is the possibility of such losses eliminated when firms are sufficiently patient? We establish next that even when communication is prohibited, there exists a critical discount factor strictly less than one above which first best is attained when $\Delta = 0$. In particular, the linear self-generating segment constructed in Proposition 1 can be implemented without communication, when the discount factor exceeds a critical value δ^{NC} (provided in the Appendix), where $\delta^{NC} \leq \delta^{FB}$. For this implementation, a lower critical discount factor is obtained without communication, because it is then easier to implement the “corner” value of the equilibrium set, (x, y) . Since the firms use productive efficiency, firm 1 has no incentive to deviate in state (L, H) ; by contrast, in state (L, L) , firm 1 produces less than unity (in the implementation we use, $q_{LL}^1 = 0$), and the off-schedule constraint binds under informative communication. By refraining from communication, the firms pool the (L, L) off-schedule constraint with the nonbinding (L, H) off-schedule constraint.

Proposition 8. Assume (4). Then, for all $\delta \in [\delta^{NC}, 1]$ and $\Delta = 0$, there exist values $y > x > 0$ such that $x + y = 2\pi^{FB} / (1 - \delta)$, and the set $[(x, y), (y, x)] \cup \mathbf{u}^{NE}$ is a self-generating set of uninformative PPE values.

Restrictions on communication thus hurt collusive ventures only if firms are moderately patient or Δ is large. At the same time, it is important to emphasize that the proof of Proposition 8 exploits the assumed ability of noncommunicating firms to randomize over continuation play. Absent this ability, for a range of discount factors firms could achieve first-best profits only if some histories were followed with informative communication.

Finally, consider unrestricted PPE. In each period, the firms first choose whether or not to use informative communication. If so, they reveal their types and face the IC-Off i^I constraints; otherwise, they choose from a restricted set of market-share and price policies, but they face the relaxed IC-Off i^U constraints. Formally,³⁹

$$\tilde{T}(V) = \{(u^1, u^2) : \exists \mathbf{z} = (\mathbf{p}, \mathbf{q}, \mathbf{v}) \in \{\mathcal{F}^U(V) \cup \mathcal{F}^I(V)\} \text{ such that for } i = 1, 2, u^i = \bar{U}^i(\mathbf{z})\} \cup \mathbf{u}^{NE}.$$

Communication enables firms to choose a policy vector from $\mathcal{F}^I(V)$ and implement market-sharing arrangements that are not available using decentralized schemes; however, when there is a significant gain from relaxing off-schedule constraints (e.g., $q_{LL}^1 < q_{LH}^1$) and when the “ideal” market shares are close enough to a scheme that can be implemented without communication, firms may refrain from communicating, choosing a policy vector from $\mathcal{F}^U(V)$. Such “breaks” in communication are especially likely when firms attempt to implement a very asymmetric utility pair.

So long as (4) holds and $\delta \geq \delta^{FO}$ is not the limiting factor, for $\Delta > 0$ there will be a region of discount factors (which contains $[\delta^{FB}, 1]$) such that firms choose to communicate on the equilibrium path. On the other hand, there may be a lower region of discount factors where, for Δ sufficiently small, firms sometimes avoid communication on the equilibrium path, and collusive profits are equal to first-best profits, less the distortion due to Δ . For such a region, the option to refrain from communication allows strictly higher profits than a purely informative PPE. The following example illustrates.

□ **Selective communication: an example.** For the parameter values from our example, when firms use Nash reversion to punish off-schedule deviations ($\lambda = 1$), we compute $\delta^{NC} = .704$, which is less than .769, the lowest discount factor that supports first best using informative

³⁹ Observe that the firms have available the same “worst punishment” irrespective of whether they choose to communicate on the equilibrium path.

communication. The difference in critical discount factors persists for each value of λ . Maintaining $\lambda = 1$ and $\Delta > 0$, firms strictly prefer to communicate in every period when $\delta \in [.769, 1)$, but for each $\delta \in (.704, .769)$, there is a Δ small enough such that firms strictly prefer a regime of no communication on the equilibrium path to a scheme of communication in every period.

However, the firms can do better still by using a strategy of selective communication. Suppose $\lambda = 1$, $\delta \in (.704, .769)$, and Δ is small but positive. Then, firms prefer to communicate (saving Δ) when implementing fairly symmetric equilibrium values (for example, following a realization of (L, L) , as in Figure 3) and to avoid communication when implementing asymmetric equilibrium values (for example following realizations of (L, H) and (H, L)). Under this scheme of selective communication, total profits are lower (due to $\Delta > 0$) when asymmetric equilibrium values are implemented.

6. Bribes

■ In this section we extend the base model to allow for bribes. The following stage is added to the extensive-form stage game: (v) firm i sends $b^i \geq 0$ to firm j ; firm j receives γb^i . The extended model is called the bribes model. Communication is not necessary to implement bribes, since the firms can condition bribes on the market shares realized *ex post*. However, to simplify the exposition, we restrict attention to informative communication. The exogenous parameter $\gamma \in [0, 1]$ describes the inefficiency of the bribe: $\gamma = 1$ corresponds to the use of money without any transaction costs; $\gamma = 0$ corresponds to no transfers; and $\gamma \in (0, 1)$ corresponds to the case where there is some probability that a bribe will be detected by antitrust authorities, or where firms can only make in-kind transfers that have some inherent inefficiency.

Formally, the utility function with bribes for firm 1 is denoted

$$U^{B1}(\hat{j}, j | z, b) = U^1(\hat{j}, j | z) + \sum_{k \in \{L, H\}} \eta_k (\gamma b_{jk}^2 - b_{jk}^1)$$

and likewise for firm 2. The on-schedule constraints, denoted IC-Oni $_U^B$ and IC-Oni $_D^B$, are redefined using U^{Bi} as the interim utility function. To represent the off-schedule constraints, we observe that optimal collusion never requires a state in which both firms send bribes, since, with $\gamma \leq 1$, the desired net transfer can be achieved most efficiently if a single bribe is made. Then the off-schedule constraint for firm 1 is⁴⁰

$$\gamma b_{jk}^2 - b_{jk}^1 + \delta(v_{jk}^1 - \underline{v}^1) \geq \max(q_{jk}^2(p_{jk} - \theta_j), q_{jk}^1(\theta_j - p_{jk})). \tag{IC-Off1 $_{jk}^B$ }$$

IC-Off2 $_{jk}^B$ is defined analogously; likewise, IC-Off-Mi B is constructed from IC-Off-Mi in the natural way. Let $\mathcal{F}^{IB}(V)$ be defined as $\mathcal{F}^I(V)$, once the utility functions and constraints from the base model are replaced with those in the bribes model. The policy vector is now (z, b) , where $z = (p, q, v)$. Finally, with *ex ante* utility given as $\bar{U}^{Bi}(z, b)$, let

$$\tilde{T}^B(V) = \{(u^1, u^2) : \exists (p, q, v, b) \in \mathcal{F}^{IB}(V) \text{ such that for } i = 1, 2, u^i = \bar{U}^{Bi}(z, b)\} \cup \mathbf{u}^{NE}.$$

We denote the set of PPE values in the bribes model as V^B , which following our previous arguments is the largest invariant set of \tilde{T}^B . Let v_s^B be the point on the Pareto frontier of V^B that gives equal utility to both agents.

We establish first that bribes do not fully replace market-share favors in implementing Pareto-efficient equilibrium values:

⁴⁰ When IC-Off1 $_{jk}^B$ holds, if firm 1 is assigned to send a bribe, it never has the incentive to withhold the bribe following production. After production, firm 1 adheres to equilibrium play if $\gamma b_{jk}^2 - b_{jk}^1 + \delta(v_{jk}^1 - \underline{v}^1) \geq 0$, which holds by IC-Off1 $_{jk}^B$. Intuitively, it is more tempting to deviate before production, so as to avoid paying the bribe and capture the market.

Proposition 9. (i) Suppose that $(r - \theta_L)/2 < \delta(v_s^{1B} - v^1)$. For all $\gamma < 1$, if $(\mathbf{p}, \mathbf{q}, \mathbf{v}, \mathbf{b})$ implements v_s^B and uses any productive efficiency ($q_{LH}^1 > 1/2$), then the associated PPE is nonstationary. If $\gamma = 1$, there exists a nonstationary PPE that implements v_s^B . (ii) Assume (4). For all $\gamma < (=) 1$, there exists $\delta^B < 1$ such that, for all $\delta \in [\delta^B, 1]$, bribes are *never* used (respectively, not necessary) along the equilibrium path in the most profitable PPE for the cartel.

To establish part (i), we note that the supposition implies that the off-schedule constraints do not bind at the symmetric point on the Pareto frontier of V^B . As in the proof of Proposition 2, the frontier thus has an open interval of slope -1 . It is therefore initially more efficient to use market-share favors than inefficient bribes. For part (ii), we recall that Proposition 1 establishes a critical discount factor beyond which first best can be attained without bribes; hence, if bribes are at all inefficient, they are not used.⁴¹

Next, we characterize the use of bribes to provide incentives for productive efficiency, when firms are not patient enough to implement first best:

Proposition 10. Fix δ and γ , and suppose that $(\mathbf{p}, \mathbf{q}, \mathbf{v}, \mathbf{b})$ implements a Pareto-efficient utility pair in V^B . Suppose that $p_{HL}, p_{LH} > \theta_H$. If $1 - \gamma < (\theta_H - \theta_L)/(p_{LH} - \theta_L)$ and $1 - \gamma < (\theta_H - \theta_L)/(p_{HL} - \theta_L)$, then the scheme uses productive efficiency.

The proof of this result follows as in Proposition 6, which established that even if the off-schedule constraints bind, firms use productive efficiency unless the continuation values are not available or require too much future inefficiency. Figure 7 illustrates how bribes augment the set of continuation values. Note that no restrictions on the discount factor are required, although the hypothesis of the theorem requires existence of a utility pair in V^B that can be implemented using pure strategies (recall the mixed-strategy static Nash equilibrium also entails productive efficiency).

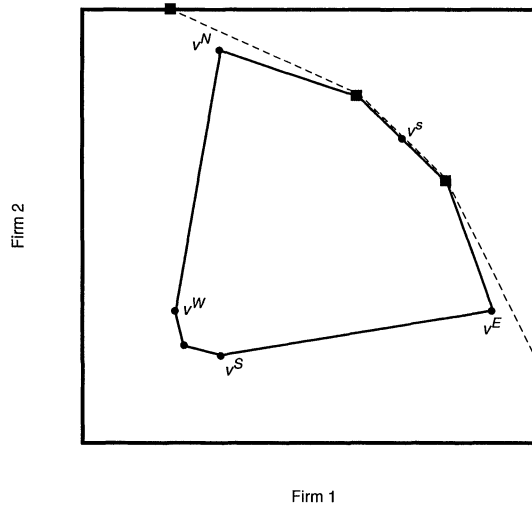
Thus, so long as bribes are suitably efficient, firms use productive efficiency to implement Pareto-efficient equilibrium values. This analysis highlights an important theme: the main factor limiting productive efficiency in an optimal collusive scheme is the availability of an instrument for efficiently transferring utility. In the absence of bribes, if firms achieve productive efficiency today, then the utility transfer is effected through market-share favors tomorrow; furthermore, as Proposition 2 establishes, this utility transfer entails a future inefficiency if in tomorrow's tied states the off-schedule constraints bind or the firms run out of market-share favors. When bribes are available, however, firms have a less-constrained instrument with which to achieve the desired utility transfer. Bribes can thus enable an improvement in productive efficiency, provided that the direct inefficiency of bribes, as measured by $(1 - \gamma)$, is sufficiently small.⁴²

These results have two main implications for applied analysis of collusion. First, we observe that market-share favors are a robust feature of collusive ventures, so long as bribes are inefficient and individual firm behavior can be tracked over time. Second, our results have subtle and potentially perverse policy implications. For many discount factors and parameter values, firms can sustain collusion at high prices, and the only issue for the cartel is the extent to which they can implement productive efficiency. Bribes then may enable the cartel to achieve greater productive efficiency, and so a policy that prohibits bribes may reduce welfare. On the other hand, for moderate discount factors, a prohibition on bribes may lower collusive profits enough that collusion takes place only at substantially lower prices. For moderately patient firms, a prohibition on bribes may raise consumer welfare.

⁴¹ In a continuum-type model, the Pareto frontier has slope equal to -1 at the Pareto-efficient equilibrium providing equal utility to both firms, if firms are sufficiently patient such that the off-schedule constraints permit small future market-share favors. Thus, for any $\gamma < 1$, even in a continuum-type model, bribes do not fully replace future market-share favors.

⁴² In Athey and Bagwell (1999), we consider the use of bribes in symmetric PPE. If $1 - \gamma < (\theta_H - \theta_L)/(r - \theta_L)$ and firms are sufficiently patient, the optimal symmetric collusive scheme is stationary, and it entails productive efficiency, pricing efficiency, and the use of bribes. This scheme can be implemented without informative communication.

FIGURE 7
BRIBES AUGMENT THE SET OF FEASIBLE CONTINUATION VALUES



7. Conclusions

■ From a methodological perspective, our analysis offers several contributions. First, our article is the first of which we are aware to provide tools for characterizing the optimal use of market-share favors by impatient firms. Depending on the antitrust environment, different instruments are available, and impatient firms may face real tradeoffs among those instruments. We identify these tradeoffs and explore them theoretically as well as by using computational examples. Second, we develop the precise connections between static and dynamic analyses of collusion, making clear the similarities and differences, and laying the groundwork for treating other repeated-game problems within the mechanism-design framework. Third, our work motivates some new questions for static mechanism design, and takes some initial steps toward addressing them.⁴³

The results in this article are motivated by the problem of collusion, but they also apply in other contexts. At a general level, our model considers interactions between agents—such as family members, workers in a firm, or politicians—who must repeatedly take actions in an environment with two main characteristics: first, each agent’s cost or benefit of taking the action changes from period to period, where the actual change is private information; and second, there are limits on the agents’ ability to use side-payments. Essentially, the repeated play of any of the standard multiagent mechanism design problems (public goods, auctions, bargaining) fits into the framework, with the additional assumption of restricted transfers.⁴⁴ Private information is easy to motivate. Family members may be privately informed about how tired they are on a particular day, and thus how costly it is to perform household work. Likewise, division heads within a firm may have private information about the efficiency of access to a resource, and politicians may have private information about the costs of legislation. The scope for transfers is also often limited: families may share a common budget, division heads may share a common resource, and payments for votes may be illegal. Social norms may also prohibit monetary transfers.⁴⁵

⁴³ For example, we examine how restrictions on transfers (for instance, to a convex set) affect optimal mechanisms. In the literature on collusion, only a limited class of restrictions on transfers has received attention. See McAfee and McMillan (1992).

⁴⁴ See also the macroeconomics literature (e.g., Green (1987) or Atkeson and Lucas (1992)), which has analyzed repeated games with private information between a central planner and a continuum of agents. A few articles (Wang (1995), Cole and Kocherlakota (1998)) consider small numbers of agents, but the focus is on existence or computational methods.

⁴⁵ Holmström and Krep (1996) study the use of “promises” in repeated games. Our analysis differs in that we bring together the tools of dynamic programming and mechanism design to characterize optimal equilibria for firms for a

In the context of the collusion application, our analysis suggests several directions for further research. For example, we show that a more antagonistic antitrust policy may have perverse welfare effects: successfully colluding firms often tolerate productive inefficiency before lowering prices. This conclusion, however, is perhaps sensitive to our Bertrand model, and it would be interesting to consider this feature further in a model with differentiated products or Cournot competition. Additionally, our work suggests new empirical directions. Allowing for a sophisticated cartel design, we find here that optimal collusion is complex, with considerable market-share instability. By contrast, Athey, Bagwell, and Sanchirico (1998) restrict attention to symmetric equilibria and show that a simple price-fixing agreement with stable market shares is then optimal for patient firms. In combination, this work may be useful in providing a theoretical framework with which to interpret the empirical factors that influence the cartel organizational form.⁴⁶ As a further example, we note that the collusion literature does not distinguish well between market-share allocation schemes that implement productive efficiency and those that do not. For example, bid-rotation schemes are common in auctions, and Comanor and Schankerman (1976) analyzed all prosecuted cases of bid rigging over a 50-year period, but they did not distinguish between “standard” bid rotation schemes and “sophisticated” bid rotation schemes that might achieve productive efficiency. Further study of the legal testimony may identify those schemes that made use of market-share favors or bribes to implement productive efficiency.

Appendix

■ Proofs of Lemmas 3–5 and Propositions 1–8 follow.

Proof of Lemma 3. Imposing pricing efficiency, productive efficiency, and Pareto-efficient continuation values, it is straightforward to show that IC-On1_D and IC-On2_D respectively bind if and only if

$$0 = [r - \theta_H]\{\eta_H(q_{HH}^1 - 1) - \eta_L q_{LL}^1\} + \delta\{\eta_H(v_{HH}^1 - v_{LH}^1) + \eta_L(v_{HL}^1 - v_{LL}^1)\},$$

and

$$0 = -[r - \theta_H]\{\eta_H q_{HH}^1 + \eta_L(1 - q_{LL}^1)\} - \delta\{\eta_H(v_{HH}^1 - v_{HL}^1) + \eta_L(v_{LH}^1 - v_{LL}^1)\}.$$

Adding the constraints yields the necessary condition $v_{HL}^1 - v_{LH}^1 = (r - \theta^H)/\delta$, and we may choose the remaining market shares and continuation values to respect the additional conditions in the lemma while satisfying each of the above constraints. *Q.E.D.*

Proof of Lemma 4. We posit that IC-Oni_D binds for all *i*, and substitute in from (1) for $U^i(L, L; \mathbf{z})$. We solve a relaxed program:

$$\begin{aligned} & \max_{\substack{q_{LL}^2, q_{LH}^2, q_{HH}^2, q_{HL}^2 \in [0,1] \\ p_{LH}, p_{HH}, p_{HL} \leq r; v_H^2, v_H^2 \leq K}} \sum_{j \in \{L, H\}} \eta_j \cdot q_{jH}^2 \cdot (p_{jH} - \theta_H) + \delta \bar{v}_H^2 + \eta_L \cdot \bar{q}_L^2 (\theta_H - \theta_L) \\ & + \lambda \left[\sum_{k \in \{L, H\}} \eta_k \cdot (1 - q_{Hk}^2) \cdot (p_{Hk} - \theta_H) + \delta \bar{v}_H^1 + \eta_L \cdot (1 - \sum_{k \in \{L, H\}} \eta_k q_{Lk}^2) (\theta_H - \theta_L) - u^1 \right] \\ & + \psi^1 \cdot \left[\sum_{k \in \{L, H\}} \eta_k q_{Hk}^2 - \sum_{k \in \{L, H\}} \eta_k q_{Lk}^2 \right] + \psi^2 \cdot [\bar{q}_L^2 - \bar{q}_H^2]. \end{aligned}$$

Let λ be the multiplier on firm 1’s utility constraint, which is nonnegative on the Pareto frontier. The multipliers on the monotonicity constraints are denoted ψ^i , and these are also nonnegative. By inspection, it is clearly optimal to set

given discount factor, and we explicitly model the tradeoff between different kinds of side-payments (future favors versus bribes).

⁴⁶ There is little existing empirical work on the determinants of cartel organizational form. See, however, the empirical analysis of American shipping cartels presented by Deltas, Serfes, and Scotte (1999). They find that some cartels used simple price-fixing agreements while other cartels were considerably more complex.

$p_{Hk} = r$, $p_{jH} = r$, and $\bar{v}_H^i = K$; then, differentiating with respect to the market-share variables, we get

$$\begin{aligned} \frac{\partial}{\partial q_{LL}^2} &: (1 - \lambda) \cdot \eta_L^2(\theta_H - \theta_L) - \psi^1 \eta_L + \psi^2 \eta_L \\ \frac{\partial}{\partial q_{HH}^2} &: (1 - \lambda)[\eta_H(r - \theta_H)] + \psi^1 \eta_H - \psi^2 \eta_H \\ \frac{\partial}{\partial q_{LH}^2} &: \eta_L(r - \theta_H) - \lambda \eta_L \eta_H(\theta_H - \theta_L) - \psi^1 \eta_H - \psi^2 \eta_L \\ \frac{\partial}{\partial q_{HL}^2} &: \eta_L \eta_H(\theta_H - \theta_L) - \lambda \eta_L(r - \theta_H) + \psi^1 \eta_L + \psi^2 \eta_H. \end{aligned}$$

(i) Under (3), if we maximize the sum of firms' utilities ($\lambda = 1$), then $\psi^1 = \psi^2 = 0$ implies that $\partial/\partial q_{LH}^2 > 0 > \partial/\partial q_{HL}^2$, which implies a boundary solution that is dominated by a symmetric solution with $q_{jk}^i = 1/2$ for all (j, k) . Now suppose that we weight the firms evenly ($\lambda = 1$), put $\psi^1 + \psi^2 > 0$, and consider asymmetric solutions ($\bar{q}_L^i > \bar{q}_H^i$). If $\psi^2 > 0$, then firm 2's monotonicity constraint binds, so that $\bar{q}_L^i = \bar{q}_H^i$. Suppose then that $\psi^1 > 0 = \psi^2$. Then, the objective is increasing in q_{HH}^2 and decreasing in q_{LL}^2 , so we take $q_{HH}^2 = 1$ and $q_{LL}^2 = 0$. But then $\bar{q}_L^i > \bar{q}_H^i$ only if $\eta_H q_{HL}^2 > \eta_H + \eta_L q_{LH}^2$, a contradiction.

Thus, we have established that the largest joint utility available to the firms is achieved by "pooling," where $\bar{q}_L^i = \bar{q}_H^i$, and that allowing for asymmetric allocations of utility will not improve the sum of utilities. This scheme satisfies all of the constraints in $\mathcal{F}_{On}^I(V)$. So, an upper bound for the sum of (current-period) utilities is given by $r - E[\theta]$. Now observe that for any $\alpha \in [0, 1]$, we can allocate $\alpha(r - E[\theta])$ to firm 1 and $(1 - \alpha)(r - E[\theta])$ to firm 2 by simply changing the market shares of the firms while maintaining $\bar{q}_L^i = \bar{q}_H^i$. Since this satisfies the on-schedule constraints, the Pareto frontier is given as in the statement of the lemma.

(ii) Under the alternative assumption that (3) fails, inspection of the program shows that profits are highest when $q_{LH}^2 = 0$ and $q_{HL}^2 = 1$. The monotonicity constraints do not bind. At these values, the relaxed program is independent of p_{LH} and p_{HL} . This scheme can be implemented by using pricing efficiency in state (H, H) ($p_{HH} = r$), $v_{jk}^i = K$ for all i, j, k , and productive efficiency. The truth-telling constraints can be satisfied as follows: find $\hat{p} < r$ to be used by all low-cost types. With $q_{LL}^i = q_{HH}^i = 1/2$, truth-telling by a high-cost firm requires

$$\frac{1}{2} \eta_H(r - \theta_H) = (\eta_H + \frac{1}{2} \eta_L)(\hat{p} - \theta_H),$$

yielding the price stated in the lemma. It is now direct to derive the utility frontier. *Q.E.D.*

Proof of Proposition 1. The formal program for determining $d^F(\lambda)$ is given by

$$\begin{aligned} d^F(\lambda) &\equiv \arg \min_{\delta \in [0, 1]} \delta \\ \text{such that } \mathbf{z} &\in \mathcal{Z}(V); \text{ for all } i, j, k, \text{ IC-Oni}_D \text{ and IC-Oni}_U \text{ hold;} \\ (x, y) &= (\bar{U}^1(\mathbf{z}), \bar{U}^2(\mathbf{z})); x + y = 2\pi^{FB}/(1 - \delta); \\ x \leq v_{jk}^i &\leq y; \text{ IC-Off}_{ijk} \text{ holds, letting } \underline{v}^i = \lambda \pi^{NE}/(1 - \delta). \end{aligned}$$

To determine δ^{FB} , which is an upper bound on $d^F(\lambda)$ that holds for all parameter values, we solve a set of equations. Consider the following system (imposing pricing efficiency, productive efficiency, and $v_{jk}^2 = 2\pi^{FB}/(1 - \delta) - v_{jk}^1$ for all (j, k)): IC-On1_D, IC-On2_D, $\bar{U}^1 = x$, $\bar{U}^2 = y$, $v_{LH}^1 = x$, $v_{HH}^1 = x$, $q_{HH}^1 = 0$, and $q_{LL}^1 = 0$. It can be verified that under our assumption that $\eta_L > 1/2$, $v_{LH}^1 < v_{LL}^1$. In particular, $v_{LL}^1 - v_{LH}^1 = (2\eta_L - 1)/\eta_L \cdot (r - \theta_H)/\delta$. Since $(2\eta_L - 1)/\eta_L \in (0, 1)$, this implies $v_{LH}^1 < v_{LL}^1 < v_{HL}^1$, where the latter inequality follows since the downward on-schedule constraints imply that $v_{HL}^1 = v_{LH}^1 + (r - \theta_H)/\delta$. It remains to verify that given our solutions to these equations, $v_{HL}^1 = x + (r - \theta_H)/\delta < y$. We can compute

$$y - x = \frac{\eta_L^2(\theta_H - \theta_L) - (r - \theta_H)(2\eta_L - 1)}{1 - \delta}.$$

This expression is always positive under our restrictions $\eta_L > 1/2$ and (4). δ^{Fon} , as stated in the text, solves $y - x = (r - \theta_H)/\delta$. It can be verified that $y - x > (r - \theta_H)/\delta$ for all $\delta > \delta^{Fon}$.

Consider now the off-schedule constraints. We observe first that IC-Off1_{LH}^I is slack, as is IC-Off-M1. Further, using the implementation described above, IC-Off1_{HH}^I implies IC-Off1_{HL}^I. We then substitute in the values for q_{jj}^1 and v_{jj}^1 computed above, impose repeated-Nash payoffs ($\lambda = 1$) as the off-equilibrium-path punishment and verify that IC-Off1_{LL}^I binds and IC-Off1_{HH}^I is slack when $\delta \geq [\eta_L + \kappa(1 - \eta_L)]/[\eta_L + \kappa(1 - \eta_L) + \eta_L^2 \kappa]$ and (4) holds. Finally, since for the endpoints of the interval, we have described a policy vector that meets all our constraints and uses as continuation values other values on the same interval, we can then construct the remainder of the line segment using convex combinations of

policy vectors to implement convex combinations of equilibrium values. This is possible because, when pricing efficiency is imposed, the constraints and utilities are linear in market shares and continuation values. Thus, we have constructed a self-generating set of equilibrium values with first-best profits to the cartel. *Q.E.D.*

Proof of Lemma 5. (i) To implement (x, y) , let IC-On 1_D hold with equality, and let $p_{jk} = r$, $v_{LH} = v_{LL} = (x, y)$, $v_{HH} = v_{HL} = (y, x)$, and $q_{HL}^1 = q_{HH}^1 = 0$. Letting $K_1 = \kappa(1 + \delta) + \delta\eta_L(1 + \eta_L)$, this yields $q_{LH}^1 = q_{LL}^1 = \delta(\kappa + \eta_L)/K_1$, and by setting $x = \bar{U}^1$ and letting $y = \bar{U}^2$, we calculate $x = \delta(\eta_L + \kappa)^2 / ((1 - \delta)K_1)$ and $y = (\eta_L + \kappa)(\delta\eta_L + \kappa) / ((1 - \delta)K_1)$. Finally, use repeated-Nash payoffs as the off-the-equilibrium-path threat point. Notice that IC-On 2_D and IC-On 2_U both hold with equality given these values, and IC-On 1_U is slack. Further, IC-Off 1_{jH}^1 is equivalent to IC-Off 1_{jL}^1 for each j , IC-Off 2_{HH}^1 and IC-Off 2_{HL}^1 are slack, and IC-Off 2_{LL}^1 implies IC-Off 2_{LH}^1 .

To analyze the remaining off-schedule constraints, a series of tedious algebraic manipulations are required. First, IC-Off 1_{HH}^1 is satisfied whenever IC-Off 1_{LL}^1 is (the additional slack is given by $(\delta\eta_L^2 + \kappa)/K_1$). Second, if we multiply both sides of IC-Off 1_{LL}^1 by the positive number $(1 - \delta)K_1$, both sides of the resulting inequality are quadratic in δ , and in the relevant range, increasing δ makes the inequality easier to satisfy. The critical value of δ where the constraint binds is the solution to that quadratic equation. Letting $A = \eta_L^2(1 + \eta_L^2) + \kappa(\kappa + \eta_L + 2\eta_L^2)$, $B = \kappa(\eta_H + \kappa) - \eta_L^2$, and $C = -\kappa(1 + \kappa)$, the relevant solution is $\delta_{1LL} = (-B + \sqrt{B^2 - 4AC})/2A$.

Third, there are some parameter values where IC-Off 2_{LL}^1 binds but IC-Off 1_{LL}^1 is slack, since q_{LL}^1 varies with parameters. If we multiply both sides of IC-Off 2_{LL}^1 by the positive number $(1 - \delta)K_1/\delta$, both sides of the resulting inequality will be linear in δ , and increasing δ makes the inequality easier to satisfy. The critical value of δ where IC-Off 2_{LL}^1 binds is given by

$$\delta_{2LL} = (\eta_L + \kappa(1 + \eta_L - \eta_L^2)) / (\eta_L + \eta_L^4 + \kappa(1 + \kappa + \eta_L + \eta_L^2)).$$

Then, for all $\delta > \max(\delta_{1LL}, \delta_{2LL})$, both IC-Off 1_{LL}^1 and IC-Off 2_{LL}^1 are slack.

(ii) When implementing the utility value $((1/2)(x + y), (1/2)(x + y))$, since prices are always equal to r , a convex combination of the policy vectors used to implement (x, y) and (y, x) can be used, so that for each i , $q_{LL}^i = 1/2$, $v_{LL}^i = (1/2)(x + y)$, and IC-Off i_{LL}^1 holds with slack. Together with the fact that $v_s^i \geq ((1/2)(x + y), (1/2)(x + y))$, this implies (5) must hold. *Q.E.D.*

Proof of Proposition 2. (i) The symmetric point of the Pareto frontier of $\bar{T}(V)$ can be implemented with $q_{jj}^i = 1/2$ and $v_{jj}^i = v_{jj}^2$. Before beginning, we observe that we can take $p_{jj} > \theta_j$ without loss of generality. To see why, observe that if $\theta_j - p_{jj} > 0$, we can raise p_{jj} by ε and lower v_{jj}^i by $\varepsilon/(2\delta)$ until we arrive at \hat{p}_{jj} and \hat{v}_{jj} , where $\theta_j = \hat{p}_{jj}$, without affecting any utilities or incentive constraints (since an optimal off-schedule deviation would ensure zero market share in state jj). To see that the resulting \hat{v}_{jj}^i is feasible, observe that given market share of $1/2$, our assumption that IC-Off i_{jj}^1 is slack implies that $(1/2)(\theta_j - p_{jj}) < \delta(v_{jj}^i - v^i)$; since the adjustments preserve this inequality, the new continuation value \hat{v}_{jj}^i must satisfy $\hat{v}_{jj}^i \geq v^i$. Since the set of feasible continuation values is convex and symmetric, it is feasible. Finally, if $\theta_j - p_{jj} = 0$, we may employ a similar adjustment, unless $v_{jj}^i = v^i$. But in this case (5) is violated.

Starting from this point, our approach is to implement an alternative utility pair, with no efficiency loss, in which \bar{U}^1 is decreased and \bar{U}^2 is increased. We define three perturbations. In perturbation 1, we lower q_{HH}^1 by $\varepsilon/((p_{HH} - \theta_L)\eta_H)$ and lower q_{LL}^1 by $\varepsilon/((p_{LL} - \theta_L)\eta_L)$. For each firm i , IC-On i_U is unaltered by this perturbation. In perturbation 2, we lower q_{HH}^1 by $\varepsilon/((p_{HH} - \theta_H)\eta_H)$ and lower q_{LL}^1 by $\varepsilon/((p_{LL} - \theta_H)\eta_L)$. For each firm i , this perturbation leaves unaltered IC-On i_D . In perturbation 3, we lower q_{jk}^1 by ε for each $(j, k) \in \Omega$. For each firm i , no on-schedule incentive constraint is altered by this perturbation. In each of the perturbations, *ex ante* utility is transferred from firm 1 to firm 2 without efficiency loss.

There are several cases to consider. Suppose first that all on-schedule incentive constraints are binding. This implies that $\bar{q}_L^i = \bar{q}_H^i$ for each i . In a symmetric implementation, this requires that $q_{jk}^i = 1/2$ for each i, j, k . Unless off-schedule constraints bind (which (5) rules out), the best way to implement this market-share arrangement is to set $p_{jk} = r$ and $v_{jk}^i = v_s^i$ for each $(j, k) \in \Omega$. But, when off-schedule constraints are slack, we can use perturbation 3 and reduce (or increase) market share for player i by ε in each state, without affecting the on-schedule constraints. This effects a transfer of utility of $\varepsilon(r - E\theta)$. Suppose second that, for a given $\psi \in \{U, D\}$, IC-On i_ψ is slack for each i . If $\psi = U$, we use perturbation 2 to engineer the desired utility transfer without violating on-schedule incentive constraints. Likewise, if $\psi = D$, we use perturbation 1. Next, we modify the argument for the case where the on-schedule constraints are slack in different directions. First, take the case where IC-On 1_D and IC-On 2_U are slack. If $p_{LL} \leq p_{HH}$, we use perturbation 1, which relaxes IC-On 2_D by $(p_{HH} - \theta_H)/(p_{HH} - \theta_L) - (p_{LL} - \theta_H)/(p_{LL} - \theta_L)$, which is positive by our assumption that $p_{LL} \leq p_{HH}$. If $p_{LL} \geq p_{HH}$, we use perturbation 2. This relaxes IC-On 1_U by $(p_{HH} - \theta_L)/(p_{HH} - \theta_H) - (p_{LL} - \theta_L)/(p_{LL} - \theta_H)$, which is positive. Similarly, in the second case, where IC-On 1_U and IC-On 2_D are slack, we proceed as follows: if $p_{LL} \leq p_{HH}$, we use perturbation 2, which relaxes IC-On 2_U by $(p_{LL} - \theta_L)/(p_{LL} - \theta_H) - (p_{HH} - \theta_L)/(p_{HH} - \theta_H)$, which is positive; and if $p_{LL} \geq p_{HH}$, we use perturbation 1, which relaxes IC-On 1_D by $(p_{LL} - \theta_H)/(p_{LL} - \theta_L) - (p_{HH} - \theta_H)/(p_{HH} - \theta_L)$, which is positive.

(ii) Suppose that (a) and the first part of (b) fail: IC-Off 1_{LL}^1 and IC-Off 1_{HH}^1 are slack, and $v_{LL}^1 > x$ and $v_{HH}^1 > x$. Then, lower v_{HH}^1 by ε/η_H and lower v_{LL}^1 by ε/η_L , and raise the corresponding values for firm 2 by the same amount

(this is possible because $v_{jj}^1 > x$ and the set of available continuation values is convex). This does not affect any on-schedule constraints, relaxes firm 2's off-schedule constraints, and decreases \bar{U}^1 and increases \bar{U}^2 with no efficiency loss, contradicting the hypothesis that (x, y) is the end point of the region with slope equal to -1 . Now consider the case where (a) and the second part of (b) fail: IC-Off1 $_{LL}^I$ and IC-Off1 $_{HH}^I$ are slack, $q_{LL}^1 > 0$ and $q_{HH}^1 > 0$, and $p_{jj} > \theta_j$ for each j . We show in Proposition 6 that under the assumptions of this proposition, $\bar{q}_L^i > \bar{q}_H^i$, which implies that for each i , one of IC-On i_D and IC-On i_U is slack. We may now apply the algorithm used in the proof of part (i) to implement a utility pair that yields lower (higher) utility for firm 1 (2), without efficiency loss, contradicting the hypothesis that (x, y) is the endpoint of a region with slope equal to -1 . Q.E.D.

Proof of Proposition 3. (i) If each IC-On i_U is slack, prices are efficient, and $q_{LH}^1 = 1$, then IC-Off1 $_{LH}^I$ and IC-Off-M1 are slack, and we can decrease q_{LH}^1 and give the market share to firm 2 without violating any on-schedule constraints. But this makes firm 1 worse off and firm 2 better off, violating the hypothesis that the scheme implements a corner of v_N^I .

(ii) Suppose that (a) and the first part of (b) fail: IC-Off1 $_{LL}^I$ and IC-Off1 $_{HH}^I$ are slack, and $v_{LL}^1 > v_N^1$ and $v_{HH}^1 > v_N^1$. Then, for ε_1 small enough, there exists an $\varepsilon_2 > 0$ such that it is possible to lower v_{HH}^1 by ε_1/η_H and lower v_{LL}^1 by ε_1/η_L , and raise v_{HH}^2 by ε_2/η_H and raise v_{LL}^2 by ε_2/η_L (this is possible because the set of available continuation values is convex and by the definition of v_N^1 as the north corner of the Pareto frontier). This does not upset any on-schedule constraints, and makes firm 1 worse off and firm 2 better off. There is potentially an efficiency loss, however. Next, we consider the case where (a) and the second part of (b) fail. We may then argue as in the proof of Proposition 2 and arrive at a contradiction. Q.E.D.

Proof of Proposition 4. The proof proceeds in a series of lemmas. Part (i) follows by Lemma A2, and part (ii) follows by Lemma A3. Q.E.D.

Lemma A1. Consider a scheme $(\mathbf{p}, \mathbf{q}, \mathbf{v})$. (T1j) If we subtract $\eta_L \varepsilon$ from v_{jH}^1 and add $\eta_H \varepsilon$ to v_{jL}^1 , \bar{U}^1 , IC-On1 $_D$ and IC-On1 $_U$ are unaffected. (T2j) If we add $\eta_H \varepsilon$ to v_{jL}^2 and subtract $\eta_L \varepsilon$ from v_{jH}^2 , \bar{U}^2 , IC-On2 $_D$ and IC-On2 $_U$ are unaffected.

Lemma A2. If $(\mathbf{p}, \mathbf{q}, \mathbf{v})$ satisfies $\mathcal{F}_{On}^I(V)$ and $v_N^1 > v_{jk}^1 > v_E^1$ for all (j, k) , then if $v_{jk}^2 < f(v_{jk}^1)$ for any (j, k) , this scheme is Pareto-dominated by another scheme that satisfies $\mathcal{F}_{On}^I(V)$, has all continuation values on the Pareto frontier of V , and uses the same prices.

Proof. Suppose that for some j , $v_{jH}^2 < f(v_{jH}^1)$ and $v_{jL}^2 < f(v_{jL}^1)$. Then, we can hold fixed firm 1's continuation values and increase v_{jH}^2 and v_{jL}^2 by the same amount without affecting firm 2's on-schedule constraints, thus increasing \bar{U}^2 . Then, suppose that $v_{jH}^2 = f(v_{jH}^1)$ and $v_{jL}^2 < f(v_{jL}^1)$. Then, apply Lemma A1, (T1j), so that neither continuation value is on the frontier. Then, both v_{jH}^2 and v_{jL}^2 can be increased, again increasing \bar{U}^2 without affecting \bar{U}^1 . The other case is analogous. Q.E.D.

Lemma A3. Suppose that $(\mathbf{p}, \mathbf{q}, \mathbf{v})$ implements a Pareto-efficient point in $\tilde{T}_{On}^I(V)$. For all (j, k) , if $v_N^1 > v_{jk}^1 > v_E^1$, then $p_{jk} = r$.

Proof. Suppose $p_{jk} < r$. Then we can increase p_{jk} by ε and decrease v_{jk}^1 and v_{jk}^2 by $(1/\delta)\varepsilon$ without affecting payoffs or on-schedule constraints. Then, we can improve utility by returning the continuation values to the frontier as in Lemma A2. Q.E.D.

Proof of Proposition 5. Under (3), Lemma 4 establishes that when the continuation value set has the shape $\{(u^1, u^2) : u^i \leq K\}$, total cartel profits go down when firms use Pareto-inefficient continuation values or prices. This logic can be applied directly here, observing that we are maximizing total profits because utility can be transferred across the firms (as in Proposition 2) under the conditions stated in the proposition. Q.E.D.

Proof of Proposition 6. First, suppose $q_{LH}^1 < 1$. Add $[\delta/(p_{LH} - \theta_L)]\varepsilon$ to q_{LH}^1 and subtract ε from v_{LH}^1 . If v_{LH} is on the Pareto frontier and $\Delta_\varepsilon^- f(v_{LH}^1) > -1$, move v_{LH}^2 along the frontier of V . Otherwise, raise v_{LH}^2 by ε (this is possible by convexity of the set of feasible continuation values, and since satisfaction of (6) implies $v_{LH}^1 > v_N^1$). This does not affect \bar{U}^1 . Consider now the effect on the interim expected utility of both firms: $U^1(H, H; \mathbf{z})$, $U^1(H, L; \mathbf{z})$, and $U^1(L, L; \mathbf{z})$ are unchanged; and $U^1(L, H; \mathbf{z})$ decreases. $U^2(L, H; \mathbf{z})$ and $U^2(L, L; \mathbf{z})$ are unchanged. $U^2(H, H; \mathbf{z})$ goes up if $-(p_{LH} - \theta_H)/(p_{LH} - \theta_L) - \max(-1, \Delta_\varepsilon^- f(v_{LH}^1)) > 0$, which when rearranged gives (6). $U^2(H, L; \mathbf{z})$ goes down if v_{LH}^2 increases by no more than ε , which it does by construction. Thus, the on-schedule incentive constraints are relaxed. Finally, none of firm 1's off-schedule constraints are affected by this shift, and firm 2's off-schedule constraints are relaxed. To see the result for q_{HL}^1 , we perform an analogous trick, subtracting $[\delta/(p_{HL} - \theta_H)]\varepsilon$ from q_{HL}^1 and adding ε to v_{HL}^1 , and noting that satisfaction of (7) implies that $v_{HL}^1 < v_E^1$ (recalling that in the definition of f , we specified a large negative slope for f when $v_{jk}^1 \geq v_E^1$). Q.E.D.

Proof of Proposition 7. Under the assumptions of the proposition, utility is fully transferable across the firms, and we can simply maximize the sum of firm utilities. Doing so leads to a symmetric scheme across states (L, H) and (H, L) , with one firm being favored over another in states (H, H) and (L, L) , if at all. Now imagine lowering q_{LH}^1 and raising q_{HL}^1 by ε , and then adjusting v_{LH}^1 and v_{HL}^2 upward by ζ until both firms' downward on-schedule constraints bind again. The

opponents' continuation values are moved along the frontier. Solving for ζ , we obtain

$$\frac{1}{1 - \eta_L(1 - \Delta_\xi^+ f(v_{LH}^1))} \frac{\varepsilon(p_{LH} - \theta_H)}{\delta}.$$

Calculations reveal that the first inequality in the statement of the proposition is necessary and sufficient for this change to lower total firm profit. The second inequality is necessary and sufficient for the firms' joint profit to decrease if we reverse this change. *Q.E.D.*

Proof of Proposition 8. The linear self-generating set of equilibria constructed in the proof of Proposition 1 implements the endpoints of the segment, (x, y) and (y, x) , using schemes that have market shares $q_{LH}^1 = 1$ and $q_{jk}^1 = 0$ for all other (j, k) . Consider a scheme whereby firm 1 chooses $\rho^1(\theta_H) = r$ and $\rho^1(\theta_L) = r - 2\Delta$, and $\rho^2(\theta_H) = r - \Delta$ and $\rho^2(\theta_L) = r - 3\Delta$. Using this scheme, the market shares are assigned appropriately. Further, each firm's announced price differs by state, so that continuation values can be contingent purely on prices. Thus, communication is not required to implement the scheme. Since firms can draw from a convex set of continuation values, all continuation values in between (x, y) and (y, x) are available to the firms, and the linear set is self-generating. To compute the critical discount factor, we follow in the first subsection of Section 4 and parameterize the worst available punishment using λ . Taking the limit as $\Delta \rightarrow 0$, using the appropriate off-schedule constraints for uninformative communication, and setting $\lambda = 1$, we compute the following bound:

$$\delta^{NC} = \max \left(\delta^{Fon}, \frac{\eta_L(2 - \eta_L) + \sqrt{(2 - \eta_L)^2 \eta_L^2 + 8\kappa(\kappa + \eta_L)}}{4(\kappa + \eta_L)} \right).$$

Q.E.D.

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