Strategy, Timing and Oligopoly Pricing: Evidence from a Repeated Game in a Timing-Controlled Gasoline Market*

September, 2005

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Abstract

A Western Australia law forces the retail prices posted by every gasoline station in the Perth metropolitan area to be set synchronously once every 24 hours. The oligopoly firms in this market are found to synchronize and homogenize intrabrand retail price increases. Short-term commitment arises endogenously and the Maskin and Tirole (1988) Edgeworth price cycle emerges as the equilibrium. The remarkable dataset generated by the experiment reveals critical phases of the Markov strategies followed by the players to generate the cycle equilibrium.

JEL: L13, L42

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* Special thanks to those industry participants who made comments on the structure of the gasoline industry in Australia. For helpful suggestions and comments, I thank John Cuddington, Ian Gale, Cheng Hsiao, Roger Lagunoff, Vai-Lam Mui, Yew-Kwang Ng and seminar participants at the 2004 International Industrial Organization Conference, 2004 Econometric Society Australasian Meetings, Australian National University, University of Melbourne, Monash University and Northeastern University. Jingjing Yang helped download the price data with superb patience and care. This research started when I was with Monash University, and received financial support from Monash University. I am solely responsible for the content of this paper.

1. Introduction

Strategic interaction is at the heart of oligopoly pricing. One of the major contributions that formalize strategic pricing is Maskin and Tirole's (1988, hereafter MT) dynamic oligopoly model. In this model, MT uses the concept of Markov perfect equilibrium to "capture the idea of reactions based on short-run commitment." Short-run commitment provides the foundation for asynchronous price setting and Markov reaction strategies. It is commonly thought that if the timing is synchronous, Markov strategy does not yield interesting outcome in the MT model, for exogenous commitment does not exist under synchronization. However, Lau (2001) shows that if strategic complementarity exists, short-term commitment can arise endogenously as the equilibrium outcome of a price and timing model. This result suggests that, even if the players are forced to set their prices synchronously, they may still be able to follow Markov strategies and reach the equilibrium outcome of the MT model.

This paper documents the pricing strategies used by the oligopoly players in a controlled market environment. Even though the firms in this market are forced to set their prices synchronously, they are found to increase their prices sequentially, follow Markov strategies and coordinate on the Edgeworth price cycle equilibrium constructed by MT.

The market studied in this paper is the gasoline market in the Perth metropolitan area,[1] Western Australia. A Western Australia state law, called the 24-hour-rule, took effect on January 2, 2001. This law requires (1) every gasoline station in the Perth metropolitan area and many other towns in the state to notify the government of its next day's retail price for each fuel type by 2:00pm each day so that the notified prices can be published on an internet website around 3:00pm, and (2) the published prices to be posted on the price board by the retailers at the beginning of the next day and to remain unchanged for 24 hours. This rule forces the

[1] Perth, located on the south-western coastline of Western Australia, is known as one of the most isolated metropolitan areas in the world. It has a population of slightly less than 1.5 million in 2003.

players in this market to set their next day's prices without observing those of their rivals', thus the timing of price setting is constrained to be synchronous. As a result of this law, the Perth gasoline market resembles closely the setup of a standard repeated game: a simultaneous-move price-setting stage game is repeated every 24 hours. Figure 1 depicts the daily Perth average price for regular unleaded gasoline from the start of the 24-hour-rule through October 31, 2003. The unit of gasoline price is Australian cents per liter. It is clear that a regular price cycle emerged about 4 months after the law took effect,[2] and this price cycle looks very similar in shape to the MT Edgeworth cycle. Is this price cycle a realization of the MT price cycle?

The MT price cycle equilibrium is generated by a set of Markov reaction strategies with two salient features. First, at the bottom of a cycle, because of the asynchronous-move assumption, the players have to resolve a coordination problem: although they all wish the price to be returned to the cycle top, each prefers to be the last to hike its price. MT assumes that the players use the mechanism of mixed strategy to resolve the coordination problem. Second, in a two-player model, once a player has hiked its price to start a new cycle, the other player's best response is to follow with a slightly smaller increase in the following period, thus forming a price leadership and followership system. The individual Edgeworth price cycles are repeated realizations of the underlying Markov strategies.

This paper examines whether the observed gasoline price cycles are random realizations of an MT cycle equilibrium by addressing three sets of questions. **First**, who are the strategic players in the Perth gasoline market that generate the price cycles? This is an important

[2] There was a regular price cycle in the Perth gasoline market before the 24-hour-rule (see, e.g., Australian Competition and Consumer Commission 2002). The experience with generating the price cycle before the 24-hour-rule may have helped the oligopoly firms to adjust to the 24-hour-rule. This, however, does not weaken this paper's contributions that short-term commitment can arise endogenously and that the firms can still coordinate on the MT Edgeworth price cycle equilibrium even if the timing is constrained to be synchronous. In fact, eliminating the price volatility was probably one of the political issues that led to the 24-hour-rule. The 24-hour-rule was mandated by the Parliament of Western Australia in December 2000 as a response to the October 2000 report, *Getting a Fair Deal for Western Australian Motorists*, by the Western Australian Parliament's Select Committee on Pricing of Petroleum Products.

question to ask since the MT price cycle is generated by the strategic interaction between a few oligopoly firms, but there are hundreds of gasoline stations in the Perth market and the oil firms in Australia by law can only own or operate about 5% of the retail stations. If the few oil firms are the strategic players, how do they control the retail price? **Second,** does the data show that short-term commitment arises in this timing-controlled market? Do the players hike their prices sequentially? If so, do they play mixed strategies to allocate the price leadership? **Third,** how do the followers react? Are the players' reactions consistent with the Markov restriction?

This paper is able to address directly these questions because of the structure of the MT model and the data available to this study. First, the MT price cycle is generated by oligopoly firms' strategic interaction in a stationary market environment. The core structure and predictions of the MT model is not driven by changing demand or cost conditions.[3] For this reason, in testing the MT model, the potential changes in the market conditions on a daily basis can be treated as random disturbances. Second, I have access to the complete record of the daily price for regular unleaded gasoline for all the gasoline stations in the Perth market over the entire sample period. This remarkable data set makes it possible to observe the players' strategy and timing in generating the price cycles without making compromising assumptions.

To preview the empirical approach and results, consider figures 2 and 3. Figure 2 plots the price level and price change from the previous day for 232 individual gasoline stations of five brands over a cycle of 6 days.[4] It is clear that price increases exhibit strong intrabrand synchronization and uniformity. This paper documents that the oil firms in the Perth market use special forms of vertical restraints (multi-site franchisee agreement and conditional price

[3] This is different from most supergame models where interesting dynamics are driven by uncertain or fluctuating demand (e.g., Green and Porter 1984, Rotemberg and Saloner 1986, Haltiwanger and Harrington 1991). Empirical studies that test these models include Porter (1983), Ellison (1994), and Borenstein and Shepard (1996).

[4] This six-day period is chosen in order to save space. The first five days constitute a full cycle and the sixth day is the starting day of the subsequent cycle. Note that the prices of the five largest brands (BP, Caltex, Shell, Mobil, and Gull) are displayed in the figure. Gull is an independent gasoline retailer. The number of stations shown in the figure for the five brands is 54, 81, 43, 20, and 34, respectively.

support) to exert great influence on the retail price. Figure 2 confirms strongly that the strategic players in the Perth market are the major oil firms (or their multi-site agents) or the independent gasoline retailers that control a large number of retail sites. Figure 3 shows the daily average price by brand for a period of 47 days.[5] It is apparent that the oligopoly firms raise their prices sequentially: one or more brands lift up their prices in big jumps and then the other brands follow on the second or third day. Figures 2 and 3 indicate that the individual price cycles can be clearly identified. The statistical properties of the key cycle parameters further indicate that the large number of observed price cycles can be viewed as repeated but independent realizations of the underlying firm strategies. Because a large sample of price cycles is observed, the underlying strategies can be uncovered with confidence.

The 24-hour-rule is a unique experiment that makes it possible to observe the oligopoly firms' strategy and timing in generating the price cycles. However, the phenomenon of gasoline price cycles is not unique in Perth under the 24-hour-rule. It had been occurring in Perth before the rule, and it has been taking place in other major Australian cities for over a decade (Australian Competition and Consumer Commission 2001). It is also taking place in a number of Canadian cities (Eckert 2002, 2003, Noel 2004b, 2005), and it was widespread in a large number of U.S. cities in the 1960s and early 1970s (Allvine and Patternson 1972). Due to severe data limitation, these studies, to be reviewed, have not attempted to address any of the three sets of issues posed in this paper.

This paper proceeds as follows. Section 2 reviews the MT approach to dynamic oligopoly pricing and related literature. Section 3 documents the industry context. Section 4 describes the data. Section 5 presents the cycle dynamics and tests the hypotheses. Section 6 concludes.

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[5] For clarity, only the four largest brands (BP, Caltex, Shell and Gull) are considered in this figure.

2. The MT Approach to Dynamic Oligopoly Pricing and Related Literature

A symmetric Bertrand duopoly game with a homogenous product is infinitely repeated in the MT dynamic pricing model. Different from the supergame framework, the players set their prices alternatingly (to capture short-term commitment) rather than simultaneously, and the strategy of each firm is defined as a Markov reaction function that specifies a price that the firm will set in response only to the price set by the other player in the previous period. MT showed that either the Edgeworth price cycle equilibrium or the kinked demand curve equilibrium can emerge as the outcome in this model.

A crucial assumption in the MT model is the existence of exogenous short-term commitment. If the players are forced to set their prices simultaneously, the prices set in the previous periods cannot serve as the state variable for the current period. It is for this reason that Markov strategy is thought not to yield interesting results if the timing is synchronous. However, if short-term commitment arises endogenously, Markov strategy may still be able to generate the MT results even if the timing of play is synchronous. The model of Lau (2001) indeed shows that short-term commitment and nonsynchronization will emerge endogenously as the equilibrium outcome of a more general model in which the players decide both the price level and whether to commit. The Lau model is an infinite-horizon timing and price game. The decision of a player in every period is two-dimensional: the level of price(s) and whether to make a commitment of two periods or no commitment. The game begins with two players making their decisions simultaneously so that either commitment or no-commitment could arise as the equilibrium outcome. Lau showed that if strategic complementarity exists, the two players are eventually committed for two periods and set their prices alternatingly.

The key to deriving the commitment result in the Lau model is the assumption that the players respond only to payoff-relevant variables. Let the product be differentiated so that strategic complementarity is present. In the absence of bootstrapping strategies,[6] a supergame of price competition is reduced to a series of one-short simultaneous-move Bertrand games with a differentiated product. An alternating-move dynamic game, on the other hand, can be viewed as a series of Stackelberg games. It is well known that the Stackelberg leader's payoff is higher than or equal to that in the simultaneous-move Bertrand game. The Stackelberg follower's payoff is also higher than the Bertrand payoff if strategic complementarity is present. Commitment thus leads to higher profits for both firms. Even though the MT model features Bertrand competition with a homogenous product, the force of strategic complementarity is present after one firm has raised its price.

An MT Edgeworth price cycle has **three** distinct phases. In what can be termed as the *falling phase*, each firm undercuts the other slightly until the price reaches the marginal cost. The size of undercutting is small because the firms do not want to rush back to the cycle bottom, since they are assumed not to use strategies of punishment nature. When the price does reach the cycle bottom, the *war of attrition phase* starts, in which the two players keep their prices at the competitive level waiting for the other player to raise its price first. The *rising phase* starts once one of the two firms decides to relent. The relenting firm hikes up its price, in a one-step jump, from the competitive level to about the monopoly level. After one firm has lifted up its price, the other firm's best response is to follow with a slightly smaller jump. The two sequential price-jumps, reminiscent of a price leadership and followership system, are due to the presence of strategic complementarity after the leader has raised its price. As long as the leader's price is higher, the follower's reaction function has a positive slope up to the monopoly

[6] In the standard supergame model of oligopoly pricing, a simultaneous-move Bertrand price competition game is discretely and infinitely repeated. Strategic interaction arises in this model because the players are assumed to follow bootstrapping strategies in the sense that they condition current prices on the entire history of the game even though past prices do not affect the payoffs in the current period.

price level. The leader, by raising its own price very high, is thus able to achieve the strategic benefit of starting a new cycle near the monopoly level.

The two firms engage in a war of attrition at the cycle bottom because both firms wish the price to be hiked, but neither would like to be the first to hike. Relenting has the properties of a public good. As mentioned, MT assumes that the players use the mechanism of mixed strategies to allocate the tasks of providing the public good over the price cycles. In a model with two symmetric firms, the two firms are equally likely to be the price leader for a given cycle. If the two players are of unequal size, as in Eckert (2003)'s extension of the MT model, the probability of being a price leader depends on their relative size. The mechanism of mixed strategies, however, may not resolve the free rider problem cleanly if the number of players is three or more. Wang (2005a) presents evidence from the trial record of a price-fixing case to show that the attempts to return price to the cycle top often failed in another Australia gasoline market with regular price cycles, despite the fact that the firms in that market used explicit communication to coordinate the price-hikes. Wang's (2005a) results suggest strongly that the coordination problem at the cycle bottom is hard to resolve if the number of players is large. It is thus not surprising that the individual gasoline stations in the Perth market are not the strategic players that generate the price cycles.

There exists a small but growing literature attempting to understand the phenomenon of gasoline price cycles. Motivated by the observation that the presence of gasoline price cycles in Canadian cities is correlated with the presence of small independent firms, Eckert's (2003) introduces size asymmetry into the MT model and shows that cycle equilibrium exists for any feasible relative firm size, but the kinked demand equilibrium cannot exist if one firm is much larger than the other. Noel (2004a) simulates the MT model and finds that price cycle can exist under a variety of market settings, including 2-player models with product differentiation, capacity constraints and market disturbances. On the empirical side, Castanias and Johnson (1993) is the first to recognize that the observed gasoline price cycles in Los Angeles in the late 1960s and early 1970s have the Edgeworth shape. Noel (2004b) also presents evidence that gasoline price cycles are more likely to occur in those Canadian markets with larger presence of independent firms. In an interesting application, Eckert (2002) finds evidence suggesting that Edgeworth cycle may explain why retail gasoline price responds quickly to wholesale price increase but slowly to wholesale price decrease. Weekly city-average price series are used in these empirical papers to study the observed price cycles.

Noel (2005) uses a self-collected data set of twice-daily retail prices for 22 gasoline stations over a four-month period to study the gasoline cycles in the Toronto gasoline market. Even a data set of twice-daily frequency, however, does not reveal the exact timing or size of the price changes, because, without any timing constraints, the firms in the Toronto market could change their prices at any time during a day. For this reason, the individual price cycles and their parameters cannot be easily identified. In addition, a small sample of retail gasoline stations does not allow one to focus directly on the pricing behavior of the vertically integrated major oil firms or independent gasoline firms in the Toronto market, which is much larger than the Perth market. Nonetheless, with the help of an econometric model based on the assumption that each retail station can have a price cycle of its own, Noel is able to separate the price data into a falling phase and a rising phase and show that the gasoline price cycles have the Edgeworth shape. Noel also finds that sites of major brands have higher estimated probabilities of initiating price hikes and sites of small brands are more likely to initiate price decreases.

In contrast, Wang's (2005a) study of the gasoline price cycle in the Australian city of Ballarat is based on a data set that records the exact timing (down to the minute) and size of the price increases. Wang (2005b) studies the nature of the stage game observed in the Perth gasoline market. Wang collected a number of gasoline stations' daily sales quantity and the wholesale prices they paid to the major oil firms. By matching the daily sales quantity with the daily price, Wang estimates the demand functions for the individual stations and finds that the stage game is very competitive (own price elasticity ranges from -5 to -19), and intertemporal substitution of demand between the stage games exists, but rather weakly. Wang (2005b) also documents the cycles in daily retail margins and sales quantities experienced by the independent stations as a result of the price cycles.

3. Industry Context[7]

3.1 The 24-hour-rule

The 24-hour-rule applies to the Perth metropolitan area and other regional centers of Western Australia (WA). As mentioned before, the rule came into effect on January 2, 2001. On that day, an internet website was launched to publish the retail fuel prices to be posted by every gasoline station at the beginning of the following day.[8] A day is defined as a calendar day, midnight to midnight, for the period before August 24, 2004, and since then is defined as the 24-hours from 6:00am to 6:00am. The website makes it very easy for internet users to search for not only today's price, but also the next day's price. Internet users can even register with the website and receive personalized fuel prices via email. Perhaps more drivers acquire price information from the evening TV news programs that broadcast the gasoline stations that post the most competitive prices for the following day. Drivers in Perth, if they wish, can search easily for the lowest retail price *before* driving their cars.

[7] This section draws heavily on the comments made by many industry participants.
[8] The website is: www.fuelwatch.wa.gov.au. The website starts with this message: "Welcome to FuelWatch - a unique Western Australian service which gives you, the motorist, the opportunity to make informed fuel purchases and potentially save hundreds of dollars a year." This website contains the background information of the 24-hour-rule.

The 24-hour-rule applies to five types of retail fuels: regular unleaded gasoline, premium unleaded gasoline, lead replacement gasoline, liquefied petroleum gas and diesel. The retail price to which the 24-hour-rule applies is the price at which the fuel is bought by customers who do not have contractual agreements with the major oil firms. Diesel is different from the other four types of fuels in that it is sold mainly to customers, such as truck companies, who have supply contracts with the oil firms. The diesel price posted on the price board applies only to diesel users who buy on the spot. Contract diesel users get an unobservable but known to be substantial discount off the posted retail diesel prices.

3.2 The Players in the Perth Gasoline Market

The strategic players in the Perth gasoline market are the few oil firms and independent gasoline retailers, not the individual gasoline stations. BP, Caltex, Mobil and Shell are the four oil firms operating in Australia. These firms are known to have great influences on the retail gasoline prices through special forms of vertical restraints to be documented in the following subsection. BP operates the only refinery in WA, and it supplies the vast majority of the petroleum products sold in this state. The other three oil firms sourced fuel products from BP through refinery exchange agreements before July 2002. These agreements are typical reciprocal trade arrangements that enable the oil firms to avoid the transportation costs of supplying customers in regions where they do not have refinery. This program collapsed in July 2002.[9] Caltex and Shell have since then started to buy fuel from BP in WA, but Mobil has been importing fuel from Singapore.

Three types of independent retailers are present in the Perth market: independent chains, independent dealer sites, and a supermarket chain. In the Perth market, Gull and Peak are the

[9] This is because BP increased the quality premium of its fuel, which was in turn triggered by the fact that, since January 2001, the fuel standard in WA had become stricter than those in other Australian states (ACCC 2002).

two major independent gasoline retail chains, and a much smaller one is Liberty. It is important to note that BP entered into an agreement to supply Gull with fuels around April 1998. Before that period, Gull imported fuels from Singapore. It is reasonable to expect that the wholesale price Gull has to pay BP is not higher than the cost of importing. For the sample period, Peak purchased from Mobil. Independent chain sites are operated on a commission agent basis. Gull and Peak have a negligible presence in the other states of Australia.

There are three types of independent dealer sites. One type carries an independent brand (Amgas, Better Choice, Kleenheat, Kwikfuel, Oasis and Wesco). The second type does not carry a brand, and most of these sites do not compete aggressively over gasoline price because selling fuel is not their main business. The retail prices for the vast majority of these sites do not exhibit regular cycles. These two types of independent dealer sites buy from the oil firms or the independent chains. Because they operate a small number of sites, they have limited ability to negotiate discounts on their fuel supplies. The third type of independent dealer sites carries one of the oil firm brands. They have supply contracts with an oil firm and pay a brand fee, but they set their retail prices independently.

Woolworths is the supermarket chain that operates retail gasoline stations. It offers a 4-cents discount to any customers whose grocery purchase from Woolworths is more than AU$ 30. The sample of this paper ends on October 31. Since then, another supermarket chain has entered into the gasoline retail markets in Perth and other major Australian cities by signing an agreement with Shell to offer a similar discount program. Woolworths has also entered into an agreement with Caltex to expand its discount program.[10]

[10] The impact of supermarkets' entry into the retail gasoline market is the subject of a separate study.

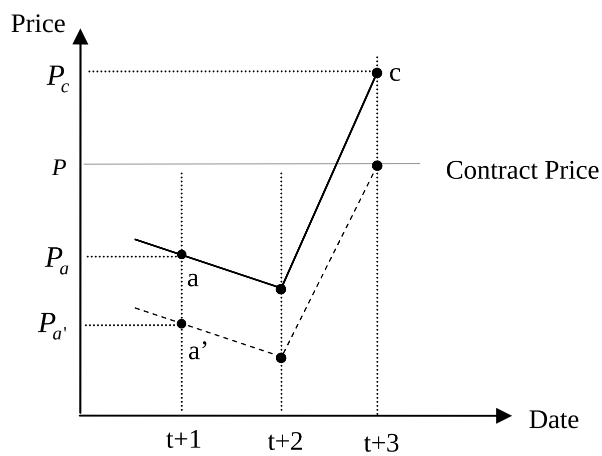
3.3 The Vertical Restraints

The oil firms in Australia use special forms of vertical restraints to influence retail prices because they can only own and operate a very small number of retail sites due to the legal constraints imposed by the legislation called the Petroleum Retail Marketing Sites Act 1980 (the Sites Act). According to the official Sites Act returns for March 2002, in the Perth market, BP operated 6 retail sites, Caltex operated 22 retail sites, and Mobil and Shell did not operate any.

Multi-site franchise agreements are used by BP, Mobil and Shell. A multi-site franchise agreement has two main features. First, each agreement covers a large number of retail sites, and this was well documented in various Australian government reports (e.g., ACCC 1996, Senate Economics Committee 2001). During the sample period, Shell had a single multi-site franchisee that operated most of the Shell branded retail sites in the Perth market. Mobil had a single franchisee too, but BP had at least three multi-site franchisees. The multi-site franchise agreements are known in the industry to have a second feature: they are consignment agreements that allow the oil firms to retain the ownership of the fuel until the fuel is sold at retail, thus giving the oil firms the right to set retail prices. For the widespread use of multi-site franchising in the US fast food markets, see Kalnins and Lafontaine (2004).

Caltex cannot engage in multi-site franchise agreements due to the constraints imposed by the Australian government in 1995 when Caltex merged with another petroleum firm. Caltex uses a different scheme, called the conditional price support, to influence the retail price of its franchisees. The conditional price support mechanism is illustrated in figure 4. Contract price, P, is the wholesale price a Caltex branded retailer has to pay Caltex when taking delivery from a Caltex terminal. This contract price is usually not the effective wholesale price. Caltex retailers can receive a price support of the size $P - P_{a'}$ from Caltex, say, on date $t+1$, under the condition that the retailer sets its retail price lower than P_a for that date. On date $t+2$, Caltex informs its franchisees that no price support will be provided on date $t+3$, but suggests a retail price P_c to be set. Most franchisees set their retail prices at P_c, thus leading to the synchronization and uniformity of Caltex retail price increases.

Figure 4: The Conditional Price Support Scheme



A Caltex franchisee receives an electronic mail message from Caltex every day that informs the franchisee of the contract price, the size of the price support and the maximum retail price allowed for the following day. Two messages sent on May 7, 2004 regarding regular unleaded gasoline read as the following:

> [Unleaded effective wholesale price] 91.25 08/05 6:00 TEMP REDUCTION OFF CONTRACT BUY PRICE IN RESPONSE TO COMPETITOR PRICES CONDITIONAL ON MAX RESALE PRICE NOT EXCEEDING 93.95 UNLEAD
>
> EFF 08/05/04, 0600 HRS, DEALER METER MAP PRICE FOR UNLEADED = 91.25 CPL, ADJUSTMENT = 12.05 CPL. [The prices shown in these two messages are slightly altered.]

The franchisee was instructed that the effective wholesale price on May 8, 2004 starting from 6:00am was 91.25 cents per liter (CPL), and the franchisee had to set a retail price lower than 93.95 cents in order to receive the price support of 12.05 cents per liter. Otherwise, the franchisee had to pay the “contract buy price” of 103.3 cents per liter. It is clear that the franchisee had to set a price between 91.25 and 93.95 cents. While most franchisees in such a situation would set their prices at 93.95 cents per liter, thus earning a retail margin of 2.70 cents, some stations, known as price discounters, set prices a bit lower than 93.95 cents. During the falling phase of a price cycle, the size of price support and the maximum retail price allowed vary from site to site. Note that the message points out explicitly that the price support is given in response to competition probably because Australian law allows the oil firms to offer their franchisees price supports of different sizes under the condition that the price support is offered to meet competition.

The price support scheme appears to be a special form of maximum resale price maintenance: both the maximum retail price allowed and the effective wholesale price are characterized by cycles, but the retail margin remains roughly constant. Note that the conditional price support scheme is common knowledge in the Australian gasoline industry (e.g., ACCC 2001), but the mechanism has not been well documented. In a period when the oil firms did not use vertical restraints, gasoline price cycles did not exist in Australia. ACCC (2001, p. 35) observed that:

> "After an introductory period, for 16 months from October 1989 the oil majors operated 'rack pricing' schemes, where they set a wholesale price at list levels without discounts or price support. During this time retail prices were much less volatile in areas where price cycles had been common. Generally, only changes in wholesale list prices were reflected in retail price movements."

Note that the oil firms in Canada are vertically integrated and the oil firms used a somewhat different 'price support' schemes to influence the retail prices in those U.S. cities that experienced gasoline price cycles in the past (Allvine and Patternson 1972, chapter 7).

4. Price Data

The retail prices used in this paper were downloaded from the internet website. This paper observes the daily station-level retail prices for regular unleaded gasoline from January 3, 2001 to October 31, 2003. It is apparent from figure 1 that the players were adjusting to the 24-

hour-rule during the first four months of 2001. This paper is focused on the price cycle after the adjustment period, which is taken to be the first five months. This paper also observes the daily prices for premium unleaded gasoline, liquefied petroleum gas and diesel. The pricing behavior of these fuel types will be discussed briefly in subsection 5.6.

Table 1 lists the average number of operating gasoline stations per day by brand over the period June 1, 2001 to October 31, 2003. It is clear that Caltex, BP and Shell are the three largest brands in the Perth market, and they have, respectively, about 88, 67, and 46 stations operating per day. Mobil, the fourth major oil firm in Perth, has 23 gasoline stations operating per day, while Gull, the largest independent brand, has 38 stations. Peak, Woolworths, Liberty and Wesco have 18, 11, 9, and 10 sites, respectively. The other small independent brands together have 6 sites operating per day. About 15 unbranded stations operate per day, and they appear as “Independent” on the website. Given that the focus of this paper is on the strategic interaction between the major oligopoly firms, section 5 considers the four major oil firms (BP, Caltex, Shell, Mobil) and the four major independent firms (Gull, Peak, Liberty and Woolworths). The brand Wesco was not operated by a single firm, but was shared by a cooperative buying group formed by independent retail sites.

It is also interesting to note that the pricing behaviors of the small independent brands or unbranded sites are quite different from those of the major oil or independent firms. Those sites usually do not follow closely the price cycle. Similarly, those stations located in such remote areas as an island off the coast or hills to the east of the city do not follow closely the price cycle either, even if they carry a major oil or independent brand. The prices for most of the small brand or unbranded sites or sites in isolated areas are more rigid. The price rigidity of a gasoline station can be measured by the average length of spells in which the station’s price remains unchanged. Table 2 reports the distribution of the average spell length across all the stations that appear in the sample period.[11] Eighty-two percent of the stations have an average spell length of less than 2 days, and the percentile starts to increase quickly around the spell length of 2 days. Column 3 of table 1 lists by brand the average number of sites with a spell length shorter than 2 days. The vast majority of the unbranded sites (13 out of 16) and Wesco sites (9 out of 10) have a spell length longer than 2 days, and half of the small independent brand sites have a spell length longer than 2 days. On the other hand, almost all the sites of Caltex, Shell, Mobil, Gull, Peak and Woolworths have a spell length shorter than 2 days. However, 13 sites carrying the BP brand and 4 sites carrying the Liberty brand have a spell length longer than 2 days. I spoke with the owner of four such BP stations and found that these four stations' prices were set independently by the owner. It is also likely that the other BP or liberty sites with a spell length longer than 2 days were independent price setters. For this reason, all sites with a spell length longer than 2 days will be ignored, even if they carry a major brand.

5. Cycle Dynamics

This section presents evidence showing that (1) the oligopoly firms hike their prices sequentially, (2) short-term commitment arises endogenously, (3) the firms appears to use mixed strategies to allocate the price leadership, and (4) the followership reactions are consistent with the Markov restriction. For these purposes, this section uses the brand average prices to analyze the oligopoly firms' pricing behavior during the rising phase of the price cycles. To return price to the cycle top, tight coordination between the oligopoly firms are needed, and this is confirmed by the strong instrabrand synchronization and uniformity in price increases. The price dispersion during the falling phase or the war of attrition phase, on the other hand, suggests that the oligopoly firms may delegate the pricing authority to the individual

[11] There are 372 gasoline stations appearing in the data set for the period after June 1, 2001. Out of these 372 stations, 245 sites appear in every day of the sample period (883 days) and 38 sites appear in 882 days.

gasoline stations during these two phases. The brand average price, therefore, cannot be used to analyze these two phases of the price cycles. Appendix 1 measures the degree of intrabrand synchronization and uniformity across the different cycle phases.

5.1 Cycle Basics

This subsection identifies the price cycles, the price leaders for each price cycle, the patterns of price leadership and followership reactions.

5.1.1 The Number of Price Cycles

It is easy to count the number of price cycles in figure 1 for the period June 1, 2001 through October 31, 2003. Let P_{it} be the dollar price posted by station i on date t, and let $\overline{P}_t$ be the average price across all the stations (with spell length shorter than 2 days) on that day. The average price $\overline{P}_t$ is said to be a *local maximum* if and only if $\overline{P}_t > \overline{P}_{t-1}$ and $\overline{P}_t > \overline{P}_{t+1}$. A local maximum price at time t is said to be a *peak* if it is bigger than either $\overline{P}_{t-1}$ or $\overline{P}_{t+1}$ by at least 0.1 cents. For the sample period, there are 105 local maximums, four of which fail to be peaks.[12] Each of the 101 peaks is associated with a *price cycle*. Thus, 101 price cycles are admitted.

5.1.2 Identifying the Individual Price Cycles

When does an individual cycle start? To the market participants or observers, this appears to be a trivial question because of the regularity with which the price cycles evolve. It is when one or more oligopoly firms hike most of their retail sites' prices in a conspicuous jump. The website that posts the retail price even issues a price-hike alert to the consumers

[12] The four local maximum prices occurred near cycle bottoms. In all four cases, the average price reached a local minimum, increased slightly (less than 0.1 cents) the next day and then decreased again on the third day. The dates on which these four local maximums occurred are June 19, 2001, October 11, 2002, December 26, 2002, and July 13, 2003.

around 3pm if the retail price for a major brand is to be hiked the following day.[13] The price-hike alerts happen to be highly consistent with the MT price cycle theory. An MT price cycle features a lead price jump from the competitive level to approximately the monopoly level. Price increases of small size does not occur in equilibrium because such moves lose market share but cannot achieve the strategic benefit of starting a new cycle at a high price. What constitutes a lead price jump for an observed gasoline price cycle hypothesized to be a random realization of an Edgeworth cycle? Given the existence of random disturbances, the size and timing of such lead price jumps should be randomly distributed, but a lead price jump must be easily recognized so that the other players could follow.

Indeed, the seven price cycles in figure 2 all have very clear lead price jumps.[14] It is apparent that BP alone led three cycles, Caltex alone led twice, Shell alone led once, and BP and Shell co-led once. What are the characteristics of these 7 cycles that make the lead price jumps conspicuous and easy to identify? First, the lead price jumps exhibit strong intrabrand synchronization and uniformity. Second, they are sizable and significantly bigger than the price changes by the other players on the same day. Third, the price changes by any of the players on the day immediately before are negative or near zero. For 91 out of the 101 price cycles, the identification of the lead price jumps is as clear cut as that for the 7 cycles shown in figure 2. The size of the identified lead price jumps ranges from 2.57 to 13.43 cents, with the average being 7.90 cents, and only 4 identified lead price jumps have a size smaller than 4.06 cents. It should be emphasized that the size of the lead price jumps is expected to vary across the observed price cycles due to the presence of market disturbances. Define the day on which the lead price jump occurs as the *first day* of a price cycle, and the day immediately before as the *last day* of the previous cycle. The maximum price jump by any of the eight players on the last

[13] Many recent price-hike alerts can be found at http://www.fuelwatch.wa.gov.au/news/dsp_news_archive.cfm
[14] The other five players' price changes do not affect the identification in any way.

day of the previous cycle ranges from -1.29 to 0.87 cents, and the median is -0.11 cents. The maximum price jump other than the lead price jumps on the first day of a cycle ranges from -1.13 to 0.91 cents, and the median is -0.05 cents.

The price leaders for each of these 91 price cycles always include BP, Caltex or Shell. In fact, none of the four independent brands or Mobil led alone for any of the 91 cycles, and only Mobil and Liberty each co-led once with BP, Caltex or Shell. This finding strongly indicates that Mobil and the four independent brands are not expected to lead in equilibrium. Indeed, Mobil alone lifted up its price by 3.40 cents on March 1, 2002, and this price jump was completely ignored by all the other 7 players: none of them lifted up their prices in the following three days. The identification of the lead price jumps for the other 10 cycles is still largely unambiguous but is not as clear cut. It is arguable that Mobil and the independent brands led or co-led two or three of those 10 cycles. Appendix 2 provides the details of these 10 cycles and identifies the leaders.

An individual *price cycle* starts when one or more lead price jumps occur, and ends the day before the next round of lead price jumps occur. Table 3 shows the day of week frequency distribution of the cycle start and peak days. Eighty nine price cycles start on Tuesday, Wednesday, Thursday or Sunday, and the probability of a cycle starts on either one of these four days is roughly equal. The *length* of a price cycle is defined as the period from the start day through the last day. Recall that an MT price cycle has three phases. The *rising phase* can be easily defined as the period from the first day to the peak day (inclusive), but the *falling phase* and the *war of attrition phase* cannot be easily separated. For this reason, the period from the peak day (exclusive) to the last day is called the *non-rising phases* of the price cycles. Table 4 tabulates the observed frequency distribution of the cycle lengths of the 101 cycles. Note that the rising phase is either 2 days (for 25 cycles) or 3 days (for 76 cycles) long. The non-rising phase is much longer and much more dispersed than the rising phase. The average length of the non-rising phase is 5.92 days with a standard deviation of 2.16 days. It is clear that the cycle is asymmetric: prices rise faster than they fall. It is worth emphasizing that the high-quality data allows us to estimate the *frequency distribution* of the cycle parameters.

5.1.3 Price Leadership and Followership Patterns

Each of the 101 price cycles starts with one or more lead price jumps, and the data shows that price leadership, in equilibrium, is solely distributed among the three largest oil brands: BP, Caltex and Shell. There are seven equilibrium price leadership types: (1) BP alone, (2) Caltex alone, (3) Shell alone, (4) BP and Caltex only, (5) BP and Shell only, (6) Caltex and Shell only, and (7) BP, Caltex and Shell. Column 2 of table 5 lists the observed frequency distribution of the seven price leadership types over the 101 price cycles. Seventy-eight price cycles have a single price leader (BP 27, Caltex 37, and Shell 14), 17 cycles have two co-leaders (BP and Caltex 7, BP and Shell 9, and Caltex and Shell 1), and 6 cycles have three co-leaders. BP is a price leader for 49 cycles, Caltex 51 cycles, and Shell 30 cycles.

Similar to price leadership, price followership differs across the brands as well. Refer to the three largest firms as the *leading brands* and the other five firms the *non-leading brands*. Figure 5 shows the price leadership and followership pattern for the three largest firms over the 101 cycles. It is clear that a leading brand, if not a leader for a given cycle, almost always follows the first day lead on the second day. There are only six exceptions, which are visible in figure 5. BP follows on the third day in four cycles for which BP is not the price leader. It appears, however, that Caltex and Shell *must* follow on the second day if they are not the price leaders for a given cycle. For two cycles, BP raised its price to start a new cycle, but Caltex or

Shell failed to follow on the second day. BP cut its price sharply on the third day.[15] Figure 6 shows the price changes by the five non-leading brands on the second and third day over the 101 cycles. It is clear that Mobil increased its price on the second day for the vast majority of the cycles, and the independent brands increased their prices either on the second day alone or the third day alone or both days.

Let $\overline{P}^{j}_{k,t}$ be the average price of brand j on day t of cycle k. Then, $\overline{P}^{j}_{\cdot,t} = \frac{1}{K}\sum_{k=1}^{K}\overline{P}^{j}_{k,t}$ is the average price of brand j on day t across K cycles. Table 6 shows the brand average prices $\overline{P}^{j}_{\cdot,t}$ on the cycle start day, peak day and other cycle days. As expected, the non-leading brands have much smaller average prices on the cycle start days, and the difference, compared with BP and Caltex's, is about 4 to 5 cents. Note that Shell's average price on the start day is about 2 cents smaller than BP and Caltex's, for Shell leads less often. It is informative to look at the brand average prices on the day between the start day and the peak day for those 76 cycles with a rising phase of 3 days. On that day, BP, Caltex and Shell's prices roughly equal each other, for all three have raised their prices by the second day, but Mobil's price is about 2 cents lower and the independent brands' prices are about 6 cents lower, for Mobil follows mostly on the second day and the independents raise their prices mostly on the third day of a cycle. On the cycle peak day, BP, Caltex, Shell and Mobil have similar average prices, which are about 2 cents higher than those of the independent brands. This may be interpreted as evidences that the independent brands initiate the price cutting. During the falling days, the price difference between the leading brands and non-leading brands is insignificant. It is revealing to note that the independent brands' average price increases from the last day of the previous cycle to the peak

[15] On June 14, 2001, BP raised its price by an average of 7.00 cents to start a new cycle, but Shell kept its price low on the second day and raised its price by 7.95 cents on June 16. BP cut its price by an average of 9.11 cents on June 16, and stayed low the following day and raised its price by 5.63 cents on June 18. On April 23, 2003, BP raised its price by 8.11 cents to start a new cycle. On the second day, the average Caltex price was increased only by 0.79 cents. BP cut its price by 9.65 cents on the third day, April 25, while Caltex raised its price by 4.26 cents. BP did not raise its price again within the cycle.

day of this cycle are much smaller than those of the oil firms. Note that Woolworths' actual transaction price is even lower because of its 4-cents discount program. The leading brands' average prices over the eight cycle days are about 1 cent higher than Mobil's, and 2 cents higher than those of the independent brands.

5.2 Relationship between the Cycles

This subsection investigates the statistical properties of the key cycle parameters. The null that the size of the lead price jumps is normally distributed cannot be rejected even at, say, the 20-percent significance level, and the same is true with the null that it is serially uncorrelated.[16] The null that cycle length is serially uncorrelated cannot be rejected at the 5-percent level by the Ljung-Box Q-statistics, but the null that cycle length is normally distributed is rejected by the various distribution tests. Note that the length of a theoretical MT Edgeworth cycle is not a constant because the players follow mixed strategies to determine when to end the war of attrition.

In the MT Edgeworth cycle equilibrium, the size of the lead price jumps is uncorrelated with the players' price changes on the preceding day, and this property can be easily tested. Define the average price change of brand j on day t of cycle k as $\Delta\overline{P}^{\,j}_{k,\,t} = \overline{P}^{\,j}_{k,t} - \overline{P}^{\,j}_{k,\,t-1}$ for $t \geq 2$, and $\Delta\overline{P}^{\,j}_{k,\,1} = \overline{P}^{\,j}_{k,1} - \overline{P}^{\,j}_{k-1,\,Last}$, where $\overline{P}^{\,j}_{k-1,Last}$ is the average price of brand j on the last day of cycle $k-1$. Define $\Delta\overline{P}^{\,j}_{k-1,\,Last} = \overline{P}^{\,j}_{k-1,Last} - \overline{P}^{\,j}_{k-1,\,Last-1}$.

Consider the following equation for BP, when it is a leader for cycle k,

(1) $\Delta\overline{P}^{\,BP}_{k,\,1} = c + \Delta\overline{P}^{\,BP}_{k-1,Last} + \Delta\overline{P}^{\,Caltex}_{k-1,Last} + \Delta\overline{P}^{\,Shell}_{k-1,Last} + \Delta\overline{P}^{\,Mobil}_{k-1,Last} + \Delta\overline{P}^{\,Gull}_{k-1,Last} + \Delta\overline{P}^{\,Peak}_{k-1,Last} + \Delta\overline{P}^{\,Liberty}_{k-1,Last} + \Delta\overline{P}^{\,Wool}_{k-1,Last} + \varepsilon^{BP}_{k,1}$,

where $\varepsilon^{BP}_{k,1}$ is the error term and *wool* stands for Woolworths. If BP follows a Markov strategy,

[16] Some price cycles have 2 or more lead price jumps, giving rise to the issue of which of them to consider for such a cycle when testing whether the lead price jumps are serially uncorrelated. It turns out that it does not affect the result in any way whether the average, maximum or minimum of the lead price jumps is used.

the players' price changes on the last day of the previous cycle should not affect the size of BP's lead price jump. Similar equations can be specified for Caltex and Shell.

The estimated results for equation (1) are reported in table 7. For BP and Caltex, the Wald test cannot reject the null that all eight slope variables are equal to zero. For Shell, the Wald test rejects the null, but none of the individual slope variables are statistically different from zero. These results confirm that the size of the lead price jumps is uncorrelated with the players' price changes on the last day of the previous cycle. The results in this section support the hypothesis that the observed gasoline price cycles are independent realizations of the underlying firm strategies.

5.3 Price Leadership: The Mixed Strategies

The basic price leadership and followership pattern suggests that Mobil and the independent brands, in equilibrium, do not attach positive probability to the pure strategy of hiking prices before observing conspicuous lead price increases. This subsection tests whether the three largest firms play mixed strategies to allocate the price leadership.

It is assumed here that the players know when to play the mixed strategies, and, for each price cycle, they always start to play the mixed strategies simultaneously. There are eight possible events occurring on a day when the firms are playing mixed strategies all together: the seven events shown in table 5, in which one or more players lift up price, and the event that none of the players hike price. If the last event happens, the players repeat the game on the following day, and one of the first seven events will eventually happen with probability one.

The probabilities of BP, Caltex, or Shell being a price leader for a given price cycle are functions of the probabilities with which they play the pure strategy of lifting up the price before observing any price jump. The probability of BP being a price leader for a given price cycle, for example, is the sum of the probabilities of four mutually exclusive events: (a) BP alone raises its price; (b) Only BP and Caltex raise their prices; (c) Only BP and Shell raise their prices, and (d) BP, Caltex and Shell all raise their prices. Since the observed frequency of being a leader for a given price cycle is approximately 50 percent for both BP and Caltex, and 30 percent for Shell, it is reasonable to expect BP and Caltex to play the pure strategy of lifting up prices with the same probability and Shell to play the pure strategy with a smaller probability. The probability with which BP/Caltex or Shell plays the pure strategy of lifting up price can then be solved analytically, and the solution is approximately 0.30 for BP/Caltex and 0.18 for Shell. The hypothesis that the three firms play mixed strategies with the estimated probabilities has three testable implications.

First, the hypothesis implies a specific distribution over the seven possible price leadership types, and the expected frequency is shown in column 3 of table 5. A simple Chi-square distribution test yields the statistic of 14.39, thus rejecting the null that the observed price leadership pattern is drawn from the distribution implied by the hypothesis. However, the expected leadership frequency distribution clearly approximates the observed frequency distribution reasonably well. The statistic is driven largely by the lower than expected frequency of event 6 (Caltex and Shell only) and the higher than expected frequency of event 7 (BP, Caltex, and Shell). If these two events with small expected frequencies are collapsed together, the null cannot be rejected at normal significance levels.

Consider the second prediction of the mixed strategy hypothesis. Let the variable $BPLed_k$ equal to 1 if BP is a price leader for the k^{th} price cycle, and 0 otherwise. Under the hypothesis, $\{BPLed_k\}, k = 1, 2, ..., 101,$ is a sequence of identical and independent Bernoulli random variables with the success probability of 50 percent. Define similarly the Bernoulli processes $\{CaLed_k\}$ and $\{ShLed_k\}$ for Caltex and Shell, respectively. The hypothesis implies that the cross correlation coefficient is about -0.41 between the BP and Caltex processes, and -0.27 between the BP and Shell processes or between the Caltex and Shell processes. The observed correlations are -0.47 (BP and Caltex), 0.02 (BP and Shell) and -0.35 (Caltex and Shell), respectively. Only the coefficient between the BP and Shell processes appears to be inconsistent with the expected value.

Consider the third prediction of the mixed strategy hypothesis. Let K_n, $n \geq 2$ denote the number of cycles after the $(n-1)^{th}$ success but before the n^{th} success for the BP process. Under the null, $\{K_n\}$, $n = 2, ..., 49$, is a sequence of identical and independent geometric random variables with the success probability of 50 percent. Note that the number of cycles before the first occurrence of price leadership is not observable, so it is ignored here. Table 8 shows the observed and expected frequency distribution of the number of cycles between leadership for the three brands. The Chi-square distribution tests reject the null for all three processes, but the observed number of cycles between leadership is not far off the predictions of the mixed strategy hypothesis.

By strict statistical standards, one might argue that the overall results in this subsection do not favor the hypothesis that the three firms play mixed strategies. However, the results do not refute the argument that the mixed strategy hypothesis approximates the observed price leadership patterns reasonably well, especially considering the many potential complicating factors in a market setting. Testing mixed strategies in market settings is typically difficult to implement. Researchers have recently turned to special field data to test the theory of mixed strategy. For example, Chiappori, Levitt and Groseclose (2002) found that mixed strategies characterize the play of professional soccer players very well.

5.4 The Leading Brands' Reaction Functions

This subsection estimates the leading brands' reaction functions and tests (1) whether the Markov restriction holds and (2) whether the price leaders show short-term commitment when waiting for other firms to follow. If BP, Caltex or Shell is not a cycle leader, they almost always follow on the second day. For this reason, a day-2 reaction function is estimated for each of the 3 leading brands. Consider the following day-2 reaction function for BP, when it is not a leader for cycle k,

(2.1)
$$\begin{aligned}\Delta\overline{P}^{BP}_{k,\,2} &= c + \Delta\overline{P}^{BP}_{k,1} + \Delta\overline{P}^{Caltex}_{k,1} + \Delta\overline{P}^{Shell}_{k,1} + CaLed_k * ShLed_k + \mathbf{\Delta\overline{P}}^{Nonleading}_{k,1} \\ &+ \Delta\overline{P}^{BP}_{k-1,\,Last} + \Delta\overline{P}^{Caltex}_{k-1,\,Last} + \Delta\overline{P}^{Shell}_{k-1,\,Last} + \mathbf{\Delta\overline{P}}^{Nonleading}_{k-1,Last} + \varepsilon^{BP}_{k,2}\end{aligned},$$

where the vector $\mathbf{\Delta\overline{P}}^{Nonleading}_{k,t} \equiv \left[\Delta\overline{P}^{Mobil}_{k,t}, \Delta\overline{P}^{Gull}_{k,t}, \Delta\overline{P}^{Peak}_{k,t}, \Delta\overline{P}^{Liberty}_{k,t}, \Delta\overline{P}^{Wool}_{k,t}\right]$ contains the price changes by the non-leading brands on date t of cycle k. This equation is quite general in that it allows BP to react to the price changes by all eight players in the previous two days. The dummy term $CaLed_k * Shled_k$ is added to capture the possibility that, when Caltex and Shell co-lead a cycle, BP's reaction intercept may be smaller. The possibility that BP's reaction slope is different as well is investigated, but rejected. The estimated results would support the Markov hypothesis if the first day price changes by Caltex and Shell have positive effects, but all the other slope terms do not have significant effects. The day-2 reaction functions for Caltex and Shell can be similarly specified.

For some cycles, there are multiple leaders, and their lead price jumps may not be equal. A leading brand may react to the difference between its first day lead jump and those of the other players on the second day. To capture this possibility, an alternative day-2 leader adjustment function is estimated for each of the three leading brands. Consider the leader adjustment function for BP, when it is a leader for cycle k:

(2.2)
$$\Delta\overline{P}^{BP}_{k,\,2} = c + LeadDiff^{BP}_k + \mathbf{\Delta\overline{P}}^{Nonleading}_{k,1} + \Delta\overline{P}^{BP}_{k-1,Last} + \Delta\overline{P}^{Caltex}_{k-1,Last} + \Delta\overline{P}^{Shell}_{k-1,Last} + \mathbf{\Delta\overline{P}}^{Nonleading}_{k-1,Last} + \mu^{BP}_{k,2},$$

where the term $LeadDiff_k^{BP}$ is defined as:

$$LeadDiff_k^{BP} = \begin{cases} \Delta\overline{P}_{k,1}^{BP} - \dfrac{\Delta\overline{P}_{k,1}^{Caltex} * CaLed_k + \Delta\overline{P}_{k,1}^{Shell} * ShLed_k}{CaLed_k + ShLed_k} & if \;\; CaLed_k + ShLed_k = 1, 2 \\ 0 & if \;\; CaLed_k + ShLed_k = 0 \end{cases} .$$

This term is zero for the 27 cycles for which BP is the sole leader, and nonzero for the other 22 cycle for which BP is a co-leader. Eighteen of the 22 nonzero values are negative. BP is expected to increase (decrease) its price on the second day if its day-1 lead price jump is much smaller (bigger) than those of Caltex and Shell. The term $LeadDiff_k^{BP}$ is thus expected to have a negative coefficient. The Markov restriction would be supported if the other terms in equation (2.2) do not have significant coefficients, and short-term commitment would be confirmed if the constant term is nonnegative. The day-2 leader adjustment functions for Caltex and Shell can be similarly specified. The accordingly defined term $LeadDiff_k^{Caltex}$ has 14 nonzero values, 13 of which are positive. The term $LeadDiff_k^{Shell}$ has 16 nonzero values, 9 of which are negative.

Table 9(a) contains the estimated results for equation (2.1). The results indicate that a leading brand, if not a leader for a given cycle, reacts positively to the day-1 price changes by the other two leading brands, but it does not respond to the day-1 price changes by any non-leading brand or itself, nor does it respond to any player’s price changes on the last day of the previous cycle (with a single exception). None of the slope coefficients in the BP equation other than Caltex’s day-1 price changes are statistically different from zero (the F-statistic is 0.83 and the p-value is 0.64). The results are very similar for the Caltex equation. The Shell equation is slightly different in that Shell’s reaction intercept is smaller when a price cycle has BP and Caltex as co-leaders.

Also reported in table 9(a) are the results for a variant of equation (2.1) that considers the day-1 price changes by the leading brands, the dummy term and the other terms in equation

(2.1) that are significant at the 10-percent level or above. The dummy term in the Caltex equation now becomes statistically negative. According to the estimated results for this specification, reacting to the average lead price increase of 7.92 cents by BP alone, Caltex and Shell increase their prices by 8.62 and 7.67 cents, respectively. Reacting to the price increase of 7.92 cents by Caltex alone, BP increases its price by 7.38 cents and Shell increases its price by 8.54 cents. The full specification yields very similar results. These results clearly support the Markov hypothesis.

Table 9(b) presents the estimated results for equation (2.2) and a variant that considers only those terms in equation (2.2) that are significant at the 10-percent level or above. As expected, the three lead difference terms are all significantly negative. As most of the lead differences for BP are negative, it adjusts upward mostly. Caltex adjusts downward mostly, and Shell adjusts both ways. If it is a sole leader, BP or Caltex keeps its price constant and Shell increases its price slightly, confirming that the leading brands show short-term commitment. The Wald test cannot reject the null that all the other terms in the BP equation have zero coefficients. Most of the price change terms in the Caltex or Shell equation do not have significant coefficients either, but a few exceptions exist. In the Shell equation, the day-1 price change by Woolworths has a significant positive effect. In the Caltex equation, Peak's price change on the last day of the previous cycle is found to have a significant negative coefficient, and this is an unexpected anomalous result.[17]

[17] To investigate the sensitivity of this finding, two more variant equations are estimated for Caltex. In one variant where BP and Shell's price changes on the last day of the previous cycle are dropped, the coefficient for Peak becomes insignificant. In the other variant where Peak's price change is dropped, BP and Shell's price changes become insignificant. This is perhaps due to the fact that Peak's price change on the cycle last day is positively correlated with both BP and Shell's price changes on that day, and the correlation coefficients are 0.58 and 0.55, respectively.

5.5 The Non-leading Brands' Reaction Functions

Figure 6 suggests that the reactions by the five non-leading brands to the first day lead price increases could happen on the second day alone, the third day alone or both days. This section estimates two (size) reaction functions for each of the five brands, one for the second day and one for the third day, and tests if the Markov restriction is supported by the data. Consider the following day-2 reaction function for non-leading brand j:

$$\begin{aligned}(3.1)\qquad \Delta\overline{P}^{\,j}_{k,\,2} = {} & c + \Delta\overline{P}^{\,BP}_{k,1} + \left(\Delta\overline{P}^{\,BP}_{k,1}\right)^2 + \Delta\overline{P}^{\,Caltex}_{k,1} + \left(\Delta\overline{P}^{\,Caltex}_{k,1}\right)^2 + \Delta\overline{P}^{\,Shell}_{k,1} + \left(\Delta\overline{P}^{\,Shell}_{k,1}\right)^2 + \Delta\overline{P}^{\,j}_{k,1} + \mathbf{\Delta\overline{P}}^{-j}_{k,1} \\ & + \Delta\overline{P}^{\,BP}_{k-1,Last} + \Delta\overline{P}^{\,Caletx}_{k-1,Last} + \Delta\overline{P}^{\,Shell}_{k-1,Last} + \Delta\overline{P}^{\,j}_{k-1,Last} + \mathbf{\Delta\overline{P}}^{-j}_{k-1,Last} + \varepsilon^{j}_{k,2}\end{aligned},$$

where the vector $\mathbf{\Delta P}^{-j}_{k,t}$ collects the price changes by the non-leading brands other than brand j on day t of cycle k. This equation allows a non-leading brand to respond to the price changes by the eight players in the previous two periods. The second order terms of the leading brands' day-1 price changes are added to capture the possibility that the independent brands have nonlinear reaction functions. Non-leading brand j's day-3 response function is similarly specified:

$$\begin{aligned}(3.2)\qquad \Delta\overline{P}^{\,j}_{k,\,3} = {} & c + \Delta\overline{P}^{\,BP}_{k,2} + \left(\Delta\overline{P}^{\,BP}_{k,2}\right)^2 + \Delta\overline{P}^{\,Caltex}_{k,2} + \left(\Delta\overline{P}^{\,Caltex}_{k,2}\right)^2 + \Delta\overline{P}^{\,Shell}_{k,2} + \left(\Delta\overline{P}^{\,Shell}_{k,2}\right)^2 + \Delta\overline{P}^{\,j}_{k,2} + \mathbf{\Delta\overline{P}}^{-j}_{k,2} \\ & + \Delta\overline{P}^{\,BP}_{k,1} + \Delta\overline{P}^{\,Caltex}_{k,1} + \Delta\overline{P}^{\,Shell}_{k,1} + \Delta\overline{P}^{\,j}_{k,1} + \mathbf{\Delta\overline{P}}^{-j}_{k,1} + \varepsilon^{j}_{k,3}\end{aligned}.$$

A player's own day-2 price changes should have a negative impact on its day-3 response.

Table 10(a) reports the estimated results for equation (3.1) and a variant specification for the independent brands that considers the leading brands' (first-order) day-1 price changes and the other terms in equation (3.1) that are found to be significant at the 10-percent level or above. Two equations are reported for Mobil as well, but for reasons to be discussed below. Preliminary analysis suggests that Mobil's day-2 response is linear. The results confirm that the independent brands do have nonlinear reaction functions. Gull and Liberty's reaction functions are nonlinear in Caltex's day-1 price change. Peak's reaction is nonlinear in both BP and Shell's day-1 price changes, and Woolworths' response is nonlinear in Caltex and Shell's price changes. All five players respond strongly to the first day price changes by BP and Caltex. Suppose BP alone increases its price by 7.92 cents on the first day. According to the estimated reaction functions (the second specification for the independents and the first specification for Mobil), Mobil, Gull, Peak, Liberty, and Woolworths, on the second day, increase their prices by 5.53, 1.90, 0.66, 2.38, and 2.46 cents, respectively. If Caltex alone raises its price by 7.92 cents on the first day, Mobil, Gull, Peak, Liberty, and Woolworths increase their prices by 5.85, 3.95, 0.52, 2.82, and 2.58 cents, respectively. These results confirm that the day-2 response by Mobil is much stronger than those by the four independent brands. If BP and Caltex co-lead on the first day, the day-2 responses by the five players are much stronger.

The vast majority of the first day price changes by the five non-leading brands do not have significant coefficients. The same is true with the price changes by all the players on the last day of the previous cycle. These results support the Markov hypothesis. However, it is again found that a few price changes, mostly in the Mobil equation, have significant negative coefficients. A tabulation of Mobil's second day price changes reveals a special pattern: its day-2 price change is below 1 cent for 12 cycles and above 2.63 cents for the other 89 cycles. If the observed day-2 price change is very small, Mobil may have decided not to increase its price on the second day. Hence, the Mobil equation may apply only to those 89 cycles for which Mobil increased its price over 2 cents. A second Mobil equation is estimated for those 89 cycles, and the results suggest the hypothesis is reasonable. The four negative responses all become statistically insignificant, but one negative coefficient, previously insignificant, now becomes significant.

Table 10(b) reports the estimated day-3 reaction functions. Also reported for each brand is a specification that considers the leading brands' (first-order) day-1 price changes and the other terms in equation (3.2) that are found to be significant at the 10-percent level or above. The day-3 reactions by Mobil, Gull and Peak are found to be nonlinear. The results confirm that all five non-leading brands' day-3 price changes are affected strongly and negatively by their own day-2 price changes. All five non-leading brands respond strongly to BP and Caltex's second day price changes, and four of them also respond to Shell's second day price change. It is interesting to note that the four independent brands all react strongly to Mobil's second day price change. A non-leading brand generally does not respond to the first or second day price changes by any non-leading brand other than itself. These results support the Markov hypothesis as well.

It can be seen that the five non-leading brands' day-3 responses to the day-1 lead price jumps is largely through the day-2 price changes by the three leading brands and Mobil. If BP alone initiates a day-1 price jump of 7.92 cents, according to the second specification, Mobil, Gull, Peak, Liberty and Woolworths' estimated day-3 responses are 1.44, 4.03, 4.43, 2.46, and 3.80 cents, respectively. If Caltex alone leads by 7.92 cents, the estimated day-3 responses for Mobil, Gull, Peak, Liberty and Woolworths' are 1.46, 2.94, 4.88, 3.38, and 4.65 cents, respectively. If a cycle has more than one leader, the non-leading brands' day-3 responses are weaker, but recall that their day-2 responses are stronger.

5.6 Other Products

Both premium unleaded gasoline and lead replacement gasoline have cycles that track the regular unleaded gasoline price cycles step by step. Liquefied petroleum gas started to have a price cycle of its own in February 2002. Its cycle length, on average, is 17 days, and the rising phase is about 4.2 days. Diesel does not have a price cycle in Perth before and after the 24-hour rule, nor does it have a price cycle in the other Australian, Canadian or U.S. cities where regular unleaded gasoline has or had price cycles.

Why is it that other grades of gasoline have price cycles that track the regular gasoline price cycles, but diesel does not have price cycles? If the prices for premium gasoline and lead replacement gasoline, substitutes to regular unleaded gasoline, do not track that of regular unleaded gasoline, consumers would have chances to substitute when the price differentials are large. A likely explanation for the lack of cycles in diesel price is that, as mentioned in section 3, the price for the majority of retail diesel transactions is not observable. The players may have to observe their rivals' prices in order to follow the Markov reaction strategies that generate the MT cycle equilibrium.

6. Conclusion

The empirical evidences presented in this paper strongly support the hypothesis that the oligopoly firms in the Perth gasoline market are following Markov reaction strategies even though they are forced by the 24-hour-rule to set prices synchronously. Why do the firms in this market follow Markov strategies? For general justifications for Markov strategy, see Maskin and Tirole (2001), who discussed the philosophical foundations of the Markov restriction, and Bhaskar and Vega-Redondo (2002), who provided a theoretical explanation that is based on the complexity cost of memory. This paper points to three specific reasons.

First, strategic complementarity often exists in price competition and it can lead to endogenous short-term commitment. Second, the Markov strategies that generate the cycle equilibrium are flexible and accommodating. The players behave quite differently in terms of their leadership role and followership manner. The size of the lead price jumps and the following price increases varies from cycle to cycle. Although not studied in this paper, it is conceivable that these flexibilities could accommodate the players' size and other asymmetries. Third, the documented Markov strategies are simple and conducive to implicit communication. It is observed that, on two occasions, BP cut its price sharply and temporarily after observing that Caltex or Shell did not follow its first day lead on the second day. One may suspect that these off-equilibrium price cuttings are used to communicate certain information. Indeed, it is well known in the industry that the major firms 'talk' to each other through their price changes. It is also reasonable to wonder if the price jumps, exhibiting high intrabrand synchronization and uniformity, has communication content as well.[18] In the absence of explicit communication, the price leader has to signal the start of a new cycle in a clear way that can be recognized by all the other players. Slade (1992, p. 273) also noted that "when players cannot meet to discuss their strategies, complex rules, which are difficult to communicate, can be counter-productive."

Other than the flexibility and easy-to-communicate properties of the documented Markov strategies, the vertical restraints apparently play critical roles in facilitating the tacit coordination on the retail price. Why not coordinate directly on the wholesale price? A potential explanation is the fact that gasoline wholesale price is largely unobservable, thus the possibility of secret wholesale price cutting exists. This argument, originally due to Telser (1960), was cited by the U.S. Supreme Court to justify the illegal status of minimum resale price maintenance.[19] The conditional price support system documented in this paper is a special form of maximum retail price maintenance. The potential reasons for the use of multi-site franchising

[18] The question is why a cycle leader increases its price to a uniform level. In order for the followers to experience the force of strategic complementarity, synchronized price increases by a *large* player appears necessary, but price uniformity may be unwarranted. Price uniformity may actually lead to efficiency loss as it does not take into account the variations in local demand and competition.

[19] Business Electronics Corp. v. Sharp Electronics Corp. 485 U.S. 717 (1988) at 725-6.

are discussed by Kalnins and Lafontaine (2004). The results in this paper suggest that multi-site franchising may also be used as a facilitating device for tacit coordination.

Edgeworth price cycle, to my knowledge, has been observed only in gasoline markets featuring either vertical integration or vertical restraints. However, price leadership and followership, which forms the rising phase of the price cycle, is observed in many industries. It is generally considered as "one of the most important institutions facilitating tacitly collusive pricing behavior." Scherer and Ross (1990, p. 346). The price leadership observed here is clearly of the Stackelberg type, and the driving force for this type of price leadership is the strategic complementarity typically found in price competition. Price leadership and followership is a special form of nonsynchronized price setting behavior. Staggered price setting is often considered an institutional feature in many macroeconomic models of price adjustment. Lau (2001) aimed to provide a micro foundation for this institutional feature. Lach and Tsiddon (1996) examined the pricing behavior of multiproduct firms and found that the timing of price changes exhibits across-firm staggering and within-firm synchronization. This paper studies a single product, but also finds within-brand synchronization and across-brand staggering.

Strategic interaction is context specific, and may take very different forms. The strategic interaction in the Perth gasoline market is captured very well by the MT approach, but the strategic interaction in other markets may be characterized well by other approaches. The various models of dynamic oligopoly pricing may be complimentary rather than competing theories.

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Figure 1: Daily Average Regular Unleaded Gasoline Price Across All Stations in Perth

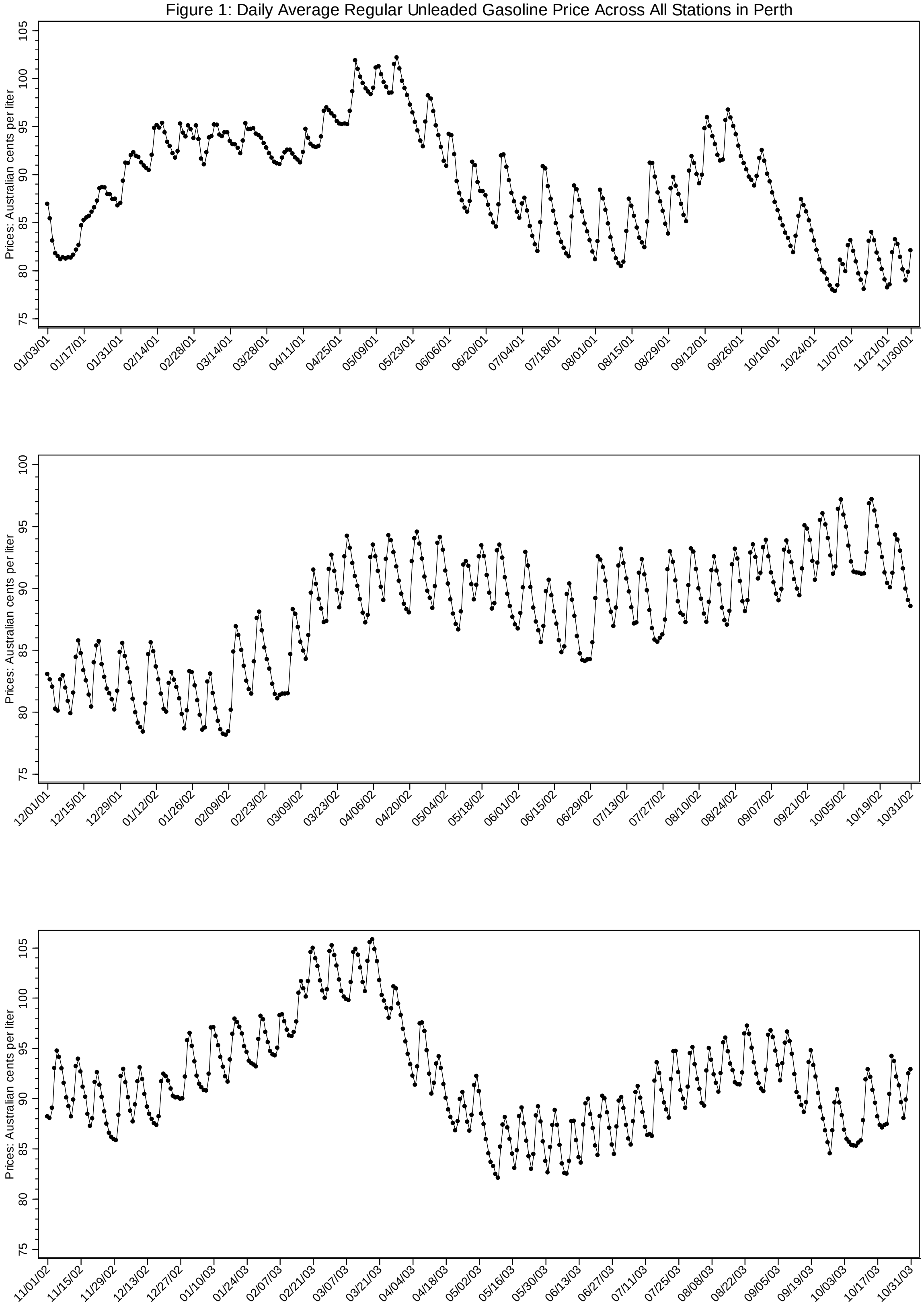
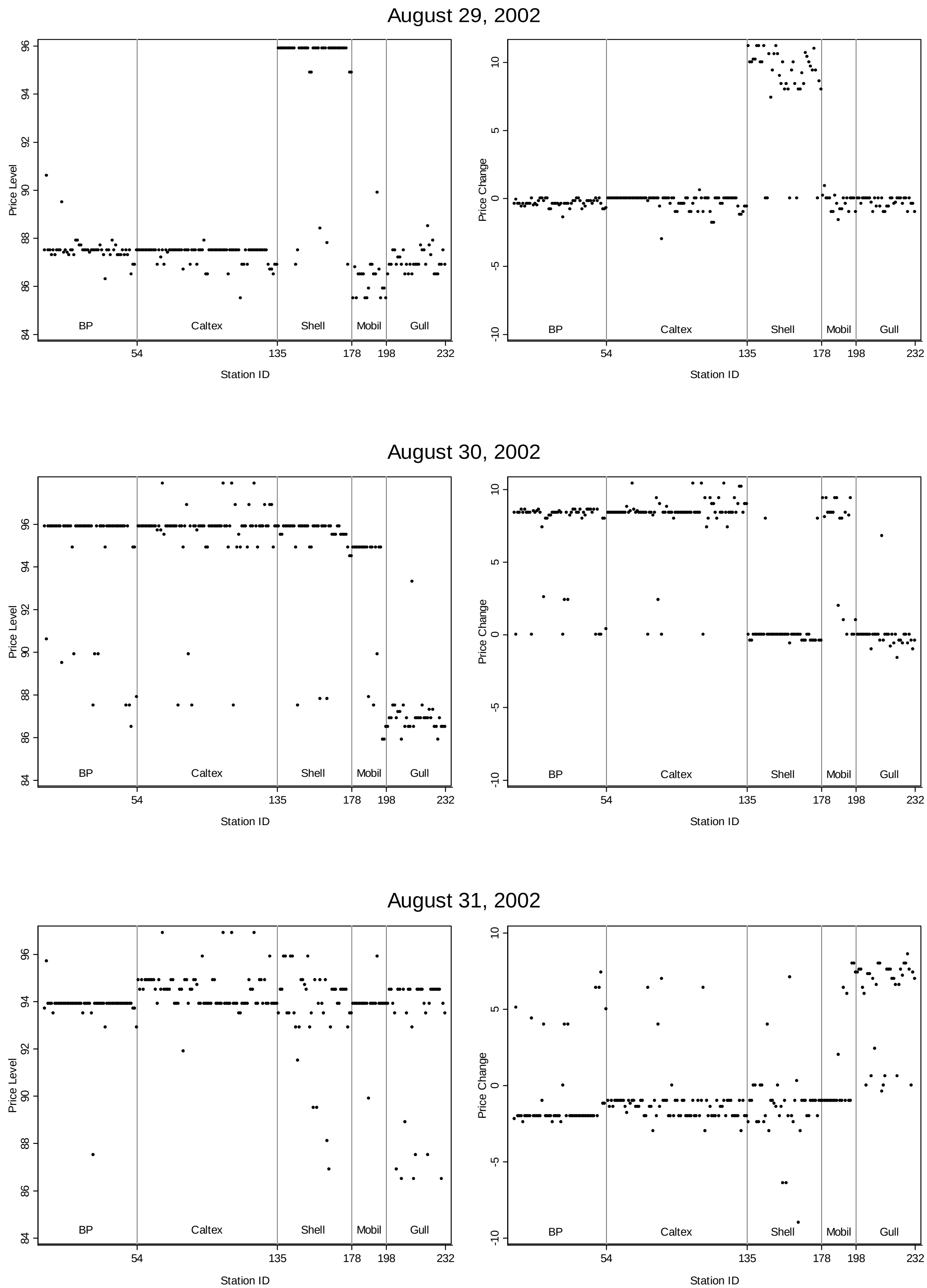
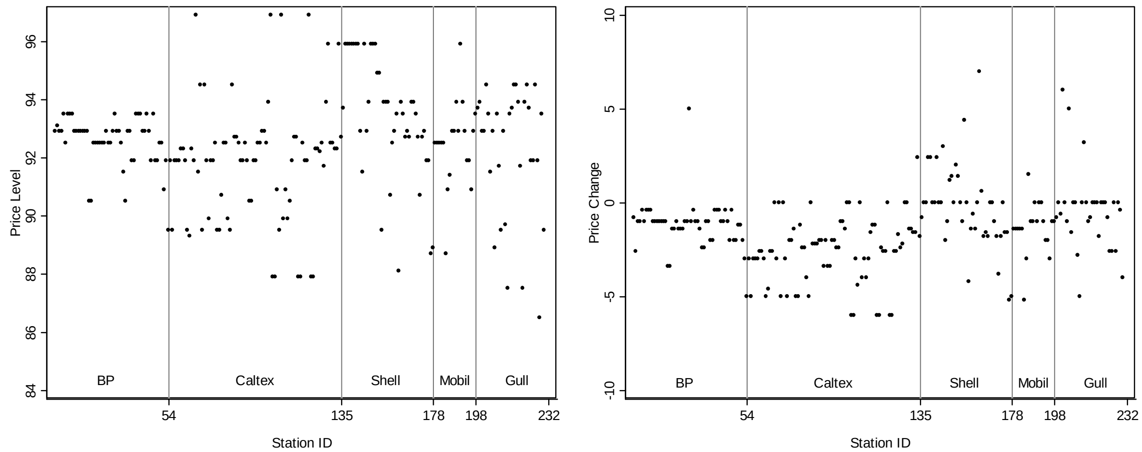


Figure 2: Individual Service Station Price and Price Change Over a Cycle of Six Days



September 1, 2002



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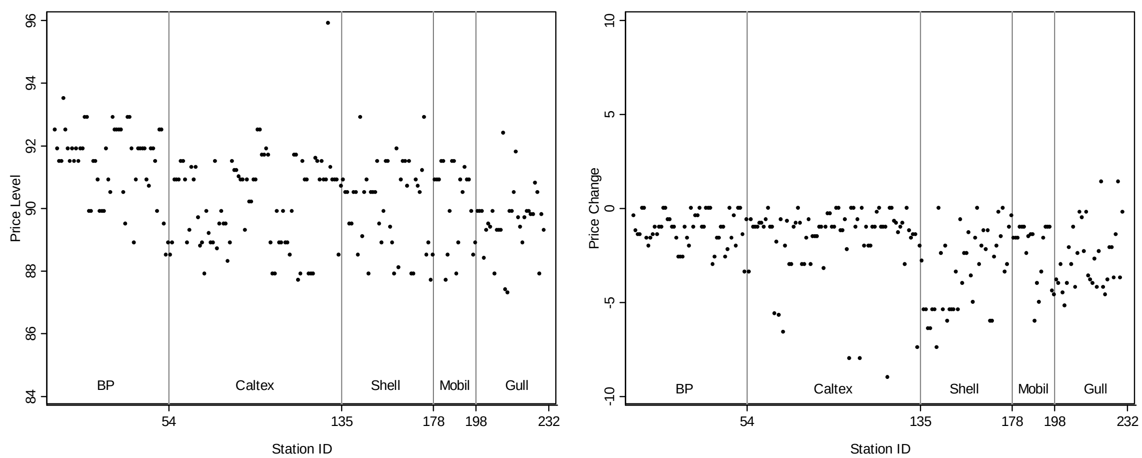

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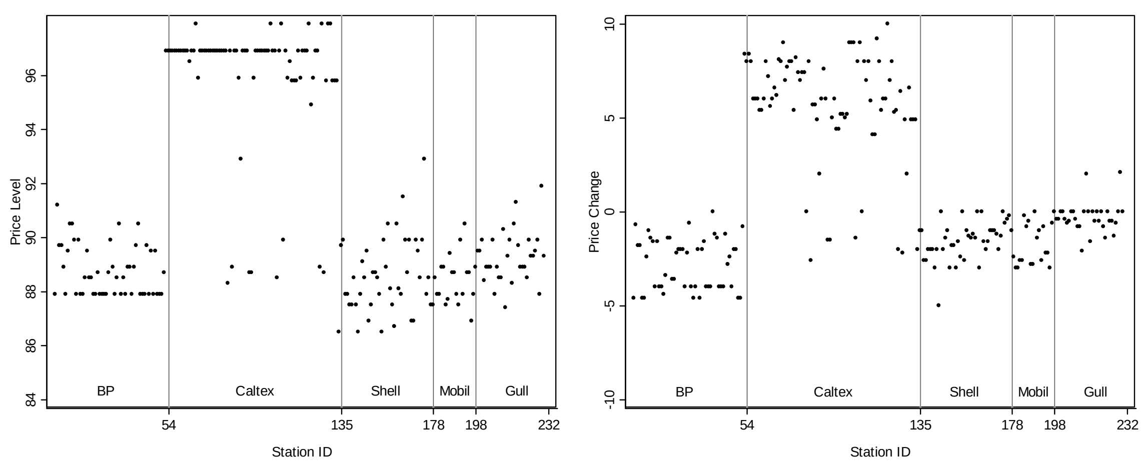


Figure 3: Daily Average Prices for Four Brands

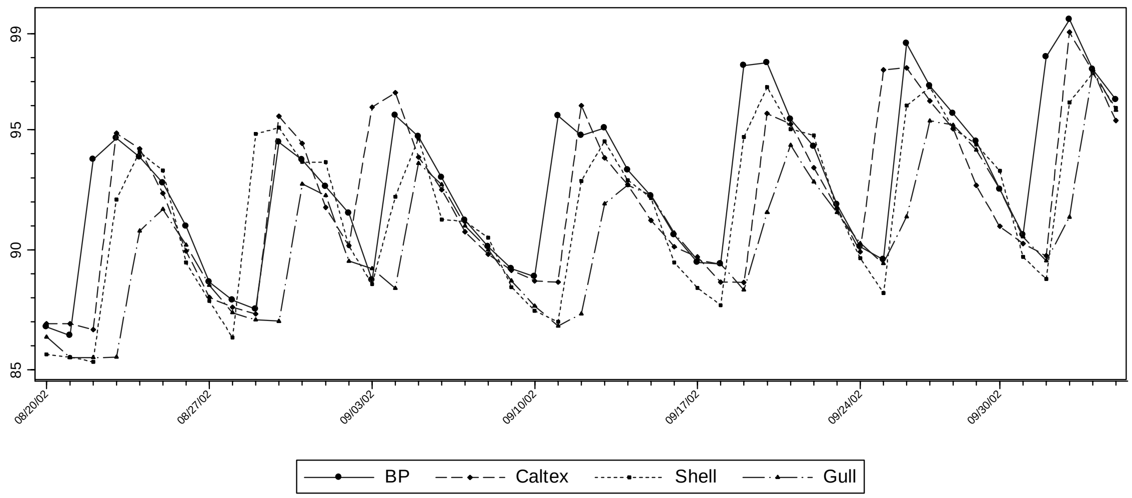
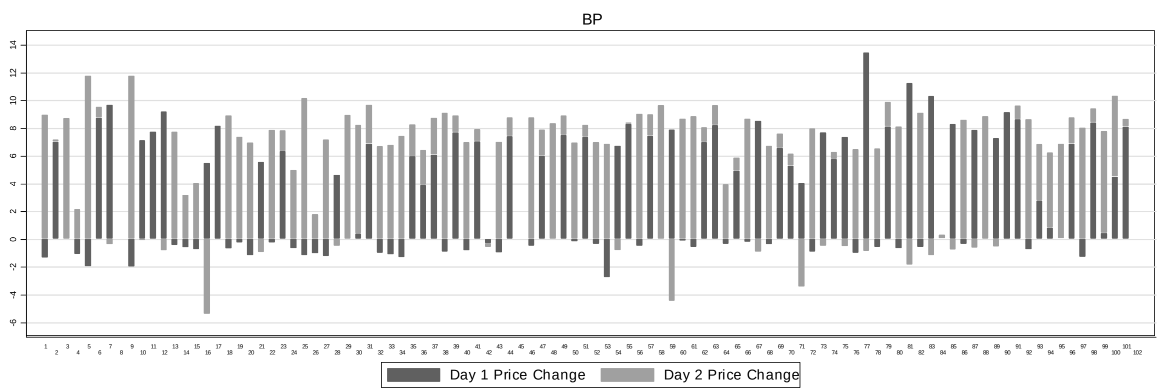
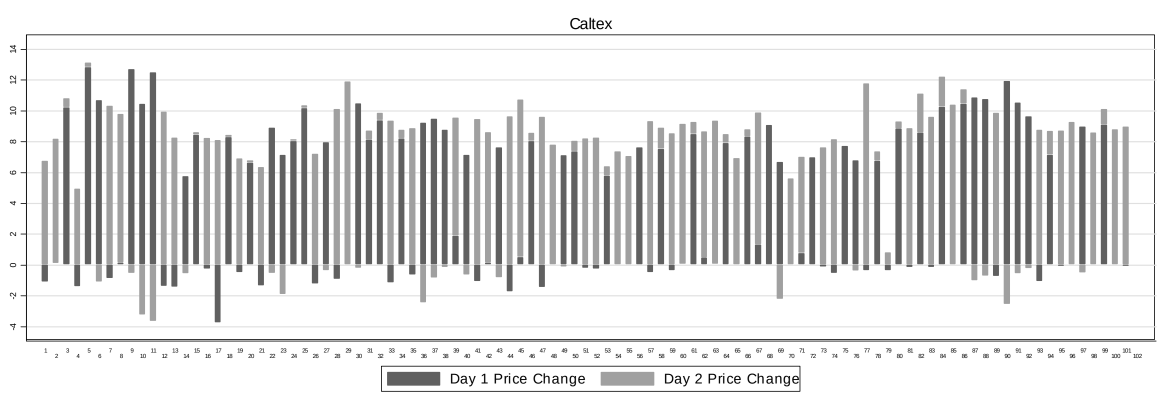


Figure 4 is in the text

Figure 5: Price Leadership and Followership Pattern for the Three Leading Firms





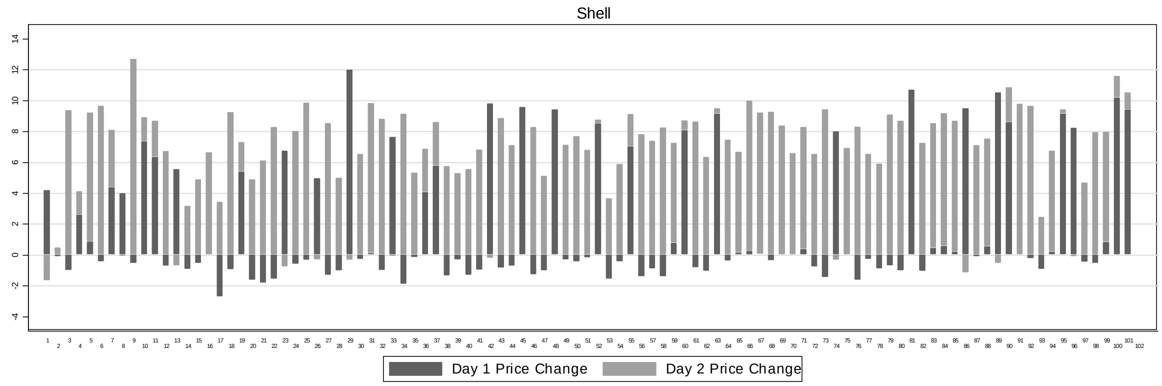
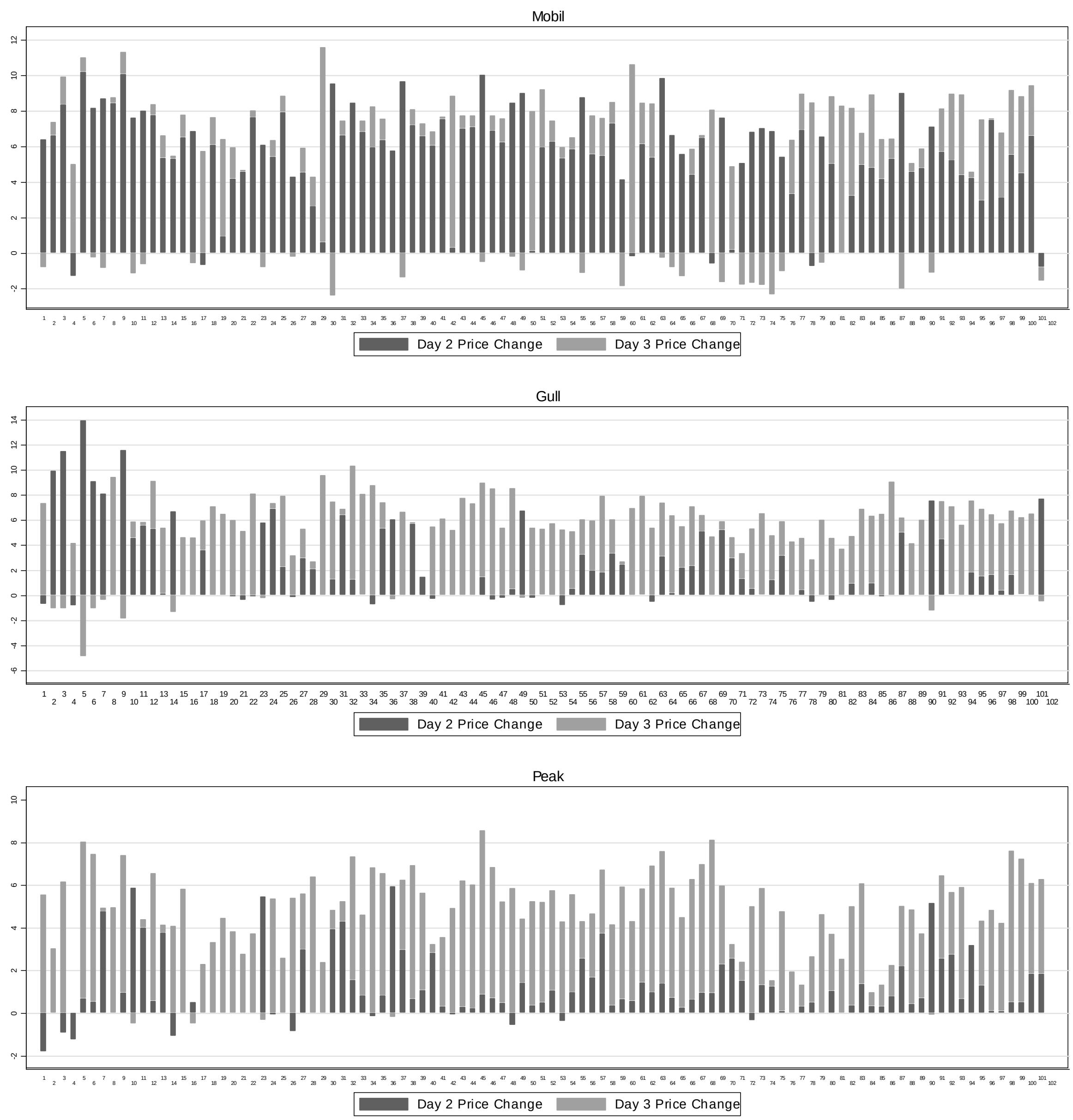


Figure 6: Price Followership Pattern for the Five Non-leading Firms



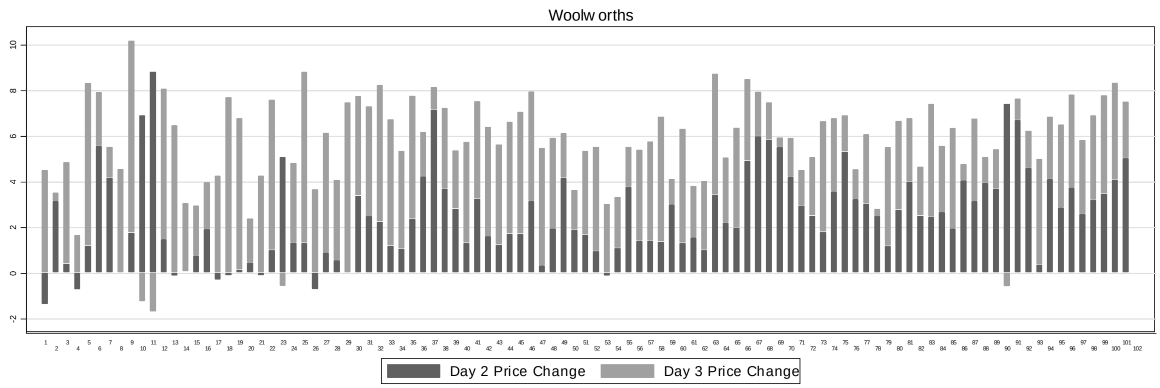


Table 1: Average Number of Gasoline Stations per Day by Brand

Brand	Average number of sites per day	Average number of sites with a spell length shorter than 2 days
BP	67	54
Caltex	88	84
Mobil	23	21
Shell	46	43
Gull	38	35
Peak	18	18
Woolworths	11	11
Liberty	9	4
Wesco	10	1
Small brands	6	3
Unbranded	16	3
All Brands	332	277

Note: The number of sites operating each day is quite stable, but not constant. Reported in each column is the average number of sites operating per day over the sample period June 1, 2001 to October 31, 2003.

Table 2: Distribution of Average Spell Length across All Stations

Percentage (%)	30	50	70	80	81.7	87	90	95	99
Percentile (days)	1.18	1.24	1.42	1.87	1.98	3.31	7.23	20.42	54

Table 3: Day of Week Frequency Distribution of Cycle Start and Peak Days

Day of week	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	1-7
Start day	6	24	21	19	5	1	25	101
Peak day	3	26	9	23	24	12	4	101

Table 4: Frequency Distribution of Cycle Lengths

Days	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	1-16
Rising phase		25	76														101
Non-rising phases	1	2	6	18	23	14	15	11	5	3	1	1	1				101
Full cycle			1		3	7	24	18	14	16	9	4	2	1	1	1	101

Table 5: Frequency Distribution of Price Leadership

Events	Observed frequency	Expected frequency
1. BP alone	27	29.19
2. Caltex alone	37	29.19
3. Shell alone	14	14.99
4. BP and Caltex only	7	12.32
5. BP and Shell only	9	6.32
6. Caltex and Shell only	1	6.32
7. BP, Caltex and Shell	6	2.67
Total:	101	101

Table 6: Brand Average Price on Different Cycle Days

Cycle day	Number of cycles	BP	Caltex	Shell	Mobil	Gull	Peak	Liberty	Woolworths
Start day	101	89.06	89.83	87.23	85.27	84.98	85.30	85.55	84.79
Rise day	76	92.70	93.94	92.47	90.61	86.23	86.15	86.58	87.09
Peak day	101	92.73	93.08	92.75	92.34	90.96	89.40	90.28	90.12
Fall day 1	101	91.26	91.22	91.64	91.24	90.80	90.06	90.33	90.74
Fall day 2	100	89.84	89.64	90.22	89.61	89.61	89.22	89.27	89.74
Fall day 3	98	88.27	88.01	88.36	88.12	88.12	87.88	87.82	88.25
Fall day 4	92	87.27	87.04	87.03	87.09	87.00	86.94	87.01	87.15
Last day	101	85.87	85.62	85.42	85.81	85.55	85.73	85.91	85.48
Difference between last day and peak day		6.86	7.46	7.33	6.53	5.41	3.67	4.37	4.64
Average		89.63	89.80	89.39	88.76	87.91	87.58	87.84	87.92

Note: Woolworths' actual brand average transaction price is much smaller than that shown in this table because of its 4-cents discount program.

Table 7: Size of the Lead Price Jumps

	BP	Caltex	Shell
Constant	7.45	9.54	9.45
	(14.82)	(17.01)	(16.59)
$\Delta\overline{P}^{BP}_{k-1,\ Last}$	0.30	0.84	1.06
	(0.32)	(1.45)	(1.08)
$\Delta\overline{P}^{Caltex}_{k-1,\ Last}$	0.026	-0.20	0.73
	(0.05)	(-0.35)	(0.96)
$\Delta\overline{P}^{Shell}_{k-1,\ Last}$	0.27	0.057	-0.005
	(0.70)	(0.16)	(-0.01)
$\Delta\overline{P}^{Mobil}_{k-1,\ Last}$	-0.67	0.55	0.84
	(-1.46)	(0.87)	(0.68)
$\Delta\overline{P}^{Gull}_{k-1,\ Last}$	-0.21	0.33	0.88
	(-0.37)	(0.62)	(0.77)
$\Delta\overline{P}^{Peak}_{k-1,\ Last}$	0.22	0.44	0.13
	(0.33)	(0.65)	(0.20)
$\Delta\overline{P}^{Liberty}_{k-1,\ Last}$	-0.087	-0.098	1.11
	(-0.18)	(-0.26)	(1.54)
$\Delta\overline{P}^{Wool}_{k-1,\ Last}$	0.17	-0.76	-0.84
	(0.31)	(-1.51)	(-0.87)
F-statistics:	0.29	1.23	3.08
Probability > F:	0.96	0.31	0.018
Adjusted R-square	-0.13	0.04	0.36
Number of cycles:	49	51	30

Note: Variable definitions are in section 5.2. T-statistics are in parentheses.

Table 8: Frequency Distribution of the Cycles between Leadership

Brand	Number of cycles between leadership	Observed frequency	Expected frequency
BP	0	15	24
	1	21	12
	2	7	6
	3+	5	7
	Chi-square statistic: 10.86		
Caltex	0	18	25.0
	1	18	12.5
	2	14	6.3
	3+	0	6.3
	Chi-square statistic: 20.24		
Shell	0	6	8.7
	1	2	6.1
	2	10	4.3
	3+	11	9.95
	Chi-square statistic: 11.4		

Table 9(a): Day-2 Followership Reaction Functions for the Three Leading Firms

	Dependent variable: day-2 price change by brand:					
	BP		Caltex		Shell	
	(1)	(2)	(1)	(2)	(1)	(2)
Constant	3.59	4.45	6.62	6.41	5.05	4.50
	(1.65)	(3.77)	(6.09)	(9.45)	(5.05)	(6.18)
$\Delta\overline{P}_{k,1}^{BP}$	-0.94		0.23	0.28	0.37	0.40
	(-1.28)		(1.94)	(2.77)	(3.18)	(4.02)
$\Delta\overline{P}_{k,1}^{Caltex}$	0.42	0.37	-0.50		0.48	0.51
	(1.94)	(2.44)	(-1.15)		(4.75)	(5.85)
$\Delta\overline{P}_{k,1}^{Shell}$	0.12	0.13	0.25	0.29	-0.083	
	(0.48)	(0.80)	(1.90)	(2.95)	(-0.18)	
$CaLed_k * ShLed_k$	3.21	-1.02				
	(0.74)	(-0.31)				
$BPLed_k * ShLed_k$			-1.95	-2.12		
			(-1.54)	(-1.93)		
$BPLed_k * CaLed_k$					-3.18	-3.01
					(-2.80)	(-2.92)
$\Delta\overline{P}_{k,1}^{Mobil}$	-0.81		-0.043		0.27	
	(-0.77)		(-0.24)		(0.67)	
$\Delta\overline{P}_{k,1}^{Gull}$	0.85		0.53		-0.087	
	(0.75)		(0.84)		(-0.16)	
$\Delta\overline{P}_{k,1}^{Peak}$	0.53		-1.14		-0.76	-0.74
	(0.67)		(-1.27)		(-1.80)	(-1.89)
$\Delta\overline{P}_{k,1}^{Liberty}$	0.43		0.13		0.23	
	(0.95)		(0.18)		(0.94)	
$\Delta\overline{P}_{k,1}^{Wool}$	-1.17		1.14		-0.37	
	(-0.98)		(1.53)		(-0.56)	
$\Delta\overline{P}_{k-1,\,Last}^{BP}$	-0.56		-0.42		-0.22	
	(-0.61)		(-0.63)		(-0.37)	
$\Delta\overline{P}_{k-1,\,Last}^{Caltex}$	0.83		-0.30		0.47	
	(0.87)		(-0.56)		(1.21)	
$\Delta\overline{P}_{k-1,\,Last}^{Shell}$	-0.75		0.44		0.03	
	(-0.88)		(1.07)		(0.11)	
$\Delta\overline{P}_{k-1,\,Last}^{Mobil}$	-0.30		-0.71		0.21	
	(-0.24)		(-1.23)		(0.57)	
$\Delta\overline{P}_{k-1,\,Last}^{Gull}$	0.91		0.69		-0.36	
	(0.91)		(1.15)		(-0.90)	
$\Delta\overline{P}_{k-1,\,Last}^{Peak}$	0.76		-0.51		-0.046	
	(0.77)		(-0.93)		(-0.09)	
$\Delta\overline{P}_{k-1,\,Last}^{Liberty}$	0.11		-0.12		0.043	
	(0.14)		(-0.23)		(0.15)	
$\Delta\overline{P}_{k-1,\,Last}^{Wool}$	-0.09		-0.15		1.27	0.99
	(-0.08)		(-0.28)		(3.45)	(4.04)
Num. of cycles	52	52	50	50	71	71
Adj. R-square	0.10	0.13	0.12	0.13	0.39	0.42

Note: Variable definitions are in section 5.2. T-statistics are in parentheses.

Table 9(b): Day-2 Leader Adjustment Functions for the Three Leading Firms

	Dependent variable: day-2 price change by brand:					
	BP		Caltex		Shell	
	(1)	(2)	(1)	(2)	(1)	(2)
Constant	-0.000	0.16	0.37	0.35	0.69	0.69
	(-0.00)	(-0.60)	(1.13)	(1.49)	(1.56)	(2.82)
$LeadDiff_k^{BP}$	-0.56	-0.44				
	(-2.55)	(-2.51)				
$LeadDiff_k^{Caltex}$			-0.62	-0.61		
			(-6.55)	(-6.90)		
$LeadDiff_k^{Shell}$					-0.44	-0.35
					(-3.15)	(-3.15)
$\Delta\overline{P}_{k,1}^{Mobil}$	-0.004		0.40		0.072	
	(-0.02)		(1.20)		(0.53)	
$\Delta\overline{P}_{k,1}^{Gull}$	0.75		0.33		-0.32	
	(0.99)		(0.79)		(-0.38)	
$\Delta\overline{P}_{k,1}^{Peak}$	-1.06		0.16		1.29	
	(-1.17)		(0.66)		(1.36)	
$\Delta\overline{P}_{k,1}^{Liberty}$	-0.37		-0.16		0.012	
	(-0.53)		(-1.10)		(0.02)	
$\Delta\overline{P}_{k,1}^{Wool}$	-1.46		-0.076		1.50	0.76
	(-1.43)		(-0.18)		(2.09)	(2.07)
$\Delta\overline{P}_{k-1,\,Last}^{BP}$	-0.028		0.62	0.46	-0.69	
	(-0.03)		(1.89)	(1.85)	(-0.81)	
$\Delta\overline{P}_{k-1,\,Last}^{Caltex}$	0.73		0.16		-0.90	
	(1.09)		(0.50)		(-1.53)	
$\Delta\overline{P}_{k-1,\,Last}^{Shell}$	-0.15		0.42	0.27	-0.79	-0.55
	(-0.34)		(1.96)	(1.96)	(-1.91)	(-1.70)
$\Delta\overline{P}_{k-1,\,Last}^{Mobil}$	-0.35		-0.43		0.85	
	(-0.65)		(-1.22)		(-0.89)	
$\Delta\overline{P}_{k-1,\,Last}^{Gull}$	0.43		-0.056		0.41	
	(0.60)		(-0.18)		(0.54)	
$\Delta\overline{P}_{k-1,\,Last}^{Peak}$	-0.13		-0.84	-0.82	0.30	
	(-0.19)		(-2.24)	(-2.84)	(0.52)	
$\Delta\overline{P}_{k-1,\,Last}^{Liberty}$	-0.38		-0.28		-1.07	
	(-0.82)		(-1.46)		(-1.64)	
$\Delta\overline{P}_{k-1,\,Last}^{Wool}$	0.51		-0.17		1.35	
	(1.04)		(-0.64)		(1.58)	
Num. of cycles	49	49	51	51	30	30
Adjusted R-square	0.12	0.10	0.50	0.51	0.33	0.33

Note: Variable definitions are in section 5.2. T-statistics are in parentheses.

Table 10(a): Estimated Day-2 Reaction Functions for the Five Non-leading Firms

	Mobil		Gull		Peak		Liberty		Woolworths	
	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
Constant	3.95	5.71	1.38	1.03	-0.67	-0.83	0.14	0.31	0.092	0.36
	(5.31)	(10.86)	(1.53)	(1.79)	(-1.66)	(-2.81)	(0.19)	(0.68)	(0.24)	(1.40)
$\Delta\overline{P}_{k,1}^{BP}$	0.20	0.12	0.22	0.24	0.39	0.45	0.43	0.30	0.39	0.31
	(3.16)	(2.73)	(1.08)	(3.60)	(4.33)	(5.30)	(2.69)	(5.58)	(4.62)	(11.16)
$(\Delta\overline{P}_{k,1}^{BP})^2$			-0.00		-0.028	-0.033	-0.017		-0.011	
			(-0.02)		(-2.73)	(-3.41)	(-0.95)		(-1.10)	
$\Delta\overline{P}_{k,1}^{Caltex}$	0.24	0.12	-0.23	-0.30	0.25	0.17	-0.32	-0.24	0.51	0.50
	(3.97)	(3.11)	(-1.03)	(-1.56)	(2.52)	(6.51)	(-1.78)	(-1.61)	(5.42)	(5.98)
$(\Delta\overline{P}_{k,1}^{Caltex})^2$			0.055	0.063	-0.008		0.053	0.045	-0.023	-0.022
			(2.48)	(3.27)	(-0.80)		(2.99)	(2.98)	(-2.40)	(-2.62)
$\Delta\overline{P}_{k,1}^{Shell}$	0.020	0.091	0.18	-0.079	0.45	0.39	-0.04	-0.041	0.39	0.35
	(0.27)	(1.77)	(0.79)	(-1.11)	(4.33)	(4.21)	(-0.20)	(-0.73)	(3.97)	(3.91)
$(\Delta\overline{P}_{k,1}^{Shell})^2$			-0.032		-0.034	-0.028	0.002		-0.023	-0.023
			(-1.17)		(-2.83)	(-2.60)	(0.08)		(-2.04)	(-2.14)
$\Delta\overline{P}_{k,1}^{Mobil}$	-0.52	-0.069	0.35		-0.018		0.15		0.069	
	(-2.35)	(0.18)	(1.42)		(-0.16)		(0.78)		(0.66)	
$\Delta\overline{P}_{k,1}^{Gull}$	-1.47	-0.74	-0.46		-0.34		-0.014		0.015	
	(-2.40)	(-1.64)	(-0.64)		(-1.07)		(-0.02)		(0.05)	
$\Delta\overline{P}_{k,1}^{Peak}$	0.52	0.15	0.41		-0.45	-0.26	-0.37		-0.046	
	(1.00)	(0.38)	(0.70)		(-1.71)	(-1.17)	(-0.79)		(-0.19)	
$\Delta\overline{P}_{k,1}^{Liberty}$	-0.94	-0.60	-0.10		0.095		-0.007		0.40	0.37
	(-2.84)	(-1.72)	(-0.27)		(0.56)		(-0.02)		(2.52)	(2.99)
$\Delta\overline{P}_{k,1}^{Wool}$	-0.13	-0.95	-0.35		0.41		-0.11		0.12	
	(-0.20)	(-2.07)	(-0.46)		(1.18)		(-0.18)		(0.36)	
$\Delta\overline{P}_{k-1,\,Last}^{BP}$	-0.056	0.38	0.61		-0.11		0.59		-0.13	
	(-0.10)	(1.01)	(0.91)		(-0.37)		(1.11)		(-0.46)	
$\Delta\overline{P}_{k-1,\,Last}^{Caltex}$	1.38	1.20	0.49		0.13		0.099		-0.12	
	(3.07)	(3.79)	(0.96)		(0.55)		(0.24)		(-0.57)	
$\Delta\overline{P}_{k-1,\,Last}^{Shell}$	0.56	0.39	-0.059		-0.50	-0.39	-0.27		-0.28	
	(1.55)	(1.58)	(-0.14)		(-2.72)	(-3.01)	(-0.84)		(-1.61)	
$\Delta\overline{P}_{k-1,\,Last}^{Mobil}$	0.38	-0.061	-0.29		0.011		0.21		0.22	
	(0.81)	(-0.18)	(-0.54)		(-0.05)		(0.50)		(0.99)	
$\Delta\overline{P}_{k-1,\,Last}^{Gull}$	-1.58	-0.59	0.41		0.29		-0.020		0.44	0.19
	(-3.21)	(-1.49)	(0.70)		(1.13)		(-0.04)		(1.80)	(1.43)
$\Delta\overline{P}_{k-1,\,Last}^{Peak}$	1.35	0.95	1.52	1.50	-0.27		0.98	0.79	-0.13	
	(2.65)	(2.51)	(2.65)	(3.83)	(-1.07)		(2.14)	(2.55)	(-0.53)	
$\Delta\overline{P}_{k-1,\,Last}^{Liberty}$	-0.41	-0.055	-0.41		0.12		-0.45		-0.052	
	(-1.10)	(-0.22)	(-0.97)		(0.61)		(-1.34)		(-0.29)	
$\Delta\overline{P}_{k-1,\,Last}^{Wool}$	0.13	-0.014	-0.45		-0.041		-0.26		-0.21	
	(0.29)	(-0.05)	(-0.89)		(-0.18)		(-0.64)		(-0.96)	
Num. of cycles	101	89	101	101	101	101	101	101	101	101
Adj. R-square	0.28	0.29	0.35	0.36	0.45	0.46	0.33	0.36	0.70	0.71

Note: Variable definitions are in section 5.2. Dependent variable is the day-2 price increases. T-statistics are in parentheses.

Table 10(b): Day-3 Reaction Functions for the Five Non-leading Firms

	Dependent variable: day-3 price increase by brand:									
	Mobil		Gull		Peak		Liberty		Woolworths	
	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
Constant	0.30	-0.092	2.19	3.74	0.69	1.64	1.28	1.56	0.39	0.46
	(0.28)	(-0.13)	(2.17)	(7.15)	(0.36)	(2.51)	(0.85)	(2.10)	(0.45)	(0.86)
$\Delta\overline{P}_{k,2}^{BP}$	0.39	0.34	0.31	0.35	0.35	0.33	0.37	0.32	0.28	0.27
	(4.19)	(4.05)	(3.47)	(4.07)	(3.17)	(3.08)	(2.77)	(5.65)	(3.59)	(3.81)
$(\Delta\overline{P}_{k,2}^{BP})^2$	-0.022	-0.023	-0.028	-0.021	-0.032	-0.028	-0.018		-0.012	-0.013
	(-2.12)	(-2.37)	(-2.75)	(-2.18)	(-2.57)	(-2.38)	(-1.24)		(-1.48)	(-1.58)
$\Delta\overline{P}_{k,2}^{Caltex}$	0.29	0.52	0.049	0.12	0.11	0.12	0.25	0.14	0.08	0.17
	(1.81)	(6.24)	(0.32)	(3.21)	(0.58)	(2.50)	(1.07)	(2.57)	(0.60)	(4.78)
$(\Delta\overline{P}_{k,2}^{Caltex})^2$	0.018		0.022		0.004		-0.001		0.015	
	(1.28)		(1.62)		(0.26)		(-0.04)		(1.28)	
$\Delta\overline{P}_{k,2}^{Shell}$	0.26	0.21	-0.13	-0.38	0.25	0.14	-0.067	-0.028	0.27	0.39
	(1.25)	(2.73)	(-0.64)	(-3.07)	(1.01)	(2.69)	(-0.23)	(-0.48)	(1.59)	(6.30)
$(\Delta\overline{P}_{k,2}^{Shell})^2$	-0.005		0.035	0.046	-0.006		0.008		0.010	
	(-0.31)		(2.27)	(3.55)	(-0.28)		(0.36)		(0.78)	
$\Delta\overline{P}_{k,2}^{Mobil}$	-0.87	-0.84	0.22	0.22	0.21	0.17	0.21	0.25	0.14	0.18
	(-15.3)	(-16.26)	(3.95)	(4.37)	(3.10)	(2.63)	(2.65)	(3.39)	(3.04)	(4.31)
$\Delta\overline{P}_{k,2}^{Gull}$	-0.000		-0.94	-0.92	0.15	0.14	0.021		0.021	
	(-0.01)		(-14.6)	(-14.6)	(1.81)	(2.41)	(0.22)		(0.39)	
$\Delta\overline{P}_{k,2}^{Peak}$	-0.14		-0.012		-0.97	-0.80	0.30	0.14	0.080	
	(-1.20)		(-0.11)		(-6.94)	(-6.62)	(1.78)	(1.02)	(0.84)	
$\Delta\overline{P}_{k,2}^{Liberty}$	0.050		0.16	0.13	-0.037		-0.69	-0.71	-0.010	
	(0.59)		(1.98)	(1.71)	(-0.37)		(-5.79)	(-8.40)	(-0.15)	
$\Delta\overline{P}_{k,2}^{Wool}$	-0.20		-0.079		0.20		-0.18		-0.74	-0.67
	(-1.49)		(-0.63)		(1.25)		(-0.96)		(-6.82)	(-8.31)
$\Delta\overline{P}_{k,1}^{BP}$	0.12		-0.093		-0.058		-0.051		0.031	
	(1.54)		(-1.25)		(-0.62)		(-0.46)		(0.48)	
$\Delta\overline{P}_{k,1}^{Caltex}$	0.42	0.42	0.13		-0.002		0.12		0.045	
	(4.14)	(4.92)	(1.34)		(-0.01)		(0.81)		(0.55)	
$\Delta\overline{P}_{k,1}^{Shell}$	0.23	0.20	0.14		0.070		0.009		0.22	0.26
	(2.38)	(2.97)	(1.54)		(0.61)		(0.07)		(2.79)	(4.58)
$\Delta\overline{P}_{k,1}^{Mobil}$	-0.73	-0.71	0.12		0.22		-0.14		0.075	
	(-5.65)	(-5.95)	(0.95)		(1.43)		(-0.73)		(0.70)	
$\Delta\overline{P}_{k,1}^{Gull}$	0.11		-0.23		-0.59		0.19		0.17	
	(0.38)		(-0.82)		(-1.66)		(0.46)		(0.70)	
$\Delta\overline{P}_{k,1}^{Peak}$	-0.079		0.50	0.36	-0.79	-0.27	0.76	0.16	0.54	0.41
	(-0.28)		(1.85)	(1.54)	(-2.35)	(-0.92)	(1.90)	(0.49)	(2.35)	(2.05)
$\Delta\overline{P}_{k,1}^{Liberty}$	0.016		-0.032		0.32		-0.34		0.005	
	(0.08)		(-0.18)		(1.38)		(-1.26)		(0.03)	
$\Delta\overline{P}_{k,1}^{Wool}$	0.12		-0.36		0.40		-0.51		-0.38	
	(0.36)		(-1.09)		(0.97)		(-1.05)		(-1.37)	
Num. of cycles	101	101	101	101	101	101	101	101	101	101
Adj. R-square	0.78	0.78	0.83	0.82	0.46	0.44	0.59	0.59	0.70	0.71

Note: Variable definitions are in section 5.2. T-statistics are in parentheses.

Appendix 1: Measuring the Degree of Synchronization and Uniformity

Figures 2 and 3 show that price increases exhibit strong intrabrand synchronization and uniformity. This feature of the data makes it possible to study the cycle rising phase by looking at the brand average prices without losing important information. A simple way of measuring the degree of intrabrand price synchronization and uniformity is to decompose the total variation in daily cross section prices or price changes into within-brand variation and between-brand variation. Consider the following two separate regressions for date t:

(A1) $$P_{it} - \overline{P}_t = b^1 + b^2 + ... + b^J ,$$

(A2) $$\Delta P_{it} - \Delta \overline{P}_t = b^1 + b^2 + ... + b^J$$

where $\Delta P_{it} = P_{it} - P_{i,t-1}$, $\Delta \overline{P}_t = (1/N)\sum_{i=1}^{N} \Delta P_{it}$, and b_j's are the brand dummies. The R-square of equation (A1) is the percent of total variation in price levels across the N stations on date t attributable to the brand effect. The R-square of equation (A2) can be similarly interpreted. Estimate these two equations separately for each day of the 101 price cycles. Take the R-squares for these equations as data, and consider the following two equations:

(A3) $$R_t^P = c + start_t + peak_t + rise_t ,$$

(A4) $$R_t^{\Delta P} = c + start_t + peak_t + rise_t .$$

The dependent variables in equation (A3) and (A4) are, respectively, the R-squares for equations (A1) and (A2). The independent variables are three dummy variables, $start_t$, $peak_t$, and $rise_t$. The variable $start_t$ takes the value of 1 if t is the start day of a cycle, and 0 otherwise; $peak_t$ is 1 if t is the peak day of a cycle, and 0 otherwise; $rise_t$ is 1 if t is in the rising phase of a price cycle, but not the start or peak day.

Note that, one might pool the observations across the different cycle phases, rather than estimate equations (A1) and (A2) on a daily basis and then use equations (A3) and (A4) to see the brand effects at different phases of the price cycle. The R-square for such a pooling regression is a weighted average of the R-squares for the daily regressions, with the weight being the total variation in each day. The two-step procedure produces a simple average of the R-squares for the daily regressions.

Only the stations of the four oil companies and the four independent brands are considered when estimating equations (A1) and (A2). The average number of stations on a given day is 259. Table A-1 presents the estimated results for equations (A3) and (A4). Between-brand variation accounts for about 77% (76%) of the total variation in price level (price difference) on the cycle start day, 64% (61%) on the rising day, and 48% (58%) on the peak day. The brand effect still exists during the cycle falling phases, but it is much weaker.

Table A-1: Ratio of Between-brand Variation to Total Variation in Different Cycle Phases

	Dependent variable	
	Ratio of daily between-brand to total variation in price level	Ratio of daily between-brand to total variation in price difference
Constant	0.225	0.258
	(34.25)	(39.59)
Start	0.545	0.503
	(31.63)	(29.45)
Peak	0.158	0.317
	(9.12)	(18.45)
Rise	0.413	0.349
	(21.08)	(17.98)
Adjusted R-square	0.60	0.58
Observation number	877	877

Note: T-statistics are in parentheses.

Appendix 2: **Identification of Price Leaders for 10 Cycles**

This appendix identifies the price leaders for 10 price cycles for which the identification is not as clear cut as that for the other 91 cycles. However, even for these 10 price cycles, the identification of the lead price jumps is still largely unambiguous. Table A-2 provides the brand average prices of the 10 cycles.

Cycles No. 39 and 72:

For these 2 price cycles, a lead price increase can be clearly identified, but whether a second player's price increase should be considered as a lead price increase as well is not as clear. For cycle No. 39, BP raised its price by 7.89 cents on May 10, 2002 to start a new cycle, but Caltex raised its price by 1.85 cents on the same day. Because Caltex increased its price by 7.69 cents on the following day, I consider Caltex as a follower instead of a leader for this cycle. For cycle No. 72, Caltex raised its price by 6.95 cents on February 19, 2003 to start a new cycle, but Peak raised its price by 1.56 cents on the same day. Given that Peak raised its price by 5.01 cents on February 21, 2003, and that an independent brand is very unlikely to lead, I do not consider Peak as a leader for this cycle.

Cycles No. 17, 23, 48, 58, and 86:

For these five cycles, the identified lead price jumps are preceded by some price increases. Cycle 17 is very special in that it is clear cut that BP jumped up its price by 8.16 cents to start a new cycle on November 5, 2001, but there are significant price increases by some other players on November 4, 2001. This is because three independent players were increasing their prices on that day to follow the lead price jump by BP on November 2, 2001.

For the other four cycles, small but not trivial price increases, ranging from 1.13 to 2.24 cents, are found on the day before the identified lead price jumps. Consider cycle No. 23. Liberty increased its price by 1.52 cents on December 18, 2001. On December 19, 2001, BP, Caltex and Shell raised their prices by 6.32, 7.12, and 6.73 cents, respectively. These price increases are followed by the other five players, including Liberty, on the following day. Is Liberty the price leader for this cycle? I consider it not. Cycles No. 48 and 58 are very similar. Cycle No. 86 is a little bit different. On June 14, 2003, Shell increased its price by 2.20 cents. On June 15, Shell increased its price by 9.50 cents again, and Caltex increased its price by 10.43 cents. The other players start to increase their prices the following day. I consider the price increases by Shell and Caltex on June 15 as the two lead price increases for this cycle.

Cycles No. 29, 67, and 71:

Cycles No. 29 and 67 are very similar in that some players increased their prices slightly (less than 1.71 cents) on the last day of the previous cycle, and a second player increased its price slightly (less than 1.56 cents) on the first day of the identified price cycles. These small increases are not considered as lead price jumps.

One may argue that Mobil led cycle No. 71. However, it decreased its price on the following day and increased its price again on the third day. Given that the data suggests strongly that Mobil and the independent brands are not expected to lead, I consider BP the cycle leader and Mobil as a follower.

Table A2: Brand Average Prices of 10 Cycles

Cycle number	Day of Cycle	Date	BP	Caltex	Shell	Mobil	Gull	Peak	Liberty	Wool
		11/02/01	5.47	-0.28	-0.02	-0.04	-1.54	0.00	-0.32	-0.18
		11/03/01	-5.43	8.20	6.63	6.85	0.00	0.51	0.00	1.91
		11/04/01	0.00	-4.16	-0.68	-0.61	4.61	-0.51	1.58	2.04
17	1	11/05/01	8.16	-3.79	-2.73	-4.43	-4.36	0.82	-1.74	-2.50
	2	11/06/01	0.00	8.08	3.41	-0.70	3.57	0.00	2.12	-0.31
	3	11/07/01	-1.70	-1.24	0.58	5.74	2.39	2.29	3.08	4.24
		12/18/01	-1.41	-1.22	-0.95	-1.06	-1.14	-0.42	1.52	-0.02
23	1	12/19/01	6.32	7.12	6.73	-0.60	-0.45	-1.08	0.30	-0.69
	2	12/20/01	1.51	-1.95	-0.80	6.07	5.78	5.46	2.00	5.07
	3	12/21/01	-2.80	3.78	-0.89	-0.83	-0.28	-0.34	-0.52	-0.60
		02/09/02	0.09	0.66	-0.17	0.00	0.00	1.71	0.00	0.04
29	1	02/10/02	0.00	0.00	11.98	-0.06	1.56	-0.06	0.40	0.07
	2	02/11/02	8.93	11.89	-0.36	0.6	0.00	0.00	0.20	0.00
	3	02/12/02	-0.67	-1.74	-0.17	10.96	9.56	2.38	8.48	7.47
		05/09/02	-0.61	-0.63	-0.77	-0.05	-0.22	-0.06	-0.40	-0.96
39	1	05/10/02	7.69	1.85	-0.34	-0.30	-1.51	0.00	0.00	-0.56
	2	05/11/02	1.22	7.69	5.27	6.57	1.47	1.07	0.40	2.80
	3	05/12/02	-1.27	-1.31	2.44	0.71	0.00	4.56	5.60	2.56
		07/27/02	-1.87	1.32	0.80	0.00	0.11	2.24	1.13	0.87
48	1	07/28/02	0.00	0.00	9.40	-0.05	0.10	-0.69	0.67	0.00
	2	07/29/02	8.33	7.77	0.05	8.45	0.47	-0.58	0.00	1.95
	3	07/30/02	0.63	-0.39	-1.27	-0.24	8.07	5.85	5.33	3.96
		10/13/02	-0.16	0.10	0.22	-0.39	-0.03	-0.10	1.33	-0.26
58	1	10/14/02	-0.05	7.50	-1.43	-0.33	0.00	0.00	0.00	-0.33
	2	10/15/02	9.63	1.37	8.23	7.28	3.31	0.35	-0.67	1.36
	3	10/16/02	-1.89	-1.92	0.97	1.20	2.74	3.79	5.33	5.48
		01/07/03	0.35	-0.63	-0.16	-0.03	0.45	1.18	0.00	-0.44
67	1	01/08/03	8.51	1.30	0.03	-1.21	0.04	-0.84	0.00	-0.05
	2	01/09/03	-0.93	8.57	9.18	6.47	5.08	0.95	1.33	5.98
	3	01/10/03	-1.06	-1.62	-0.45	0.17	1.31	6.02	1.87	1.95
		02/13/03	0.56	0.18	0.12	4.02	0.00	0.00	-0.40	0.33
71	1	02/14/03	4.03	0.73	0.35	-2.22	0.41	0.18	2.67	0.55
	2	02/15/03	-3.45	6.25	7.91	5.06	1.31	1.52	3.33	2.94
	3	02/16/03	6.31	-0.06	-0.54	-1.81	2.05	0.88	0.00	1.55
		02/18/03	-1.16	-1.75	-0.60	-1.26	-0.64	0.32	-0.27	-0.97
72	1	02/19/03	-0.93	6.95	-0.80	0.52	-0.97	1.56	-0.27	-0.91
	2	02/20/03	7.98	-0.09	6.53	6.81	0.51	-0.35	0.00	2.50
	3	02/21/03	-1.40	-1.40	0.07	-1.70	4.81	5.01	4.57	2.56
		06/14/03	-0.10	-2.17	2.20	-0.78	-1.33	-0.04	0.00	-1.53
86	1	06/15/03	-0.38	10.43	9.50	-0.10	0.08	0.00	0.00	-0.05
	2	06/16/03	8.58	0.95	-1.17	5.30	0.00	0.79	1.85	4.05
	3	06/17/03	-2.34	-1.21	-0.53	1.12	9.05	1.46	2.50	0.70