Calculating the damage of a cartel subject to transition periods: the international uranium cartel in the 1970s[1]

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Abstract

The theory about cartel pricing and descriptive price statistics suggests that the price path over a cartel life cycle can be subject to gradual, non-linear transitions where the price path moves from (to) the non-collusive to (from) the collusive equilibrium. Ignoring such transitions can lead to biased estimates of the cartel and damage effects. Smooth transition regression (STR) models are a class of models well suited to capture such transitions, also under realistic conditions when the transition start and end dates are uncertain and when the two transitions are asymmetric. We evaluate the international uranium cartel during the 1970s using both the mainstream approach based on a linear specification with a dummy variable to capture the cartel, and a STR model. We are the first to use STR models in the evaluation of a cartel/damage effect. Using the STR model, we find that the damage effect is about 18 times higher as compared to the mainstream model.

Keywords: cartel, damage, transition, uranium, smooth transition regression models

JEL Classification: C18, L42, L72

1. Introduction

An increasing number of unlawful cartels have been detected in both Europe and the US in recent years.[2] In antitrust cases, Competition Authorities and courts ultimately want to determine how much higher prices were during cartel periods relative to competitive periods in order to calculate the size of the economic damage inflicted on consumers and/or downstream firms. While private antitrust cases involving damage calculations have also increased in number, claimants are often unsuccessful in such litigations (Renda et al., 2007). The European Commission's Green Paper published in 2005 stated that "…the robust quantification of the caused damage is one of the key barriers to a further promotion of antitrust damage action." (Hüschelrath et al., 2013, p. 98).

The evaluation method most commonly used, both in scientific and legal investigations, is to rely on aggregate field data and estimate a reduced form price equation by regressing the price on cost and demand shifters and a dummy variable that takes the value of one in time periods when the (suspected) cartel was active (e.g. European Commission, 2013). The estimated coefficient associated with the cartel dummy will reveal the difference between competitive prices and cartel prices. Using the formulation proposed by Davis and Garcés (2010, p. 354), the analyst gets a measure of the direct economic damage by multiplying the cartel coefficient with the traded quantity.

While this modelling strategy is simple and intuitive, it ignores theoretical findings that the cartel price does not begin and end with sudden level shifts, but rather that the price path gradually evolves from one equilibrium to the next. Generally, such transitions can occur because of 1) incentive compatibility, i.e. a joint desire to maintain the stability of the cartel, 2) concerns about detection, which may also affect lawful cartels since they might want to keep themselves hidden from industrial buyers, 3) the possibility of the cartelised product being provided by firms that are not cartel members, and 4) uncertainty about stability, driven by, for example, lack of trust among participating firms.[3] More specifically, Harrington (2004a) develops formal theory and shows that profit-maximising cartels raise the price gradually at the beginning of a cartel in order to trade the increasing profit against the increasing likelihood of detection. He shows that the slope of the price series during this transition

[2] Statistics for Europe is provided by the European Commission; see http://ec.europa.eu/competition/cartels/statistics/statistics.pdf

[3] See the general cartel literature, e.g. Harrington and Skrzypacz (2011).

depends on how patient firms are (the discount rate) and the number of firms. Moreover, after the dissolution of a cartel, Harrington (2004b) shows that the price can gradually move towards the competitive equilibrium when firms are engaged in post-cartel litigations. In this situation, he finds that the (absolute of the) downward slope is negatively correlated with the length of the cartel and the level of industry concentration, i.e. the longer the duration of the cartel and the higher the industry concentration, the slower the return to the competitive price level. Thus, it should be noted that the mechanisms influencing the characteristics of the price path during the two transitions are different. This implies that one cannot generally assume that the transitions are symmetric.

The important insight is that if a cartel is subject to gradual transitions and those transitions are ignored, e.g. that the start and end are modelled as two instantaneous level shifts, then the collusive effect is wrongly and inefficiently estimated. Naturally, this will lead to corresponding problems when calculating the size of the damage effect. One simple empirical approach to reduce these problems is to exclude transition data from the analysis (Harrington, 2004b). However, since the transition end dates are unknown, empiricists would potentially need to exclude several observations with a high probability of also discarding useful information. Since real investigations often suffer from limited access to data, this approach can substantially reduce efficiency, and still one cannot be sure of having excluded all transition observations. A second approach is to impose strong assumptions about the functional form of the transition periods, e.g. that the price path evolves linearly (such an approach is used by Hüschelrath el at., 2013). A third approach is to include the lagged price as an explanatory variable. An example that builds on that principle is Bolotova et al. (2008) who evaluate the citric acid and lysine price cartels.[4] Such dynamic models predict a smooth price path and thus, transitions will be implicitly controlled for. However, there are two problems with dynamic models when applied to cartels with gradual transitions. First, the 'transitions' that are generated reflect the persistence of the entire price series and not the cartel transitions specifically. Second, if there are transitions both at the beginning and the end of the cartel, then the transitions will be symmetrical. As pointed out above, symmetry is generally a strong assumption and, as shown in Section 2, that assumption is clearly violated in the empirical case that we investigate. Moreover, linear dynamic models contain no

[4] Bolotova et al. (2008) use a specification where the persistence can be different during non-collusive and collusive periods. However, their model is nevertheless designed to capture general persistence without specific concerns about the transitions.

information about timing and duration of the transitions; they only incorporate the persistence of the price process via the autoregressive coefficient.

All these approaches either ignore the transitions or make strong assumptions about their characteristics, which greatly increases the risk that the size of the damage is inaccurately estimated.[5] To remedy this problem, we consider an alternative approach based on Smooth Transition Regression (STR) models,[6] where the transitions are modelled by smooth nonlinear functions. Importantly, the parameter estimates of a STR model provide information about the shape (as a function of time) and the start/end dates of the transitions. A priori, symmetry is not a restriction because each transition is modelled individually. To the best of our knowledge, we are the first to estimate the damage effect, taking the potential transition effects into account without making strong assumptions about the shape or timing of the transitions. Thereby we also provide an explicit way of empirically controlling for the theoretical findings by Harrington (2004a, b)

We apply the STR-model to the stock market price of the international uranium market that was influenced by a price cartel in the 1970s. The methodological approach is particularly well suited for this data since only one cartel episode took place and delayed, gradual transition periods are clearly visible in the data (details provided in Section 2). A battery of statistical tests is applied, and strong empirical support in favour of the STR model is found. Our results also show that using the simple dummy-variable approach without transitions leads to a much worse data fit and a damage effect that is 18 times smaller than when we use the STR-model.

The remainder of the paper is structured in the following way. In Section 2 we provide some background information about the uranium market, previous empirical studies based on the global uranium market and, in particular, information about the cartel during the 1970s, which has not been empirically scrutinised before. Section 3 describes the data. Section 4 outlines our empirical approach and presents the results. Section 5 concludes the paper.

[5] See Boswijk et al. (2017) for further details about the econometric issues involved when estimating a cartel effect, including when start and end dates are unknown.
[6] See Teräsvirta et al. (2010), for details about this class of models.

2. The Uranium market

Energy economists have not paid much attention to the uranium price cartel in the 1970s, but they have instead modelled demand-supply characteristics, and focused on particular energy market characteristics such as the long lifetime of mining and production facilities, changed preferences about nuclear energy production (due to accidents and increased environmental concerns), the sharp oil price increases in 1973 and 1979 and energy security issues. Amavilah (1995) specifies a system consisting of five reduced form models where the price model, which is one of the five models, includes production, previous uranium and substitute/complement prices, and uranium inventory as explanatory variables. The author emphasises that any realistic price model must include the price(s) of alternative energy sources. Kahouli's (2011) methodological approach is similar. She also estimates a system consisting of five models with a price model specification that is identical to that of Amavilah (1995), except that inventory is replaced with uranium reserves. Based on annual data, relevant results of these two studies are: 1) the demand for uranium is not significantly influenced by the price of uranium, and 2) estimated coefficients are different when different sub-samples are used. The first finding is important because it reduces concerns that production is endogenous when price is used as the dependent variable. The second finding suggests that data can be influenced by structural breaks, such as a cartel.

Amavilah (1995) acknowledges that there was an *attempt* at a cartel in his discussion of the characteristics of the uranium market, but no efforts are made to control for that in the estimations. Kahouli (2011) does not mention the cartel at all. One reason for why the cartel has not received more attention by economists can be that several essential details of it are still unknown to the public; e.g. the founders of the cartel remain unknown. Nevertheless, Venturini (1982) and others[7] have established that the cartel transferred a substantial surplus from consumers to producers. The uranium cartel consisted of the five major uranium producing nations (governments and companies) of the world, i.e. Canada, Australia, France, United Kingdom and South Africa. The cartel is claimed to have started in February 1972 when representatives of these countries and several mining firms met in Paris and set up rules for quotas and minimum prices. Some uncertainty exists about the starting

[7] E.g., see Spar (1994) and Utton (2006) for further details.

month. May 1972 has also been suggested (and months in-between February and May 1972). The cartel was exposed in the international media in August 1976 when an environmentalist group leaked information to the media. The working of the cartel was administered by the office of the Commissioner of Atomic Energy in Paris that received all purchase requests and divided the orders among the cartel members. Thus, the Office functioned as a clearinghouse, coordinating all the main quantities and prices in the global market. The break-down of the cartel was followed by tensions among cartel members during several years and Westinghouse Corporation initiated several lengthy litigation and negotiation processes that were settled out of court around 1979-1980. Westinghouse was a manufacturer of nuclear reactors and it had entered into contractual agreements with several clients where they had committed to supply new reactors and uranium at a low price.

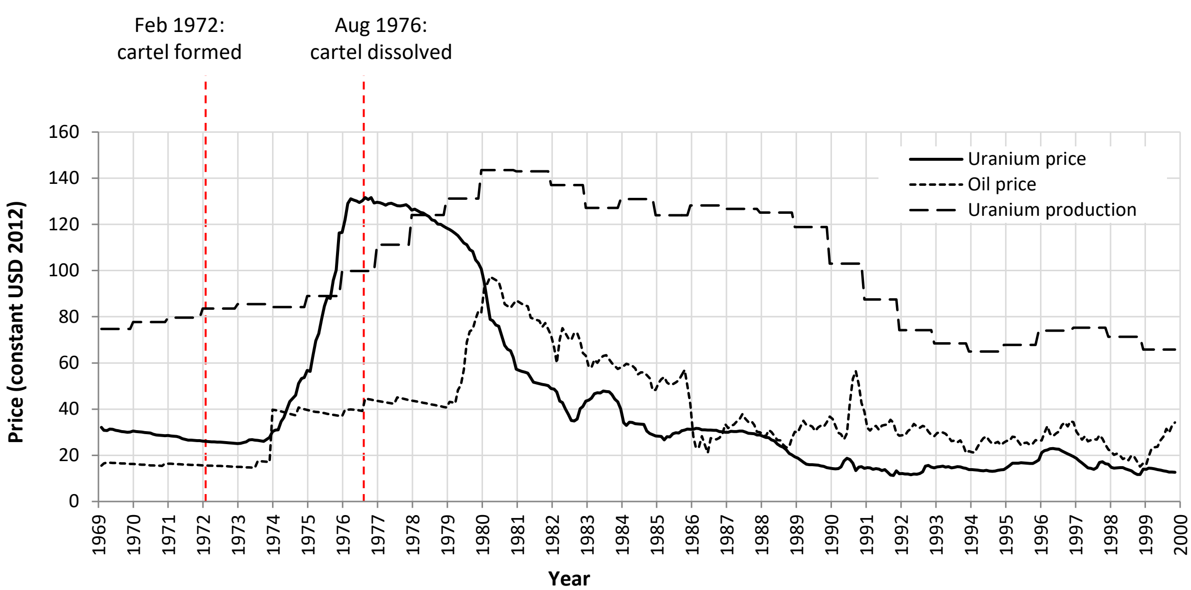
Figure 1 shows the monthly Uranium price from January 1969 to December 1999 with the start and end dates of the cartel. Several interesting characteristics of the cartel are revealed. First, there was a negligible effect of the cartel during 1972 and 1973[8] but in 1974, the price started to increase. Then, it took another two years until the price reached what appears to be the cartel equilibrium. Second, about 6 months after the cartel equilibrium had been reached, the cartel was revealed (August 1976) but the price remained at a high level for several years. In 1980, the price dropped sharply but it was not until sometime during the mid-1980s that the price had returned to the level where it was prior to 1972. In other words, there are obvious transition periods and there are indications that the durations/slopes of the two transitions are asymmetric. Taken together, the cartel seems to have affected the uranium price for at least a decade. Third, when the uranium price was at its highest level, it seems that the cartel had increased the price by a factor 5-6. While other factors could have contributed to this increase, it has been claimed that the high price levels during the 1970s were primarily due to the cartel (LeClair, 2000, p. 165).

It is likely that other events also affected the uranium price in the 1970s and 1980s. Examples include the oil crises in 1973 and 1979, disruptions in oil supply due to military conflicts between Iran and Iraq (from 1980 to 1988), increased demand for uranium caused by the expanding nuclear power industry and discoveries of new uranium deposits, e.g. the McArthur River deposit in Canada, which was

[8] Harry Swain, a former director-general for uranium, coal, electricity and nuclear energy in the Department of Energy, Mines and Resources in Canada, claimed that this was because of the difficult negotiations in which cartel members were involved (*The Globe and Mail*, 12th July, 2011).

discovered in 1988 and in 2014 was still the mine that produced the most uranium in the world (production began in 1999). In this study, we include oil prices and uranium production, which are also plotted in Figure 1, to control for oil market shocks and long-term changes in the uranium market. To control for the structural break in expectations of future supply, led by the McArthur discovery, we consider that the market could have shifted to a different equilibrium around 1988 and stayed at that level for all subsequent years, i.e. until the end of 1999. Shifts in the expectations of future supply can have an immediate and substantial effect on the price because buyers can decide to postpone their purchases if they believe the price will drop in the future.

Figure 1. Monthly uranium price (USD/lb U_3O_8), monthly oil price (USD/barrel) and annual uranium production (normalised lb U_3O_8).



Notes. Prices in USD, constant 2012 values, from February 1969 to December 1999. Production from 1969 to 1999, normalised with sample average and multiplied with 100. Sources: Uranium price is from The Ux Consulting Company, LLC; oil price is from Dow Jones & Co. and uranium production is from OECD/NEA (2006).

3. Data

We use five different variables in our analysis: 1) p_t^{uran}, which is the monthly price of uranium (USD/lb U3O8) in USD, constant 2012 values, from February 1969 to December 1999, collected from The Ux Consulting Company, LLC; 2) q_t, which is the annual world uranium production (lb U3O8) from 1969 to

1999, collected from the OECD/NEA (2006); 3) p_t^{oil}, which is the monthly oil price (USD per barrel) in USD, constant 2012 values, from February 1969 to December 1999, collected from Dow Jones & Co.;[9] 4) cartel dates collected (and double-checked) from various public sources; and a 5) dummy variable to capture the structural break in expectations of future uranium supply. In our linear models (see Section 4), this variable takes the value of zero in all periods prior to January 1989, and the value of one in all other periods. In the STR models, this variable is continuous and subject to a gradual transition. The end date of the sample period is set at a date when there is no suspicion that the price is still influenced by the cartel. Since the year 2000, the uranium industry has been affected by several mine floods and accidents (e.g. Fukushima), which is why post-1999 data is excluded.[10] The total number of estimable observations is 371 when no lags of the dependent variable are included as the explanatory variable.

3.1 Descriptive statistics

Table 1 displays descriptive statistics for the entire period, as well as for the pre-cartel, cartel and post-cartel periods. The statistics show that the uranium price was higher during the cartel period as compared to the pre- and post-cartel periods (the price difference is significant at the 1% level). Moreover, the volatility (measured by the standard deviation) of the uranium price increases during the cartel period and this effect persists into the post-cartel period. The uranium production increases slightly over the three periods and although the volatility is relatively low throughout the entire sample period, it is higher in the post-cartel period. The oil price is subject to a more pronounced positive trend and like the uranium price, its volatility is higher in the last two periods.

The correlations in Table 2 reveal relevant associations between the variables. First, we know that the uranium production was rather stable, with a slight increase during the 1970s, constant in the 1980s and decreasing in the 1990s. This persistent development reflects the slow-moving nature of the industry where decisions about mine extraction, the building of nuclear plants and the composition of energy sources in countries' electricity production mixes are inherently costly to change. So while prices can, and do, change in the short run, production can take decades to respond to price signals. This is also why we treat the production as pre-determined in the econometric analysis in Section 4.[11]

[9] Source: http://www.forecasts.org/data/data/OILPRICE.htm.

[10] The impact of these events on the industry were likely long-lasting and dynamic and without further knowledge about their forms, it is wise to restrict our sample and exclude them.

[11] Note that this assumption is also supported by the previous literature presented in Section 2.

This gives rise to a negative correlation between the uranium price and uranium production in the pre-cartel period, a strong positive correlation in the cartel period, and a positive but weaker correlation in the post-cartel period. The changing sign of the correlation between the different periods should be seen as a sign that the price changes quickly (by non-market forces) whereas production only responds slowly to those price changes. Hence, with the cartel strongly affecting the price series, it is not possible to identify the positive relationship between the price and quantity that one would expect in a supply model. It is also noteworthy that the correlation between the uranium and oil prices is relatively strong in all periods. One explanation for that is that they both capture general energy demand shocks. However, we know that the price for oil was strongly influenced by the two oil crises in the 1970s and supply disruptions in the 1980s.

Table 1. Descriptive statistics.

Variable (unit)	**Mean**	**Std. Dev.**	**Min**	**Max**
Entire sample: Feb 1969 – Dec 1999				
Uranium price (USD/lb U3O8)	41.580	35.918	11.239	131.63
Uranium production (thousand lb U3O8tU)	10517	2764	6825.1	15099
Oil price (USD per barrel)	37.376	19.319	14.560	97.330
Pre-cartel period: Feb 1969 – Jan 1972				
Uranium price (USD/lb U3O8)	29.051	1.6691	26.162	32.100
Uranium production (thousand lb U3O8tU)	8164.2	234.0	7864.1	8782.9
Oil price (USD per barrel)	16.083	0.4005	15.383	16.862
Cartel period: Feb 1972 – Aug 1976				
Uranium price (USD/lb U3O8)	56.043	37.605	25.067	131.06
Uranium production (thousand lb U3O8tU)	9219.8	571.2	8782.9	10498
Oil price (USD per barrel)	29.112	11.607	14.560	40.719
Post-cartel period: Sep 1976 – Dec 1999				
Uranium price (USD/lb U3O8)	40.350	37.065	11.239	131.63
Uranium production (thousand lb U3O8tU)	11074	2950	6825	15099
Oil price (USD per barrel)	41.738	19.437	15.027	97.330

Table 2. Correlation matrix.

Variable	Uranium price	Uranium production	Oil price
Entire sample: Jan 1969 – Dec 1999			
Uranium price	1.000		
Uranium production	0.435	1.000	
Oil price	0.430	0.756	1.000
Pre-cartel period: Jan 1969 – Jan 1972			
Uranium price	1.000		
Uranium production	-0.862	1.000	
Oil price	0.451	-0.515	1.000
Cartel period: Feb 1972 – Aug 1976			
Uranium price	1.000		
Uranium production	0.918	1.000	
Oil price	0.681	0.500	1.000
Post-cartel period: Sep 1976 – Dec 1999			
Uranium price	1.000		
Uranium production	0.495	1.000	
Oil price	0.461	0.730	1.000

3.2 Pre-testing

3.2.1 Unit root

It is important to pre-test all series for unit roots to avoid a problem with spurious regression (see Granger and Newbold, 1974). The unit root tests that we adopt is the traditional test by Elliott, Rothenberg and Stock (1996) and also the test by He and Sandberg (2006), henceforth abbreviated ERS and HS, respectively. We notice that the ERS may lack power against structural break alternatives, whereas, in fact, the HS test is designed to direct power against such alternatives. The outcomes of the unit root pre-testing results are reported in Table 3.

Table 3. Unit root pre-testing.

Variable	ERS	HS
p_t^{uran}	NR	R (**)
q_t	NR	R (*)
p_t^{oil}	NR	R (**)

Notes. NR and R abbreviate no rejection and rejection, respectively, of the null hypothesis of a unit root. ** and * signify rejection at the 5% and the 10% significance level, respectively.

As we can see in Table 3, using the HS (ERS) test we (fail to) reject the unit root null hypothesis (at least at a 10% significance level) for all series. In this case we rely on the outcomes by the HS test since this test, as mentioned, directs power against nonlinear alternatives such as the one observed in Figure 1. This also means that the levels of the log price series are used in the subsequent analysis and we do not expect any problems with spurious regressions[12] and a co-integration framework of the series is also ruled out.

3.2.2 Linearity

Based on previous theoretical findings and a visual inspection of the price series in Figure 1, we hypothesise that the cartel effect is characterised by two gradual transition effects.[13] In this section, we provide additional, statistical support for this hypothesis. Specifically, we apply the linearity test by Jansen and Teräsvirta (1996), henceforth the JT-test, to the uranium price series.[14] The null hypothesis of a linear model is soundly rejected in favour of an alternative model with structural changes (p-value: 0.007). Thus, the claim of potential structural changes suggested by a visual inspection of the series in Figure 1 is supported, and it appears worthwhile to model the price series using a nonlinear regression model.

4. Empirical findings

4.1 Model specifications

We begin by specifying a baseline model for the uranium price. Like Amavilah (1995) and Kahouli (2011), we ignore the cartel and simply model the price as a function of the uranium production quantity and the price of oil, but adding the dummy variable that represents the shock in supply expectations. This can be formulated as:

[12]Noteworthy, using a model in first-difference is undesirable since it makes it more difficult (if not impossible) to identify the cartel effect.

[13] In fact, we tested for the presence of two structural changes against the alternatives of zero, one and also three changes. We found strong support for two changes (the results are available upon request).

[14] The alternative hypothesis for the JT test in our case is a nonlinear model with two structural breaks in the intercept.

$$p_t^{uran} = \alpha_0 + \alpha_1 q_t + \alpha_2 p_t^{oil} + \alpha_3 d_t^{SupSho} + \varepsilon_t, \quad (1)$$

where t is the time period, p_t^{uran} is the uranium price, q_t is the uranium production, p_t^{oil} is the oil price, d_t^{SupSho} is the shock in supply expectations, ε_t is the random noise and α_0, α_1, α_2 and α_3 are the parameters to be estimated. As an extension, we follow the main tradition in the empirical cartel literature and formulate a model according to the principles proposed by Davis and Garcés (2010, p. 354):

$$p_t^{uran} = \alpha_0 + \alpha_1 q_t + \alpha_2 p_t^{oil} + \alpha_3 d_t^{SupSho} + \alpha_4 d_t^{Cart} + \varepsilon_t, \quad (2a)$$

where notations are as in (1), with the addition that d_t^{Cart} is an indicator for the cartel dummy that takes the value of one in the periods from February 1972 to August 1976, and zero in all other periods. The cartel effect, i.e. α_4, is positive and significant but Figure 1 reveals that this definition of d_t^{Cart} is naïve. In the same spirit as the STR model (described below), one can instead redefine d_t^{Cart} in (2a) by $d_t^{Cart*} = 1$ where $t \in [t_1;\ t_2]$ and zero elsewhere, and where t_1 and t_2 denote start and end periods of the cartel to be determined by the data. This yields the model:

$$p_t^{uran} = \alpha_0 + \alpha_1 q_t + \alpha_2 p_t^{oil} + \alpha_3 d_t^{SupSho} + \alpha_4 d_t^{Cart*} + \varepsilon_t. \quad (2b)$$

In (2b), the start and end periods t_1 and t_2 are found by minimising the sum of squared residuals of the estimated model. Furthermore, the model in (2b) is a natural competitor to the STR model in the sense that it does not impose any restrictions on when the cartel started or ended, but it is still restrictive in the sense that the transitions take place instantaneously.

In our next extensions, we remedy the shortcomings of Models (1), (2a) and (2b) that ignore transition periods and adopt an STR model that accommodates up to three gradual price transitions. More specifically, the STR model that we use is defined as:

$$p_t^{uran} = \eta_1 + (\eta_2 - \eta_1)G_t^1 + (\eta_3 - \eta_2)G_t^2 + (\eta_4 - \eta_3)G_t^3 + \alpha_1 q_t + \alpha_2 p_t^{oil} + \varepsilon_t, \quad (3)$$

where transitions are modelled via the logistic cumulative distribution functions (CDF):

$$G_t^i = [1 + \exp(-\gamma_i(t - c_i))]^{-1}, i = 1, 2, 3.$$

These CDF's are bounded (between 0 and 1), non-decreasing functions of time, and the parameter γ_i represents the speed of transition from one regime to another[15] and the parameter c_i represents the centre of each transition, indicating a particular point in time. As an identifying restriction, we set $\gamma_i > 0$ and since the second transition must occur after the first and the third after the second, we also impose the restrictions $1 < c_1 < c_2 < c_3 < T$. With these definitions of the CDF's, it should be clear that G_t^1 and G_t^2 are meant to capture the formation and dissolution of the cartel, and G_t^3 is supposed to capture the transition caused by the shift in supply expectations in 1988. Although the STR model in (3) is a flexible model, it is a model without dynamics. Hence, by including two lags of p_t^{uran}, i.e. p_{t-1}^{uran} and p_{t-2}^{uran}, as explanatory variables in (3), we arrive at our final candidate model:[16]

$$p_t^{uran} = \eta_1 + (\eta_2 - \eta_1)G_t^1 + (\eta_3 - \eta_2)G_t^2 + (\eta_4 - \eta_3)G_t^3 + \rho_1 p_{t-1}^{uran} + \rho_2 p_{t-2}^{uran} + \alpha_1 q_t + \alpha_2 p_t^{oil} + \varepsilon_t. \quad (4)$$

The reason for why we allow for lagged values of the dependent variable is to allow for a dynamic model that avoids the problem with serially correlated errors that can affect the estimation results.

In Models (3) and (4), the G_t^i functions for $i = 1, 2$ allow us to formally test if the cartel effect is symmetric or not by testing the $H_0: \gamma_1 = \gamma_2$ (i.e., symmetry) against the alternative hypothesis $H_A: \gamma_1 \neq \gamma_2$ (i.e., no symmetry). As explained in Section 1, Harrington (2004a, b) has pointed out that the transition at the beginning is influenced by other economic forces than the transition at the end, so symmetry cannot generally be assumed. It is also useful to understand that if γ is not significantly different from zero, then we can rule out the existence of a transition (and that the cartel shifted the price level), and if γ approaches infinity, the cartel instantaneously shifted the price. Thus, (3) and (4) incorporate (1) and (2b) as special cases.

Taken together, (3) and (4) imply that the intercept of p_t^{uran} can change gradually from η_1 to η_2 to η_3 and then to η_4 as time passes; i.e. this model mimics the pricing behaviour that is observed in Figure

[15] A low (high) value implies a slow (quick) transition between regimes.

[16] The reason for two lags follows both from the use of AIC and BIC and the outcome of the LB test; see Table 4 for details.

1. To this end, the parameters η_1 and η_3 can be seen as indicators for the non-collusive price levels and η_2 represents the cartel price level. The shift in the supply expectations level is measured by η_4. As before, the parameters α_1 and α_2 measure the impact of quantity and oil price.

4.2 Estimation

All estimation results are presented in Table 4. Turning our attention first to Models (1), (2a) and (2b), which are estimated using OLS, all their coefficients are significant at the 1% level. In terms of the duration of the cartel, we take as given that the cartel lasted from February 1972 to August 1976 in Model (2a), i.e. 55 months, whereas the estimated cartel duration in Model (2b) equals 77 months, starting in June 1974 (= t_1) and ending in October 1980 (= t_2). As clearly shown, the models progressively fit the data better, with the SSE reduced by 17% (72%) when moving from Model (1) to Model (2a) (Model (2b)). Similar improvements of the goodness-of-fit are observed when comparing the AICs- and BICs values. As expected for a supply model, production has a positive sign. The sign of the oil price is positive for Models (1) and (2a) but negative for Model (2b), giving ambiguous clues about whether oil is a substitute or a complement to uranium. We remain agnostic about the true relationship, noting that neither Amavilah (1995) nor Kahouli (2011) find a significant relationship between the uranium and oil prices.[17]

Next, the parameters of the STR model are estimated by the methods of nonlinear least squares (NLS).[18,19] Suitable starting values are obtained by applying the method suggested by Franses and van

[17] Remember that it is the wholesale, and not the consumer, market that is studied in this paper. In the consumer market, we would expect different energy sources to be substitutes. In the wholesale market, different sources of energy can be sources simultaneously.

[18] The NLS estimation is carried out in GAUSS 12 using the Optmum package. The GAUSS code for the NLS estimation of STR models is available from the authors upon request.

[19] That is, the estimator of θ is obtained by:

$$\hat{\theta} = argmin_{\theta\in\mathbb{R}} \sum_{t=1}^{T} \varepsilon_t^2,$$

where $\varepsilon_t = p_t^{uran} - \left[\eta_1 + (\eta_2 - \eta_1)G_t^1 + (\eta_3 - \eta_2)G_t^2 + (\eta_4 - \eta_3)G_t^3 + \alpha_1 q_t + \alpha_2 p_t^{oil}\right]$ and $\varepsilon_t = p_t^{uran} - \left[\eta_1 + (\eta_2 - \eta_1)G_t^1 + (\eta_3 - \eta_2)G_t^2 + (\eta_4 - \eta_3)G_t^3 + \rho_1 p_{t-1}^{uran} + \rho_2 p_{t-2}^{uran} + \alpha_1 q_t + \alpha_2 p_t^{oil}\right]$ for Model (3) and Model (4), respectively. Moreover, under some regularity conditions (see, e.g. Pötscher and Prucha, 1997), we have that the estimator $\hat{\theta}$ (appropriately scaled and centred) is asymptotically normally distributed, i.e. $\sqrt{T}(\hat{\theta} - \theta_0) \to_d N(0, \Psi)$ where θ_0 designates the true parameter vector, and the variance-covariance matrix Ψ is consistently estimated by a sandwich-type estimator

$$\hat{\Psi} = \left[T^{-1} \sum_{t=1}^{T} \frac{\partial^2 \varepsilon_t^2}{\partial\theta\partial\theta'}\Big|_{\theta=\hat{\theta}}\right]^{-1} \times \left[T^{-1} \left(\sum_{t=1}^{T} \frac{\partial \varepsilon_t}{\partial\theta} \times \frac{\partial \varepsilon_t}{\partial\theta'}\right)\Big|_{\theta=\hat{\theta}}\right] \times \left[T^{-1} \sum_{t=1}^{T} \frac{\partial^2 \varepsilon_t^2}{\partial\theta\partial\theta'}\Big|_{\theta=\hat{\theta}}\right]^{-1},$$

which we use in the computations of the standard errors of the parameter estimates.

Dijk (2000, pp. 90-92). The NLS estimation results for the STR models in (3) and (4) are also reported in Table 4. Analysing the results for the STR models, it is first noticed that all variables enter significantly (at least at the 10% level). In particular, the cartel effect (η_2) is highly significant in both (3) and (4). This effect will be discussed in more detail below. Furthermore, to get an enhanced understanding of the estimated STR model, we will demonstrate and discuss the estimation results making use of Figure 2 (based on Model 4). In this figure, we illustrate: (a) the estimated model; (b) the smooth transition functions G_{1t}, G_{2t}, and G_{3t}; (c) the time-varying intercept due to the cartel effect (G_{1t} and G_{2t}) and the shock in supply expectations (G_{3t}); and (d) the residual series.

As a complement to the goodness-of-fit statistics shown in Table 4, Panel A in Figure 2 graphically illustrates the uranium price series (the same as in Figure 1) and the fitted line of Model (4).[20] It is clear that the transition periods are well incorporated in Model (4).

In Panel B, the estimated smooth transition functions G_t^1, G_t^2, and G_t^3 are plotted as a function of time. In particular, it is seen that the G_t^1 function is centred around March 1974 (corresponding to $c_1 \approx 70$). Similarly, the G_t^2 function is centred around February 1980 (corresponding to $c_2 \approx 129$). Moreover, a key observation in Panel B is that the prices adjust much more quickly when going from the non-collusive to the cartel price than when returning to the non-collusive price after the cartel has been dissolved. This insight is also revealed in Table 4 since γ_1 is significantly higher (0.208) than γ_2 (0.101). This also implies that the cartel effect is clearly asymmetric with the transition from the low non-collusive price being less persistent than the transition from the high cartel price. Based on the estimated G_t^1 and G_t^2 functions, one can also determine the start and end dates of the cartel. Panel B reveals that the starting period is late 1972, which confirms the opinion that the effect of the cartel was delayed. The estimated end date of the last transition is considerably delayed, with the graph suggesting an end date in the mid-1980s. Hence, the slow transition back to the non-collusive level implies that it took 8-10 years until the cartel effect had disappeared completely. Naturally, such an asymmetry cannot be adequately captured by a simple dummy variable approach. In the subsequent calculation of the damage effect, this leads us to attach considerably more confidence to the damage effect based on the STR model, as compared to the simple dummy variable.

[20] The corresponding graphs for Model (3) are included in Figure A1 in Appendix A.

Table 4. Estimation results.

Variable	Model (1) Coeff. (Std Error)	Model (2a) Coeff. (Std. Error)	Model (2b) Coeff. (Std. Error)	Model (3) Coeff. (Std. Error)	Model (4) Coeff. (Std. Error)
α_0: Single intercept	$45.063^{(***)}_{[***]}$	$36.76^{(***)}_{[***]}$	$27.93^{(***)}_{[***]}$		
α_1: Uranium production	$-1.2 \times 10^{-6}{}^{(***)}_{[***]}$	$-6.1 \times 10^{-7}{}^{(***)}_{[***]}$	$-8.0 \times 10^{-7}{}^{(***)}_{[***]}$	$-8.5 \times 10^{-7}{}^{(***)}_{[***]}$	$-2.4 \times 10^{-7}{}^{(***)}_{[***]}$
α_2: Oil price	$0.604^{(***)}_{[***]}$	$0.598^{(***)}_{[***]}$	$0.448^{(***)}_{[***]}$	$0.177^{(***)}_{[***]}$	$-0.023^{()}_{[***]}$
α_3: Supply shock	$-36.825^{(***)}_{[***]}$	$-33.26^{(***)}_{[***]}$	$-18.514^{(***)}_{[***]}$		
α_4: Cartel dummy		$7.482^{)}$	$80.08^{(***)}_{[***]}$		
η_1: Pre-cartel intercept				$32.15^{(***)}_{[***]}$	$5.365^{(**)}_{[***]}$
η_2: Cartel intercept				$135.2^{(***)}_{[***]}$	$18.55^{(***)}_{[***]}$
η_3: Post-cartel intercept, prior to shock in supply expectations				$37.42^{(***)}_{[***]}$	$9.208^{(***)}_{[***]}$
η_4: Post-cartel intercept, after shock in supply expectations				$16.77^{(***)}_{[***]}$	$3.925^{(**)}_{[***]}$
ρ_1: One-period lagged uranium price					$1.107^{(***)}_{[***]}$
ρ_2: Two-period lagged uranium price					$-0.214^{(***)}_{[***]}$
γ_1: Transition speed, beginning of cartel				$0.227^{(***)}_{[***]}$	$0.208^{(***)}_{[***]}$
c_1: Location of transition, beginning of cartel				$75.36^{(***)}_{[***]}$	$69.56^{(***)}_{[***]}$
γ_2: Transition speed, end of cartel				$0.128^{(***)}_{[***]}$	$0.101^{()}_{[*]}$
c_2: Location of transition, end of cartel				$132.3^{(***)}_{[***]}$	$129.4^{(***)}_{[**]}$
γ_3: Transition speed, supply shock				$0.170^{(***)}_{[***]}$	$0.042^{()}_{[*]}$
c_3: Location of transition, supply shock				$236.3^{(***)}_{[***]}$	$220.6^{(***)}_{[***]}$
SSE	298552	296765	27616	4125.6	630.74
AIC	2478.8	2478.6	1602.4	914.83	225.82
BIC	2494.4	24.98.1	1621.9	961.76	280.57
LB(4), p-value	0.000	0.000	0.000	0.000	0.356
LJB, p-value	0.000	0.000	0.000	0.000	0.000
Observations	369	369	369	369	369

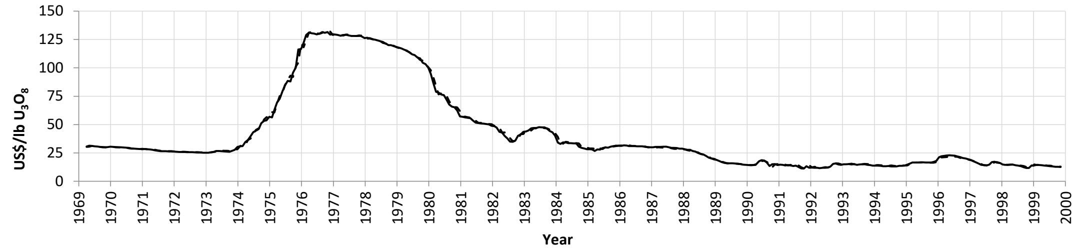
Notes. ***, **, and * denote significance at the 1%, 5% and 10% level, respectively. If significance is reported in parentheses, then OLS or NLS standard errors are used. If instead heteroscedasticity and autocorrelation consistent (HAC) OLS or NLS standard errors are used, significance is reported in square brackets. SSE signifies a sum of squared residuals for the estimated model. AIC and BIC designate the Akaike and the Bayesian Information Criteria, respectively. LB(4) is the Ljung-Box test of no remaining 4th-order auto-correlation of the residual series. LJB reports the outcome for the Lomnicki, Jarque and Bera normality test of the residual series.

Panel C in Figure 2 shows how the cartel effect varies over time when using the STR model. The cartel follows a hump-shaped pattern where the two cartel transitions are smooth and asymmetric – a pattern that is clearly visible in this graph. Linking this to the results in Table 4, the price starts at η_1 (=5.365), increases to η_2 (=18.55) and then falls down to η_3 (9.208).

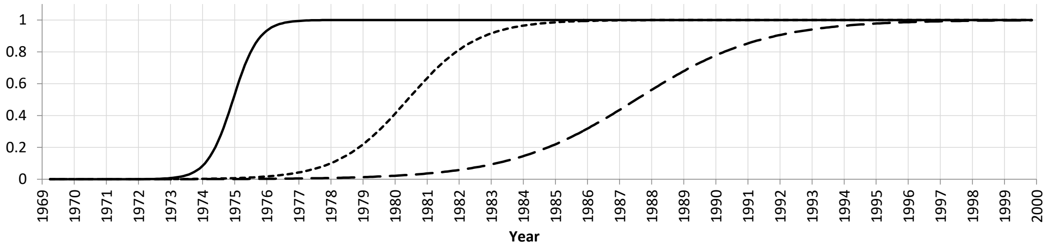
Finally, Panel D shows the estimated (standardized) residual series and the corresponding 95% confidence intervals. The residual series behave reasonably well (only a few extreme values outside the 95% confidence bands – dashed lines). In Table 4 we also see that the null hypothesis of residuals being normally distributed is strongly rejected. Moreover, Table 4 shows that we have a potential problem with remaining auto-correlation in the residual series for all models except Model 4 (revealed by the LB(4) test), which controls for auto-correlation through the inclusion of lagged uranium prices, i.e. $p_{t-1}^{uran}$and p_{t-2}^{uran}. This shows that (4) provides a distinct advantage over (3), other than a pure goodness-of-fit.

Figure 2. Characteristics of the model (4).

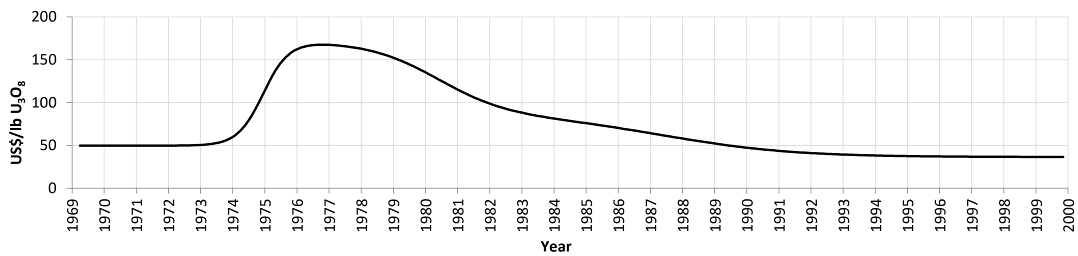
Panel A. The uranium price, p_t^{uran}, (solid line) and the estimated uranium price, $\hat{p}_t^{uran}$ (dashed line).



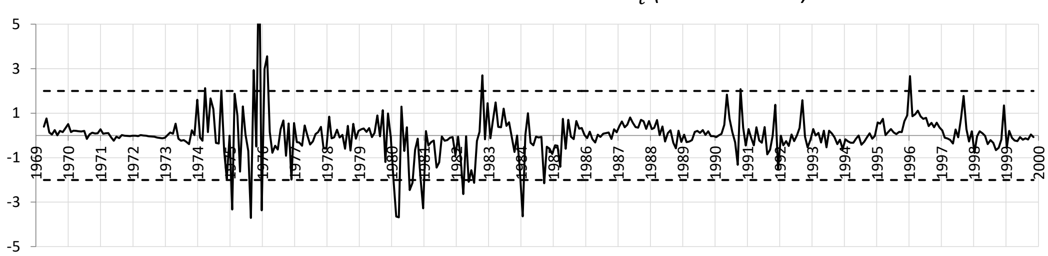
Panel B. The estimated transition functions G_t^1, G_t^2 and G_t^3.



Panel C. The estimated time-varying intercept.



Panel D. The estimated residual series $\hat{\varepsilon}_t$ (standardised).



4.3 Damage calculation

This section calculates the financial damage that was inflicted on buyers as a result of the price cartel. In the first step, we calculate the price in each time period using Models (2a), (2b) (3) and (4). The expected average prices are calculated as:

Model (2a):

$$E\left(p_t^{uran} \middle| q_t = \bar{q}, p_t^{oil} = \bar{p}_t^{oil}, d_t^{Cart} = 1, d_t^{SupSho}\right) -$$
$$E\left(p_t^{uran} \middle| q_t = \bar{q}, p_t^{oil} = \bar{p}_t^{oil}, d_t^{Cart} = 0, d_t^{SupSho}\right) \approx \hat{\alpha}_4 = 7.482,$$

where the cartel dummy takes the value of 1 in periods from February 1972 to August 1976.

Model (2b):

$$E\left(p_t^{uran} \middle| q_t = \bar{q}, p_t^{oil} = \bar{p}_t^{oil}, d_t^{Cart*} = 1, d_t^{SupSho}\right) -$$
$$E\left(p_t^{uran} \middle| q_t = \bar{q}, p_t^{oil} = \bar{p}_t^{oil}, d_t^{Cart*} = 0, d_t^{SupSho}\right) \approx \hat{\alpha}_4 = 80.085,$$

where the cartel dummy takes the value of 1 in periods from June 1975 to January 1980.

Model (3):

$$E\left(p_t^{uran} \middle| q_t = \bar{q}, p_t^{oil} = \bar{p}_t^{oil}, G_t^1, G_t^2, G_t^3\right) -$$
$$E\left(p_t^{uran} \middle| q_t = \bar{q}, p_t^{oil} = \bar{p}_t^{oil}, G_t^1 = G_t^2 = 0, G_t^3\right) \approx (\hat{\eta}_2 - \hat{\eta}_1)\hat{G}_t^1 + (\hat{\eta}_3 - \hat{\eta}_2)\hat{G}_t^2.$$

Model (4):

$$E\left(p_t^{uran} \middle| q_t = \bar{q}, p_t^{oil} = \bar{p}_t^{oil}, G_t^1, G_t^2, G_t^3\right) -$$
$$E\left(p_t^{uran} \middle| q_t = \bar{q}, p_t^{oil} = \bar{p}_t^{oil}, G_t^1 = G_t^2 = 0, G_t^3\right) \approx \frac{(\hat{\eta}_2 - \hat{\eta}_1)\hat{G}_t^1 + (\hat{\eta}_3 - \hat{\eta}_2)\hat{G}_t^2}{(1 - \hat{\rho}_1 - \hat{\rho}_2)}.$$

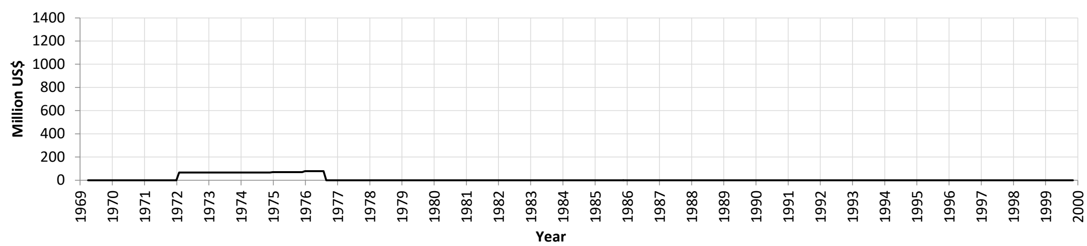
The damage (in dollars) is obtained by multiplying the above average cartel prices with q_t, i.e. $E(\cdot) \times q_t$. The damages for each model, as a function of time, are shown in Figure 3.

Finally, the estimated total damage caused by the cartel using the four different models can be calculated as the area under the corresponding graphs in Figure 3. Executing these calculations gives damage effects of 3,794 million USD for Model (2a), 53,583 million USD for Model (2b), 67,710 million

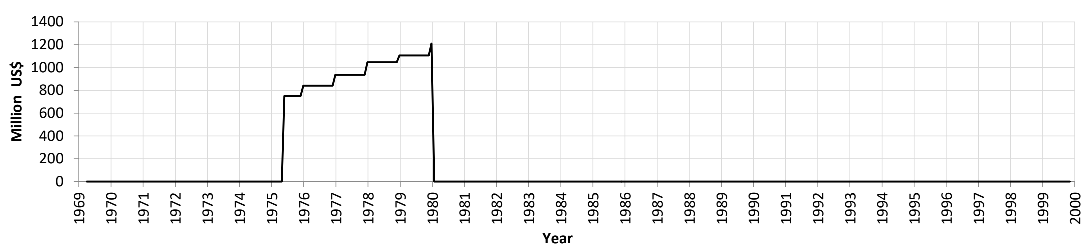
USD for Model (3) and 68,555 million USD for Model (4). Thus, using a simple dummy variable approach where we do not allow the price to be subject to transitions, which is standard in the cartel literature, results in a damage effect that is only about 5% of the effect when we use either of the two STR models. If we allow for delayed but discrete price changes, i.e. Model (2b), then the damage effect amounts to almost 80% of the effect using the STR model.

Figure 3. Estimated damage for Models (2a), (2b) and (4).

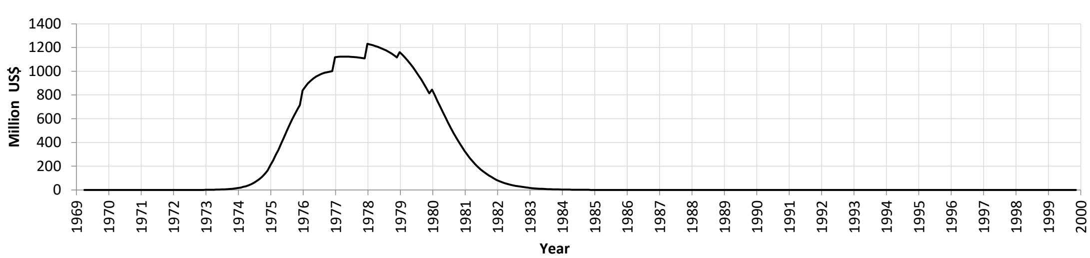
Panel A. Damage effect Model (2a)



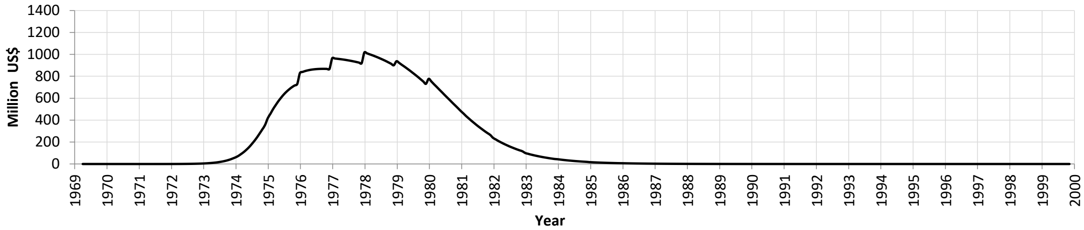
Panel B. Damage effect Model (2b)



Panel C. Damage effect Model (3)



Panel C. Damage effect Model (4)



5. Conclusions

Economic theory about cartel pricing developed by Harrington (2004a, b) has found that prices can evolve gradually from a non-collusive to a collusive equilibrium, and back to a non-collusive equilibrium again. However, the empirical literature has not developed any approaches that incorporate such transitions, and the calculated damage effects may therefore be (very) inaccurate. In this paper, we use a Smooth Transition Regression (STR) model to calculate the damage effect of a price cartel when the start and end of the cartel are subject to delayed, gradual movements.

We are the first to incorporate the transitions in the estimation and we allow for realistic characteristics, such as unknown start and end dates; the analyst often only knows that the cartel started before a certain date and it is likewise unknown for how long the information that has been exchanged during the cartel period is useful after the cartel has been dissolved.

Based on the international uranium cartel in the 1970s, we identify very pronounced transitions and in terms of goodness-of-fit, the STR model clearly outperforms the standard dummy-variable model used in the empirical cartel literature, supporting Harrington's (2004a, b) models. The estimated damage effect using the STR model is 18 times larger when using the STR model, as compared to the benchmark.

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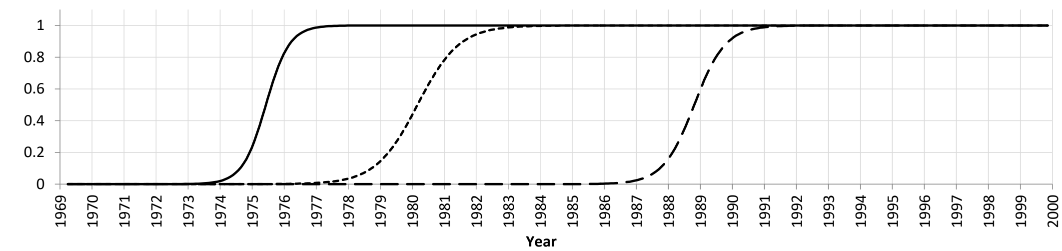
Appendix A.

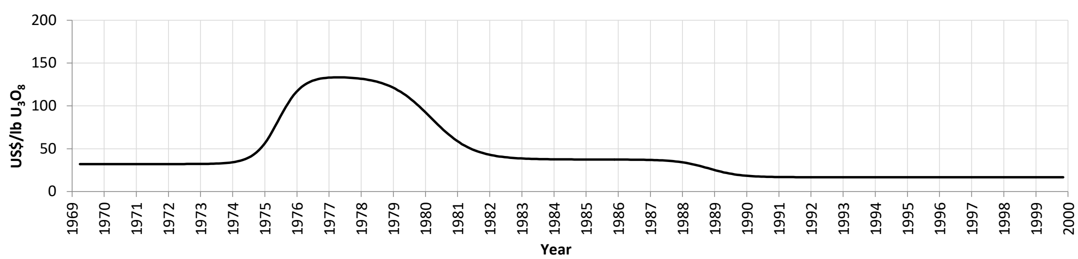
Figure A1. Characteristics of the model (3).

Panel A. The uranium price, p_t^{uran}, (solid line) and the estimated uranium price, $\hat{p}_t^{uran}$ (dashed line).

Panel B. The estimated transition functions G_t^1, G_t^2 and G_t^3.



Panel C. The estimated time-varying intercept.



Panel D. The estimated residual series $\hat{\varepsilon}_t$ (standardised).