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Economic and Econometric Analyses of the World Petroleum Industry, Energy Subsidies, and Air Pollution

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Economic and Econometric Analyses of the World Petroleum Industry, Energy Subsidies, and Air Pollution

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Abstract

The decisions made by petroleum producers in the world oil market are both dynamic and strategic, and are thus best modeled as a dynamic game. In the first chapter of my dissertation, I review the literature on the world oil market and discuss my research on econometric modeling of the world oil market as a dynamic game. My research on econometric modeling of the world oil market as a dynamic game research builds on the previous literature by combining three erstwhile separate dimensions of modeling the world oil market: dynamic optimization, game theory, and econometrics.

In the second chapter of my dissertation, I develop and estimate a structural econometric model of the dynamic game among petroleum-producing firms in the world petroleum market. My model incorporates the dynamic behavior and strategic interactions that arise as petroleum-producing firms make their investment, production, merger, and acquisition decisions. I allow firms that are at least partially state-owned to have objectives other than profit maximization alone. I use the structural econometric model to analyze the effects of changes in OPEC membership, a ban on mergers, the privatization of state-owned oil companies, and demand shocks on the petroleum industry. Although I do not assume or impose that OPEC producers collude to maximize joint profits, but instead infer the strategy and payoffs for OPEC firms from the data, I find that OPEC behaves in such a way that is consistent with its mission and also with cartel behavior. Results of counterfactual simulations also show that a ban on mergers would decrease average firm payoff for both OPEC and non-OPEC firms, and decrease consumer surplus.

Gasoline taxes have been touted by many economists as an efficient and relatively simple tool to address environmental concerns and other problems associated with gasoline consumption. Nevertheless, rather than removing subsidies and increasing gasoline taxes, many countries still subsidize gasoline, which may have the opposite effect of exacerbating air pollution and other problems associated with gasoline consumption. The Iranian government has heavily subsidized petroleum products since the early 1980s. As a result of these energy subsidies and artificially low national energy price, Iran is one of the most energy-intensive countries in the world. The Iranian government has recently taken a series of measures to reform and cut back on the energy subsidies. In the third chapter of my dissertation, I evaluate the effects of the Iranian subsidy reform on air quality using a regression discontinuity design. My results provide evidence across multiple different empirical specifications that the subsidy reform in Iran led to improvements in air quality. In particular, the first subsidy reform event, which increased gasoline prices and implemented a gasoline consumption quota; and the second subsidy reform event, which increased energy prices and decreased energy subsidies, both led to declines in concentrations of CO, O_3, and NO_2. In contrast, the fourth subsidy reform event, which increased fuel prices but removed the gasoline consumption quota, was less effective in reducing air pollution.

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CHAPTER 1

ECONOMETRIC MODELING OF THE WORLD OIL MARKET AS A DYNAMIC GAME

1.1 Introduction

The decisions made by petroleum producers in the world oil market are both dynamic and strategic, and are thus best modeled as a dynamic game. In this chapter, we review the literature on the world oil market and discuss our research on econometric modeling of the world oil market as a dynamic game. Our research on econometric modeling of the world oil market as a dynamic game research builds on the previous literature by combining three erstwhile separate dimensions of modeling the world oil market: dynamic optimization, game theory, and econometrics.

In Lin Lawell (2019), we develop and estimate an empirical dynamic model of the world oil market based on optimal control theory, and use this model to test for market power.

In Kheiravar et al. (2019) , we develop and estimate a structural econometric model of the dynamic game among petroleum-producing firms based on dynamic programming and game theory, and we apply this model to firm-level panel data on oil and gas exploration, development, production, mergers, acquisitions, and reserves. We then use the structural econometric model to analyze the effects of government policies, changing geopolitical landscapes, and new technologies on the petroleum industry.

Our results show that dynamic behavior and strategic interactions are important aspects of the world oil market that must be accounted for in empirical analyses of the world oil market.

The balance of this chapter proceeds as follows. In Section 1.2, we explain why the world oil market should be modeled as a dynamic game. We review the related literature in Section 1.3. In Section 1.4, we discuss our research in Lin Lin Lawell (2019), in which we develop an empirical dynamic model of the world oil market based on optimal control theory. In Section 1.5, we discuss our research in Kheiravar et al. (2019), in which we develop and estimate a structural econometric model of the dynamic game among petroleum-producing firms based on dynamic programming and game theory. Section 1.6 concludes.

1.2 The world oil market as a dynamic game

The decisions made by petroleum producers in the world oil market are both dynamic and strategic. The production decisions of oil and gas producers are dynamic because petroleum is a nonrenewable resource; as a consequence, current extraction and production affect the availability of reserves for future extraction and production. The exploration, development, merger, and acquisition decisions of petroleum producers are dynamic because they are irreversible investments, because their payoffs are uncertain, and because petroleum producers have leeway over the timing of these investment decisions. Since the profits from investment and production decisions depend on market conditions such as the oil price that vary stochastically over time, an individual firm operating in isolation that hopes to make dynamically optimal decisions would need to account for the option value to waiting before making these irreversible investments (Dixit and Pindyck, 1994).

The decisions of petroleum-producing firms are not only dynamic but strategic as well. Petroleum producers consider not only future market conditions but also their competitors' investment and production activities when making their current decisions. Since the production decisions of other firms affect the prices of oil and natural gas, and therefore affect a firm's current payoff from production, and since the investment and production decisions of other firms affect future values of state variables which affect a firm's future payoff from producing and investing, petroleum-producing firms must anticipate the production and investment strategies of other firms in order to make a dynamically optimal decision. As a consequence, there are strategic interactions between petroleum-producing firms.

Because the decisions made by petroleum producers in the world oil market are both dynamic and strategic, they are best modeled as a dynamic game. In our previous work in Lin (2011a), we show that assuming the world oil market is static and perfectly competitive yields unrealistic empirical results, and therefore that econometric models of the world oil market should incorporate the dynamic and strategic dimensions of the world oil market.

1.3 Related literature

Economists have long been interested the world oil market. The theoretical model of optimal nonrenewable resource extraction was first examined by Hotelling (1931), who developed the insight that dynamic optimization and dynamic behavior are critical for analyzing the world oil market.

The dynamic optimization model and framework for the world oil market developed by Hotelling (1931) has since been expanded upon by many others to allow for such features as stock effects in extraction costs (Solow and Wan, 1976; Hanson, 1980; Farzin, 1992); exploration (Pindyck, 1978b; Pesaran, 1990); market imperfections (Stiglitz, 1976; Khalatbari, 1977; Sweeney, 1977; Cremer and Salehi-Isfahani, 1991); technological progress (Farzin, 1992, 1995; Lin et al., 2009; Lin and Wagner, 2007); outward-shifting demand (Chapman, 1993; Chapman and Khanna, 2000); uncertainty (Hoel, 1978; Pindyck, 1980a); risk (Young and Ryan, 1996); drilling activity (Anderson et al., 2018); stochastic and volatile output price and production cost (Almansour and Insley, 2016); tax policy (Leighty and Lin, 2012); and oil contracts (Ghandi and Lin, 2012; Ghandi and Lin Lawell, 2019)

Gaudet (2007) provides a recent review of factors that can potentially help bridge the gap between the basic Hotelling rule of natural resource exploitation and the historical behavior resource prices. Lin (2009b) shows that even the most basic Hotelling model yields insights.

Recognizing the importance of strategic interactions in addition to dynamic behavior in the world oil market, the dynamic optimization model and framework for the world oil market developed by Hotelling (1931) has also been expanded upon to allow for such features as Nash-Cournot behavior (Salant, 1976; Ulph and Folie, 1980) and OPEC behavior (Hnyilicza and Pindyck, 1976; Pindyck, 1978a; Cremer and Weitzman, 1976). Until recently, much of the empirical literature on the world petroleum market was from over three decades ago (Adelman, 1962; Kennedy, 1974; Nordhaus, 1980; Gately, 1984; Griffin, 1985; Lin, 2011a; Espinasa et al., 2017). Cremer and

Salehi-Isfahani (1991) provide a survey of models of the oil market. Many previous empirical studies of world petroleum market use a static model. Lin (2011a) shows that assuming the world oil market is static and perfectly competitive yields unrealistic empirical results, and therefore that econometric models of the world oil market should incorporate the dynamic and strategic dimensions of the world oil market.

There is also a literature analyzing strategic behavior in the world petroleum market, and particularly the behavior of OPEC (Griffin, 1985; Matutes, 1988; Golombek et al., 2014; Gulen, 1996; Farzin, 1985; Alhajji and Huettner, 2000a,b; Kaufmann et al., 2004; Almoguera et al., 2011; Hochman and Zilberman, 2015; Okullo and Reynès, 2016; Baumeister and Kilian, 2017; Genc, 2017; Asker et al., 2018; Ghoddusi et al., 2017). For detailed background information on the world energy industry, see the classic text by Dahl (2015). For a detailed review of the literature on oil market modeling and OPEC's behavior, see Al-Qahtani et al. (2008).

1.4 An empirical dynamic model of the world oil market

The mission of OPEC is to ”coordinate and unify the petroleum policies of its Member Countries” (Organization of Petroleum Exporting Countries [OPEC], 2017); however, it is unclear whether OPEC behaves as a cartel. As a step towards better understanding and modeling the world oil market and OPEC in particular, our work in Lin Lin Lawell (2019) estimates a Hotelling model of the world oil market and tests whether OPEC countries colluded and whether non-OPEC countries behaved as price takers or oligopolists over the period 1970-2004.

Our research in Lin Lawell (2019) makes several important contributions to the existing literature. First, it takes to data the theoretical model of optimal nonrenewable resource extraction that was first examined by Hotelling (1931), and later expanded upon by many others (see e.g., Cremer and Weitzman, 1976; Solow and Wan, 1976; Pindyck, 1978a,b, 1980a; Hanson, 1980; Pesaran, 1990; Farzin, 1992, 1995; Lin, 2009b; Lin et al., 2009; Lin and Wagner, 2007; Leighty and Lin, 2012; Ghandi and Lin, 2012; Anderson et al., 2018; Ghandi and Lin Lawell, 2019).

Unlike many previous empirical studies of the petroleum market, which use a static model, in Lin Lawell (2019) we estimate a Hotelling model of the world petroleum market, which is a dynamic model. The dynamics in Lin Lawell (2019) arise from the nonrenewable nature of the resource.

A second contribution is that our work in Lin Lawell (2019) builds upon existing empirical studies of nonrenewable resource markets by addressing the identification problem that arises in empirical analyses of supply and demand. Because the observed equilibrium prices and quantities are simultaneously determined in the supply-and-demand system, instrumental variables are needed to address the endogeneity problem (Lin, 2011a).

The third contribution is that our work in Lin Lawell (2019) develops a Hotelling model that enables one to test for the market conduct of OPEC and non-OPEC producers.

Our empirical dynamic model in Lin Lawell (2019) is based on taking an optimal control theory-based Hotelling model to data. In particular, we use the first-order conditions from an optimal control theory model of optimal nonrenewable resource extraction under different market conditions to formulate a general supply-side first-order condition that we then estimate with data.

According to our results in Lin Lawell (2019), results of the analysis by decade support OPEC countries colluding as the dominant cartel producer and non-OPEC countries behaving as an oligopolistic fringe. Market demand has become more inelastic over time over the period of study. The estimated shadow prices are jointly significant, which is consistent with the hypothesis that a Hotelling model, which accounts for the nonrenewable nature of the resource, is a more appropriate model for the world oil market than a static model is. Our results in Lin Lawell (2019) therefore show that dynamic behavior and strategic interactions are important aspects of the world oil market that must be accounted for in empirical analyses of the world oil market.

1.5 A structural econometric model of the dynamic game among petroleum-producing firms

In Kheiravar et al. (2019), we develop and estimate a structural econometric model of the dynamic game among petroleum-producing firms in the world petroleum market. Our model allows firms that are at least partially state-owned to have objectives other than profit maximization alone. We apply this model to panel data on firm-level oil and gas exploration, development, production, mergers, acquisitions, and reserves along with data on oil and gas prices to study the behavior of the top 50 oil and natural gas producing companies in the world.

We then use the parameters estimated from our structural econometric model to simulate counterfactual scenarios to analyze the effects of changes in OPEC membership, the privatization of state-owned oil companies, a ban on mergers, and demand shocks on the petroleum industry. There are several advantages to using a dynamic structural model to analyze the investment, production, merger, and acquisition decisions of petroleum-producing firms. First, unlike reduced-form models, a structural approach explicitly models the dynamics of these decisions. The production decisions of oil and gas producers are dynamic because petroleum is a nonrenewable resource; as a consequence, current extraction and production affect the availability of reserves for future extraction and production. The exploration, development, merger, and acquisition decisions of petroleum producers are dynamic because they are irreversible investments, because their payoffs are uncertain, and because petroleum producers have leeway over the timing of these investment decisions. Since the profits from investment and production decisions depend on market conditions such as the oil price that vary stochastically over time, an individual firm operating in isolation that hopes to make dynamically optimal decisions would need to account for the option value to waiting before making these irreversible investments (Dixit and Pindyck, 1994).

A second advantage of our model of the dynamic game between petroleum producers is that it models the strategic nature of the decisions of petroleum-producing firms. Petroleum producers consider not only future market conditions but also their competitors' investment and production activities when making their current decisions. Since the production decisions of other firms affect the prices of oil and natural gas, and therefore affect a firm's current payoff from production, and since the investment and production decisions of other firms affect future values of state variables which affect a firm's future payoff from producing and investing, petroleum-producing firms must anticipate the production and investment strategies of other firms in order to make a dynamically optimal decision. As a consequence, there are strategic interactions between petroleum-producing firms.

A third advantage of our structural model is that it enables us to estimate the effect of each state variable on the expected payoffs from exploration, development, production, merger, and acquisition decisions, and therefore enables us to estimate parameters that have direct economic interpretations. Our dynamic model accounts for the continuation value, which is the expected value of the value function next period. With the structural model we are able to estimate parameters in the payoffs from exploration, development, production, merger, and acquisition, since we are able to structurally model how the continuation values relate to the payoffs from each of these decisions. A fourth advantage of our structural model is that we are able to model the interdependence of petroleum-producing firms' value functions. When one firm merges with or acquires another firm, the value of the other firm with which it merges or acquires is given by that other firm's value function, which is the present discounted value of the entire stream of per-period payoffs of that other firm, and which accounts for the options that that other firm has to explore, develop, produce, merge, and acquire. Thus, a firm's value function depends on the expected value of other firms with which it has the option to merge or acquire. Therefore, the firms' value functions are interdependent.

A fifth advantage of our structural model is that we can use the parameter estimates from our structural model to simulate various counterfactual scenarios. We use our estimates to simulate counterfactual scenarios to analyze the effects of changes in OPEC membership, the privatization of state-owned oil companies, a ban on mergers, and demand shocks on the petroleum industry. We build on the literature on structural econometric models of dynamic games. In Lin (2013), we develop and estimate a structural model of the multi-stage investment timing game in offshore petroleum production. When individual petroleum-producing firms make their exploration and development investment timing decisions, positive information externalities and negative extraction externalities may lead them to interact strategically with their neighbors. If they do occur, strategic interactions in petroleum production would lead to a loss in both firm profit and government royalty revenue. The possibility of strategic interactions thus poses a concern to policy-makers and affects the optimal government policy. In Lin (2013), we examine whether these inefficient strategic interactions take place on U.S. federal lands in the Gulf of Mexico. In particular, we analyze whether one firm's production decisions and profits depend on the decisions of firms owning neighboring tracts of land. The empirical approach is to estimate a structural econometric model of the firms' multi-stage investment timing game.

In our model of the dynamic game among petroleum-producing firms in the world petroleum market in Kheiravar et al. (2019), a firm's decisions may depend on the decisions of other firms through several channels. First, aggregate output of oil and natural gas affect the prices of oil and natural gas faced by each firm; as a consequence, owing to market power, each firm's production decisions affect the prices faced by all firms. Second, aggregate output, aggregate reserves, and aggregate capital expenditures affect each firm's policy functions. Thus, each firm's decisions depend on the aggregate output and capital expenditure of all other firms, and on the aggregate reserves of all other firms. Third, aggregate output affects the transition densities for the global state variables. Thus, production decisions of each firm affect future values of the state variables, which then affect the payoffs and decisions of all firms. There are several sources of uncertainty in our model of a dynamic game in Kheiravar et al. (2019). First, future values of the state variables are stochastic. Second, each player receives private information shocks. Third, there are shocks to oil demand and regional natural gas demand. Fourth, merger and acquisition costs are private information to each firm, and are not observed by either other firms or the econometrician.

We assume that each firm optimizes its behavior conditional on the current state variables, other firms' strategies and its own private shocks, which results in a Markov perfect equilibrium (MPE). In a Markov perfect equilibrium, the optimal strategy for each firm should therefore yield an expected present discounted value of the entire stream of per-period payoffs at least as high as the expected present discounted value of the entire stream of per-period payoffs from any alternative strategy. We estimate the structural econometric model in two steps. In the first step, we characterize the equilibrium policy functions for the firms' decisions regarding exploration, development, production, merger, and acquisition as functions of state variables by using reduced-form regressions correlating actions to states. We also estimate the transition density for the state variables. We then calculate value functions using forward simulation following methods in Hotz et al. (1994) and Bajari et al. (2007). In the second step, using the condition for a Markov perfect equilibrium, we find the parameters that minimize any profitable deviations from the optimal policy as given by the policy functions estimated in the first step.

An innovation we make in our econometric method arises since a firm's own value function depends on the expected value of the value function of other firms that the firm may acquire or with which the firm may merge. We address the endogeneity of value functions using a fixed point algorithm.

We use the structural econometric model to analyze the effects of changes in OPEC membership, the privatization of state-owned oil companies, a ban on mergers, and demand shocks on the petroleum industry.

1.6 Conclusion

The decisions made by petroleum producers in the world oil market are both dynamic and strategic, and are thus best modeled as a dynamic game. In this chapter, we review the literature on the world oil market and discuss our research on econometric modeling of the world oil market as a dynamic game. Our research on econometric modeling of the world oil market as a dynamic game research builds on the previous literature by combining three erstwhile separate dimensions of modeling the world oil market: dynamic optimization, game theory, and econometrics.

Our results show that dynamic behavior and strategic interactions are important aspects of the world oil market that must be accounted for in empirical analyses of the world oil market.

In ongoing and future work, we hope to use our structural econometric model to better understand how government policies, changing geopolitical landscapes, and disruptive technologies, such as shale oil and gas, and new batteries for electric vehicles, impact future business models, the competition of fuels, and the composition of future energy demand. We would also like to use our structural econometric model to analyze how industry will respond to regulatory and/or societal demands for reduced greenhouse gas emissions and improved environmental quality; to examine how the oil industry might transition to more sustainable fuels; and to better understand what is required for early alternative fuel transitions to succeed. In future work, we hope to use our structural econometric model modeling outcomes to help inform decision-making and policy design. In particular, we hope to help petroleum firms better respond to government policies, and to help policy-makers better design sustainable energy policies.

The results of our research will be of interest to academics, policy-makers, entrepreneurs, and business practitioners, including oil companies, alike.

CHAPTER 2

A STRUCTURAL ECONOMETRIC MODEL OF THE DYNAMIC GAME BETWEEN PETROLEUM PRODUCERS IN THE WORLD PETROLEUM MARKET

2.1 Introduction

Fossil fuels supply more than 80 percent of the energy consumed in the world (U.S. Energy Information Administration, 2013). Oil and natural gas provide a large share of energy consumption, and getting access to secure sources of oil and natural gas is of huge importance for any economy (Finley, 2012). The production and consumption of oil and natural gas raise concerns about climate change, fossil fuel price volatility, energy security, and possible fossil fuel scarcity.

In this paper, we develop and estimate a structural econometric model of the dynamic game among petroleum-producing firms in the world petroleum market. Our model incorporates the dynamic behavior and strategic interactions that arise as petroleum-producing firms make their investment, production, merger, and acquisition decisions. We allow firms that are at least partially state-owned to have objectives other than profit maximization alone. We apply our model to annual firm-level panel data on oil and gas exploration, development, production, mergers, acquisitions, and reserves along with data on oil and gas prices to study the behavior of the top 50 oil and natural gas producing companies in the world. We then use the parameters estimated from our structural econometric model to simulate counterfactual scenarios to analyze the effects of changes in OPEC membership, a ban on mergers, the privatization of state-owned oil companies, and demand shocks on the petroleum industry.

There are several advantages to using a dynamic structural model to analyze the investment, production, merger, and acquisition decisions of petroleum-producing firms. First, unlike reduced-form models, a structural approach explicitly models the dynamics of these decisions. The production decisions of oil and gas producers are dynamic because petroleum is a nonrenewable resource;

as a consequence, current extraction and production affect the availability of reserves for future extraction and production. The exploration, development, merger, and acquisition decisions of petroleum producers are dynamic because they are irreversible investments, because their payoffs are uncertain, and because petroleum producers have leeway over the timing of these investment decisions. Since the profits from investment and production decisions depend on market conditions such as the oil price that vary stochastically over time, an individual firm operating in isolation that hopes to make dynamically optimal decisions would need to account for the option value to waiting before making these irreversible investments (Dixit and Pindyck, 1994).

A second advantage of our structural model of the dynamic game between petroleum producers is that it models the strategic nature of the decisions of petroleum-producing firms. Petroleum producers consider not only future market conditions but also their competitors' investment and production activities when making their current decisions. Since the production decisions of other firms affect the prices of oil and natural gas, and therefore affect a firm's current payoff from production; and since the investment and production decisions of other firms affect future values of state variables which affect a firm's future payoff from producing and investing, petroleum-producing firms must anticipate the production and investment strategies of other firms in order to make a dynamically optimal decision. As a consequence, there are strategic interactions between petroleum-producing firms. In addition, the uncertainty over the production and investment strategies of other firms is another reason there is an option value to waiting before investing (Dixit and Pindyck, 1994).

A third advantage of our structural model is that it enables us to estimate the effect of each state variable on the expected payoffs from exploration, development, production, merger, and acquisition decisions, and therefore enables us to estimate parameters that have direct economic interpretations. Our dynamic model accounts for the continuation value, which is the expected value of the value function next period. With the structural model we are able to estimate parameters in the payoffs from exploration, development, production, merger, and acquisition, since we are able to structurally model how the continuation values relate to the payoffs from each of these decisions.

A fourth advantage of our structural model is that we are able to model the interdependence of petroleum-producing firms' value functions. When one firm merges with or acquires another firm, the value of the other firm with which it merges or acquires is given by the other firm's value function, which is the present discounted value of the entire stream of per-period payoffs of the other firm, and which accounts for the options that the other firm has to explore, develop, produce, merge, and acquire. Thus, a firm's value function depends on the expected value of other firms with which it has the option to merge or acquire. As a consequence, the firms' value functions are interdependent.

A fifth advantage of our structural model is that we can use the parameter estimates from our structural model to simulate various counterfactual scenarios. We use our estimates to simulate counterfactual scenarios to analyze the effects of changes in OPEC membership, a ban on mergers, the privatization of state-owned oil companies, and demand shocks on the petroleum industry.

Although we do not assume or impose that OPEC producers collude to maximize joint profits, but instead infer the strategy and payoffs for OPEC firms from the data, we find that OPEC behaves in such a way that is consistent with its mission and also with cartel behavior. Results of counterfactual simulations also show that a ban on mergers would decrease average firm payoff for both OPEC and non-OPEC firms, and decrease consumer surplus.

The balance of our paper proceeds as follows. Section 3.2 reviews the previous literature. Section 2.3 presents our structural econometric model. We describe our data in Section 3.4. We present our results in Section 2.5. Section 2.6 presents our counterfactual simulations. Section 2.7 concludes.

2.2 Literature Review

2.2.1 Models of the world petroleum market

We build on the empirical literature on the world petroleum market, much of which is from over three decades ago (Adelman, 1962; Kennedy, 1974; Nordhaus, 1980; Gately, 1984; Griffin, 1985;

Lin, 2011b; Espinasa et al., 2017). Cremer and Salehi-Isfahani (1991) provide a survey of models of the oil market. Many previous empirical studies of world petroleum market use a static model; one exception is Lin Lawell (2019). Unlike previous empirical studies of the petroleum market that use a static model, we estimate a dynamic model of the world petroleum market.

We also build on the literature analyzing strategic behavior in the world petroleum market, and particularly the behavior of OPEC (Griffin, 1985; Matutes, 1988; Golombek et al., 2014; Gulen, 1996; Farzin, 1985; Alhajji and Huettner, 2000a,b; Kaufmann et al., 2004; Almoguera et al., 2011; Fang et al., 2014; Hochman and Zilberman, 2015; Okullo and Reynès, 2016; Baumeister and Kilian, 2017; Genc, 2017; Ghoddusi et al., 2017; Asker et al., 2018; Lin Lawell, 2019). For detailed background information on the world energy industry, see the classic text by Dahl (2015). For a detailed review of the literature on oil market modeling and OPEC's behavior, see Al-Qahtani et al. (2008).

Our dynamic model of oil production builds on the theoretical model of optimal nonrenewable resource extraction that was first examined by Hotelling (1931), and then expanded upon by many others (see e.g., Solow and Wan (1976); Hanson (1980); Pesaran (1990); Pindyck (1978b, 1980b); Farzin (1992, 1995); Young and Ryan (1996); Lin and Wagner (2007); Lin (2009b); Lin et al. (2009); Gao et al. (2009); Leighty and Lin (2012); Almansour and Insley (2016); Zhang and Lin Lawell (2017); Brown et al. (2017); Ghandi and Lin Lawell (2019); Anderson et al. (2018); van Veldhuizen and Sonnemans (2018)).

2.2.2 Models of mixed oligopoly and state-owned firms

The second strand of literature upon which we build is that on mixed oligopoly and state-owned firms. A mixed oligopoly is defined as an oligopolistic market structure with a relatively small number of firms for which the objective of at least one firm differs from that of other firms (de Fraja and Delbono, 1990), as opposed to a private oligopoly in which all firms have the objective of profit maximization. Usually in a mixed oligopoly there is a public firm competing with a multitude of profit-maximizing firms (Poyago-Theotoky, 2001). A market in which there are both private and public firms is then a mixed oligopoly because the firms owned by private agents aim to maximize profits, whereas the publicly owned firms are interested in optimizing social targets (de Fraja and Delbono, 1990).

de Fraja and Delbono (1989) study a situation in which private and public firms pursue different objectives and compete both using only market instruments. Fjell and Pal (1996) consider a mixed oligopoly model in which a state-owned public firm competes with both domestic and foreign private firms. White (1996) and Poyago-Theotoky (2001) analyze output subsidies in the presence of a mixed oligopoly. de Fraja and Valbonesi (2009) find that behavior which would be deemed anti-competitive for a profit maximizing oligopolist may be in line with the objective function of a public, welfare-maximizing supplier. Lutz and Pezzino (2014) show that mixed competition is always socially desirable compared to a private duopoly regardless of the type of competition in the short run and the equilibrium quality ranking. Bennett and La Manna (2012) find that whenever a mixed oligopoly is viable, then aggregate output, aggregate costs, and welfare are the same with and without the public firm. Haraguchi and Matsumura (2016) compare price and quantity competition in a mixed oligopoly in which one state-owned public firm competes against private firms.

In comparing private and state-owned oil firms, Ohene-Asare et al. (2017) find that private oil companies outperform state-owned oil companies and that state-owned firms suffer from scale inefficiencies. Cabrales et al. (2017) assess the impact of domestic fuel subsidies and employment on the performance of national oil companies by developing a model that clarifies the trade-offs among non-commercial objectives and the market value, production, and reinvestment of national oil companies.

A related literature is that on the objectives of state-owned firms. Chen and Lin Lawell (2019) develop and estimate a random coefficients mixed oligopolistic differentiated products model to analyze supply, demand, and the effects of government policy in the Chinese automobile market, a market that includes both private and state-owned firms. Their structural econometric model of a mixed oligopolistic differentiated products market allows different consumers to vary in how much they like different car characteristics on the demand side, and state-owned automobile companies to have different objectives than private automobile companies on the supply side.

Ghandi and Lin (2012) model the dynamically optimal oil production on Iran's offshore Soroosh and Nowrooz fields, which have been developed by Shell Exploration through a buy-back service contract. In particular, they examine the National Iranian Oil Company's (NIOC) actual and contractual oil production behavior and compare it to the production profile that would have been optimal under the conditions of the contract. They find that the contract's production profile is different from optimal production profile for most discount rates, and that the NIOC's actual production rates have not maximized profits.

2.2.3 Dynamic structural econometric models

Structural econometric models of dynamic behavior have been applied to bus engine replacement (Rust, 1987), nuclear power plant shutdown decisions (Rothwell and Rust, 1997), water management (Timmins, 2002), air conditioner purchase behavior (Rapson, 2014), wind turbine shutdowns and upgrades (Cook and Lin Lawell, 2019), copper mining decisions (Aguirregabiria and Luengo, 2016), long-term and short-term decision-making for disease control (Carroll et al., 2019a), the adoption of rooftop solar photovoltaics (Feger et al., 2017; Langer and Lemoine, 2018), supply chain externalities (Carroll et al., 2019b), vehicle scrappage programs (Li and Wei, 2013), vehicle ownership and usage (Gillingham et al., 2016), agricultural productivity (Carroll et al., 2018), organ transplant decisions (Agarwal et al., 2018), and the spraying of pesticides (Sambucci et al., 2019).

Structural econometric models of dynamic games include the model developed by Pakes, Ostrovsky, and Berry (2007), which has been applied to the multi-stage investment timing game in offshore petroleum production (Lin, 2013), to ethanol investment decisions (Thome and Lin Lawell, 2019), and to the decision to wear and use glasses (Ma et al., 2019); and the model developed by Bajari et al. (2015), which has been applied to ethanol investment (Yi and Lin Lawell, 2019a,b). Structural econometric models of dynamic games have also been applied to fisheries

(Huang and Smith, 2014), dynamic natural monopoly regulation (Lim and Yurukoglu, 2018), Chinese shipbuilding (Kalouptsidi, 2018), the market for smartphones and tablets (Kehoe et al., 2018), industrial policy (Barwick et al., 2018), and coal procurement (Jha, 2019).

Lin (2013) develops and estimates a structural model of the multi-stage investment timing game in offshore petroleum production. When individual petroleum-producing firms make their exploration and development investment timing decisions, positive information externalities and negative extraction externalities may lead them to interact strategically with their neighbors. If they do occur, strategic interactions in petroleum production would lead to a loss in both firm profit and government royalty revenue. The possibility of strategic interactions thus poses a concern to policy-makers and affects the optimal government policy. Lin (2013) examines whether these inefficient strategic interactions take place on U.S. federal lands in the Gulf of Mexico. In particular, she analyzes whether a firm's production decisions and profits depend on the decisions of firms owning neighboring tracts of land. The empirical approach is to estimate a structural econometric model of the firms' multi-stage investment timing game. Lin (2009a) uses a reduced-form model to examine whether strategic interactions take place during petroleum exploration.

In this paper, we apply the structural econometric model of a dynamic game that was developed by Bajari, Benkard, and Levin (2007). This model has been applied to the cement industry (Ryan, 2012; Fowlie et al., 2016), to the production decisions of ethanol producers (Yi et al., 2019), to migration decisions (Rojas Valdés et al., 2018, 2019), to the global market for solar panels (Gerarden, 2019), to the digitization of consumer goods (Leyden, 2019), and to climate change policy (Zakerinia and Lin Lawell, 2019).

Ryan (2012) uses a structural econometric model to measure the welfare costs of the 1990 Clean Air Act Amendments on the US Portland cement industry. Unlike typical static cost analyses, which ignore the sunk costs of entry and investment, Ryan (2012) explicitly accounts for the dynamic effects resulting from a change in the cost structure resulting from the regulation. His results show that the Clean Air Act Amendments increased the sunk costs of entry, which negatively affected potential entrants and partially benefited incumbents because of lower ex post competition.

Fowlie et al. (2016) build on this structural econometric model to analyze market-based emissions regulation.

Yi, Lin Lawell, and Thome (2019) use a structural econometric model of a dynamic game to analyze the effect of government subsidies and the Renewable Fuel Standard (RFS) on the US ethanol industry. They use the estimated parameters to evaluate three different types of subsidy: a production subsidy, an investment subsidy, and an entry subsidy, each with and without the RFS. While conventional wisdom and some of the previous literature favor production subsidies over investment subsidies, and while historically the federal government has used production subsidies to support ethanol, their results show that, for the ethanol industry, investment subsidies and entry subsidies are more cost-effective than production subsidies for inducing investment that otherwise would not have occurred.

2.3 Methodology

We model the dynamic game among the top 50 petroleum producers in the world. Exploration and development are important components of the petroleum production process. Exploration entails making capital expenditures to invest in drilling rigs needed for exploratory drilling. Development entails making capital expenditures to invest in production platforms needed to develop and extract the reserve (Dixit and Pindyck, 1994; Lin, 2013). In addition to production and investment, petroleum-producing firms also engage in mergers and acquisitions. We therefore focus on modeling the production, investment, merger, and acquisition decisions of petroleum-producing firms.

In particular, each period, each petroleum producer decides how much oil and natural gas to produce; how much to spend on each type of capital expenditure (exploration, development, and acquisition); whether to acquire another firm or be acquired by another firm; and whether to merge with another firm. The actions a_i of each firm i are assumed to be functions of a set of state variables and private information:

$$a_i = \sigma_i(s, \varepsilon_i), \tag{2.1}$$

where s is a vector of publicly observable state variables and ε_i is a vector of private information shocks to firm i which are not observed by either other firms or the econometrician. These private information shocks include idiosyncratic firm-specific shocks to merger and acquisition costs.

We include the following firm-specific state variables: oil and natural gas reserves; cumulative oil and natural gas output; cumulative exploration, acquisition, and development expenditure; percentage of state ownership; whether the firm is a member of OPEC; whether the firm merged in the previous year; and whether the firm acquired another firm in the previous year. We include the following global state variables: average industry rate of return on capital for mining and quarry; average capital compensation on other machinery and equipment; world population; world GDP; world motor vehicles; world road sector gasoline fuel consumption; and world electricity production from oil and natural gas sources.

The production, investment, merger, and acquisition decisions of a petroleum-producing firm i affect firm i's own per-period payoff $\pi_i(s, a, \varepsilon_i; \theta)$; the per-period payoff of other firms; and the distribution of future state variables, including firm-specific state variables such as firm i's own oil and natural gas reserves, as well as global state variables that affect all firms.

The firm-specific state variables for whether the firm merged in the previous year, and for whether the firm acquired another firm in the previous year evolve deterministically as a function of the firm's merger and acquisition decisions in the previous year. The transition densities for each of the remaining state variables are stochastic, and depend on the lagged value of that state variable and also potentially on the lags of other state variables and lagged actions.

In our transition densities for oil and natural gas reserves, we do not assume any fixed finite amount for the reserves. This is consistent with the common practice in the natural resource economics literature of modeling potential reserves as infinite; potential reserves are probably infinite, although the amount that is economical to extract is finite, and technological progress and new discoveries will always make more reserves available and feasible for extraction (Farzin, 1992; Lin, 2009b). Thus, for the transition densities for oil and natural gas reserves, we allow the distribution of reserves the next period to depend on the reserves, production, exploration, development, and merger and acquisitions this period, and we let the data tell us what the transition density is. Our econometric model allows for reserves to increase or decrease over time.

We model the oil market as a world market. The world demand for oil is given by:

$$\begin{aligned} Q_{oil} &= D_{oil}(p_{oil}) \\ &= \alpha_{10} + \alpha_{11} p_{oil} + X'_{oil}\alpha_{1x} + \nu_1, \end{aligned} \tag{2.2}$$

where Q_{oil} is world oil quantity; p_{oil} is world oil price; X_{oil} is a vector of demand shifters for world oil; and ν_1 is a shock to oil demand.

Unlike the oil market, the natural gas market is not necessarily a world market. Due to the lack of a global pipeline network, the market for natural gas is mostly defined by proximity to supply sources and the availability of a pipeline. We consider 6 separate regional markets r for natural gas: Africa; Asia and Oceania; Eurasia; Europe; the Middle East; and the Americas. The regional demand for natural gas in each region r is given by:

$$\begin{aligned} Q_{ng_r} &= D_{ng_r}(p_{ng_r}) \\ &= \alpha_{20_r} + \alpha_{21_r} p_{ng_r} + X'_{ng_r}\alpha_{2x_r} + \nu_{2_r}, \end{aligned} \tag{2.3}$$

where Q_{ng_r} is regional natural gas quantity for region r; p_{ng_r} is regional natural gas price for region r; X_{ng_r} is a vector of demand shifters for regional natural gas in region r; and ν_{2_r} is a shock to regional natural gas demand in region r.

The prices of oil and natural gas are determined by the following inverse demand functions:

$$\begin{aligned} p_{oil} &= D_{oil}^{-1}(Q_{oil}) \\ &= -\frac{\alpha_{10}}{\alpha_{11}} + \frac{1}{\alpha_{11}} Q_{oil} - \frac{1}{\alpha_{11}} X_{oil}' \alpha_{1x} - \frac{1}{\alpha_{11}} \nu_1 \end{aligned} \tag{2.4}$$

$$\begin{aligned} p_{ng_r} &= D_{ng_r}^{-1}(Q_{ng_r}) \\ &= -\frac{\alpha_{20_r}}{\alpha_{21_r}} + \frac{1}{\alpha_{21_r}} Q_{ng_r} - \frac{1}{\alpha_{21_r}} X_{ng_r}' \alpha_{2x_r} - \frac{1}{\alpha_{21_r}} \nu_{2_r}. \end{aligned} \tag{2.5}$$

We assume the costs of oil and natural gas production for each company i are given by the following production cost functions:

$$c_{i,oil}(q_{i,oil}, z_{i,oil}; \delta_{11}, \delta_{12}, \delta_{13}, \delta_{14}) = \delta_{11} q_{i,oil} + \delta_{12} q_{i,oil}^2 + \delta_{13} z_{i,oil} + \delta_{14} q_{i,oil} \cdot z_{i,oil} + \delta_{15} q_{i,oil} \cdot q_{i,ng} \tag{2.6}$$

$$c_{i,ng}(q_{i,ng}, z_{i,ng}; \delta_{21}, \delta_{22}, \delta_{23}, \delta_{24}) = \delta_{21} q_{i,ng} + \delta_{22} q_{i,ng}^2 + \delta_{23} z_{i,ng} + \delta_{24} q_{i,ng} \cdot z_{i,ng} + \delta_{25} q_{i,ng} \cdot q_{i,oil}, \tag{2.7}$$

where $q_{i,oil}$ and $q_{i,ng} = \sum_{r=1}^{6} q_{i,ng_r}$ are firm i's oil and natural gas production output, respectively; $z_{i,oil}$ and $z_{i,ng}$ are firm i's oil and natural gas reserves, respectively; and δ_{11}, δ_{12}, δ_{13}, δ_{14}, δ_{21}, δ_{22}, δ_{23}, δ_{24}, and $\delta_5 \equiv (\delta_{15} + \delta_{25})$ are among the parameters θ to be estimated.

We allow for nonlinearities with respect to both output and reserves in the oil and natural gas production costs in equations (2.6) and (2.7) so that oil and natural gas production may exhibit increasing or decreasing returns to scale, or both. We allow the costs and marginal costs of production to potentially depend on the stock of reserves remaining in the ground, a dependence natural resource economists refer to as 'stock effects', by including oil and natural gas reserves and their interactions with oil and natural gas output in the respective production cost functions. There are several possible reasons why marginal production costs may increase when there are fewer reserves remaining in the ground. First, oil (or natural gas) extraction costs may increase as less oil (or natural gas) reserve remains in the ground if the resource needs to be extracted from greater depths as it is being depleted. Second, costs may increase if well pressure declines as more of the reserve is depleted. Third, since different grades of oil (or natural gas) may differ in their extraction costs, and since production may move towards more expensive grades as the stock of cheaper grades diminishes, the marginal cost of extraction may increase as the stock of cheaper grades and therefore the total stock decreases (Lin, 2009b; Zhang and Lin Lawell, 2017).

Since we cannot separately identify the coefficient δ_{15} on the interaction between oil and natural gas output in the oil production cost from the coefficient δ_{25} on the interaction between oil and natural gas output in the natural gas production cost, we estimate one coefficient on the interaction between oil and natural gas output in the oil and natural gas production cost: $\delta_5 \equiv (\delta_{15} + \delta_{25})$, which represents any cost synergies from joint production and other supply-side links in oil and natural gas (Roberts and Gilbert, 2018).

The per-period production profit $\bar{\pi}_i(s, a; \theta)$ for company i from the production of oil and natural gas is thus given by:

$$\begin{aligned}
&\bar{\pi}_i(s, a; \theta) \\
&= \underbrace{\left(D_{oil}^{-1}(Q_{oil})\, q_{i,oil} - \delta_{11} q_{i,oil} - \delta_{12} q_{i,oil}^2 - \delta_{13} z_{i,oil} - \delta_{14} q_{i,oil} \cdot z_{i,oil} - \delta_{15} q_{i,oil} \cdot q_{i,ng}\right)}_{\text{Profit from production of oil}} \\
&+ \underbrace{\left(\sum_{r=1}^{6} D_{ng_r}^{-1}(Q_{ng_r})\, q_{i,ng_r} - \delta_{21} q_{i,ng} - \delta_{22} q_{i,ng}^2 - \delta_{23} z_{i,ng} - \delta_{24} q_{i,ng} \cdot z_{i,ng} - \delta_{25} q_{i,ng} \cdot q_{i,oil}\right)}_{\text{Profit from production of natural gas}}.
\end{aligned} \tag{2.8}$$

In addition to producing oil and natural gas, firms can invest in capital using three forms of capital expenditure: exploration, development, and acquisition capital expenditure.[1] Let x_i be the

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[1] Acquisition capital expenditures include expenditures for acquiring machinery and any other type of asset.

total capital expenditure of firm i, which is given by:

$$x_i = x_{i,exp} + x_{i,dvp} + x_{i,acq}, \tag{2.9}$$

where $x_{i,exp}$, $x_{i,dvp}$, and $x_{i,acq}$ are firm i's exploration, development, and acquisition capital expenditures, respectively.

In addition to production and investment, petroleum-producing firms also make decisions about mergers and acquisitions. There are several possible reasons for mergers and acquisitions in the petroleum industry that are captured by our model. First, owing to nonlinearities with respect to both output and reserves in the production profit function in equation (2.8), oil and natural gas production may exhibit increasing or decreasing returns to scale, or both. As a consequence, firms may benefit from changing their scale via mergers and acquisitions. Second, there may be other synergies between firms as well, including cost synergies, knowledge synergies, organizational synergies, and management synergies. As we explain below, these additional synergies are captured in our policy functions and transition densities. Third, firms may benefit from any increase in market power as a result of a merger or acquisition. Market power motivations are captured in part by the inverse demand function and any resulting markup from market power. Fourth, some firms may be particularly well suited for mergers and acquisitions, as captured in our model by idiosyncratic private information shocks to the costs and benefits of mergers and acquisitions that firms receive.

Firm i's payoffs $\Phi_i(s, a_i, \sigma_{-i}, \varepsilon_i; \theta)$ from mergers and/or acquisition are given by:

$$\Phi_i(s, a_i, \sigma_{-i}, \varepsilon_i; \theta) = \begin{cases} -\Gamma_i^B + EV_j(s; \sigma, \theta) \cdot \eta_1 & \text{if firm } i \text{ acquires firm } j \\ \Gamma_i^S & \text{if firm } i \text{ is acquired by firm } j \\ -\Lambda_i + EV_j(s; \sigma, \theta) \cdot \eta_2 & \text{if firms } i \text{ and } j \text{ merge into one firm,} \end{cases}$$

where σ_{-i} are the strategies played by all firms other than firm i; Γ_i^B is the fixed cost to firm i of acquiring other firm; Γ_i^S is the fixed benefit to firm i from being acquired; Λ_i is the fixed cost to firm i of merging; and $EV_j(s;\sigma,\theta)$ is the expected value of the value function $V_j(s;\sigma,\theta)$ for firm j, which depends on the strategies σ played by all firms. Firm i's idiosyncratic fixed payoffs Γ_i^B, Γ_i^S, and Λ_i of acquiring, being acquired, and merging, respectively, are private information to firm i, and are thus included in the vector ε_i of private information shocks to firm i.

Using the inverse demand for oil and natural gas given by equations (2.4) and (2.5), we calculate the consumer surplus from oil and natural gas consumption, CS_{oil} and CS_{ng_r} respectively, as follows:

$$\begin{aligned} CS_{oil} &= \int_0^{Q_{oil}} D_{oil}^{-1}(x)dx - p_{oil}Q_{oil} \\ &= \left(\frac{-\alpha_{10} - X_{oil}'\alpha_{1x} - \nu_1}{\alpha_{11}}\right) Q_{oil} + \frac{1}{2\alpha_{11}} Q_{oil}^2 - p_{oil}Q_{oil} \end{aligned} \tag{2.10}$$

$$\begin{aligned} CS_{ng_r} &= \int_0^{Q_{ng_r}} D_{ng_r}^{-1}(x)dx - p_{ng_r}Q_{ng_r} \\ &= \left(\frac{-\alpha_{20_r} - X_{ng_r}'\alpha_{2x_r} - \nu_{2_r}}{\alpha_{21_r}}\right) Q_{ng_r} + \frac{1}{2\alpha_{21_r}} Q_{ng_r}^2 - p_{ng_r}Q_{ng_r}. \end{aligned} \tag{2.11}$$

Total consumer surplus CS from oil and natural gas consumption is therefore given by:

$$CS = CS_{oil} + \sum_{r=1}^{6} CS_{ng_r}. \tag{2.12}$$

We assume that private firms care solely about profit, while firms that are at least partially state-owned may also put some weight on the consumer surplus faced by that firm. The consumer surplus CS_i faced by a firm i is not the same as world consumer surplus CS, however. We define the consumer surplus for oil faced by firm i as the world consumer surplus for oil times firm i's oil production as a fraction of world oil production (where world oil production is total oil production over the top 50 firms). For each natural gas region, we define consumer surplus for natural gas in that region faced by firm i as the world consumer surplus for natural gas in that region times firm i's natural gas production in that region as a fraction of total natural gas production in the region (where total natural gas production in a region is the natural gas production in that region summed over the top 50 firms).

The consumer surplus CS_i faced by firm i is therefore given by the following weighted sum of the consumer surplus from oil and the consumer surplus from natural gas in each region, where the weights are given by firm i's respective share in the total production of oil and regional natural gas:

$$CS_i = CS_{oil}\frac{q_{i,oil}}{Q_{oil}} + \sum_{r=1}^{6} CS_{ng_r}\frac{q_{i,ng_r}}{Q_{ng_r}}. \tag{2.13}$$

The per-period payoff $\pi_i(s, a, \varepsilon_i; \theta)$ for each firm i is therefore as follows:

$$\begin{aligned}\pi_i(s, a, \varepsilon_i; \theta) = &(1 - O_{i,state}) \underbrace{\bar{\pi}_i(s, a; \theta)}_{\text{production profit}} + O_{i,state} \left((1 - \rho_{CS}) \underbrace{\bar{\pi}_i(s, a; \theta)}_{\text{production profit}} + \rho_{CS} CS_i \right) \\ &+ \omega_1 O_{i,state} + \omega_2 O_{i,OPEC} + \underbrace{\Phi_i(s, a_i, \sigma_{-i}, \varepsilon_i; \theta)}_{\text{M\&A}} - \underbrace{x_i}_{\text{capex}} + \delta_0,\end{aligned} \tag{2.14}$$

where $O_{i,state}$ denotes the fraction of state ownership in firm i; ρ_{CS} is the weight that a firm that is at least partially state-owned puts on consumer surplus; $O_{i,OPEC}$ denotes a dummy variable for whether firm i is an OPEC member; and δ_0 is a constant.

Identification of the weight ρ_{CS} that a state-owned firms put on consumer surplus comes from variation in the fraction of state ownership among firms. Identification of the cost parameters comes from the realized firm behavior, including the realized behavior of private firms which care solely about profit.

Although the mission of OPEC is to 'coordinate and unify the petroleum policies of its Member Countries' (Organization of Petroleum Exporting Countries [OPEC], 2017), it is unclear whether

OPEC behaves as a cartel (Baumeister and Kilian, 2016, 2017; Lin Lawell, 2019; Parnes, 2018). Thus, rather than assume or impose that OPEC producers collude to maximize joint profits, we instead allow the strategies and payoffs for OPEC and non-OPEC firms to differ, and infer the strategy and payoffs for OPEC firms from the data. In particular, we estimate the oil and natural gas policy functions for OPEC firms and non-OPEC firms separately, and we include a dummy variable $O_{i,OPEC}$ for whether firm i is an OPEC member in the per-period payoff function.

As the per-period payoff $\pi_i(s, a, \varepsilon_i; \theta)$ for each firm i is linear in parameters θ, we can write the per-period payoff as the following:

$$\pi_i(s, a, \varepsilon_i; \theta) = \Psi_i(s, a, \varepsilon_i) \cdot \theta. \tag{2.15}$$

The expected present discounted value $V_i(s; \sigma, \theta)$ of the entire stream of per-period payoffs for firm i as a function of its strategy σ is given by:

$$\begin{aligned} V_i(s; \sigma, \theta) =& \mathbb{E}\left[\sum_{t=0}^{\infty} \beta^t \pi_i(s, a, \varepsilon_i; \theta)\right] \\ =& \mathbb{E}\left[\sum_{t=0}^{\infty} \beta^t \Psi_i(\sigma(s_t, \varepsilon_t), s_t, \varepsilon_{it})\right] \cdot \theta \\ =& W_i(s; \sigma) \cdot \theta, \end{aligned} \tag{2.16}$$

where the vector of terms W_i does not depend on the vector of parameters θ.

We cannot directly estimate the parameters in the unconditional distributions for the idiosyncratic firm-specific fixed payoffs Γ_i^B, Γ_i^S, and Λ_i to each firm i of acquiring, being acquired, and merging, respectively, since firms only undertake actions of acquiring, being acquired, and merging when the respective firm-specific fixed payoffs are sufficiently favorable.

Thus, we instead estimate the conditional expectations of the idiosyncratic firm-specific fixed payoffs Γ_i^B, Γ_i^S, and Λ_i to each firm i of acquiring, being acquired, and merging as functions of the probabilities p_B, p_S, and p_M of acquiring another firm, being acquired by another firm, and merging with another firm. Since these strategy probabilities capture the relevant information faced by a firm at a specific state, the conditional distributions of the fixed payoffs of acquiring, being acquired, and merging are also each a function of these probabilities (Ryan, 2012); if another alternative becomes more attractive, which would be reflected in a higher choice probability for this alternative, the draw of the fixed payoffs of acquiring, being acquired, and merging should represent such preference. In particular, we estimate the conditional expectations of the idiosyncratic firm-specific fixed payoffs Γ_i^B, Γ_i^S, and Λ_i to each firm i of acquiring, being acquired, and merging each as second-order polynomials of the probabilities p_B, p_S, and p_M of acquiring another firm, being acquired by another firm, and merging with another firm.

We assume that each firm chooses its production, investment, and merger and acquisition strategy to maximize the expected present discounted value $V_i(s;\sigma,\theta)$ of its entire stream of per-period payoffs, conditional on the current state variables, other firms' strategies, and its own private shocks, which results in a Markov perfect equilibrium (MPE). The optimal strategy $\sigma_i^*(s)$ for each firm i should therefore satisfy the following condition that, for all state variables s and alternative strategies $\tilde{\sigma}_i(s)$, the optimal strategy $\sigma_i^*(s)$ yields an expected present discounted value of the entire stream of per-period payoffs at least as high as the expected present discounted value of the entire stream of per-period payoffs from any alternative strategy $\tilde{\sigma}_i(s)$:

$$V_i(s;\sigma_i^*(s),\sigma_{-i},\theta,\varepsilon_i) \geq V_i(s;\tilde{\sigma}_i(s),\sigma_{-i},\theta,\varepsilon_i). \tag{2.17}$$

In our dynamic game, a firm's decisions may depend on the decisions of other firms through several channels. First, aggregate output of oil and natural gas affect the prices of oil and natural gas faced by each firm; as a consequence, owing to market power, each firm's production decisions affect the prices faced by all firms. Second, aggregate output, aggregate reserves, and aggregate capital expenditures affect each firm's policy functions. Thus, each firm's decisions depend on the aggregate output and capital expenditure of all other firms, and on the aggregate reserves of all other firms. Third, aggregate output affects the transition densities for the global state variables. Thus, production decisions of each firm affect future values of the state variables, which then affect the payoffs and decisions of all firms.

There are several sources of heterogeneity among firms in our model of the dynamic game between petroleum producers in the world petroleum market. First, firms differ in whether they are private or at least partially state-owned. We allow firms that are at least partially state-owned to have objectives other than profit maximization alone. Second, firms differ in their values of firm-specific state variables, the evolution of which may depend in part on previous actions they have taken. These firm-specific state variables include oil and natural gas reserves; cumulative oil and natural gas output; cumulative exploration, acquisition, and development expenditure; percentage of state ownership; whether the firm is a member of OPEC; whether the firm merged in the previous year; and whether the firm acquired another firm in the previous year. Third, firms differ in their idiosyncratic firm-specific fixed payoffs Γ_i^B, Γ_i^S, and Λ_i of acquiring, being acquired, and merging, respectively. Fourth, firms differ in their idiosyncratic draws from the mixed strategies given by their policy functions.

There are several sources of uncertainty in our model of a dynamic game. First, future values of the state variables are stochastic. Second, there are shocks to oil demand and regional natural gas demand. Third, merger and acquisition costs are private information to each firm i, and are not observed by either other firms or the econometrician. Fourth, the actual actions drawn from the mixed strategies given by the policy functions are stochastic.

The structural parameters θ to be estimated include the parameters in the per-period payoff function; and the distributions of the fixed payoffs to merging, acquiring, and being acquired.

Finding a single equilibrium is computationally costly even for problems with a simple structure. In more complex problems – as in the case of our dynamic game between petroleum producers in the world petroleum market, where many agents and decisions are involved – the computational burden is even more important, particularly if there may be multiple equilibria. Bajari, Benkard, and Levin (2007) propose a method for recovering the dynamic parameters of the payoff function without having to compute any single equilibrium. The crucial mathematical assumption to be able to estimate the parameters in the payoff function is that, even when multiple equilibria are possible, the same equilibrium is always played.

We estimate the structural econometric model in two steps. In the first step, we characterize the equilibrium policy functions for the firms' decisions regarding exploration, development, production, merger, and acquisition as functions of state variables by using reduced-form regressions correlating actions to states. We also estimate the transition density for the state variables. We then calculate value functions using forward simulation following methods in Hotz et al. (1994) and Bajari, Benkard, and Levin (2007). In the second step, using the condition for a Markov perfect equilibrium in equation (2.17), we find the parameters θ that minimize any profitable deviations from the optimal policy as given by the policy functions estimated in the first step.

An innovation we make in our econometric method arises since a firm's own value function $V_i(s; \sigma, \theta)$ depends on the expected value of the value function $EV_j(s; \sigma, \theta)$ of other firms that the firm may acquire or with which the firm may merge. We address the endogeneity of value functions using a fixed point algorithm.

2.4 Data

We construct an annual firm-level panel data set of the top 50 oil and natural gas producing companies each year. The original source of data is the Petroleum Intelligence Weekly published by Energy Intelligence Group, which reports annual information on different operational criteria as well as financial and other measures of size for each of the top 50 oil and natural gas producing companies. This data set includes firm-level data on oil and natural gas output, oil and natural gas reserves,[2] capital expenditures, and percentage of state ownership. Each year, the top 50 firms are determined by production as reported in the Petroleum Intelligence Weekly.

The top 50 oil and natural gas producing firms supply a significant share of global supply of oil. As seen in Figure 2.1 in Appendix A, on average over 70% of the global supply is produced by the top 50 oil and natural gas producing firms.

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[2] The reserves data reflect 'proved reserves', which U.S. Energy Information Administration (2018a) defines as 'volumes of oil and natural gas that geologic and engineering data demonstrate with reasonable certainty to be recoverable in future years from known reservoirs under existing economic and operating conditions'.

We use membership information from the Organization of Petroleum Exporting Countries (OPEC) to construct a dummy variable that takes the value of 1 for a firm if it is a state-owned company owned by an OPEC member country.

We obtain annual oil and natural gas prices from the U.S. Energy Information Administration. We obtain average hourly earning of workers in oil and gas extraction industry from the U.S. Bureau of Labor Statistics.

We also use data on financial indicators averaged over 10 OECD countries as reported in the EU KLEMS database. These indicators include industry rate of return on capital in mining and quarry; average capital compensation on transport equipment in mining and quarry; average capital compensation on other machinery and equipment in mining and quarry; average capital compensation on total non-residential investment in mining and quarry; and average capital compensation on other assets in mining and quarry. Capital compensation is the price of capital times the quantity of capital, which under constant returns to scale is the value added minus labor compensation. We use capital compensation as our measure of capital costs, including costs of drilling rigs and production platforms, in the oil and gas industry.

We use data on world GDP, world population, world electricity production from oil and natural gas, world road sector fuel consumption, and world motor vehicles from the World Bank.

Unlike the oil market, the natural gas market is not necessarily a global market. Due to the lack of a global pipeline network, the market for natural gas is mostly defined by proximity to supply sources and the availability of a pipeline. In order to estimate separate natural gas demand functions for 6 different regional markets, we collect and construct regional natural gas prices using data from the EIA, and regional population and GDP data from the World Bank. Our 6 regional natural gas markets are Africa; Asia and Oceania; Eurasia; Europe; the Middle East; and the Americas.

Africa accounts for about 2.8% of global natural gas consumption, the lowest natural gas consumption share out of all our 6 regions. We use data from Algeria, Egypt, Equatorial Guinea, Libya, Mozambique, and Nigeria to construct an average natural gas price for Africa.

The Asia and Oceania region accounts for just below 15% of global natural gas consumption. We use data from Australia, Brunei, Burma, China, Indonesia, and Malaysia to construct an average natural gas price for Asia and Oceania.

Eurasia accounts for over 20% of global natural gas consumption and is home to a significant share of the world's natural gas resources, which makes this region a net natural gas exporter. We use data along from Azerbaijan, Georgia, Kazakhstan, Russia, Turkmenistan, Ukraine, and Uzbekistan to construct an average natural gas price for Eurasia.

European Union (EU) countries account for about 20% of global natural gas consumption. Russia is the major supplier of EU natural gas imports. We use data from EU members and Turkey to construct an average natural gas price for Europe.

The Middle East accounts for just below 10% of global natural gas consumption, but is home to a significant share of the world's natural gas resources, which makes the region a net exporter of natural gas. We use data from Iran, Iraq, Oman, Qatar, UAE, and Yemen to construct an average natural gas price for the Middle East.

North and South America together account for about 32% of global natural gas consumption, and aside from the insignificant liquefied natural gas imports from outside of the continent, it is disconnected from natural gas markets in other parts of the world. Over the last decade, the North American natural gas market has been experiencing a boom as a result of the boost in shale gas extraction in the United States. We use data from Canada, Mexico, United States, Argentina, Bolivia, Brazil, Colombia, Peru, and Trinidad and Tobago to construct an average natural gas price for the Americas.

Since we only observe total annual natural gas production for each firm, but do not observe each firm's natural gas production in each of the 6 regional natural gas markets, we make the following assumptions about each firm's share of natural gas production in each regional market.

We assume that oil and gas companies that are not state-owned divide up their total natural gas production each year to each region according to each region's average share of total natural gas consumption.

For oil and gas companies that are at least partially state-owned, if the state-owned company is in a country that does not export natural gas, then we assume that the state-owned company only sells to its own regional market.

For oil and gas companies that are at least partially state-owned and are in a country that exports natural gas, we assume that each year these state-owned companies allocate the production that is not already allocated to their own region to all regions (including their own) according to the respective region's average natural gas import shares. The regional average natural gas import shares are calculated as follows: for each region-year, we calculate what fraction of total natural gas imports (over all regions in the world) that year is imported into that region. We then average each region's annual fraction of imports over all years.

Thus, we assume that a state-owned company that is in a country that exports natural gas allocates a portion (equal to one minus its export share) of its natural gas production to its own region, and then allocates the remaining export share to all regions (including its own) according to the 6 regional natural gas import shares. The state-owned company's own region is double counted because the company may be exporting to another country in its own region.

Our data includes all acquisitions made by the top 50 firms, even if the firm being acquired by a top 50 firm was itself not among the top 50 firms. In addition, during the time period of our data set, any top 50 firms that were acquired were only ever acquired by other top 50 firms. We therefore observe and model all acquisition activity of the top 50 firms, even if the acquiree was not a top 50 firm.

During the time period of our data set, there were 3 mergers among the top 50 firms. Conoco and Phillips merge in 2000 to become ConocoPhillips. Exxon and Mobil merge in 1998 to become ExxonMobil. Sidanco and Tyumen Oil merge in 2002, after which they drop out of the top 50 firms.

While we do not observe and therefore do not explicitly model mergers between a top 50 firm and a firm that is not among the top 50 firms, we do observe and model the resulting effects of these unobserved mergers on the state variables (including reserves) and actions of the top 50 firm involved in the merger. In particular, unobserved mergers with non-top 50 firms are captured by the error terms in our policy functions and transition densities, and their effects on state variables and actions are therefore accounted for in our model. Although mergers with a firm that is not among the top 50 firms are not directly included in our per-period payoff function, but only indirectly through their effects on state variables and actions, this is justified by our assumption that, conditional on the state variables and actions we do observe, the expected value of the opportunity to merge with a non-top 50 firm is negligible relative to the other terms we include in the per-period payoff function, as the expected value of non-top 50 firms is smaller than those of top 50 firms, and, when weighted by the probability of merging with a non-top 50 firm, is even smaller still.

Summary statistics for the action variables, firm-level state variables, and price variables over the years 2000-2005 are presented in Tables 2.1 to 2.3; summary statistics for the same variables over the entire period of the data set are in Tables 2.12 to 2.14 in Appendix A. Summary statistics for the regional and global state variables are in Table 2.4.

2.5 Results

2.5.1 Oil demand

We use annual oil production data of the top 50 producers over the period 1987-2011 along with oil price data to estimate the oil demand equation (2.2).

Because observed equilibrium prices and quantities are simultaneously determined in the supply-and-demand system, instrumental variables are needed to address the endogeneity problem (Manski, 1995; Goldberger, 1991; Angrist et al., 2000; Lin, 2011b). We instrument for oil price using either real average weekly earnings for support activities in oil and gas extraction or lagged real average weekly earnings for support activities in oil and gas extraction. These variables are supply shifters that affect the costs of producing oil but not the demand for oil, and therefore serve as good instruments for oil price. The first-stage F-statistics are over 12 in both specifications of oil demand, and the instruments pass tests of underidentification and weak-instrument-robust inference.

Estimation results for oil demand are reported in Table 2.15 in Appendix A. The coefficient on crude oil price is significant and negative in both specifications of the model, which makes sense as it indicates a downward sloping demand curve for crude oil. Demand for oil is increasing with world GDP per capita, which has a significant coefficient in both specifications of the model.[3]

Our estimated price elasticity of oil demand ranges from -0.18 to -0.32, which is in the range of previous estimates of price elasticity of oil demand in the literature. For example, Cooper (2003) estimates that the long-run price elasticity of oil demand falls within the range -0.18 to -0.45 for the G7 group of countries: Canada, France, Germany, Italy, Japan, the United Kingdom, and the United States. As expected, since we estimate the price elasticity for the residual demand for oil sold by the top 50 producers, our estimated price elasticity of this residual oil demand is more elastic than global demand. For example, Caldara et al. (2018) derive VAR-consistent elasticities of of -0.14 for global oil demand.

We use specification (2) for our structural model, since using the lagged real average weekly earnings for support activities in oil and gas extraction as an instrument may more convincingly satisfy the exclusion restriction, since the realized oil price and oil market in one year is unlikely to have had an effect on real average weekly earnings for support activities in oil and gas extraction in the previous year.

2.5.2 Regional natural gas demand

Unlike the global market for oil, natural gas markets are more regional due to lack of a global natural gas pipeline networks and natural gas prices change regionally. We estimate regional natural gas demand functions for 6 regions: Africa; Asia and Oceania; Eurasia; Europe; the Middle East; and the Americas. We use data on regional natural gas prices and quantity along with regional GDP and population to estimate the regional natural gas demand equation (2.3) for each region.

We instrument for natural gas prices using average capital compensation and lagged real aver-

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[3] When included, natural gas prices do not have any significant effect on oil demand. Thus, because we are limited in the number of regressors we can include owing to our small sample size, we do not include natural gas prices in our specification of oil demand.

age weekly earnings for oil and gas extraction as well as support activities in oil and gas extraction, and total natural gas reserves. These variables are supply shifters that affect the costs of producing natural gas but not demand for natural gas, and therefore serve as good instruments for natural gas price.

Tables 2.16- 2.21 in Appendix A report the estimated results for regional natural gas demand for each region respectively. The first-stage F-statistics as well as the p-values for underidentification, weak-instrument-robust inference, and overidentification tests are also reported. The specifications used in our structural model are indicated with a dagger (†).

While regional natural gas demand is weakly downward sloping for each region, there is variation in the demand parameters across regions, which provides support for our estimating separate regional natural gas demand functions for each of the 6 regions. As seen in the first column of Table 2.18, the coefficient for natural gas price is negative and significant for the Eurasian natural gas market. The coefficient on regional GDP is also positive and significant for all regions.

The weak instrument robust inference tests test whether the coefficient on price (the endogenous regressor) is significant. The null hypothesis tested is that the coefficient on price in the structural equation is equal to zero, and, in addition, that the overidentifying restrictions are valid. Thus, when we pass both the weak instrument robust inference test (p-value ≤ 0.05) and the overidentification test (p-value > 0.05), as is the case with Eurasia, the Middle East, and the Americas, the coefficient on price is significant.[4]

Taken together, our results show a significant negative elasticity of demand for regional natural gas in Eurasia, the Middle East, and the Americas.

2.5.3 Policy functions

Each period, each petroleum producer decides how much oil and natural gas to produce and how much to spend on each type of capital expenditure. Using our panel data on the top 50 petroleum

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[4] When included, oil price does not have any significant effect on natural gas demand. Thus, because we are limited in the number of regressors we can include owing to our small sample size, we do not include oil price in our specifications of regional natural gas demand.

producers, we estimate policy functions for these decision variables which correlate actions to states. We include dummies for having merged or acquired in the previous year as regressors to capture any synergies or returns to scale in production and/or investment resulting from mergers and acquisitions. The estimation results are reported in Table 2.22 in Appendix A.

Although the mission of OPEC is to ‘coordinate and unify the petroleum policies of its Member Countries’ (Organization of Petroleum Exporting Countries [OPEC], 2017), it is unclear whether OPEC behaves as a cartel (Baumeister and Kilian, 2016, 2017; Lin Lawell, 2019; Parnes, 2018). Thus, rather than assume or impose that OPEC producers collude to maximize joint profits, we instead allow the strategies and payoffs for OPEC and non-OPEC firms to differ, and infer the strategy and payoffs for OPEC firms from the data. Thus, since OPEC firms may have different production policies from non-OPEC firms, we estimate the oil and natural gas production policy functions for OPEC firms separately; these results are reported in Table 2.23 in Appendix A.

Comparing the oil production policy functions for non-OPEC firms in Table 2.22 in Appendix A with those for OPEC firms in Table 2.23 in Appendix A, we find that the magnitude of the coefficient on oil reserves is smaller for OPEC firms than for non-OPEC firms, while the magnitude of the coefficient on cumulative oil output is larger for OPEC firms than for non-OPEC firms. Thus, oil reserves has a smaller marginal correlation with oil production for OPEC firms than for non-OPEC firms, while cumulative oil output has a larger marginal correlation with oil production for OPEC firms than for non-OPEC firms. This suggests that the oil production strategy for OPEC firms depends less on oil reserves and more on cumulative (or historical) oil output than does the oil production strategy for non-OPEC firms.

In addition to production and investment, each firm also decides whether to acquire another firm or be acquired by another firm, and whether to merge with another firm. In order to estimate the policy function for merger and acquisition decisions, we define a merger and acquisition action variable which takes the value of 1 for merger, 2 when a firm acquires another firm, and 0 otherwise. We use a multinomial logit regression model to estimate this policy function. Since OPEC firms and firms that are 100% state-owned never merge or acquire, we exclude these firms from the estimation. Estimation results for policy function on merger and acquisition are reported in Table 2.24 in Appendix A. We use specification (4) in the structural estimation.

For firms that do not merge or acquire, these firms may choose to be acquired by another firm. We use a logit regression model to estimate this policy function, once again excluding OPEC firms and firms that are 100% state-owned, since they are never acquired by others, and also excluding firms that merge or acquire. Estimation results for policy function for being acquired are reported in Table 2.25 in Appendix A. We use specification (2) in the structural estimation.

2.5.4 Transition densities

The firm-specific state variables for whether the firm merged in the previous year, and for whether the firm acquired another firm in the previous year evolve deterministically as a function of the firm's merger and acquisition decisions in the previous year. The transition densities for each of the remaining state variables are stochastic, and depend on the lagged value of that state variable and also potentially on the lags of other state variables and lagged actions.

We estimate the transition densities for firm-level oil reserves and natural gas reserves by regressing reserves on lagged reserves, lagged output, lagged capital expenditures in exploration, lagged capital expenditures in development, lagged percent state ownership, lagged dummy for merger, and lagged dummy for acquisition, all at the firm level. Similarly we estimate a transition density for percentage of state ownership. The results are presented in Table 2.26 in Appendix A.

In our transition densities for oil and natural gas reserves, we do not assume any fixed finite amount for the reserves. This is consistent with the common practice in the natural resource economics literature of modeling potential reserves as infinite; potential reserves are probably infinite, although the amount that is economical to extract is finite, and technological progress and new discoveries will always make more reserves available and feasible for extraction (Farzin, 1992; Lin, 2009b). Thus, for the transition densities for oil and natural gas reserves, we regress reserves on lagged reserves, lagged output, lagged exploration capital expenditure, lagged development capital expenditure, lagged percent state ownership, lagged dummy for merger, and lagged dummy for acquisition, and we let the data tell us what the transition density is. Our econometric model allows for reserves to increase or decrease over time.

The results for the transition density for world population, which depends on lagged world population, are presented in Table 2.27. The results for the transition density for world GDP per capita, which depends on lagged world GDP per capita, are presented in Table 2.28 in Appendix A.

The results for the transition density for regional population, which depends on lagged regional population, for each of the 6 regions of the world are presented in Table 2.29. The results for the transition density for regional GDP, which depends on lagged regional GDP, for each of the 6 regions of the world are presented in Table 2.30 in Appendix A.

The transition densities for average industry rate of return on capital, average capital compensation on other machinery and equipment, average capital compensation on total non-residential investment, world road sector gasoline fuel consumption, world motor vehicles, world electricity production from natural gas sources, and world road sector gasoline from oil sources are in Tables 2.31 to 2.37, respectively, in Appendix A. For each of these state variables, we regress the state variable on the lagged value of the state variable, as well as on the lagged values of other relevant state variables and lagged values of aggregate reserves and aggregate production variables. In some cases, relevant state variables were dropped due to collinearity.

The lagged values of aggregate reserves and aggregate production are significant in most transition densities, which means that the investment and production decisions of other firms affect the future values of state variables that affect a firm's future payoff from producing and investing, and therefore that firms must anticipate the production and investment strategies of other firms in order to make a dynamically optimal decision. There is thus an important strategic component in firms' production and investment decisions.

2.5.5 Structural parameters

The structural parameters θ we estimate include the parameters in the per-period payoff function, and the distributions of the fixed payoffs to merging, acquiring, and being acquired. We set the discount factor β to 0.9.

Our estimates of the parameters in the per-period payoff function are presented in Table 2.5. Our estimated parameters in the per-period payoff function show that there are nonlinearities with respect to both output and reserves in the production profit function. Thus, oil and natural gas production may exhibit increasing or decreasing returns to scale, or both. As a consequence, firms may benefit from changing their scale via mergers and acquisitions.

The coefficient δ_5 in oil and natural gas production cost on the interaction between oil and natural gas output is significant and negative, which is evidence of cost synergies between oil and natural gas production, which may include joint production and other supply-side links in oil and gas (Roberts and Gilbert, 2018).

Both the percentage of state ownership and being an OPEC member have a significant positive effect on the per-period payoff. While our model allows firms that are at least partially state-owned to have different objectives from private firms, we find that state-owned firms do not put any weight on consumer surplus, as we estimate ρ_{CS} to be a precise zero.

Our estimates of the distribution of fixed payoffs to merger and acquisition are presented in Table 2.6. The fixed benefits from being acquired, the fixed costs of acquiring another firm, and the fixed costs of merging each have a significant and positive mean, but a large significant standard deviation as well. Thus, the idiosyncratic fixed payoffs to merger and acquisition vary greatly by firm and year.

Welfare statistics, including firm payoffs for all firms, OPEC firms, and non-OPEC firms; and consumer surplus are presented in Table 2.38 in Appendix A. The expected firm payoff is significant and positive on average, but can be negative for some firms in some years. Expected total consumer surplus is several orders of magnitude larger than expected total firm payoff.

2.5.6 Model validation

To assess the goodness of fit of our structural econometric model, we compare the actual values of the action variables observed in the data with the action variables predicted by our structural econometric model for the period 2000-2005. Summary statistics of the actual values of the action variables observed in the data over the period 2000-2005 are presented in Table 2.1. Summary statistics of the action variables predicted by our structural econometric model for the period 2000-2005 are presented in Table 2.39 in Appendix A. When comparing the summary statistics of the actual and model predicted action variables, it appears that our structural econometric model does a fairly good job matching the actual data.

Our econometric estimation entails finding the parameters θ that minimize any profitable deviations from the optimal strategy as given by the estimated policy functions. Table 2.40 in Appendix A presents each firm's probability of having an economically significant profitable deviation from their estimated optimal strategy under our estimated structural parameters. We define and calculate a firm's probability of having an economically significant profitable deviation as the fraction of alternative strategies simulated that would yield a payoff, as evaluated using our estimated structural parameters, more than one billion dollars per year higher than would the optimal strategy as given by our estimated policy functions. One billion dollars per year is roughly 7% of the expected maximum firm payoff.

There are 65 firms that appear in the top 50 oil and natural gas producing companies for at least 1 year over the period 2000 to 2005. As seen in Table 2.40 in Appendix A, most of the firms do not have any economically significant profitable deviations from their estimated optimal strategy under our estimated parameters, which suggests that our parsimonious model does a fairly good job explaining the behavior of these firms. The probability of having an economically significant profitable deviation is statistically significant at a 5% level and greater than 0.1 for only a few firms: Chevron, ExxonMobil, Gazprom, and the Iraq National Oil Company (INOC).

To examine how a firm's probability of having an economically significant profitable deviation relates to observable firm characteristics, we analyze the firm-level determinants of any statistically significant non-zero probability of having an economically significant profitable deviation. To do so, we regress the probabilities of having an economically significant profitable deviation that are significant at a 5% level on whether the firm is an OPEC member, its state ownership, its initial oil reserves, and its initial natural gas reserves. In this regression, the value of the dependent variable is zero for firms whose probability of an economically significant profitable deviation is not significant at a 5% level. As seen in Table 2.41 in Appendix A, a firm's probability of having an economically significant profitable deviation is positively correlated with the firm's natural gas reserves. Thus, our model does not perfectly explain the behavior of firms with large natural gas reserves, and therefore may better explain the world oil market than natural gas markets. In future work we hope to better incorporate and model additional complexities of the natural gas industry, and to obtain more recent data to enable us to include shale as well.

Our measure of profitable deviations might be a conservative upper bound, since some of the alternative strategies that we find to yield profitable deviations for a firm might not actually be feasible for the firm, for example owing to capital or liquidity constraints that we do not observe, assume, impose, or explicitly model.[5] Thus, our parsimonious model appears to do a fairly heroic and remarkable job of modeling the notoriously complex world petroleum market.

2.6 Counterfactual Simulations

We use the estimated parameters from our structural econometric model to run counterfactural simulations to analyze the effects of changes in OPEC membership, a ban on mergers, the privatization of state-owned oil companies, and demand shocks on the petroleum industry over the period 2000-2005. For each counterfactual scenario, we compare the production, investment, mergers and acquisitions, firm payoffs, and consumer surplus under that counterfactual scenario with those un-

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[5] The alternative strategies $\tilde{\sigma}_i(s)$ we simulate are pertubations to the optimal strategy $\sigma_i^*(s)$ that shift the estimated production or investment policy function upwards or downwards by up to two times the observed standard deviation of the respective production or investment action variable in the data; and that shift the estimated policy functions for the merger and acquisition probabilities upwards or downwards by up to 0.20. Not all of these alternative strategies might actually be feasible for a firm. It may not be feasible, for example, for some firms to increase their oil production by two times the standard deviation of oil production over all top 50 firms. Similarly, as another example, it may not be feasible for some firms to increase their exploration capital expenditure by two times the standard deviation of exploration capital expenditure over all top 50 firms .

der the base-case status quo simulation of no counterfactual change using two-sample t-tests.

There are several channels through which each counterfactual change may affect firm payoffs, consumer surplus, and welfare. First, the counterfactual change (e.g., in OPEC membership) may affect firm payoffs directly. Second, the counterfactual change may affect production, investment, and merger and acquisition decisions which affect firm payoffs and consumer surplus. Third, changes in actions and/or state variables resulting from the counterfactual change may affect future values of the state variables, which may affect future actions and/or welfare. Our estimates of the changes in firm payoffs, consumer surplus, and welfare that arise in each counterfactual simulation capture all channels through which the counterfactual scenario may affect firm payoffs, consumer surplus, and welfare.

In analyzing the short-run effects of the counterfactual scenarios, we assume that the counterfactual changes we simulate are ones that firms and consumers neither anticipate nor expect to be permanent; and that the counterfactual scenario does not change which equilibrium is played. We therefore assume that the oil and natural gas demand functions, policy functions, transition densities of unaffected state variables, and structural parameters we estimate themselves do not change under the different counterfactual scenarios.

2.6.1 OPEC membership scenarios

We simulate a counterfactual OPEC membership scenario in which all firms are members of OPEC.

When simulating the effects of counterfactual changes in OPEC membership, we assume that the oil and natural gas demand functions; the policy functions for OPEC and non-OPEC firms as a function of state variables; the evolution of state variables as a function of lagged state variables and lagged actions; and parameters in the per-period payoff function for OPEC and non-OPEC do not change when OPEC membership changes, but instead that what changes is whether a particular firm is an OPEC firm or not, and therefore whether the appropriate policy function that governs a particular firm's decision-making is that for an OPEC or non-OPEC firm, and whether the appropriate per-period payoff is that for an OPEC or non-OPEC firm.

Table 2.7 presents results of two-sample t-tests comparing the welfare from the counterfactual OPEC membership scenario to the welfare from the base-case status quo simulation. Table 2.8 presents results of two-sample t-tests comparing each of the action variables (output, investment, and mergers and acquisitions) from the counterfactual OPEC membership scenario to the action variables from the base-case status quo simulation.

According to the results, including all firms in OPEC causes firms to decrease oil production, leading to increases in the average firm payoff, increases in oil prices, and decreases in consumer surplus.

Our result that including all firms in OPEC increases average firm payoff is consistent with OPEC's mission to 'coordinate and unify the petroleum policies of its Member Countries and ensure the stabilization of oil markets in order to secure an efficient, economic and regular supply of petroleum to consumers, a steady income to producers and a fair return on capital for those investing in the petroleum industry' (Organization of Petroleum Exporting Countries [OPEC], 2017).

Our result that including all firms in OPEC causes firms to decrease oil production, leading to increases in the average firm payoff, increases in oil prices, and decreases in consumer surplus is also consistent with the assessment of the U.S. Energy Information Administration (2018b) that 'Crude oil production by the Organization of the Petroleum Exporting Countries (OPEC) is an important factor that affects oil prices. This organization seeks to actively manage oil production in its member countries by setting production targets. Historically, crude oil prices have seen increases in times when OPEC production targets are reduced. OPEC member countries produce about 40 percent of the world's crude oil. Equally important to global prices, OPEC's oil exports represent about 60 percent of the total petroleum traded internationally. Because of this market share, OPEC's actions can, and do, influence international oil prices.'

2.6.2 Ban on mergers

We also simulate a counterfactual scenario in which mergers between top 50 firms are banned.[6]

When simulating the effects of a counterfactual merger ban, we assume that the oil and natural gas demand functions; the policy functions for production, investment, and acquisitions as functions of state variables, which include lagged merger and acquisition decisions; the transition densities for state variables as functions of lagged state variables and lagged actions, which include lagged merger and acquisition decisions; and the parameters in the per-period payoff function do not change as a result of the counterfactual merger ban. We therefore interpret this merger ban as a ban on mergers that firms neither anticipate nor expect to be permanent.

Table 2.9 presents results of two-sample t-tests comparing the welfare from the merger ban scenario to the welfare from the base-case status quo simulation. Table 2.10 presents results of two-sample t-tests comparing each of the action variables (output, investment, and mergers and acquisitions) from the merger ban scenario to the action variables from the base-case status quo simulation.

According to the results, banning mergers would decrease oil and natural gas output, decrease investment, increase acquisitions, decrease average firm payoff for both OPEC and non-OPEC firms, and decrease consumer surplus. We also find that the negative effect of a merger ban on average firm payoff is more severe for non-OPEC firms than for OPEC firms, in both absolute and percentage change terms.

The result that banning mergers has a larger negative effect on non-OPEC firms than on OPEC firms is likely because OPEC firms do not engage in mergers; thus, banning mergers by non-OPEC firms imposes a constraint on non-OPEC firm decision-making that has a larger negative effect on non-OPEC firms.

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[6] As we do not observe and therefore do not explicitly model mergers between a top 50 firm and a firm that is not among the top 50 firms, we are unable to run a counterfactual simulation banning mergers between a top 50 firm and a firm that is not among the top 50 firms. Unobserved mergers with non-top 50 firms are captured in our structural model by the error terms in our policy functions and transition densities.

2.6.3 Privatization scenarios

We simulate three counterfactual privatization scenarios. In the first privatization scenario, we simulate all firms having 0% state ownership (i.e., all firms privatized). In the second privatization scenario, we simulate all firms as being 50% state-owned. In the third privatization scenario, we simulate all firms being 100% state-owned.

When simulating counterfactual privatization scenarios, we assume that the oil and natural gas demand functions; the policy functions for firms that are 100% state-owned and firms less than 100% state-owned as a function of state variables; the evolution of state variables as a function of lagged state variables and lagged actions; and parameters in the per-period payoff function for state-owned and non-state-owned firms do not change when state ownership changes, but instead that what changes is the firm's state ownership, and therefore whether the appropriate policy function that governs a particular firm's decision-making is that for firm that is 100% state-owned or not, and whether the appropriate per-period payoff is that for a state-owned and non-state-owned firm.

Table 2.11 presents results of two-sample t-tests comparing the welfare from the privatization scenarios to the welfare from the base-case status quo simulation.

According to the results, privatizing all firms decreases average firm payoff for both OPEC and non-OPEC firms. Since the percentage of state ownership has a significant positive effect on a firm's per-period payoff, privatizing all firms decreases the average firm payoff.

Making all firms 50% state-owned decreases average firm payoff for OPEC firms and increases average firm payoff for non-OPEC firms. Since the percentage of state ownership has a significant positive effect on a firm's per-period payoff, decreasing the percentage state ownership of OPEC firms from 100% to 50% decreases the average firm payoff for OPEC firms. In contrast, since the average state ownership of non-OPEC firms in our data set is 36.69%, making all firms 50% state-owned increases the average state ownership of non-OPEC firms in our data set, thus increasing average firm payoff for non-OPEC firms.

Making all firms 100% state-owned increases has no significant effect on the average firm payoff for OPEC firms, but increases the average firm payoff for non-OPEC firms. Since OPEC firms are already all 100% state-owned, making all firms 100% state-owned does not change the percentage state ownership of OPEC firms. Since the percentage of state ownership has a significant positive effect on a firm's per-period payoff, increasing the percentage state ownership of all non-OPEC firms to 100% increases the average firm payoff for non-OPEC firms.

2.6.4 Demand shock

We also simulate counterfactual shocks to oil demand and natural gas demand. For example, demand shocks may arise due to disruptive technologies, such as shale oil and gas and new batteries for electric vehicles. We specify these shocks as shocks that change the constant in the oil and natural gas demand functions.

In the counterfactual demand shock simulations, we evaluate the short-run effects of shocks to demand that neither firms nor consumers anticipate nor expect to be permanent. We assume that the oil and natural gas demand functions, policy functions, transition densities of unaffected state variables, and structural parameters we estimate themselves do not change under the demand shock.

In the first counterfactual scenario, the constant in oil demand decreases by 10% and the constant in regional natural gas demand decreases by 10% for each region. In the second counterfactual scenario, the constant in oil demand decreases by 25% and the constant in regional natural gas demand decreases by 25% for each region. In the third counterfactual scenario, the constant in oil demand decreases by 10%. In the fourth counterfactual scenario, the constant in oil demand decreases by 25%.

We also simulate a set of counterfactual scenarios, one for each region, in which the constant in regional natural gas demand decreases by 25% for that region only; and another set of counterfactual scenarios, one for each region, in which the constant in regional natural gas demand increases by 25% for that region only.

Tables 2.42-2.44 in Appendix B present results of two-sample t-tests comparing the welfare from the demand shock scenarios to the welfare from the base-case status quo simulation.

According to the results, whether they increase or decrease demand, shocks to oil and/or natural gas demand may increase or decrease firm payoffs, and tend to decrease consumer surplus, at least in the short run.

2.7 Discussion and Conclusions

In this paper, we develop and estimate a structural econometric model of the dynamic game among petroleum-producing firms to analyze the effects of economic factors, strategic factors, and government policy on the world petroleum market. Our parsimonious model does a fairly heroic and remarkable job of modeling the notoriously complex world petroleum market and generating results that align with economic theory and/or previous assessments – anecdotal, qualitative, empirical, or otherwise – of the industry.

According to the results of our structural econometric model, oil and natural gas production may exhibit increasing or decreasing returns to scale, or both. As a consequence, firms may benefit from changing their scale via mergers and acquisitions. In addition, we find evidence of cost synergies between oil and natural gas production, which may include joint production and other supply-side links in oil and gas (Roberts and Gilbert, 2018).

We also find that both the percentage of state ownership and being an OPEC member have a significant positive effect on the per-period payoff. However, while our model allows firms that are at least partially state-owned to have different objectives from private firms, we find that state-owned firms do not put any weight on consumer surplus.

We use the estimated parameters from our structural econometric model to run counterfactual simulations to analyze the effects of changes in OPEC membership, a ban on mergers, the privatization of state-owned oil companies, and demand shocks on the petroleum industry.

Although the mission of OPEC is to ‘coordinate and unify the petroleum policies of its Member Countries’ (Organization of Petroleum Exporting Countries [OPEC], 2017), it is unclear whether OPEC behaves as a cartel (Baumeister and Kilian, 2016, 2017; Lin Lawell, 2019; Parnes, 2018).

Thus, rather than assume or impose that OPEC producers collude to maximize joint profits, we instead allow the strategies and payoffs for OPEC and non-OPEC firms to differ, and infer the strategy and payoffs for OPEC firms from the data. In particular, we estimate the oil and natural gas policy functions for OPEC firms and non-OPEC firms separately, and we include a dummy variable $O_{i,OPEC}$ for whether firm i is an OPEC member in the per-period payoff function.

Our results for the oil production policy functions for OPEC and non-OPEC firms suggest that the oil production strategy for OPEC firms depends less on oil reserves and more on cumulative (or historical) oil output than does the oil production strategy for non-OPEC firms. While we do not assume or impose that OPEC producers collude to maximize joint profits, nor do we explicitly model any particular repeated game strategy, trigger strategy, or other strategy that might support collusion, our result that the oil production policy function for OPEC firms depends more on cumulative (or historical) oil output than does the oil production strategy for non-OPEC firms is possibly consistent with a repeated game strategy that depends on a long history of play. By allowing the Markov state-space strategy of OPEC firms to depend on aggregated and cumulative measures of historical play, our model may capture and therefore allow for the reduced-form implications of a number of repeated game strategies, trigger strategies, or other strategies that might support collusion (Fudenberg and Tirole, 1998; Maskin and Tirole, 2001; Doraszelski and Escobar, 2010). We hope to allow for more complicated repeated game strategies, trigger strategies, or other strategies that might support collusion, including tit-for-tat strategies whose reduced-form implications may not be fully captured by a Markov state-space strategy that depends on aggregated and cumulative measures of historical play rather than the entire history of past play, and to develop techniques for estimating dynamic games that allow for such strategies, in future work.

Our estimated structural parameters show that being an OPEC member has a significant positive effect on the per-period payoff. While we remain agnostic in this paper as to what this dummy variable for being an OPEC member represents in the per-period payoff, it is possible that what is captured in this significant positive effect may include some measure of the joint per-period payoffs to OPEC firms and/or some measure of transfers or benefits from joint profit maximization among OPEC firms.

According to the results from our counterfactual OPEC membership scenario, including all firms in OPEC increases the average firm payoff. This result is consistent with OPEC's mission to 'coordinate and unify the petroleum policies of its Member Countries and ensure ... a steady income to producers' (Organization of Petroleum Exporting Countries [OPEC], 2017). Our result that including all firms in OPEC causes firms to decrease oil production, leading to increases in the average firm payoff, increases in oil prices, and decreases in consumer surplus is also consistent with the assessment of the U.S. Energy Information Administration (2018b) that OPEC 'seeks to actively manage oil production in its member countries by setting production targets' and that 'Historically, crude oil prices have seen increases in times when OPEC production targets are reduced.'

Thus, although it is unclear whether OPEC behaves as a cartel (Baumeister and Kilian, 2016, 2017; Lin Lawell, 2019; Parnes, 2018), and even though we do not assume or impose that OPEC producers collude to maximize joint profits, but instead infer the strategy and payoffs for OPEC firms from the data, we find that OPEC behaves in such a way that is consistent with its mission to increase the average firm payoff of its member countries, and that is also consistent with cartel behavior of decreasing oil production in order to increase oil price. It is important to note that we generated outcomes for production, firm payoffs, oil prices, and consumer surplus that were consistent with cartel behavior without assuming joint profit maximization, but rather with a dummy variable for being an OPEC member in the per-period payoff function and with policy functions that differed between OPEC and non-OPEC firms. Thus, while our results may be consistent with cartel behavior, they may also be consistent with alternative non-collusive stories for why the strategies and payoffs for OPEC and non-OPEC firms differ and may lead to outcomes that are beneficial to OPEC firms, harmful to consumers, and consistent with cartel behavior.

According to the results from our counterfactual merger ban scenario, a ban on mergers would decrease average firm payoff for both OPEC and non-OPEC firms, and also decrease consumer surplus. This is consistent with theoretical predictions that mergers in nonrenewable resource oligopolies can be profitable (Benchekroun et al., 2019). We find that banning mergers has a larger negative effect on non-OPEC firms than on OPEC firms, likely because OPEC firms do not engage in mergers, so banning mergers by non-OPEC firms imposes a constraint on non-OPEC firm decision-making that has a larger negative effect on non-OPEC firms.

According to the results from our counterfactual privatization scenarios, privatizing all firms decreases the average firm payoff for both OPEC and non-OPEC firms. Making all firms 50% state-owned decreases the average firm payoff for OPEC firms, but increases the average firm payoff for non-OPEC firms. Making all firms 100% state-owned has no significant effect on the average firm payoff for OPEC firms, but increases the average firm payoff for non-OPEC firms. The intuition for our privatization results is as follows: since the percentage of state ownership has a significant positive effect on a firm's per-period payoff, increasing the percentage state ownership increases the average firm payoff.

We also find that, whether they increase or decrease demand, shocks to oil and/or natural gas demand may increase or decrease firm payoffs, and tend to decrease consumer surplus. Thus, while shocks to oil and/or natural gas demand may or may not benefit firms, they tend to have adverse effects on consumers, at least in the short run. We hope to further analyze the effects of demand shocks on the world petroleum market in future work.

There are several potential avenues for future work that we hope to pursue. First, as mentioned, we hope to further analyze the effects of demand shocks on the world petroleum market in future work. Second, in future work we hope to obtain international data on annual firm-level crude oil and natural gas storage to enable us to analyze the role of crude oil and natural gas storage on price dynamics, including the possible role of crude and natural gas storage as a buffer to demand shocks (Williams and Wright, 1991). Third, we hope in future work to complement our analysis of mergers and acquisitions by further analyzing other forms of cooperation between firms, including production sharing or service-type contracts between state-owned oil companies and international oil companies (Ghandi and Lin, 2012, 2014; Ghandi and Lin Lawell, 2019). Fourth, as we found that firms that are at least partially state-owned do not put any weight on consumer surplus, we hope to further analyze other alternative objectives for state-owned firms, as well as alternative means of calculating the consumer surplus for the set of consumers each state-owned firm may care about, in future work.

Fifth, in future work we hope to further analyze the strategies and behavior of OPEC and OPEC firms. For example, as mentioned, we hope in future work to develop techniques for estimating dynamic games to allow for more complicated repeated game strategies, trigger strategies, or other strategies that might support collusion, including tit-for-tat strategies whose reduced-form implications may not be fully captured by a Markov state-space strategy that depends on aggregated and cumulative measures of historical play rather than the entire history of past play. Sixth, in future work we hope to incorporate and model additional complexities of the natural gas industry, and to obtain more recent data to enable us to include shale gas and shale oil as well. Seventh, in future work we hope to develop techniques for analyzing counterfactual scenarios that might change the equilibrium being played. Eighth, in future work we hope to further model additional complexities of mergers and acquisitions, building on the stochastically alternating-move game of dynamic oligopoly of mergers the hard disk drive industry developed by Igami and Uetake (2019).

Last but not least, in future work we hope to extend our model to incorporate environmental externalities arising from oil and natural gas production and consumption, which would then enable us to simulate and analyze sophisticated counterfactual scenarios regarding global environmental policy, and subsequently to design environmental policies that maximize net benefits to society, and that best benefit both firms and consumers with minimal adverse distributional consequences.

2.8 Figures and Tables

Table 2.1: Summary statistics for action variables (2000-2005)

Variable	# Obs	Mean	Std. Dev.	Min	Max
Oil output (KBD)	300	1214.441	1466.5487	11	11035
Natural gas output (MCFD)	300	3445.546	7242.888	44	53135
Exploration capex (million 2005 US$)	94	595.9822	453.5993	-13.232	1828.14
Development capex (million 2005 US$)	94	2640.832	2268.744	0	9045
Acquisition capex (million 2005 US$)	93	1133.271	2651.709	-142.899	17625
Dummy for M&A at time t					
merging with another firm	300	0.0133	0.1149	0	1
acquiring another firm	300	0.0233	0.1512	0	1
being acquired by another firm	300	0.0167	0.1282	0	1
OPEC firms' production only					
Oil output (KBD)	67	2445.269	2324.396	135	11035
Natural gas output (MCFD)	67	3419.313	2687.751	112	8485
Non-OPEC firms' production only					
Oil output (KBD)	233	860.5119	819.4949	11	3754
Natural gas output (MCFD)	233	3453.09	8096.542	44	53135

Table 2.2: Summary statistics for firm level state variables (2000-2005)

Variable	# Obs	Mean	Std. Dev.	Min	Max
OPEC membership at time t (dummy)	300	0.2233	0.4171	0	1
State ownership (in percentage)	300	48.48641	45.74817	0	100
Oil reserves (million barrels)	300	19820.82	44090.61	50	264200
Natural gas reserves (BCF)	300	85529.82	207369.9	420	1320000

Table 2.3: Summary statistics for prices of oil and natural gas (2000-2005)

Variable	# Obs	Mean	Std. Dev.	Min	Max
Crude oil price, Brent (2005 US$/bbl)	6	35.98517	9.791585	28.7883	54.4341
Natural gas price, US (2005 US$/mmbtu)	6	5.756597	1.755797	3.97939	8.91567
Regional natural gas price (2005 US$/mmbtu)					
Africa	5	5.643	2.4304	3.3171	9.679
Asia & Oceania	5	9.7815	1.4431	8.2034	11.764
Eurasia	5	0.9509	0.2714	0.7106	1.3715
Europe	5	7.1918	1.8749	5.1571	9.7842
Middle East	5	6.263	1.0773	5.3768	8.1295
America	5	5.8928	1.8119	3.9221	8.5541

Table 2.4: Summary statistics for regional and global state variables

Variable	# Obs	Mean	Std. Dev.	Min	Max
Avg capital compensation (million 2005 US$)					
on transport equipment	24	132.322	57.204	21.891	243.422
on other machinery and equipment	24	2086.081	870.891	415.203	4141.958
on total non-residential investment	24	4078.227	2371.123	847.457	10639.06
Average industry rate of return on capital	24	0.144	0.04	0.08	0.232
World GDP per capita (2005 US$)	25	6475.482	691.679	5456.522	7642.35
World population (million people)	25	5970.799	575.621	4985.892	6942.765
World electricity production (kWh)					
from oil sources	25	1.04e+12	1.02e+11	8.08e+11	1.19e+12
from natural gas sources	25	2.71e+12	1.17e+12	8.28e+11	4.85e+12
World road sector gasoline					
fuel consumption (kt of oil equivalent)	18	827537.6	50057.57	730584	898004
World motor vehicles (per 1,000 people)	10	156.73	11.225	142.4	180.18
Average weekly earnings (2005 US$)					
for oil and gas extraction	25	892.2796	65.31246	803.238	1023.57
for supporting activities in oil and gas	22	789.4748	92.58307	681.1732	978.1636
Regional GDP (trillion 2005 US$)					
Africa	25	0.817	0.507	0.408	2.13
Asia and Oceania	25	9.19	4.3	3.81	20.7
Eurasia	25	0.871	0.691	0.0722	2.6
Europe	25	11.9	4.68	5.59	20.8
Middle East	25	0.885	0.622	0.304	2.52
Americas	25	13.3	5.15	6.1	23.2
Regional population (million people)					
Africa	25	797	144	578	1050

Table 2.4: (continued)

Variable	# Obs	Mean	Std. Dev.	Min	Max
Asia and Oceania	25	3340	321	2780	3820
Eurasia	25	287	2.548955	281	291
Europe	25	574	18.6	540	604
Middle East	25	168	30.2	120	221
Americas	25	823	80.3	689	948

Table 2.5: Estimated parameters in per-period payoff function

Description		Estimated parameters
Coefficient in oil production cost on:		
Oil production (KBD*1e-4)	δ_{11}	-20.0970 ***
		(1.1779)
Oil production squared	δ_{12}	-0.1591 ***
		(0.0093)
Oil reserves (bbl)	δ_{13}	1.1744 ***
		(0.0688)
Oil production × Oil reserves	δ_{14}	-0.7277 ***
		(0.0426)
Coefficient in natural gas production cost on:		
NG production (MCF*1e-4)	δ_{21}	0.0200 ***
		(0.0012)
NG production squared	δ_{22}	-0.0140 ***
		(0.0008)
NG reserves (KCF)	δ_{23}	-0.2700 ***
		(0.0158)
NG production × NG reserves	δ_{24}	-0.0772 ***
		(0.0045)
Coefficient in oil and natural gas production cost on:		
Oil production × NG production	δ_5	-11.4587 ***
		(0.6716)
Coefficient in per-period payoff on:		
Percentage of state ownership	ω_1	0.3787 ***
		(0.0222)
OPEC member (dummy)	ω_2	2.8945 ***
		(0.1696)
EV of other firm if acquire (billion \$)	η_1	0.1710 ***
		(0.0100)
EV of other firm if merge (billion \$)	η_2	0.3976 ***
		(0.0233)
Percent state ownership × Consumer surplus (billion \$)	ρ_{CS}	0.0000 ***
		(0.0000)
Constant	δ_0	0.0000 ***
		(0.0000)

Notes: Per period payoffs are in billion dollars. Standard errors in parentheses.

Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 2.6: Estimated distribution of fixed payoffs to merger and acquisition

		Mean	Standard Deviation
Fixed costs of acquiring another firm	Γ_i^B	0.1037*** (0.0062)	0.1401*** (0.0083)
Fixed benefits from being acquired	Γ_i^S	0.0487 *** (0.0031)	0.0724 *** (0.0048)
Fixed costs of merging	Λ_i	0.0588*** (0.0035)	0.0767*** (0.0045)

Note: Per period payoffs are in billion dollars. Standard errors in parentheses.

Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 2.7: Changes in welfare from base case when all firms are members of OPEC

	All firms
Expected total firm payoff	53.6844 ***
Expected avg firm payoff	1.0737 ***
Min firm payoff	0.0620 ***
Max firm payoff	0.1101
Expected total consumer surplus	-4.90e+09***

Notes: Table reports the difference between the value of the respective welfare statistic under the counterfactual scenario in which all firms are members of OPEC, and the value of the respective welfare statistic under the base-case status quo simulation of no counterfactual change. Firm payoffs and consumer surplus are in billion dollars per year. Significance codes from two-sample t-tests comparing the welfare from the counterfactual OPEC membership scenario to the welfare from the base-case status quo simulation: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 2.8: Change in action variables from base case when all firms are members of OPEC

	All firms
Oil output (KBD)	-317.1271***
Natural gas output (MCFD)	-1728.641 ***
Exploration capex (2005 US$)	-138.822 ***
Development capex (2005 US$)	-392.5024 ***
Acquisition capex (2005 US$)	-261.2711***

Notes: Table reports the difference between the respective action variable under the counterfactual scenario in which all firms are members of OPEC, and the respective action variable under the base-case status quo simulation of no counterfactual change. Significance codes from two-sample t-tests comparing the action variables from the counterfactual OPEC membership scenario to the welfare from the base-case status quo simulation: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 2.9: Changes in welfare from base case under merger ban

	All firms	OPEC firms	Non-OPEC firms
Expected total firm payoff	-6.9851 ***	-1.1974 ***	-5.7876 ***
Expected avg firm payoff	-0.1397 ***	-0.1092 ***	-0.1497***
Min firm payoff	0.0000	0.0000	-0.3014 ***
Max firm payoff	-0.1662 *	-0.2494 ***	1.9774 ***
Expected total consumer surplus	-3.60e+09 ***		

Notes: Table reports the difference between the value of the respective welfare statistic under the counterfactual merger ban, and the value of the respective welfare statistic under the base-case status quo simulation of no counterfactual change. Firm payoffs and consumer surplus are in billion dollars per year. Significance codes from two-sample t-tests comparing the welfare from the counterfactual merger ban scenario to the welfare from the base-case status quo simulation: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 2.10: Change in action variables from base case under merger ban

	All firms	OPEC firms	Non-OPEC firms
Oil output (KBD)	-282.7638***	-43.2392 **	-179.203 ***
Natural gas output (MCFD)	-706.1913***	-38.5162*	-1001.348 ***
Exploration capex (2005 US$)	-112.7563***	12.7991 *	-72.2011 ***
Development capex (2005 US$)	-337.2594***	31.7296 *	-226.6801***
Acquisition capex (2005 US$)	-63.2232***	3.404179 **	-132.3239 ***
merging			
acquiring another firm	0.0154 ***		0.01997 ***
being acquired by another firm	0.0059 ***		0.0076 ***

Notes: Table reports the difference between the respective action variable under the counterfactual merger ban scenario, and the respective action variable under the base-case status quo simulation of no counterfactual change. Significance codes from two-sample t-tests comparing the action variables from the counterfactual merger ban scenario to the welfare from the base-case status quo simulation: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 2.11: Changes in welfare from base case under different privatization scenarios

	All firms	OPEC firms	Non-OPEC firms
State ownership=0%			
Expected total firm payoff	-15.1576 ***	-4.8248 ***	-10.3328 ***
Expected avg firm payoff	-0.3032 ***	-0.3737 ***	-0.2700 ***
Min firm payoff	-0.1173 ***	-0.1173 ***	-0.4109 ***
Max firm payoff	0.0627	0.0627	-2.2536 ***
Expected total consumer surplus	2.00e+10***		
State ownership=50%			
Expected total firm payoff	-7.0886 ***	-10.5162 ***	3.4276 ***
Expected avg firm payoff	-0.1418 ***	-0.8911 ***	0.0828 ***
Min firm payoff	-0.1764 ***	-0.1764 ***	0.1763 ***
Max firm payoff	-1.2226 ***	-1.2226 ***	-1.7623 ***
Expected total consumer surplus	2.26e+10 ***		
State ownership=100%			
Expected total firm payoff	19.6248 ***	-0.2815	19.906 ***
Expected avg firm payoff	0.3925 ***	0.0393	0.5053 ***
Min firm payoff	0.1348 ***	0.1348 ***	0.3734 ***
Max firm payoff	0.0798	0.0798	2.4763 ***
Expected total consumer surplus	3.26e+10 ***		

Notes: Table reports the difference between the value of the respective welfare statistic under the counterfactual privatization scenario, and the value of the respective welfare statistic under the base-case status quo simulation of no counterfactual change. Firm payoffs and consumer surplus are in billion dollars per year. Significance codes from two-sample t-tests comparing the welfare from the counterfactual privatization scenario to the welfare from the base-case status quo simulation: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

2.9 Appendix A

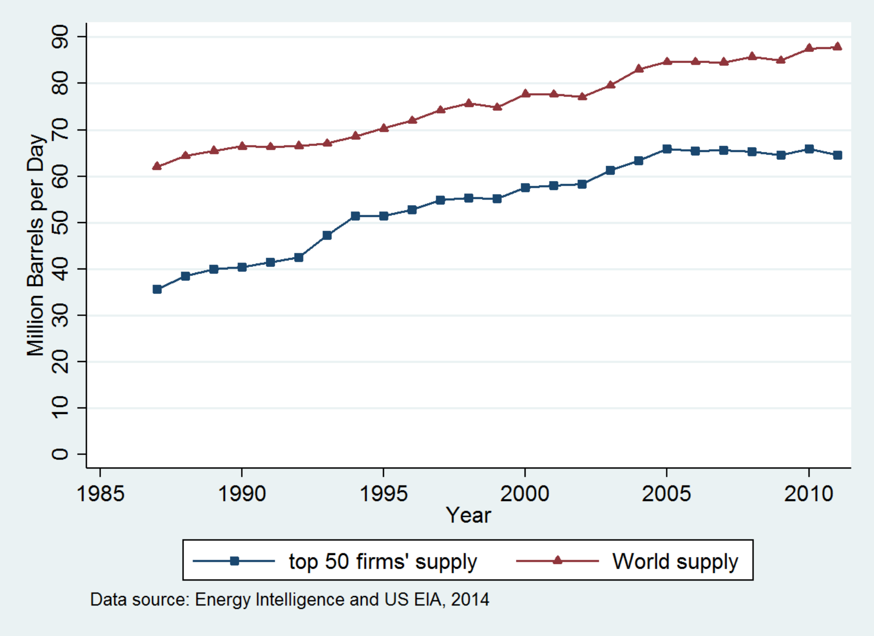

Figure 2.1: World oil supply vs top 50 producers supply in MMBD

Table 2.12: Summary statistics for action variables

Variable	# Obs	Mean	Std. Dev.	Min	Max
Oil output (KBD)	1250	1089.934	1407.45	4	11035
Natural gas output (MCFD)	1250	2951.507	6528.964	0	55901.06
Exploration capex (million 2005 US$)	300	520.385	596.664	-13.232	2760.085
Development capex (million 2005 US$)	300	1743.55	2043.468	0	9045
Acquisition capex (million 2005 US$)	295	531.016	1720.282	-142.899	17625
Dummy for M&A at time t					
merging with another firm	1296	0.005	0.067	0	1
acquiring another firm	1296	0.012	0.11	0	1
being acquired by another firm	1296	0.009	0.095	0	1

Table 2.13: Summary statistics for firm level state variables

Variable	# Obs	Mean	Std. Dev.	Min	Max
OPEC membership at time t (dummy)	1316	0.211	0.408	0	1
State ownership (in percentage)	1316	49.858	46.344	0	100
Oil reserves (million barrels)	1250	19473.12	45401.37	22	296501
Natural gas reserves (BCF)	1250	72399.95	177989.3	0	1320000

Table 2.14: Summary statistics for prices of oil and natural gas

Variable	# Obs	Mean	Std. Dev.	Min	Max
Crude oil price, Brent (2005 US$/bbl)	25	35.6445	23.3058	13.6616	90.5464
Natural gas price, US (2005 US$/mmbtu)	25	3.6833	2.14151	1.5439	8.9157
Regional natural gas price (2005 US$/mmbtu)					
Africa	9	6.0782	2.2554	3.3171	9.6790
Asia & Oceania	9	12.1561	3.2825	8.2034	18.1676
Eurasia	9	1.3760	0.5569	0.7106	2.1370
Europe	9	10.2351	4.0633	5.1570	16.6824
Middle East	9	8.8214	3.4490	5.3768	15.1544
America	9	6.8508	2.2628	3.9221	10.7228

Table 2.15: Estimated demand function for oil

	Dependent variable is: Oil quantity (KBD)	
	(1)	(2)†
Crude oil price, Brent (2005 US$/bbl)	-274.6**	-495.3*
	(102.1)	(205.8)
World GDP per capita (2005 US$)	17.66*	36.69*
	(8.427)	(16.35)
World population (million people)	1.936	-19.40
	(9.522)	(18.09)
World electricity production from oil sources (kWh)	-1.11e-08	-4.02e-08
	(1.60e-08)	(2.89e-08)
Constant	-50081.5	-7019.2
	(27851.5)	(45755.7)
Instruments used:		
Average weekly earning		
for support activities in oil and gas extraction	Y	
for support activities in oil and gas extraction (lagged)		Y
First stage F-statistic	21.62	12.44
p-value of underidentification test	0.0035	0.0488
p-value of weak-instrument-robust inference tests	0.0092	0.0002
Price elasticity of oil demand	-0.1796**	-0.3240*
	(0.0668)	(0.1346)
N	22	21
R^2	0.951	0.888
Root MSE	1810	2516

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.
† Specification used in structural model.

Table 2.16: Estimated regional demand function for natural gas for Africa

	Dependent variable is: Regional natural gas consumption (MCFD)			
	(1)†	(2)	(3)	(4)
Natural gas regional price,(US$/mmbtu)	-2.213	-7.540	-14.97	-5.894
	(20.03)	(19.93)	(20.66)	(21.04)
Regional GDP (US$)	1.14e-09***	1.15e-09***	1.17e-09***	4.64e-10
	(1.14e-10)	(1.13e-10)	(1.15e-10)	(5.66e-10)
Regional population				0.00000456
				(0.00000355)
Constant	1688.1***	1706.9***	1732.9***	-1742.0
	(133.4)	(133.0)	(135.4)	(2713.4)
Instruments used:				
Lagged average weekly earnings (2005 US$)				
for oil and gas extraction	N	Y	Y	Y
for supporting activities in oil and gas	Y	Y	Y	N
Avg capital compensation (million 2005 US$)				
on other machinery and equipment	Y	N	Y	N
on transport equipment	Y	Y	N	N
on total non-residential investment	Y	Y	Y	Y
Avg industry rate of return on capital	Y	Y	Y	Y
Aggregate gas reserve (BCF)	Y	Y	Y	N
First stage F-statistic	17.61	74.20	2.60	5.38
p-value of underidentification test	0.1777	0.1746	0.2017	0.0478
p-value of weak-instrument-robust inference tests	0.3282	0.0001	0.0068	0.3675
p-value of Sargan-Hansen overidentification test	0.5603	0.2362	0.3701	0.3350
Price elasticity of natural gas demand	-0.0047	-0.0160	-0.0318	-0.0125
	(0.0425)	(0.04228)	(0.0438)	(0.0446)
N	9	9	9	9
R^2	0.932	0.932	0.931	0.945
Root MSE	114.8	114.5	115.7	103.4

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.
† Specification used in structural model.

Table 2.17: Estimated regional demand function for natural gas for Asia and Oceania

	Dependent variable is: Regional natural gas consumption (MCFD)				
	(1)†	(2)	(3)	(4)	(5)
Natural gas regional price,(US$/mmbtu)	-76.94	-30.18	-195.4	-22.75	-355.8
	(189.6)	(206.8)	(304.2)	(178.2)	(353.0)
Regional GDP (US$)	5.77e-10*	5.46e-10*	6.56e-10*	5.41e-10*	7.63e-10*
	(2.53e-10)	(2.52e-10)	(3.20e-10)	(2.41e-10)	(3.81e-10)
Regional population	0.0000135*	0.0000129*	0.0000151	0.0000129*	0.0000171
	(0.00000637)	(0.00000625)	(0.00000772)	(0.00000608)	(0.00000922)
Constant	-39914.4	-37989.0	-44790.6	-37683.5	-51393.2
	(20404.5)	(20014.5)	(24743.0)	(19447.4)	(29540.3)
Instruments used:					
Avg capital compensation (million 2005 US$)					
on other machinery and equipment	N	N	Y	N	N
on transport equipment	N	N	N	Y	N
on total non-residential investment	N	N	N	N	Y
Avg industry rate of return on capital	Y	Y	N	Y	N
Aggregate gas reserve (BCF)	Y	N	Y	Y	N
First stage F-statistic	2.67	2.38	0.71	1.79	1.31
p-value of underidentification test	0.0437	0.0275	0.2103	0.0906	0.0667
p-value of weak-instrument-robust inference tests	0.8001	0.8813	0.6690	0.2002	0.0939
p-value of Sargan-Hansen overidentification test	0.6459	NA	0.7563	0.2290	NA
Price elasticity of natural gas demand	-0.0651	-0.0255	-0.16543	-0.0193	-0.3012
	(0.1605)	(0.1751)	(0.2575)	(0.1509)	(0.2989)
N	9	9	9	9	9
R^2	0.984	0.985	0.979	0.985	0.970
Root MSE	337	323.8	381.5	322	459.8

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.
† Specification used in structural model.

Table 2.18: Estimated regional demand function for natural gas for Eurasia

	Dependent variable is: Regional natural gas consumption (MCFD)	
	(1)†	(2)
Natural gas regional price,(US$/mmbtu)	-5960.0***	-6039.3***
	(420.7)	(482.2)
Regional GDP (US$)	4.99e-09***	5.06e-09***
	(3.57e-10)	(4.07e-10)
Regional population	-0.00135***	-0.00135***
	(0.0000574)	(0.0000581)
Constant	408719.2***	409082.8***
	(16435.4)	(16636.3)
Instruments used:		
Lagged average weekly earnings (2005 US$)		
for supporting activities in oil and gas	Y	Y
for oil and gas extraction	Y	N
Avg capital compensation on transport equipment (million 2005 US$)	Y	Y
Avg industry rate of return on capital	N	Y
First stage F-statistic	13.23	1.76
p-value of underidentification test	0.0350	0.0826
p-value of weak-instrument-robust inference tests	0.0000	0.0000
p-value of Sargan-Hansen overidentification test	0.2582	0.0755
Price elasticity of natural gas demand	-0.3857***	-0.3909***
	(0.0272)	(0.0312)
N	9	9
R^2	0.990	0.990
Root MSE	126.9	128.2

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.
† Specification used in structural model.

Table 2.19: Estimated regional demand function for natural gas for Europe

	Dependent variable is: Regional natural gas consumption (MCFD)	
	(1)†	(2)
Natural gas regional price,(US$/mmbtu)	-169.9	-344.7
	(165.2)	(185.5)
Regional GDP (US$)	5.15e-10***	6.11e-10***
	(1.44e-10)	(1.55e-10)
Regional population	-0.0000783	-0.0000361
	(0.0000679)	(0.0000730)
Constant	59235.9	34714.0
	(38457.1)	(41355.9)
Instruments used:		
Lagged average weekly earnings (2005 US$)		
for supporting activities in oil and gas	Y	N
for oil and gas extraction	Y	Y
Avg capital compensation (million 2005 US$)		
on total non-residential investment	N	Y
Avg industry rate of return on capital	Y	N
Aggregate gas reserve (BCF)	Y	N
First stage F-statistic	9.36	7.63
p-value of underidentification test	0.0738	0.0243
p-value of weak-instrument-robust inference tests	0.0000	0.0014
p-value of Sargan-Hansen overidentification test	0.0451	0.1406
Price elasticity of natural gas demand	-0.0899	-0.1824
	(0.0874)	(0.0982)
N	9	9
R^2	0.833	0.817
Root MSE	331	346.8

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.
† Specification used in structural model.

Table 2.20: Estimated regional demand function for natural gas for the Middle East

	Dependent variable is: Regional natural gas consumption (MCFD)		
	(1)†	(2)	(3)
Natural gas regional price,(US$/mmbtu)	-12.14	-38.25	-37.77
	(47.81)	(50.26)	(50.23)
Regional population	0.000146***	0.000152***	0.000152***
	(0.0000126)	(0.0000132)	(0.0000132)
Constant	-18265.8***	-19250.5***	-19232.7***
	(2027.4)	(2118.4)	(2117.0)
Instruments used:			
Lagged average weekly earnings (2005 US$) for oil and gas extraction	Y	Y	N
Avg capital compensation (million 2005 US$) on total non-residential investment	Y	Y	Y
Avg industry rate of return on capital	Y	N	N
First stage F-statistic	49.67	57.38	103.23
p-value of underidentification test	0.0478	0.0241	0.0063
p-value of weak-instrument-robust inference tests	0.0019	0.4334	0.4296
p-value of Sargan-Hansen overidentification test	0.0612	0.3753	NA
Price elasticity of natural gas demand	-0.0112	-0.0352	-0.0348
	(0.0441)	(0.0463)	(0.0463)
N	9	9	9
R^2	0.99	0.989	0.989
Root MSE	177.1	180.7	180.6

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.
† Specification used in structural model.

Table 2.21: Estimated regional demand function for natural gas for the Americas

	Dependent variable is: Regional natural gas consumption (MCFD)				
	(1)†	(2)	(3)	(4)	(5)
Natural gas regional price,(US$/mmbtu)	-85.00	-67.54	-80.89	-74.39	-39.23
	(85.49)	(86.38)	(85.30)	(84.32)	(108.8)
Regional GDP (US$)	3.17e-10***	3.08e-10***	3.15e-10***	3.12e-10***	2.37e-10
	(6.64e-11)	(6.65e-11)	(6.63e-11)	(6.58e-11)	(3.12e-10)
Regional population					0.00000594
					(0.0000288)
Constant	26750.5***	26792.2***	26760.3***	26775.8***	22518.3
	(849.0)	(844.7)	(847.4)	(844.9)	(20904.6)
Instruments used:					
Lagged average weekly earnings (2005 US$)					
for supporting activities in oil and gas	N	N	N	Y	Y
for oil and gas extraction	Y	Y	Y	Y	N
Avg capital compensation (million 2005 US$)					
on other machinery and equipment	N	N	N	N	Y
on transport equipment	N	N	N	N	Y
on total non-residential investment	Y	N	Y	Y	Y
Avg industry rate of return on capital	Y	Y	Y	Y	Y
Aggregate gas reserve (BCF)	N	Y	Y	Y	N
First stage F-statistic	16.65	10.48	10.13	8.36	4.15
p-value of underidentification test	0.0369	0.0418	0.0750	0.1236	0.1305
p-value of weak-instrument-robust inference tests	0.0135	0.0001	0.0000	0.0000	0.0000
p-value of Sargan-Hansen overidentification test	0.1309	0.0426	0.0727	0.1195	0.0614
Price elasticity of natural gas demand	-0.0184	-0.0146	-0.0175	-0.0161	-0.0085
	(0.0185)	(0.0187)	(0.0185)	(0.01829)	(0.0236)
N	9	9	9	9	9
R^2	0.785	0.787	0.785	0.786	0.788
Root MSE	386.6	384.3	385.9	385	383

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

† Specification used in structural model.

Table 2.22: Estimation results for policy functions

	Dependent variable is:				
	Oil output	Natural gas output	Exploration capex	Development capex	Acquisition capex
Avg capital compensation (million 2005 US$)					
on transport equipment	0.761	4.030	2.246	7.716	10.85
	(2.655)	(7.666)	(5.110)	(14.23)	(21.58)
on other machinery and equipment	0.0934	0.491	0.177	0.520	0.546
	(0.172)	(0.496)	(0.331)	(0.921)	(1.397)
on total non-residential investment	0.131	0.549	0.219	0.162	0.127
	(0.208)	(0.602)	(0.401)	(1.117)	(1.694)
on other assets	0.0225	-0.148	-0.190	-0.810	0.0379
	(0.238)	(0.688)	(0.459)	(1.278)	(1.938)
Oil reserves (million Barrels)	0.102***	-0.0298*	0.000859	-0.00840	-0.0380
	(0.00475)	(0.0137)	(0.00914)	(0.0254)	(0.0386)
Natural gas reserves (BCF)	0.0111***	0.0996***	0.0205***	0.0490***	0.0184
	(0.00163)	(0.00470)	(0.00313)	(0.00872)	(0.0132)
Avg weekly earning (2005 US$)					
on oil and gas extraction	1.260	5.709	3.450	4.734	-6.329
	(2.339)	(6.753)	(4.501)	(12.53)	(19.01)
on supporting activities in oil and gas	0.874	4.311	3.434	7.274	-0.546
	(2.373)	(6.852)	(4.567)	(12.72)	(19.29)
Cumulative oil output (KBD)	0.0113*	-0.0779***	0.0101	0.0408	-0.00104
	(0.00474)	(0.0137)	(0.00912)	(0.0254)	(0.0385)
Cumulative gas output (MCFD)	-0.000100	0.0240***	-0.00340	-0.00831	0.00561
	(0.00167)	(0.00481)	(0.00321)	(0.00893)	(0.0135)

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 2.22: (continued)

	Dependent variable is:				
	Oil output	Natural gas output	Exploration capex	Development capex	Acquisition capex
Aggregate oil output (KBD)	-0.00424	-0.0315	-0.00614	0.000890	-0.0116
	(0.0252)	(0.0727)	(0.0485)	(0.135)	(0.205)
Aggregate gas output (MCFD)	-0.000200	0.00737	0.00407	0.00377	-0.0120
	(0.00625)	(0.0180)	(0.0120)	(0.0335)	(0.0508)
Cumulative					
exploration capex (2005 US$)	0.0340	-0.0343	0.186***	0.0371	0.109
	(0.0183)	(0.0528)	(0.0352)	(0.0980)	(0.149)
development capex (million 2005 US$)	-0.00169	0.0727***	-0.0547***	0.0487	-0.0420
	(0.00608)	(0.0176)	(0.0117)	(0.0326)	(0.0495)
acquisition capex (million 2005 US$)	0.00137	0.0315**	-0.0186*	0.0191	0.0314
	(0.00404)	(0.0117)	(0.00778)	(0.0217)	(0.0329)
Aggregate					
exploration capex (million 2005 US$)	0.0143	0.0732	-0.0168	0.0104	0.181
	(0.0733)	(0.212)	(0.141)	(0.393)	(0.596)
development capex (million 2005 US$)	0.00849	0.0224	0.00821	-0.0103	0.00210
	(0.0114)	(0.0329)	(0.0219)	(0.0611)	(0.0926)
acquisition capex (million 2005 US$)	-0.00572	-0.0300	-0.00720	0.00700	-0.0250
	(0.0109)	(0.0315)	(0.0210)	(0.0584)	(0.0886)
Aggregate oil reserves (million barrels)	-0.00480	-0.0198	-0.00717	-0.00923	-0.00395
	(0.00553)	(0.0160)	(0.0106)	(0.0296)	(0.0449)
Aggregate gas reserves (BCF)	0.000108	0.000539	0.000304	0.000799	0.000647
	(0.000218)	(0.000630)	(0.000420)	(0.00117)	(0.00177)

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 2.22: (continued)

	Dependent variable is:				
	Oil output	Natural gas output	Exploration capex	Development capex	Acquisition capex
World GDP per capita (2005 US$)	-1.234	-6.065	-3.163	-5.290	7.063
	(2.275)	(6.567)	(4.377)	(12.19)	(18.49)
Percentage of state ownership	1.158**	-7.148***	-3.318***	-6.515**	-2.339
	(0.426)	(1.230)	(0.820)	(2.283)	(3.463)
Lag dummy for merger	204.3	1617.3***	-145.3	-421.1	-234.9
	(161.0)	(464.7)	(309.7)	(862.5)	(1308.1)
Lag dummy for acquiring another firm	177.2	414.5	-119.1	-122.6	4035.3***
	(92.10)	(265.9)	(177.2)	(493.5)	(748.5)
Constant	9036.9	42039.7	17489.3	25295.1	-33943.4
	(14302.4)	(41292.6)	(27522.5)	(76637.4)	(116237.7)
N	252	252	252	252	252
R^2	0.933	0.950	0.617	0.748	0.255
Root MSE	206.94	597.46	398.22	1108.9	1681.8

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 2.23: Oil and natural gas production policy functions for OPEC firms

	Dependent variable is:	
	Oil output	Natural gas output
Avg capital compensation (million 2005 US$)		
on transport equipment	-4.065	-10.62
	(34.87)	(42.65)
on other machinery and equipment	-0.204	-0.834
	(1.402)	(1.715)
on total non-residential investment	-0.0981	-0.0783
	(0.304)	(0.372)
on other assets	0.459	1.415
	(2.110)	(2.581)
Oil reserves (million Barrels)	0.0176^{***}	0.000415
	(0.00144)	(0.00176)
Natural gas reserves (BCF)	0.000524	0.00186^{***}
	(0.000266)	(0.000326)
Avg weekly earning (2005 US$)		
on supporting activities in oil and gas	-0.586	-2.412
	(7.484)	(9.155)
Cumulative oil output (KBD)	0.0386^{***}	-0.00133
	(0.00537)	(0.00657)
Cumulative gas output (MCFD)	0.0119^{***}	0.103^{***}
	(0.00346)	(0.00423)
Aggregate oil output (KBD)	0.0282	0.0148
	(0.122)	(0.149)
Aggregate gas output (MCFD)	-0.00801	-0.00309
	(0.0344)	(0.0421)
Aggregate oil reserves (million barrels)	0.000392	0.00662
	(0.0149)	(0.0182)
Aggregate gas reserves (BCF)	-0.0000213	-0.000514
	(0.00187)	(0.00229)
World GDP per capita (2005 US$)	2.316	1.402
	(7.867)	(9.624)
World population	-8.492	-8.726
	(38.08)	(46.58)

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 2.23: (continued)

	Dependent variable is:	
	Oil output	Natural gas output
Aggregate exploration capex (million 2005 US$)	-0.00534	0.00711
	(0.226)	(0.277)
Aggregate development capex (million 2005 US$)	0.0110	0.0203
	(0.101)	(0.123)
Aggregate acquisition capex (million 2005 US$)	0.00231	0.0196
	(0.0643)	(0.0787)
Constant	30697.6	36317.5
	(205966.5)	(251941.4)
N	173	173
R^2	0.900	0.863
Root MSE	725.51	887.45

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 2.24: Multinomial logit regression of decisions on merger and acquisitions for non-OPEC firms that are not 100% state-owned

	(1)	(2)	(3)	(4)†	(5)
0: Base outcome					
1: Merge					
Oil reserves (million barrels)	-0.000969	-0.0184	-0.000678	-0.000692	-0.0241
	(0.00115)	(16.30)	(0.000923)	(0.000915)	(38.84)
Natural gas reserves (BCF)	0.000171	0.00623	0.000106	0.0000843	0.00625
	(0.000191)	(2.830)	(0.000155)	(0.000147)	(8.071)
Cumulative oil output (KBD)	0.000629	0.00901	0.000477	0.000389	0.0142
	(0.000749)	(15.23)	(0.000681)	(0.000558)	(20.92)
Cumulative natural gas output (MCFD)	-0.0000306	0.00313	-0.0000275	-0.0000449	
	(0.000259)	(10.78)	(0.000215)	(0.000151)	
Avg industry rate of return on capital	-95.99		-65.55		
	(64.26)		(41.02)		
Avg capital compensation (million 2005 US$)					
on other machinery and equipment		-0.964			-0.901
		(212.1)			(133.0)
on total non-residential investment	0.00105	0.00532		0.000208	0.00519
	(0.00119)	(4.109)		(0.000715)	(2.559)
Percentage of state ownership	-3.835	-5.975	-3.905	-3.359	-5.160
	(601.5)	(2604.6)	(627.0)	(464.2)	(1581.6)
Lag dummy for merger	-14.09	222.8	-15.09	-15.77	210.2
	(308979.2)	(1682718.4)	(213014.2)	(126734.6)	(1829812.3)
Lag dummy for acquiring another firm	-20.97	-7.690	-20.86	-19.15	-14.89
	(46820.3)	(399914.3)	(54990.4)	(37619.4)	(564250.7)

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

† Specification used in structural model.

Table 2.24: (continued)

	(1)	(2)	(3)	(4)†	(5)
Cumulative exploration capex (million 2005 US$)	-0.00174	-0.0825	-0.00138	-0.000288	-0.0694
	(0.00175)	(42.33)	(0.00148)	(0.000939)	(22.40)
Cumulative development capex (million 2005 US$)	0.000363	0.0163	0.000314	0.0000469	0.0152
	(0.000457)	(4.922)	(0.000438)	(0.000327)	(4.906)
Cumulative acquisition capex (million 2005 US$)	-0.000364	-0.00801	-0.000204	-0.000237	-0.00782
	(0.000451)	(2.525)	(0.000413)	(0.000368)	(1.918)
Constant	4.092	1377.3	4.216	-4.408	1290.8
	(4.837)	(310162.1)	(4.736)	(2.483)	(177846.4)
2: Acquire another firm					
Oil reserves (million barrels)	-0.000999	-0.000756	-0.00102	-0.00108*	-0.000132
	(0.000571)	(0.000500)	(0.000570)	(0.000533)	(0.000384)
Natural gas reserves (BCF)	-0.000236*	-0.000483*	-0.000234*	-0.000224*	-0.0000764
	(0.000109)	(0.000197)	(0.000108)	(0.000101)	(0.0000697)
Cumulative oil output (KBD)	0.0000650	0.000553	0.0000465	-0.0000236	-0.000295
	(0.000293)	(0.000395)	(0.000282)	(0.000245)	(0.000218)
Cumulative natural gas output (MCFD)	-0.000350*	-0.000708**	-0.000343*	-0.000331*	
	(0.000151)	(0.000273)	(0.000146)	(0.000138)	
Avg industry rate of return on capital	-41.81		-37.44		
	(34.26)		(25.80)		
Avg capital compensation (million 2005 US$)					
on other machinery and equipment		-0.0109*			-0.00257
		(0.00513)			(0.00199)
on total non-residential investment	0.000173	-0.000193		-0.000366	-0.000747
	(0.000826)	(0.000640)		(0.000586)	(0.000513)

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

† Specification used in structural model.

Table 2.24: (continued)

	(1)	(2)	(3)	(4)†	(5)
Percentage of state ownership	-0.0203	-0.0880	-0.0148	-0.0129	-0.00616
	(0.0534)	(0.0583)	(0.0459)	(0.0448)	(0.0382)
Lag dummy for merger	-23.17	-25.86	-22.41	-21.00	-26.71
	(139116.7)	(1075955.0)	(95709.8)	(52089.2)	(1071192.3)
Lag dummy for acquiring another firm	-22.49	-29.56	-21.74	-20.94	-27.23
	(53086.1)	(369831.2)	(37340.2)	(26521.0)	(503787.3)
Cumulative exploration capex (million 2005 US$)	0.00136	0.00127	0.00142	0.00162*	0.00170
	(0.000854)	(0.00101)	(0.000802)	(0.000792)	(0.000945)
Cumulative development capex (million 2005 US$)	0.0000737	0.000293	0.0000560	0.0000163	-0.000403
	(0.000291)	(0.000423)	(0.000276)	(0.000259)	(0.000305)
Cumulative acquisition capex (million 2005 US$)	0.000314*	0.000376*	0.000329*	0.000326*	0.000186
	(0.000146)	(0.000162)	(0.000133)	(0.000141)	(0.000103)
Constant	0.817	15.15	0.822	-2.402	2.439
	(2.967)	(8.012)	(2.964)	(1.901)	(3.743)
N	244	244	244	244	244
pseudo R^2	0.484	0.724	0.474	0.420	0.553

Notes: Standard errors in parentheses. Significance codes: $^{*}\ p < 0.05$, $^{**}\ p < 0.01$, $^{***}\ p < 0.001$.

† Specification used in structural model.

Table 2.25: Logit regression of decisions on selling (being acquired) for non-OPEC firms that are not 100% state-owned

	(1)	(2)†	(3)	(4)	(5)
Oil reserves (million barrels)	-0.000225	-0.000217	-0.000198	-0.000110	-0.000262
	(0.000239)	(0.000239)	(0.000239)	(0.000231)	(0.000173)
Natural gas reserves (BCF)	-0.0000643	-0.0000640	-0.0000706	-0.0000816	-0.0000576
	(0.0000702)	(0.0000704)	(0.0000733)	(0.0000761)	(0.0000644)
Cumulative oil output (KBD)	0.0000341	0.0000391	0.0000279	0.00000187	0.0000868
	(0.000193)	(0.000203)	(0.000204)	(0.000182)	(0.0000807)
Cumulative natural gas output (MCFD)	0.0000140	0.0000151	0.0000234	0.0000277	
	(0.0000566)	(0.0000587)	(0.0000597)	(0.0000543)	
Avg industry rate of return on capital	-41.99**		-31.07*		
	(15.79)		(12.13)		
Avg capital compensation (million 2005 US$)					
on other machinery and equipment		-0.00365*			-0.00367*
		(0.00159)			(0.00159)
on total non-residential investment	0.000364	-0.000117		-0.0000388	-0.000112
	(0.000256)	(0.000201)		(0.000146)	(0.000200)
Percentage of state ownership	-0.00456	-0.00743	-0.00152	-0.00413	-0.00904
	(0.0158)	(0.0155)	(0.0153)	(0.0145)	(0.0143)
Constant	0.947	3.846	0.908	-3.035***	3.909
	(1.546)	(2.757)	(1.507)	(0.703)	(2.747)
N	574	600	574	600	600
pseudo R^2	0.158	0.171	0.138	0.057	0.171

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.
† Specification used in structural model.

Table 2.26: Estimated transition densities for oil and natural gas reserves and state ownership

	Dependent variable is:		
	Oil reserves (million barrels)	Natural gas reserves (BCF)	percentage of state ownership
Lag oil reserves (million barrels)	0.774***	-0.789***	-0.000521
	(0.0590)	(0.127)	(0.000424)
Lag natural gas reserves (BCF)	-0.00558	0.941***	0.000337**
	(0.0175)	(0.0378)	(0.000125)
Lag oil output (KBD)	1.785***	7.502***	0.00379
	(0.460)	(0.993)	(0.00331)
Lag natural gas output (MCFD)	-0.142	-0.585*	-0.00237*
	(0.129)	(0.278)	(0.000924)
Lag exploration capex (million 2005 US$)	-0.353	-1.077	-0.00263
	(0.304)	(0.655)	(0.00218)
Lag development capex (million 2005 US$)	-0.0513	0.0464	0.000445
	(0.113)	(0.244)	(0.000814)
Lag acquisition capex (million 2005 US$)	-0.0206	-0.0896	-0.000134
	(0.0492)	(0.106)	(0.000354)
Lag Percentage of state ownership	-4.954	-5.762	0.868***
	(3.254)	(7.024)	(0.0233)
Lag dummy for merger	4199.2***	13760.5***	-0.0118
	(995.3)	(2148.5)	(7.160)
Lag dummy for acquiring another firm	1147.0*	6993.3***	-2.989
	(540.3)	(1166.3)	(3.886)
Constant	319.1	30.32	1.372
	(184.2)	(397.6)	(1.307)

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 2.26: (continued)

	Dependent variable is:		
	Oil reserves (million barrels)	Natural gas reserves (BCF)	percentage of state ownership
N	249	249	252
R^2	0.913	0.968	0.920
Root MSE	1381.7	2982.8	9.9398

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 2.27: Estimated transition density for world population

	Dependent variable is: World population (million people)
Lag world population (million people)	0.994^{***}
	(0.000149)
Constant	116.8^{***}
	(0.890)
N	1203
R^2	1.000
Root MSE	2.8701

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 2.28: Estimated transition density for GDP per capita

	Dependent variable is: World GDP per capita (2005 US$)
Lag world GDP per capita (2005 US$)	1.003^{***}
	(0.00411)
Constant	71.11^{**}
	(26.59)
N	1203
R^2	0.980
Root MSE	95.064

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 2.29: Estimated transition densities for regional population

	Dependent variable is: Regional population					
	Africa	Asia and Oceania	Eurasia	Europe	Middle East	Americas
Lag regional population	1.022***	0.982***	0.815***	0.979***	1.014***	0.991***
	(0.000793)	(0.000535)	(0.0797)	(0.0192)	(0.00553)	(0.00132)
Constant	2377399.5**	102604406.2***	53407212.6*	14702775.6	1865626.2	18512826.5***
	(632438.5)	(1781063.3)	(22869701.1)	(11008355.2)	(927779.4)	(1082268.0)
N	24	24	24	24	24	24
R^2	1.000	1.000	0.826	0.992	0.999	1.000
Root MSE	5.2e5	8.0e5	9.8e5	1.6e6	7.6e5	4.9e5

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 2.30: Estimated transition densities for regional GDP

	Dependent variable is: Regional GDP (2005 US$)					
	Africa	Asia and Oceania	Eurasia	Europe	Middle East	Americas
Lag regional GDP	1.153***	1.151***	1.062***	1.005***	1.146***	1.041***
	(0.0439)	(0.0379)	(0.0862)	(0.0520)	(0.0597)	(0.0221)
Constant	-4.48941e+10	-6.11064e+11	5.56731e+10	5.59495e+11	-3.05928e+10	1.92957e+11
	(3.83697e+10)	(3.56436e+11)	(8.55987e+10)	(6.42472e+11)	(5.78489e+10)	(3.03131e+11)
N	24	24	24	24	24	24
R^2	0.969	0.977	0.873	0.944	0.944	0.990
Root MSE	9.2e10	6.6e11	2.5e11	1.1e12	1.5e11	5.1e11

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 2.31: Estimated transition density for avg industry rate of return on capital

	Dependent variable is: Avg industry rate of return on capital for mining and quarry
Lag avg industry rate of return on capital for mining and quarry	-1.005***
	(0.0295)
Lag aggregate oil reserves (million Barrels)	0.000000987***
	(2.86e-08)
Lag aggregate natural gas reserves (BCF)	-5.80e-08***
	(2.11e-09)
Lag avg capital compensation (million 2005 US$)	
on other machinery and equipment	-0.0000540***
	(0.00000144)
on total non-residential investment	0.00000925***
	(0.00000105)
Lag world road sector gasoline fuel consumption (kt of oil equivalent)	0.00000241***
	(0.000000115)
Lag world population (million people)	-0.000926***
	(0.0000281)
Lag world GDP per capita (2005 US$)	-0.0000776***
	(0.00000757)
Lag world electricity production (kWh)	
from natural gas sources	2.98e-13***
	(9.28e-15)
from oil sources	-1.03e-12***
	(2.45e-14)
Lag aggregate output of all firms	
Oil (KBD)	0.000000341
	(0.000000325)
Natural gas (MCFD)	-0.00000177***
	(0.000000121)
Constant	4.296***
	(0.0779)
N	750
R^2	0.970
Root MSE	0.00613

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 2.32: Estimated transition density for avg capital compensation on other machinery and equipment

	Dependent variable is: Avg capital compensation on other machinery and equipment
Lag avg industry rate of return on capital for mining and quarry	1365.0^{***}
	(348.4)
Lag aggregate oil reserves (million barrels)	0.0196^{***}
	(0.000348)
Lag aggregate natural gas reserves (BCF)	-0.00105^{***}
	(0.0000287)
Lag avg capital compensation (million 2005 US$)	
on other machinery and equipment	0.0439^{*}
	(0.0188)
on total non-residential investment	-0.0155
	(0.0129)
Lag world road sector gasoline fuel consumption (kt of oil equivalent)	0.0479^{***}
	(0.00123)
Lag world population (million people)	-12.85^{***}
	(0.288)
Lag world GDP per capita (2005 US$)	-4.037^{***}
	(0.103)
Lag world electricity production (kWh)	
from natural gas sources	$5.33\text{e-}09^{***}$
	(1.26e-10)
from oil sources	$-3.48\text{e-}09^{***}$
	(2.70e-10)
Lag aggregate output of all firms	
Oil (KBD)	-0.100^{***}
	(0.00431)
Natural gas (MCFD)	-0.00540^{***}
	(0.00152)
Constant	48009.7^{***}
	(1023.5)
N	799
R^2	0.984
Root MSE	84.461

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 2.33: Estimated transition density for avg capital compensation on total non-residential investment

	Dependent variable is: Avg capital compensation on total non-residential investment
Lag avg industry rate of return on capital for mining and quarry	-9793.8***
	(1027.7)
Lag aggregate oil reserves (million barrels)	0.0238***
	(0.00103)
Lag aggregate natural gas reserves (BCF)	-0.00133***
	(0.0000847)
Lag avg capital compensation (million 2005 US$)	
on other machinery and equipment	-1.862***
	(0.0554)
on total non-residential investment	0.288***
	(0.0382)
Lag world road sector gasoline fuel consumption (kt of oil equivalent)	0.0913***
	(0.00363)
Lag world population (million people)	-18.10***
	(0.850)
Lag world GDP per capita (2005 US$)	2.459***
	(0.303)
Lag world electricity production (kWh)	
from natural gas sources	2.57e-09***
	(3.73e-10)
from oil sources	-2.77e-08***
	(7.96e-10)
Lag aggregate output of all firms	
Oil (KBD)	-0.221***
	(0.0127)
Natural gas (MCFD)	-0.0479***
	(0.00447)
Constant	52944.6***
	(3018.8)
N	799
R^2	0.988
Root MSE	249.12

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 2.34: Estimated transition density for world road sector gasoline fuel consumption

	Dependent variable is: World road sector gasoline fuel consumption (kt of oil equivalent)
Lag avg industry rate of return on capital for mining and quarry	-67174.8***
	(7757.0)
Lag aggregate oil reserves (million barrels)	0.0681***
	(0.00774)
Lag aggregate natural gas reserves (BCF)	-0.00510***
	(0.000639)
Lag avg capital compensation (million 2005 US$)	
on other machinery and equipment	-3.795***
	(0.418)
on total non-residential investment	1.360***
	(0.288)
Lag world road sector gasoline fuel consumption (kt of oil equivalent)	0.656***
	(0.0274)
Lag world population (million people)	125.3***
	(6.413)
Lag world GDP per capita (2005 US$)	-40.56***
	(2.286)
Lag world electricity production (kWh)	
from natural gas sources	-5.56e-08***
	(2.81e-09)
from oil sources	-8.99e-08***
	(6.01e-09)
Lag aggregate output of all firms	
Oil (KBD)	2.995***
	(0.0960)
Natural gas (MCFD)	0.378***
	(0.0338)
Constant	-226225.2***
	(22785.8)
N	799
R^2	0.998
Root MSE	1880.3

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 2.35: Estimated transition density for world motor vehicles

	Dependent variable is: World motor vehicles (per 1,000 people)
Lag aggregate oil reserves (million barrels)	-0.000708***
	(0.000154)
Lag avg capital compensation (million 2005 US$) on total non-residential investment	0.0283**
	(0.0102)
Lag world road sector gasoline fuel consumption (kt of oil equivalent)	0.000419*
	(0.000200)
Lag world motor vehicles (per 1,000 people)	1.232***
	(0.341)
Lag world electricity production (kWh)	
from natural gas sources	-1.25e-10***
	(3.35e-11)
from oil sources	7.30e-11
	(1.53e-10)
Lag aggregate oil output of all firms (KBD)	0.0144***
	(0.00355)
Constant	-375.4
	(384.0)
N	432
R^2	0.847
Root MSE	4.2212

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 2.36: Estimated transition density for world electricity production from natural gas sources

	Dependent variable is: World electricity production from natural gas sources (kWh)
Lag avg industry rate of return on capital for mining and quarry	-1.00546e+12***
	(5.49455e+10)
Lag aggregate oil reserves (million barrels)	667398.1***
	(54844.7)
Lag aggregate natural gas reserves (BCF)	-1946.8
	(4529.8)
Lag avg capital compensation (million 2005 US$)	
on other machinery and equipment	-137198427.2***
	(2959959.6)
on total non-residential investment	-38581285.1***
	(2040441.5)
Lag world road sector gasoline fuel consumption (kt of oil equivalent)	-958016.6***
	(193818.5)
Lag world population (million people)	1.23760e+09***
	(45427800.1)
Lag world GDP per capita (2005 US$)	447240369.9***
	(16189014.5)
Lag world electricity production (kWh)	
from natural gas sources	-0.391***
	(0.0199)
from oil sources	-2.678***
	(0.0425)
Lag aggregate output of all firms	
Oil (KBD)	27159110.5***
	(680113.6)
Natural gas (MCFD)	11117179.1***
	(239226.4)
Constant	-6.26490e+12***
	(1.61399e+11)
N	799
R^2	1.000
Root MSE	1.3e10

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 2.37: Estimated transition density for world electricity production from oil sources

	Dependent variable is: World electricity production from oil sources (kWh)
Lag avg industry rate of return on capital for mining and quarry	-1.29705e+12***
	(4.12199e+10)
Lag aggregate oil reserves (million barrels)	-554911.8***
	(41144.2)
Lag aggregate natural gas reserves (BCF)	48747.4***
	(3398.2)
Lag avg capital compensation (million 2005 US$) on other machinery and equipment	21049440.2***
	(2220549.6)
on total non-residential investment	22978949.9***
	(1530730.9)
Lag world road sector gasoline fuel consumption (kt of oil equivalent)	-116019.6
	(145401.9)
Lag world population (million people)	-70654784.0*
	(34079749.4)
Lag world GDP per capita (2005 US$)	127831765.8***
	(12144932.3)
Lag world electricity production (kWh) from natural gas sources	-0.186***
	(0.0150)
from oil sources	-0.0661*
	(0.0319)
Lag aggregate output of all firms Oil (KBD)	10355770.0***
	(510218.5)
Natural gas (MCFD)	-555873.4**
	(179466.7)
Constant	1.18372e+12***
	(1.21081e+11)
Observations	799
R^2	0.988
Root MSE	1.0e10

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 2.38: Welfare

Variable	All firms	OPEC firms	Non-OPEC firms
Expected total firm payoff	63.0721 ***	37.0672 ***	26.0049 ***
	(11.2308)	(4.4646)	(6.7669)
Expected avg. firm payoff	1.2614 ***	3.3048 ***	0.6719 ***
	(0.2246)	(0.3960)	(0.1749)
Min firm payoff	-3.9834 ***	-3.9834 ***	-0.6357 *
	(0.2105)	(0.2105)	(0.2554)
Max firm payoff	14.3074 ***	14.3074 ***	10.3077 ***
	(0.9821)	(0.9821)	(0.9953)
Expected total consumer surplus	3.12e+10 ***		
	(6.48e+09)		

Notes: Firm payoffs and consumer surplus are in billion dollars per year.

Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 2.39: Summary statistics for action variables predicted by structural model (2000-2005)

	All firms		OPEC firms		Non-OPEC firms	
Variable	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Oil output (KBD)	1503.514 ***	1796.073 ***	2512.852 ***	2562.346 ***	1028.842 ***	967.779 ***
	(43.788)	(71.594)	(160.515)	(113.881)	(11.299)	(8.659)
Natural gas output (MCFD)	3874.760 ***	7502.254 ***	3336.468 ***	3383.802 ***	4135.609 ***	8784.601 ***
	(155.890)	(103.774)	(231.449)	(141.766)	(122.972)	(124.555)
Capital expenditure on						
Exploration (million 2005 US$)	679.122 ***	897.901 ***	1126.927 ***	1139.218 ***	466.955 ***	657.581 ***
	(19.319)	(9.175)	(35.132)	(10.234)	(20.062)	(11.838)
Development (million 2005 US$)	1832.241 ***	2577.189 ***	3091.026 ***	3421.532 ***	1232.528 ***	1766.299 ***
	(22.778)	(21.113)	(84.241)	(28.691)	(15.390)	(18.242)
Acquisition (million 2005 US$)	776.833 ***	1376.407 ***	499.663 ***	954.628 ***	908.868 ***	1517.305 ***
	(19.530)	(26.413)	(8.003)	(8.435)	(27.168)	(32.139)
Dummy for M&A at time t						
merging	0.174 ***	0.379 ***			0.225 ***	0.418 ***
	(0.002)	(0.001)			(0.001)	(0.001)
acquiring another firm	0.048 ***	0.212 ***			0.062 ***	0.240 ***
	(0.004)	(0.009)			(0.005)	(0.010)
being acquired by another firm	0.003 ***	0.036 ***			0.003 ***	0.041 ***
	(0.000)	(0.002)			(0.000)	(0.003)

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 2.40: Probability of an economically significant profitable deviation by firm

Company	Probability of an economically significant profitable deviation
ADNOC	0.0250 *** (0.0003)
Anadarko	0.0000 (0.0012)
Apache	0.0000 (0.0000)
BG	0.0000 (0.0000)
BHP	0.0000 (0.0000)
BP	0.0166 *** (0.0000)
Burlington	0.0000 (0.0000)
Canadian Natural (CNR)	0.0000 (0.0000)
Chevron	0.1166 *** (0.0031)
CNPC	0.0500 *** (0.0008)
CPC (Taiwan)	0.0500 *** (0.0008)
Conoco Phillips	0.0000 (0.0011)
Devon Energy	0.0000 (0.0000)
Ecopetrol	0.0000 (0.0000)
EGPC	0.0000 (0.0000)
El Paso Energy	0.0000

Notes: We define and calculate a firm's probability of having an economically significant profitable deviation as the fraction of alternative strategies simulated that would yield a payoff, as evaluated using our estimated structural parameters, more than one billion dollars per year higher than would the optimal strategy as given by our estimated policy functions. Standard errors in parentheses.

Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 2.40: (continued)

Company	Probability of an economically significant profitable deviation
	(0.0000)
Encana	0.0000 (0.0000)
Eni	0.0083 *** (0.0000)
ExxonMobil	0.2083 *** (0.0007)
Gazprom	0.2416 *** (0.0002)
Hess Corporation	0.0500 *** (0.0011)
INOC	0.1083 *** (0.0024)
KazMunayGas	0.0000 (0.0000)
KPC	0.1000*** (0.0000)
Libya NOC	0.0000 (0.0000)
Lukoil	0.0166 *** (0.0001)
Marathon Oil	0.0166 *** (0.0004)
NIOC	0.0083 *** (0.0001)
Nippon Mitsubishi	0.0500 *** (0.0090)
NNPC	0.0416 *** (0.0000)
Norsk Hydro	0.0333 *** (0.0011)
Occidental	0.0000

Notes: We define and calculate a firm's probability of having an economically significant profitable deviation as the fraction of alternative strategies simulated that would yield a payoff, as evaluated using our estimated structural parameters, more than one billion dollars per year higher than would the optimal strategy as given by our estimated policy functions. Standard errors in parentheses.

Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 2.40: (continued)

Company	Probability of an economically significant profitable deviation
	(0.0000)
OMV	0.0000
	(0.0000)
ONGC	0.0000
	(0.0000)
PDO	0.0000
	(0.0000)
PDV	0.0666 ***
	(0.0001)
Pemex	0.0083 ***
	(0.0009)
Pertamina	0.0583 ***
	(0.0000)
Petro-Canada	0.0000
	(0.0037)
Petrobras	0.0500
	(0.0000)
Petroecuador	0.0000
	(0.0000)
Petronas	0.0333 ***
	(0.0000)
Phillips	0.0000
	(0.0000)
QP	0.0750 ***
	(0.0010)
Repsol	0.0083 ***
	(0.0002)
Rosneft	0.0333 ***
	(0.0005)
Royal Dutch Shell	0.0916 ***
	(0.0012)
Saudi Aramco	0.04160 ***

Notes: We define and calculate a firm's probability of having an economically significant profitable deviation as the fraction of alternative strategies simulated that would yield a payoff, as evaluated using our estimated structural parameters, more than one billion dollars per year higher than would the optimal strategy as given by our estimated policy functions. Standard errors in parentheses.

Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 2.40: (continued)

Company	Probability of an economically significant profitable deviation
	(0.0000)
Sibneft	0.0000
	(0.0000)
Sidanco	0.0000
	(0.0001)
Sinopec	0.0000
	(0.0000)
Slavneft	0.0000
	(0.0000)
SOCAR	0.0000
	(0.0000)
Sonatrach	0.1166 ***
	(0.0013)
SPC	0.0000
	(0.0000)
Statoil	0.0000
	(0.0000)
Surgutneftegas	0.0000
	(0.0000)
Talisman Energy	0.0000
	(0.0000)
Tatneft	0.0000
	(0.0000)
Texaco	0.0000
	(0.0000)
TNK-BP	0.0000
	(0.0000)
Total	0.0000
	(0.0001)
Tyumen Oil	0.0000
	(0.0000)
Unocal Corporation	0.0000

Notes: We define and calculate a firm's probability of having an economically significant profitable deviation as the fraction of alternative strategies simulated that would yield a payoff, as evaluated using our estimated structural parameters, more than one billion dollars per year higher than would the optimal strategy as given by our estimated policy functions. Standard errors in parentheses.

Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 2.40: (continued)

Company	Probability of an economically significant profitable deviation
	(0.0000)
Yukos	0.0000
	(0.0003)

Notes: We define and calculate a firm's probability of having an economically significant profitable deviation as the fraction of alternative strategies simulated that would yield a payoff, as evaluated using our estimated structural parameters, more than one billion dollars per year higher than would the optimal strategy as given by our estimated policy functions. Standard errors in parentheses.

Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 2.41: Determinants of a firm's probability of an economically significant profitable deviation

	Dependent variable is: Statistically significant probability of an economically significant profitable deviation
OPEC membership (dummy)	0.02330
	(0.0189)
State ownership (in percentage)	-0.0001
	(0.0001)
Oil reserves (million barrels)	-2.76e-08
	(1.53e-07)
Natural gas reserves (BCF)	1.05e-07***
	(2.75e-08)
Constant	0.0243**
	(0.0077)
N	300
R^2	0.069

Notes: The value of the dependent variable is zero for firms whose probability of an economically significant profitable deviation is not significant at a 5% level. We define and calculate a firm's probability of having an economically significant profitable deviation as the fraction of alternative strategies simulated that would yield a payoff, as evaluated using our estimated structural parameters, more than one billion dollars per year higher than would the optimal strategy as given by our estimated policy functions. Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

2.10 Appendix B

Table 2.42: Changes in welfare from base case under different demand shocks

	All firms	OPEC firms	Non-OPEC firms
1: Constant in both oil and all regional natural gas demand functions decreases by 10%			
Expected total firm payoff	-7.8270 ***	-8.3398 ***	0.5129
Expected avg firm payoff	-0.1565 ***	-0.6933 ***	0.0081
Expected total consumer surplus	-1.09E+10 ***		
2: Constant in both oil and all regional natural gas demand functions decreases by 25%			
Expected total firm payoff	-4.5229 ***	-7.2810 ***	2.7582 ***
Expected avg firm payoff	-0.0905 ***	-0.5970 ***	0.0656 ***
Expected total consumer surplus	-5.78E+09 ***		
3: Constant in oil demand function decreases by 10%			
Expected total firm payoff	-4.2786 ***	-5.5973 ***	1.3187 **
Expected avg firm payoff	-0.0856 ***	-0.4439 ***	0.0287 **
Expected total consumer surplus	-1.09E+10 ***		
4: Constant in oil demand function decreases by 25%			
Expected total firm payoff	3.2723 ***	1.8484 ***	1.4239 ***
Expected avg firm payoff	0.0654 ***	0.2330 ***	0.0314 **
Expected total consumer surplus	-3.77E+08		

Notes: Table reports the difference between the value of the respective welfare statistic under the counterfactual demand shock scenario, and the value of the respective welfare statistic under the base-case status quo simulation of no counterfactual change. Firm payoffs and consumer surplus are in billion dollars per year. Significance codes from two-sample t-tests comparing the welfare from the counterfactual demand shock scenario to the welfare from the base-case status quo simulation: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 2.43: Changes in welfare from base case under different demand shocks

	All firms	OPEC firms	Non-OPEC firms
5: Constant in natural gas demand function for Africa decreases by 25%			
Expected total firm payoff	-3.1588 ***	-1.6232 ***	-1.5356 ***
Expected avg firm payoff	-0.0632 ***	-0.1475 ***	-0.0395 ***
Expected total consumer surplus	-3.08E+09 ***		
6: Constant in natural gas demand function for Asia & Oceania decreases by 25%			
Expected total firm payoff	8.5882 ***	6.2976 ***	2.2906 ***
Expected avg firm payoff	0.1718 ***	0.6374 ***	0.0537 ***
Expected total consumer surplus	1.01E+10 ***		
7: Constant in natural gas demand function for Eurasia decreases by 25%			
Expected total firm payoff	2.2239 **	-0.0138	2.2377 ***
Expected avg firm payoff	0.0445 **	0.0637	0.0523 ***
Expected total consumer surplus	-9.77E+08		
8: Constant in natural gas demand function for Europe decreases by 25%			
Expected total firm payoff	-3.4513 ***	-1.6069 ***	-1.8444 ***
Expected avg firm payoff	-0.0690 ***	-0.1462 ***	-0.0475 ***
Expected total consumer surplus	-3.38E+09 ***		
9: Constant in natural gas demand function for Middle East decreases by 25%			
Expected total firm payoff	-4.8333 ***	-7.1310 ***	2.2977 ***
Expected avg firm payoff	-0.0967 ***	-0.5834 ***	0.0538 ***
Expected total consumer surplus	-6.08E+09 ***		
10: Constant in natural gas demand function for America decreases by 25%			
Expected total firm payoff	-6.4455 ***	-4.4568 ***	-1.9886 ***
Expected avg firm payoff	-0.1289 ***	-0.4042 ***	-0.0515 ***
Expected total consumer surplus	-5.48E+09 ***		

Notes: Table reports the difference between the value of the respective welfare statistic under the counterfactual demand shock scenario, and the value of the respective welfare statistic under under the base-case status quo simulation of no counterfactual change. Firm payoffs and consumer surplus are in billion dollars per year. Significance codes from two-sample t-tests comparing the welfare from the counterfactual demand shock scenario to the welfare from the base-case status quo simulation: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 2.44: Changes in welfare from base case under different demand shocks

	All firms	OPEC firms	Non-OPEC firms
11: Constant in natural gas demand function for Africa increases by 25%			
Expected total firm payoff	-10.0762 ***	-6.3787 ***	-3.6974 ***
Expected avg firm payoff	-0.2015 ***	-0.6434 ***	-0.0905 ***
Expected total consumer surplus	-9.88E+09 ***		
12: Constant in natural gas demand function for Asia & Oceania increases by 25%			
Expected total firm payoff	3.3807 ***	0.2934	3.0873 ***
Expected avg firm payoff	0.0676 ***	0.0916 **	0.0741 ***
Expected total consumer surplus	-2.28E+09 ***		
13: Constant in natural gas demand function for Eurasia increases by 25%			
Expected total firm payoff	-1.1374	-0.1513	-0.9862 *
Expected avg firm payoff	-0.0227	-0.0138	-0.0254 *
Expected total consumer surplus	-1.77E+08		
14: Constant in natural gas demand function for Europe increases by 25%			
Expected total firm payoff	-7.2221 ***	-4.8451 ***	-2.3770 ***
Expected avg firm payoff	-0.1444 ***	-0.4386 ***	-0.0615 ***
Expected total consumer surplus	-5.48E+09 ***		
15: Constant in natural gas demand function for Middle East increases by 25%			
Expected total firm payoff	-7.7741 ***	-5.8515 ***	-1.9226 ***
Expected avg firm payoff	-0.1555 ***	-0.5320 ***	-0.0496 ***
Expected total consumer surplus	-1.56E+10 ***		
16: Constant in natural gas demand function for America increases by 25%			
Expected total firm payoff	-1.1550	-3.9475 ***	2.7925 ***
Expected avg firm payoff	-0.0231	-0.2939 ***	0.0665 ***
Expected total consumer surplus	-7.58E+09 ***		

Notes: Table reports the difference between the value of the respective welfare statistic under the counterfactual demand shock scenario, and the value of the respective welfare statistic under under the base-case status quo simulation of no counterfactual change. Firm payoffs and consumer surplus are in billion dollars per year. Significance codes from two-sample t-tests comparing the welfare from the counterfactual demand shock scenario to the welfare from the base-case status quo simulation: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

CHAPTER 3

THE EFFECTS OF FUEL SUBSIDIES ON AIR QUALITY: EVIDENCE FROM THE IRANIAN SUBSIDY REFORM

3.1 Introduction

Gasoline consumption an important source of air pollution and a major environmental concern in urban areas (Lin and Prince, 2009; Lin Lawell, 2017). Motor vehicles are the primary source of carbon monoxide (CO), and an important source of volatile organic compounds (VOC) and nitrogen oxides (NO_x, which consist of both nitrogen oxide (NO) and nitrogen dioxide (NO_2)) responsible for the formation of photochemical smog and ground-level ozone (O_3). Vehicular emissions also contribute to the ambient air concentrations of sulfur dioxide (SO_2) and particulate matter (PM_{10}) (U.S. Environmental Protection Agency, 1994; Zhang et al., 2017; Beaudoin and Lin Lawell, 2019).

Gasoline taxes have been touted by many economists as an efficient and relatively simple tool to address environmental concerns and other problems associated with gasoline consumption. Nevertheless, rather than removing subsidies and increasing gasoline taxes, many countries still subsidize gasoline (Lin Lawell, 2017), which may have the opposite effect of exacerbating the environmental concerns and other problems associated with gasoline consumption.

Coady et al. (2017) estimates such global post-tax fossil fuel subsidies and has found that they have reached a staggering \$4.9 trillion worldwide in 2013 and \$5.3 trillion in 2015, representing 6.5% of global GDP. Using detailed measurements of net gasoline taxes and subsidies, Ross et al. (2017) find that 33 countries subsidized gasoline for at least one 12-month period from 2003 to 2015, and 9 countries subsidized gasoline for the entire period. In general, these subsidizing countries also kept their gasoline prices fixed and were economically dependent on oil or natural gas exports. The researchers also find that while two-thirds of the countries in their sample increased their net gasoline taxes from 2003 to 2015, the global mean gasoline tax fell by 13.3 percent due to a shift in consumption towards states that maintain gasoline subsidies or that have low taxes. The data also reveal variation in net gasoline taxes and subsidies across different regions of the world. Europe and North America have the highest net taxes, while oil-rich countries in the Middle East and North Africa have the lowest net taxes. Countries that subsidized gasoline were economically dependent on oil and gas exports, perhaps due to political pressure to distribute resource revenues (Ross et al., 2017).

The prevalence of gasoline subsidies worldwide and the fall in the global mean gasoline tax may exacerbate air pollution owing to the resulting increase in gasoline consumption. Nevertheless, whether gasoline subsidies actually increase air pollution, and the effects of gasoline subsidies on different air pollutants, remain open empirical question not fully addressed in the previous literature, particularly for oil-rich countries in the Middle East and North Africa that have the lowest net taxes.

The Iranian government has heavily subsidized petroleum products since the early 1980s. As a result of these energy subsidies and artificially low national energy price, Iran is one of the most energy-intensive countries in the world. As seen in Figure 3.1, Iran had the highest pre-tax energy subsidies (including subsidies on petroleum, electricity, natural gas, and coal) as a percentage of the GDP amongst the 19 countries in the Middle East and North Africa in 2011.

The Iranian government has recently taken a series of measures to reform and cut back on the energy subsidies. In this paper, we evaluate the effects of the Iranian subsidy reform on air quality using a regression discontinuity design.

Our results provide evidence across multiple different empirical specifications that the subsidy reform in Iran led to improvements in air quality. In particular, the first subsidy reform event, which increased gasoline prices and implemented a gasoline consumption quota; and the second subsidy reform event, which increased energy prices and decreased energy subsidies, both led to declines in concentrations of CO, O_3, and NO_2. In contrast, the fourth subsidy reform event, which increased fuel prices but removed the gasoline consumption quota, was less effective in reducing air pollution.

The balance of our paper proceeds as follows. Section 3.2 reviews the previous literature. Section 3.3 presents an overview of the Iranian Subsidy Reform Plan. We describe our data in Section 3.4. We present out empirical analysis in Section 3.5. We discuss our results and conclude in Section 3.6.

3.2 Previous Literature

3.2.1 Fossil Fuel Subsidies

One strand of literature upon which we build is the literature on fossil fuel subsidies.

Fuje (2018) studies the welfare effects of fossil fuel subsidies through their impacts on food prices. Using a time regression discontinuity design, the author studies the Ethiopian subsidy reform program and finds that removal of fuel subsidies results in higher grain price dispersion which could in turn have heterogeneous welfare effects on different districts in Ethiopia depending on the district's relative share of income from grains.

Gelan (2018) conducts a simulation experiment to study the economic and emission effects of removing energy subsidies in Kuwait. Results indicate that a 25% reduction in subsidies for three energy products could result in significant price hikes and marginally decline the GDP. Under a different scenario a reduction in subsidies combined with transfers could reduce the negative effects of removing subsidies on GDP. This paper suggests that subsidy reform should be combined with demand side stimulus or supply side initiatives to encourage energy conservation.

Aune et al. (2017) look at the oil market impacts and welfare effects of subsidy removal in OPEC and non-OECD countries. They show that the consumption of oil in transport sector of OPEC countries significantly decreases due to phasing out subsidies. This in turn reduces the oil prices and increases consumption in other regions. They also find that total welfare in OPEC is higher mainly due to increase in oil production profits although consumers are worse off.

Zhao et al. (2019) develop an economic optimization model for oil and gas extraction to analyze the effects of producer subsidy removal, and use the model to simulate various scenarios of phasing out producer subsidies in U.S. federal and state regulation on optimal production using field data from the Gulf of Mexico.

Ferraresi et al. (2018) study the effect of decentralization (defined as an increase in the number of government levels) on fuel subsidies using a panel of 108 countries. Their results indicate that both diesel and gasoline subsidies are decreased as governments become more decentralized. Their results also indicate that the decrease in subsidies due to decentralization is more significant when political accountability is lower.

Ghoddusi and Rafizadeh (2018) study the effect of fuel subsidy reform on the behavior of gasoline consumers using three major fuel subsidy reform events in Iran. Their results indicate consistent decline in the gasoline price elasticity following each subsidy reform event.

3.2.2 Fossil Fuels and Iran

In addition to the literature on fossil fuel subsidies, we also build upon the literature on fossil fuels in Iran.

Ghandi and Lin (2012) examine the National Iranian Oil Company's (NIOC) actual and contractual oil production behavior on Iran's offshore Soroosh and Nowrooz fields, which have been developed by Shell Exploration through a buy-back service contract.

Ghoddusi et al. (2018) apply difference-in-differences and panel estimation methods to estimate the price elasticity of gasoline smuggling in Iran. Their results indicate that the foreign-to-home gasoline price ratios have a significant effect on the elasticity of demand.

Farzanegan and Krieger (2018) study the short and long run responses of income inequality to positive per capita oil and gas rent shocks in Iran, and find a positive and statistically significant response of income inequality to oil rent booms within 4 years of the shock.

3.3 Background

3.3.1 Air Pollution in Iran

The air in Tehran, the capital of the Islamic Republic of Iran (IRI), is amongst the most polluted in the world (Heger and Sarraf, 2018). There are more than 17 million vehicular trips per day in Tehran (Hosseini and Shahbazi, 2016), and many of the vehicles have outdated technology (Heger and Sarraf, 2018). Topography and climate add to the pollution problem: Tehran is at a high altitude and is surrounded by the Alborz Mountain Range, which traps polluted air; and temperature inversion, a phenomenon particularly occurring during the winter months, prevents the pollutants from being diluted. Rapid population growth, industrial development, urbanization, and increasing fuel consumption make reducing air pollution in Tehran difficult (Heger and Sarraf, 2018).

Iran's Department of the Environment estimates that 85 percent of nitrogen oxides emissions (which include NO_2 emissions) and over 90 percent of hydrocarbon (HC) and carbon monoxide (CO) emissions in Tehran are caused by motor vehicles (Zerbonia and Soraya, 1978). Other studies estimate that approximately 80 percent nitrogen oxides (which include NO_2), PM_{10}, and CO in Tehran are produced by mobile sources (Azarmi and Arhami, 2017).

In Tehran, 70 percent of particular matter emissions come from mobile sources (vehicles). Power plants and refineries are responsible for about 20 percent of particular matter emissions; industrial sources and gas terminals emit 8 percent; and households and commercial sources are responsible for the remaining 2 percent (Heger and Sarraf, 2018).

3.3.2 Iranian Subsidy Reform

In Iran, domestic energy prices, including gasoline prices, are set administratively rather than by the market. The Iranian government has heavily subsidized petroleum products, utilities, as well as a few food products for over three decades since the early 1980s. These subsidies were originally introduced to manage the economic challenges during the war against Iraq. As seen in Figure 3.1, Iran had the highest pre-tax energy subsidies (including subsidies on petroleum, electricity, natural gas, and coal) as a percentage of the GDP amongst the 19 countries in the Middle East and North Africa in 2011. The World Bank (2016) estimated the overall indirect subsidies in 2007-2008 to be $77.2 billion, about 27 percent of the country's GDP. Prior to the recent subsidy reforms, an average Iranian household of four received about $4,000 annually in various subsidies on oil and natural gas alone (Guillaume et al., 2011). Over the last four decades, energy prices in Iran have changed only a handful of times, each time after remaining constant for long period. As a result of these energy subsidies and artificially low national energy price, Iran is one of the most energy-intensive countries in the world.

Redistribution of wealth and helping the poor is the primary reason for energy subsidies. Many countries in this region have started subsidy reform programs as they realized that there are huge economic costs hidden in their subsidy programs and the wealth redistribution was inefficient since the benefits go mainly to the wealthy. Pricing energy below cost is inefficient as it leads to overconsumption and causes deadweight loss. Under certain assumptions about supply and demand elasticities, Davis (2014) estimates the annual deadweight loss caused by fuel subsidies worldwide to be over $44 billion in year 2012.

In addition to deadweight loss, there are other distortions caused by pricing energy below cost which increases the economic cost of energy subsidies. These include, for instance, environmental damages caused by overconsumption among the major external costs of subsidies.

The Iranian government has recently taken a series of measures to reform and cut back on the energy subsidies. The first subsidy reform event took place on June 27, 2007. As part of the first subsidy reform event, in order to control fuel smuggling activities the government announced a price hike for gasoline and issued a fuel card for each vehicle owner introducing a 60 liter monthly quota for each vehicle. The 60 liter monthly quota (with roll over) was for gasoline and premium gasoline only. After the introduction of fuel card (gasoline card) each vehicle could buy 60 liters of gasoline or premium gasoline per month at the ”subsidized” price, after which they have to pay the higher price. For example, after the first reform event on June 27, 2007, a fuel card holder could buy 60 liters of gasoline at 1000 IRR (100 Iranian Toman [1]) per liter, and once the 60 liter quota is used they had to pay 4000 IRR (400 Toman) per liter. To buy gasoline exceeding the 60 liter quota one had to pay a significantly higher price. This price hike was another component of the first subsidy reform event.

The second subsidy reform event took place on December 18, 2010, when the Iranian government implemented the first phase of the Iranian subsidy reform plan, announcing a significant increase in energy prices as well as the prices of subsidized agricultural products (by up to 20 times). Under this plan, the government removed an estimated US$50-US$60 billion dollars in subsidies on key staples such as petroleum products and utilities. The government used the savings to provide universal direct monthly cash transfers to each household, direct assistance to enterprises adjusting to the new price structure, and direct assistance to the government agencies to help pay for higher energy bills.

The third subsidy reform event took place on April 24, 2014, when the Iranian government implemented the second phase of the Iranian subsidy reform plan, decreasing subsidies further and causing fuel prices to experience another significant increase.

The fourth subsidy reform event took place on May 27, 2015, when the Iranian government announced even higher fuel prices and abandoned the gasoline consumption quota restriction and the fuel card program altogether.

Table 3.1 lists the 4 major Iranian subsidy reform events. Table 3.2 summarizes the energy and utility prices during the subsidy reform.

Before event 2, the first phase of subsidy reform which took place on December 18, 2010, the daily gasoline consumption on average was between 54-55 million liters. Just over 3 weeks later, the daily average gasoline consumption reported to be 44 million liters on Jan 10, 2011. This is a decline of 10 million liters, or 18.5%, in gasoline consumption in the national level. There was also a 11 million liter reduction in daily diesel fuel consumption in transportation sector, and a 20 million cubic meter reduction in daily natural gas consumption (Khajehpour, 2018)

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[1] Each Iranian Toman is equivalent to 10 IRR

Nevertheless, as seen in Figures 3.2.A-3.2.B, gasoline consumption continued to have an upward trend following events 2, 3, and 4. In contrast, as seen in Figures 3.3.A-3.3.B, diesel consumption had a downward trend following events 3 and 4.

As seen in Figure 3.4, even despite the Iranian subsidy reform, gasoline prices in Iran continue to be among the lowest in the world in 2017.

3.4 Data

For our air quality data, we use data from the Tehran Air Quality Control Company[2] on the daily average concentrations and hourly mean concentrations of five air pollutants (CO, O_3, NO_2, SO_2, and PM_{10}) from 24 monitoring stations in Tehran over the period March 21, 2007 to March 19, 2017 (corresponding to the dates 1386/1/1 to 1395/29/12 in the Iranian Calendar).

From the hourly mean air quality data, we create variables for the daily maximum pollution concentration for each of the five air pollutants. For each pollutant, each day, and each monitoring station, this is the maximum value of all hourly values of that pollutant for that day and monitoring station. For each pollutant, there is a separate observation of the daily maximum pollution level for that pollutant for each day for each monitoring station.

The weather data are from the Mehrabad Airport and IKI Airport weather monitoring stations. This is daily data on two weather stations near Tehran. Mehrabad Airport and IKI Airport are the two airports serving Tehran and there is daily weather data available for these two stations. The source of the weather data is the National Oceanic and Atmospheric Administration (NOAA) (2018).

Figure 3.5 shows the local air quality monitoring stations across Tehran. Figure 3.6 shows both the local air quality monitoring stations across Tehran and the weather monitoring stations near Tehran.

Table 3.3 presents the summary statistics for the daily average pollution concentration and the daily maximum pollution concentration for each of the five air pollutants (CO, O_3, NO_2, SO_2, and

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[2] `http://air.tehran.ir/`

PM_{10}).

Table 3.4 presents the summary statistics for the weather data, averaged over both weather stations near Tehran. Table 3.5 presents the summary statistics for the weather data using data from the Mehrabad Airport weather monitoring station, which is closer to our air quality monitoring stations, only. The weather data are very similar whether or not we average over both stations or use just the data from the closer station. The correlation coefficient between daily average temperature averaged across both airports and daily average temperature at Mehrabad airport is 0.9989. The correlation coefficient between daily maximum sustained wind speed averaged across both airports and daily maximum sustained wind speed at Mehrabad airport is 0.8723. As shown below, our empirical results are robust to whether or not we average the weather data over both stations or use just the weather data from the closer station.

Figure 3.7 plots mean daily pollution levels for each of the five pollutants for the time period 1997 to 2009. Mean daily pollution levels are constructed by averaging the hourly mean concentration over all hours in a day and over all monitoring stations. The vertical lines indicate the dates when each of the four subsidy reform events: June 27, 2007; December 18, 2010; April 24, 2014; and May 27, 2015.

3.5 Empirical analysis

To analyze the impact of the energy subsidy reform on air quality, we use a regression discontinuity design. A regression discontinuity design can be used when observations can be ordered according to a forcing (or running) variable and then the treatment is assigned above a given threshold. In our case, the forcing variable is time and the threshold is the date a phase of the Iranian subsidy reform plan was implemented (Percoco, 2014). Previous studies that have used a regression discontinuity design with time as the forcing variable to evaluate environmental and energy policy include Davis (2008); Auffhammer and Kellogg (2011); Salvo and Wang (2017); Zhang et al. (2017); Hausman and Rapson (2018) provide an excellent review of these studies and a guide for practitioners. In a regression discontinuity design, there is no value of the forcing variable at which we observe both treatment and control observations; instead, we extrapolate across covariate values, at least in a neighborhood of the discontinuity (Angrist and Pischke, 2009; Imbens and Lemieux, 2008).

We augment our polynomial regression discontinuity estimator with covariates entering in an additively separable, linear-in-parameters way; Calonico et al. (2019) shows that the resulting covariate-adjusted regression discontinuity estimator remains consistent for the standard regression discontinuity treatment effect and can achieve substantial efficiency gains relative to the unadjusted regression discontinuity estimator.

In particular, we use the following regression discontinuity design for each pollutant j:

$$\ln y_{ijt} = \beta_1 D_{1t} + \beta_2 D_{2t} + \beta_3 D_{3t} + \beta_4 D_{4t} + x_t'\gamma + \tau_t + \alpha_i + \epsilon_{ijt}, \tag{3.1}$$

where y_{ijt} is the amount of pollutant j measured at station i on day t, D_{nt} is a subsidy reform indicator variable which equals one for all the days covered by subsidy reform event n and zero otherwise, x_t is a vector of covariates, τ_t are year effects, and α_i is a station fixed effect. We include four subsidy reform indicators D_{nt} in the specification, one for each of the four events of the subsidy reform listed in Table 3.1, where D_{nt} is equal to 1 if day t is after event n and before event $n+1$, and 0 otherwise. The vector of covariates x_t includes indicator variables for month of the year and day of the week; fourth-order polynomials in log daily average temperature and log daily maximum sustained wind speed; and a ninth-order polynomial time trend.[3] The coefficients of interest are the coefficients β_n on the four events n of the subsidy reform, as they capture the effect of the different events of the subsidy reform on air quality.

Our regression discontinuity design addresses the potential bias caused by time-varying omitted variables. Within a narrow time window, the unobserved factors influencing air quality are likely to be similar so that observations when the subsidy reform was not in effect provide a comparison

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[3] The validity of regression discontinuity estimates of causal effects depends on whether the polynomial models provide an adequate description of the counterfactual conditional mean of the dependent variable, conditional on time. If not, then what may look like a jump due to treatment might simply be an unaccounted-for nonlinearity in the counterfactual conditional mean function (Angrist and Pischke, 2009). We therefore use a higher order polynomial to account for any nonlinearities in the counterfactual conditional mean function. We use a ninth-order polynomial time trend because the ninth-order time trend term is often significant, and because our results are robust to whether we also include a tenth-order time trend term.

group for observations when the subsidy reform was in effect.

The station fixed effects α_i control for time-invariant station heterogeneity. The indicator variables for month of the year control for monthly variation in driving patterns and other factors that affect air quality. Similarly, the indicator variables for day of the week control for intra-week variation in driving patterns and other factors that affect air quality.

For the year effects τ_t, we define each year to be from July 1st to June 30th so that events 2 and 3, which are the events during which there were the largest changes in prices, occur almost in the middle of each corresponding year.

Figure 3.8 plots residuals from a regression of log daily average pollution concentration levels on weather and seasonality covariates and station fixed effects for each of the five air pollutants (CO, O_3, NO_2, SO_2, and PM_{10}). The fitted lines are the predicted values of a regression of these residuals on subsidy reform dummies and a ninth-order polynomial time trend. Again, the vertical lines indicate the dates of each subsidy reform event. For all pollutants, the ninth-order polynomial seems to describe the underlying time trend adequately while maintaining some degree of smoothness. According to Figure 3.8, events 1 and 2 seem to led to a drop in daily average pollution concentrations for all five air pollutants; and daily average pollution concentrations for O_3 and NO_2 appear to have declined at each of the 4 events. The effects of events 3 and 4 on daily average concentrations of CO, SO_2, and PM_{10} appear more mixed, however.

The results from the regression discontinuity using daily average pollution concentration levels and a ninth-order polynomial time trend are shown in Table 3.6.A. For each pollutant, each row reports coefficients corresponding to different driving subsidy reform event indicator variables. Following Davis (2008), we report standard errors that are robust to heteroskedasticity and arbitrary correlation within 5-week clusters. Since we analyze the effects of the driving restrictions on 5 different pollutants, we apply the Bonferroni correction to adjust for multiple hypothesis testing (Bland and Altman, 1995; Napierala, 2012). According to the results, each of the four subsidy reform events has a significant negative effect on the daily average concentrations of each of the five air pollutants (CO, O_3, NO_2, SO_2, and PM_{10}). The results are robust to whether we use an eighth-order polynomial time trend (Table 3.6.B) or tenth-order polynomial time trend (Table 3.6.C) instead.[4] The results are also robust to whether we average the weather data over both weather stations near Tehran, or if we instead use just the weather data from the Mehrabad Airport weather monitoring station, which is closer to our air quality monitoring stations 3.7.A-3.7.B.

The magnitudes of our significant coefficients in Tables 3.6.A-3.7.B range from 0.2150 to 0.8397, meaning that the respective event of the subsidy reform can decrease the daily average concentration of the respective pollutant by 21.50 to 83.97 percentage points. As seen in the summary statistics in Table 3.3, the standard deviations of the daily average pollution concentrations are quite large, and the maximum values of the daily average pollution concentrations can be up to 179.67 times the minimum value of the the daily average pollution concentrations of the respective pollutant. Thus, increases in daily average or daily maximum pollution concentrations of 21.50 to 83.97 percentage points as a result of the subsidy reform events are reasonable, since the range in daily average pollution concentrations can be even higher.

Figure 3.9 plots residuals from a regression of log daily maximum pollution concentrations levels on weather and seasonality covariates and station fixed effects for each of the 5 pollutants. The weather covariates are a fourth-order polynomial in log daily average temperature and log daily max sustained wind speed. The seasonality covariates include dummies for each month of the year and dummies for each day of the week. The fitted lines are the predicted values of a regression of these residuals on subsidy reform dummies and a ninth-order polynomial time trend. Again, the vertical lines indicate the dates of each subsidy reform event. For all pollutants, the ninth-order polynomial seems to describe the underlying time trend adequately while maintaining some degree of smoothness. According to Figure 3.9, events 1 and 2 seem to led to a drop in daily maximum pollution concentrations for all five air pollutants; and daily maximum pollution concentrations for O_3 and NO_2 appear to have declined at each of the 4 events. The effects of events 3 and 4 on daily maximum concentrations of CO, SO_2, and PM_{10} appear more mixed, however.

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[4] For all our regression discontinuity models with higher-order polynomial time trends, the results are identical whether we use a ninth-order polynomial or a tenth-order polynomial. We therefore do not present the results using a tenth-order polynomial time trend in the subsequent variants of our model.

The results from the regression discontinuity using daily maximum pollution concentration levels are shown in Table 3.8.A. According to the results, each of the four subsidy reform events has a significant negative effect on the daily maximum concentrations of each of the five air pollutants (CO, O_3, NO_2, SO_2, and PM_{10}). The results are robust to whether we use an eighth-order polynomial time trend (Table 3.8.B) or tenth-order polynomial time trend instead. The results are also robust to whether we average the weather data over both weather stations near Tehran, or if we instead use just the weather data from the Mehrabad Airport weather monitoring station, which is closer to our air quality monitoring stations 3.9.A-3.9.B

The magnitudes of our significant coefficients in Tables 3.8.A-3.9.B range from 0.2870 to 1.0972, meaning that the respective event of the subsidy reform can decrease the d daily maximum concentration of the respective pollutant by 28.70 to 109.72 percentage points. As seen in the summary statistics in Table 3.3, the standard deviations of the daily maximum pollution concentrations are quite large, and the maximum values of the daily maximum pollution concentrations can be up to 191.33 times the minimum value of the daily maximum pollution concentrations of the respective pollutant. Thus, increases in daily average or daily maximum pollution concentrations of 28.70 to 108.72 percentage points as a result of the subsidy reform events are reasonable, since the range in daily average and daily maximum pollution pollutant concentrations can be even higher.

An underlying assumption for regression discontinuity designs is that the forcing variable, which in our case is time, should be balanced around the cutoff, which in the case of our regression discontinuity model of the effect of the first event of the subsidy reform is the implementation of the first event of the subsidy reform on June 27, 2007 (Imbens and Lemieux, 2008; Lee and Lemieux, 2010; Beach and Jones, 2017). To examine the distribution of the forcing variable (time) at the threshold (the implementation of the first event of the subsidy reform on June 27, 2007), we plot the number of observations per week against the week away from June 27, 2007 for each pollutant. The results for each pollutant are in Figure 3.10. As these graphs show, the distribution is continuous around the threshold, so the forcing variable is balanced around the cutoff. This continuity of the distribution around the threshold is evidence against any manipulation of whether air quality measurements were taken before or after the subsidy reform.

The cutoff for our regression discontinuity model of the effect of the second event of the subsidy reform is the implementation of the second event of the subsidy reform on December 18, 2010. To examine the distribution of the forcing variable (time) at the threshold (the implementation of the second event of the subsidy reform on December 18, 2010), we plot the number of observations per week against the week away from December 18, 2010 for each pollutant. The results for each pollutant are in Figure 3.11. As these graphs show, the distribution is continuous around the threshold, so the forcing variable is balanced around the cutoff. This continuity of the distribution around the threshold is evidence against any manipulation of whether air quality measurements were taken before or after the subsidy reform.

The cutoff for our regression discontinuity model of the effect of the third event of the subsidy reform is the implementation of the third event of the subsidy reform on April 24, 2014. To examine the distribution of the forcing variable (time) at the threshold (the implementation of the third event of the subsidy reform on April 24, 2014), we plot the number of observations per week against the week away from April 24, 2014 for each pollutant. The results for each pollutant are in Figure 3.12. As these graphs show, the distribution is continuous around the threshold, so the forcing variable is balanced around the cutoff. This continuity of the distribution around the threshold is evidence against any manipulation of whether air quality measurements were taken before or after the subsidy reform.

The cutoff for our regression discontinuity model of the effect of the fourth event of the subsidy reform is the implementation of the fourth event of the subsidy reform on May 27, 2015. To examine the distribution of the forcing variable (time) at the threshold (the implementation of the fourth event of the subsidy reform on May 27, 2015), we plot the number of observations per week against the week away from May 27, 2015 for each pollutant. The results for each pollutant are in Figure 3.13. As these graphs show, the distribution is continuous around the threshold, so the forcing variable is balanced around the cutoff. This continuity of the distribution around the threshold is evidence against any manipulation of whether air quality measurements were taken before or after the subsidy reform.

Another underlying assumption for regression discontinuity designs is that there are no discontinuous changes in the control variables at the time of the various subsidy reform events. To examine if there were any discontinuous changes in the control variables at the time of the various subsidy reform events, Tables 3.10 and 3.11 present results of regression discontinuity analyses of our daily weather variables: log daily average temperature and log daily maximum sustained wind speed, respectively. None of the subsidy reforms had any significant effect on any of the weather variables.

To further examine differences in the effects of the different events of the subsidy reform, we also run a 'post-reform' set of regressions in which we redefine the four subsidy reform indicators D_{nt} in the specification to equal to 1 if day t is after event n, even if a subsequent event has begun, and 0 otherwise.

As seen in Tables 3.12.A-3.12.B, for the 'post-reform' regressions, the subsidy reform events generally have a significant negative effect on daily average pollution concentrations, though the effect is no longer negative and significant for all pollutants for all events. In addition, event 3 now has a significant positive effect on daily average concentrations of CO and SO_2, and event 4 now has a significant positive effect on daily average concentrations of SO_2 and PM_{10}.

Similarly, as seen in Tables 3.13.A-3.13.B, for the 'post-reform' regressions, the subsidy reform events generally have a significant negative effect on daily maximum pollution concentrations, though the effect is no longer negative and significant for all pollutants for all events. In addition, event 3 now has a significant positive effect on daily maximum concentrations of CO, and event 4 now has a significant positive effect on daily maximum concentrations of SO_2 and PM_{10}.

To examine the robustness of our results, we run placebo tests for each of our regression discontinuity regression models using placebo subsidy reform dates instead of the actual subsidy reform dates as the treatment. If we do not find significant treatment effects where there has been no treatment, then this means that our results are robust to our tests.

Since the implementation of the first event of the subsidy reform on June 27, 2007 took place on the fourth Wednesday of the month, we choose as our placebo date for the first subsidy reform event a fourth Wednesday prior to the first event of the subsidy reform: Wednesday, March 28, 2007. For the placebo test of the first event of the subsidy reform, we use data from before the first subsidy reform event only (i.e., before June 27, 2007).

Since the implementation of the second event of the subsidy reform on December 18, 2010 took place on the third Saturday of the month, we choose as our placebo dates for the second subsidy reform event a third Saturdays of the month, and, following Imbens and Lemieux (2008), one that was roughly in the middle of the relevant sample period between the first and second subsidy events: Saturday, June 21, 2008. For the placebo test of the second event of the subsidy reform, we use data from after the first subsidy reform event but before the second subsidy reform event only (i.e., after June 27, 2007 but before December 18, 2010).

Since the implementation of the third event of the subsidy reform on April 24, 2014 took place on the fourth Thursday of the month, we choose as our placebo date for the third subsidy reform event a fourth Thursday, and, following Imbens and Lemieux (2008), one that was roughly in the middle of the relevant sample period between the second and third subsidy events: Thursday, June 27, 2013. For the placebo test of the third event of the subsidy reform, we use data from after the second subsidy reform event but before the third subsidy reform event only (i.e., after December 18, 2010 but before April 24, 2014).

Since the implementation of the fourth event of the subsidy reform on May 27, 2015 took place on the fourth Wednesday of the month, we choose as our placebo date for the fourth subsidy reform event a fourth Wednesday of the month, and, following Imbens and Lemieux (2008), one that was roughly in the middle of the relevant sample period between the third and fourth subsidy events: Wednesday, November 19, 2014. For the placebo test of the fourth event of the subsidy reform, we use data from after the third subsidy reform event but before the fourth subsidy reform event only (i.e., after April 24, 2014 but before May 27, 2015).

The results of the placebo tests of the regression discontinuity models using daily average pollution concentration levels and a ninth-order polynomial time trend in Table 3.12.A) are presented in Table 3.14. As seen in Table 3.14, none of the placebo treatment effects are significant and negative for any of the pollutants, and the one placebo treatment effects that is statistically significant at a 5% level is positive, not negative. Thus, since we do not find any significant negative treatment effects where there has been no treatment, and since we find very few significant treatment effects where there has been no treatment, this means that our results are robust to our tests.

The results of the placebo tests of the regression discontinuity models using daily maximum pollution concentration levels are shown in Table 3.13.A are presented in Table 3.15. As seen in Table 3.15, none of the placebo treatment effects are significant and negative for any of the pollutants, and the one placebo treatment effect that is statistically significant at a 5% level is positive, not negative. Thus, since we do not find any significant negative treatment effects where there has been no treatment, and since we find very few significant treatment effects where there has been no treatment, this means that our results are robust to our tests.

Automobile emissions are not a primary source of emissions of SO_2, which may be more related to industrial activity than to driving behavior (Zhang et al., 2017). In Tehran, industrial sources, domestic and commercial heating are responsible for nearly all the SO_2 emissions (Massoudi, 1977). Thus, following Gallego et al. (2013), we include SO_2 as a control variable rather than as a dependent variable, in order to control for any changes in industrial activity that may have been correlated with the energy subsidy reform events.

As seen in Tables 3.16.A-3.16.B, when controlling for SO_2, event 1 no longer has a statistically significant effect on the daily average concentrations of any of the remaining pollutants (O_3, CO, NO_2, PM_{10}); event 2 has a significant negative effect on daily average concentrations of O_3 and CO; event 3 has a significant negative effect on daily average concentrations of NO_2 and PM_{10}; and event 4 has a significant positive effect on the daily average concentration of PM_{10}.

Similarly as seen in Tables 3.17.A-3.17.B, when controlling for SO_2, event 1 has a significant positive effect on the daily maximum concentration of PM_{10}; event 2 has a significant negative effect on daily maximum concentrations of O_3 and CO; event 3 has a significant negative effect on daily maximum concentrations of NO_2 and PM_{10}; and event 4 has a significant positive effect on the daily maximum concentration of PM_{10}.

We also run regression discontinuity regressions for each event that use only data from a time window before and after each respective event, where the window range from a window spanning 8 weeks before to 8 weeks after the event; to a window spanning 50 weeks before to 50 weeks after the event. As seen in the results for events 1-4 are in Tables 3.18.A-3.18.D, respectively, events 1 and 2 tend to have effects on pollutants, when significant, that are negative; while events 3 and 4 have effects on pollution, when significant, that can be positive or negative. As seen in Tables 3.19.A-3.19.D, results are similar when we use SO_2 as a control rather than a dependent variable.

Gelman and Imbens (2018) recommend using local polynomial regressions instead of high-order global polynomials in regression discontinuity design. We therefore run a set of specifications using the local polynomial regression discontinuity robust bias-corrected confidence intervals and inference procedures developed in Calonico et al. (2014), Calonico et al. (2018), and Calonico et al. (2019). The confidence intervals are constructed using a bias-corrected regression discontinuity estimator together with a novel standard error estimator proposed in Calonico et al. (2014). In particular, the confidence intervals are constructed using an alternative asymptotic theory for bias-corrected local polynomial estimators in the context of regression discontinuity designs, which leads to a different asymptotic variance in general and thus justifies a new standard error estimator. Bandwidth choices that minimize asymptotic mean squared error (MSE) are derived following Imbens and Kalyanaraman (2012). Calonico et al. (2014) find that the resulting data-driven confidence intervals performed very well in simulations, suggesting in particular that they provide a robust (to the choice of bandwidths) alternative when compared to the conventional confidence intervals routinely employed in empirical work. Hyytinen et al. (2018) similarly find that bias-corrected regression discontinuity design estimates that apply robust inference are in line with the experimental estimate from an experiment that takes place exactly at the cutoff.

In particular, we run the local linear regression discontinuity regressions with robust confidence intervals proposed in Calonico et al. (2014) of residuals from a regression of log daily average pollution concentration levels on weather and seasonality covariates, station fixed effects, and year effects for each of the five air pollutants (CO, O_3, NO_2, SO_2, and PM_{10}). We similarly run the local linear regression discontinuity regressions with robust confidence intervals proposed in Calonico et al. (2014) of residuals from a regression of log daily maximum pollution concentration levels on weather and seasonality covariates and station fixed effects for each of the five air pollutants (CO, O_3, NO_2, SO_2, and PM_{10}). The weather covariates are a fourth-order polynomial in log daily average temperature and log daily max sustained wind speed. The seasonality covariates include dummies for each month of the year and dummies for each day of the week.

Residual plots that plot residuals from a regression of log daily average pollution concentration levels on weather and seasonality covariates, station fixed effects, and year effects on a local linear regression discontinuity regression on day, using data within a window of 20 weeks before to 20 weeks after each respective event, are presented in Figures 3.14.A-3.14.D for the daily average pollution concentrations and Figures 3.15.A-3.15.D for the daily maximum pollution concentrations. The residual plots suggest that events 1, 2, and 3 each caused declines in the daily average and daily maximum concentrations of each pollutant, but the effects of event 4 are more mixed.

The regression results of the local linear regression discontinuity regressions with robust confidence intervals for windows ranging from 8 to 50 weeks before and after each respective event are presented in Tables 3.20.A-3.20.D. Event 1 has a significant negative effect on daily maximum and daily average O_3 and PM_{10}, and a significant negative effect on daily average NO_2 in the short run. Event 2 has a significant negative effect on daily maximum and daily average CO, O_3, and NO_2. Event 3 has a significant negative effect on daily maximum and daily average SO_2. Event 4 has a significant negative effect on daily maximum and daily average O_3 and NO_2, but a significant positive effect on daily average PM_{10}.

We run placebo tests of the local linear regression discontinuity regressions with robust confidence intervals for windows ranging from 8 to 50 weeks before and after each respective event in Tables 3.21.A-3.21.D. Results of the placebo tests show that none of the placebo treatment effects are significant and negative for any of the pollutants, and that the few placebo treatment effects that are statistically significant at a 5% level are positive, not negative. Thus, since we do not find any significant negative treatment effects where there has been no treatment, and since we find very few significant treatment effects where there has been no treatment, this means that our results are robust to our tests.

When we control for SO_2, the results of the local linear regression discontinuity regressions with robust confidence intervals for windows ranging from 8 to 50 weeks before and after each respective event are presented in Tables 3.22.A-3.22.D. Event 1 has a significant negative effect on daily maximum and daily average PM_{10}, and a significant negative effect on daily maximum O_3. Event 2 has a significant negative effect on daily maximum and daily average CO, O_3, and NO_2; but a significant positive effect on daily average and daily maximum PM_{10} in the short run. Event 3 has a significant positive effect on daily maximum and daily average NO_2 in the long run. Event 4 has a significant negative effect on daily maximum and daily average O_3, but a significant positive effect on daily average and daily maximum PM_{10}.

We also run a set of local linear regression discontinuity regressions with robust confidence intervals where we bootstrap the standard errors over both stages of the estimation, where the first-stage regression of log daily average pollution concentration levels on weather and seasonality covariates, station fixed effects, and year effects from which we derive residuals; and the second stage is the local linear regression of residuals. In particular, monitoring stations are randomly drawn from the data set with replacement to generate multiple independent panels each with the sample number of stations in the original data set. We then run both stages on each of the new panels. The standard errors are then formed by taking the standard deviation of the bias-corrected local-polynomial regression discontinuity estimates from each of the panels. Only CO and O_3 had enough observations to run this bootstrap, and only for windows ranging from 10 to 50 weeks before and after each respective event. The results are presented in Tables 3.23.A-3.23.D. Event 1 has a significant negative effect on daily average and daily maximum O_3. Event 2 has a significant negative effect on daily average and daily maximum O_3, and a significant negative effect on daily average CO. Event 3 has a significant positive effect on daily average and daily maximum O_3 in the longer run, and a significant positive effect on daily average CO. Event 4 has a significant negative effect on daily average and daily maximum O_3.

We also run a set of local linear regression discontinuity regressions with robust confidence intervals where we bootstrap the standard errors over both stages of the estimation, this time using SO_2 as a control. Only CO and O_3 had enough observations to run this bootstrap, and only for windows ranging from 30 to 50 weeks before and after each respective event. The results are presented in Tables 3.24.A-3.24.D. Event 1 has a significant negative effect on daily average and daily maximum O_3. Event 2 has a significant negative effect on daily average and daily maximum O_3, and on daily average and daily maximum CO. Event 3 has a significant positive effect on daily average O_3 in the longer run. Event 4 has a significant negative effect on daily maximum O_3.

We also run a set of regressions allowing for adjustment over time, adapting a model developed by Gallego et al. (2013). As these adjustment models do not pass the placebo tests, however, this evidence is weak at best and we therefore do not present these results.

3.6 Discussion and Conclusion

In Tehran, motor vehicle emissions are major sources of CO, O_3, NO_2, and PM_{10} (Zerbonia and Soraya, 1978; Azarmi and Arhami, 2017; Heger and Sarraf, 2018), but not a primary source of SO_2 (Massoudi, 1977; Zhang et al., 2017).

Our results provide evidence across multiple different empirical specifications that the subsidy reform in Iran, especially first two subsidy reform events, led to improvements in air quality and declines in concentrations of CO, O_3, and NO_2.

The possible effects of changes in driving on ozone (O_3) are more complicated. A secondary pollutant, ozone is not emitted directly but is formed in ambient air in the presence of sunlight by chemical reactions involving nitrogen oxides (NO_x), which consist of nitrogen oxide (NO) and nitrogen dioxide (NO_2); and volatile organic compounds (VOCs) (Lin, 2000; Lin et al., 2000, 2001; Lin, 2010). Higher emissions of NO_x do not always result in higher levels of ozone pollution; in some cases, higher NO_x emissions may actually decrease ozone, a phenomenon known as NO_x titration (Lin, 2010). Nevertheless, we find evidence that subsidy reform can decrease O_3.

Vehicles fueled by gasoline have different effects on air pollution than do vehicles fueled by diesel, and these effects vary by air pollutant. In the absence of particle traps, diesel CO emissions are similar to those from gasoline. However, "modern" diesel vehicles with particle traps have lower CO emissions and lower hydrocarbon emissions than gasoline vehicles (Jacobson et al., 2004). Diesel vehicles with or without a particle trap and without a NO_x control device emit 4-30 times more NO_x than do gasoline vehicles (Jacobson et al., 2004). In addition, diesel vehicles have higher particulate matter emission rates than gasoline vehicles (Onursal and Gautam, 1997; Zhang et al., 2017). Diesel vehicles with or without a particle trap and without a NO_x control device also emit a higher ratio of NO_2 to NO than do gasoline vehicles, and as a consequence, may increase O_3 particularly under certain circumstances (Jacobson et al., 2004; Zhang et al., 2017).

As seen in Figures 3.2.A-3.2.B, gasoline consumption continued to have an upward trend following events 2, 3, and 4. Moreover, Ghoddusi and Rafizadeh (2018) find that the gasoline price elasticity declined following each subsidy reform event. In contrast, as seen in Figures 3.3.A-3.3.B, diesel consumption had a downward trend following events 3 and 4.

There are several possible explanations for why the first subsidy reform event, which increased gasoline prices and implemented a gasoline consumption quota; and the second subsidy reform, which increased energy prices and decreased energy subsidies, both led to declines in concentrations of CO, O_3, and NO_2; but event 3, which further increased fuel prices; and event 4, which increased fuel prices even more but removed the gasoline consumption quota, had more mixed results.

First, our result that the later subsidy reform events were less effective in reducing air pollution is consistent with the result of Ghoddusi and Rafizadeh (2018) that consumers were becoming less responsive to increases in fuel prices at each subsequent subsidy reform event, since this would mean that energy consumption, and hence air pollution, would not decline as much in the later subsidy reform events.

Second, event 4 may have been less effective in reducing air pollution because it removed the gasoline consumption quota. As seen in Figures 3.2.A-3.2.B, gasoline consumption continued to have an upward trend following events 2, 3, and 4.

Third, there are news reports indicating that around the time of event 4, Tehran experienced about a week of very dry weather with high winds, which may explain the significant increase in PM$_1$0 concentrations at the time of event 4. This news article about the air quality of Tehran during last week of May 2015 also mentions that particulate matters are reported to be migrating from western Iran towards Tehran (Khabaronline.ir, 2015).

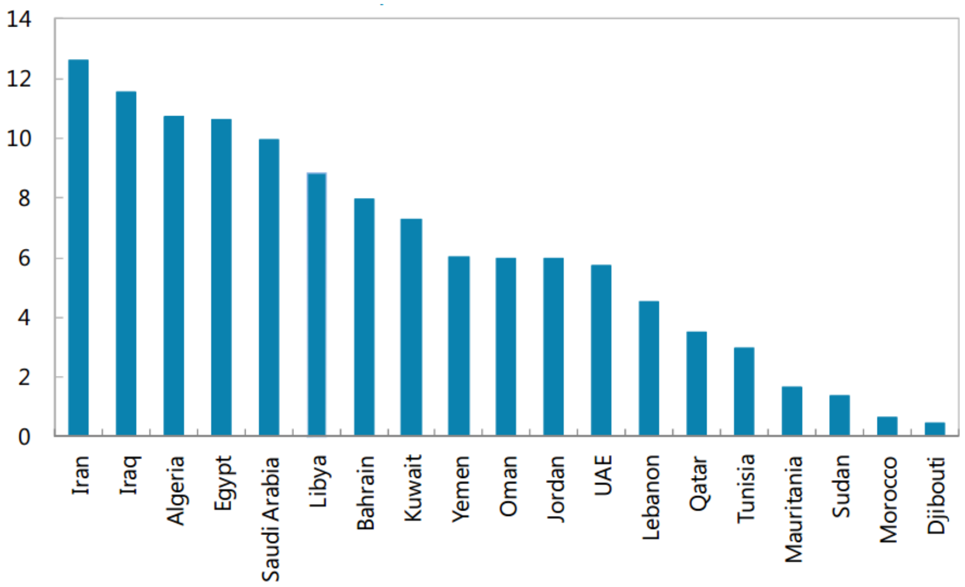
Our results provide evidence across multiple different empirical specifications that the subsidy reform in Iran led to improvements in air quality. In particular, the first subsidy reform event, which increased gasoline prices and implemented a gasoline consumption quota; and the second subsidy reform event , which increased energy prices and decreased energy subsidies, both led to declines in concentrations of CO, O_3, and NO_2. In contrast, the fourth subsidy reform event, which increased fuel prices but removed the gasoline consumption quota, was less effective in reducing air pollution.

In future work, we hope to obtain sufficiently detailed data to enable us to better understand and tease out the mechanisms that led the later subsidy reform events to be less effective than the earlier subsidy reform events in reducing air pollution. In addition, in future work we hope to analyze the health impacts of the changes in air quality resulting from the subsidy reform.

Gasoline taxes have been touted by many economists as an efficient and relatively simple tool to address environmental concerns and other problems associated with gasoline consumption. Nevertheless, rather than removing subsidies and increasing gasoline taxes, many countries still subsidize gasoline, which may have the opposite effect of exacerbating air pollution and other problems associated with gasoline consumption. Our research shows that energy subsidy reform and the removal of fuel subsidies can have the beneficial effect of reducing air pollution.

3.7 Tables and figures

Figure 3.1: Pre-tax energy subsidies (as percent of GDP) in countries across the Middle East and North Africa, 2011.



Data source: Sdralevich et al. (2014).

Table 3.1: Description of the important events during the study period

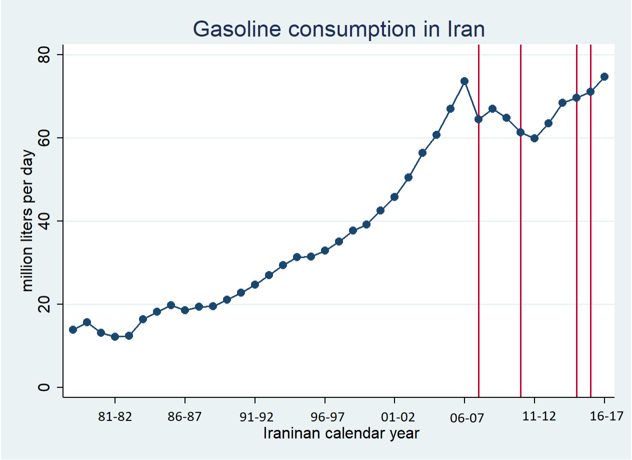
Event Date:		Description:
1:	June 27, 2007	25% price hike for gasoline and similar price increases for other transportation fuels. This price hike accompanied the introduction of the vehicle fuel card program that introduced a 60 liter/vehicle monthly quota on gasoline consumption after which gasoline can be purchased with an additional premium.
2:	December 18, 2010	First phase of the Iranian subsidy reform plan implemented, involving higher energy prices and the decrease in energy subsidies.
3:	Apr 24, 2014	Second phase of the Iranian subsidy reform plan began, involving even higher fuel prices.
4:	May 27, 2015	Government announced even higher fuel prices and abandoned the quota on gasoline consumption and fuel card program.

Table 3.2: Energy and utility prices in Iran after each event during the study period (10 IRR)

Subsidized fuel/utility:	unit 10 IRR per	Event 1 6/27/07	Event 2 12/18/10	Event 3 4/24/14	Event 4 5/27/15
Gasoline	ℓ	100(400)	400(700)	700(1000)	1000
Premium gas	ℓ	150	500(800)	800(1100)	1200
Diesel fuel	ℓ	16.5	150(350)	250(500)	300
Kerosene	ℓ	16.5	100	150	150
Mazut (Fuel oil)	ℓ	9.5	200	250	300
Aviation fuel	ℓ	100	400	500	600
LPG (Liquefied Petroleum Gas)	kg	5.7	180	210	230
LNG (Liquefied Natural Gas)	kg	40	540	650	
CNG (Compressed natural gas)	m^3	40	300	450	
Natural gas (residential) Winter	m^3	13.2	70	20% ↑	
Natural gas (residential) Summer	m^3	13.2	120	20% ↑	
Electricity (residential)	kWh	12.9	45-75	24% ↑	
Water (residential)	m^3	127	262.3	20% ↑	

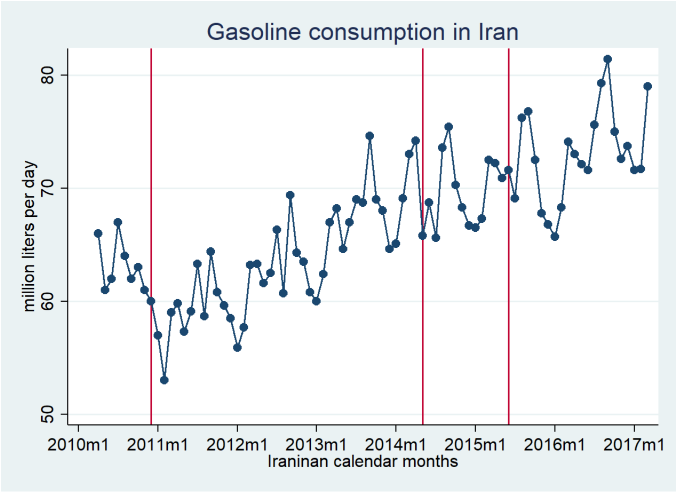
Note: Values inside parentheses are prices for volumes exceeding the 60 liter (ℓ) quota.

Figure 3.2.A: Annual gasoline consumption in Iran, 1978-2017



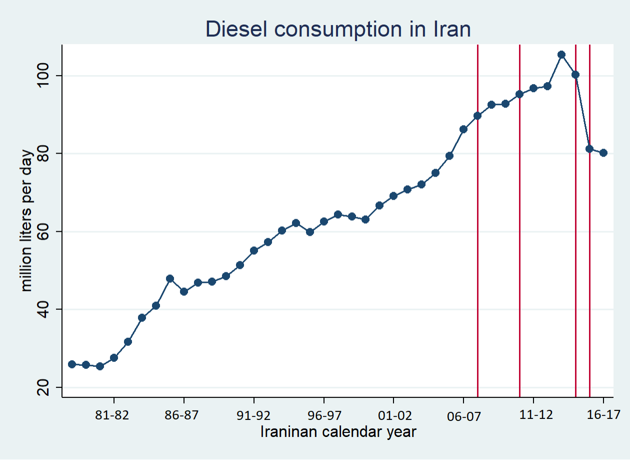
Data source: National Iranian Oil Refining and Distribution Company (2018)

Figure 3.2.B: Monthly gasoline consumption in Iran



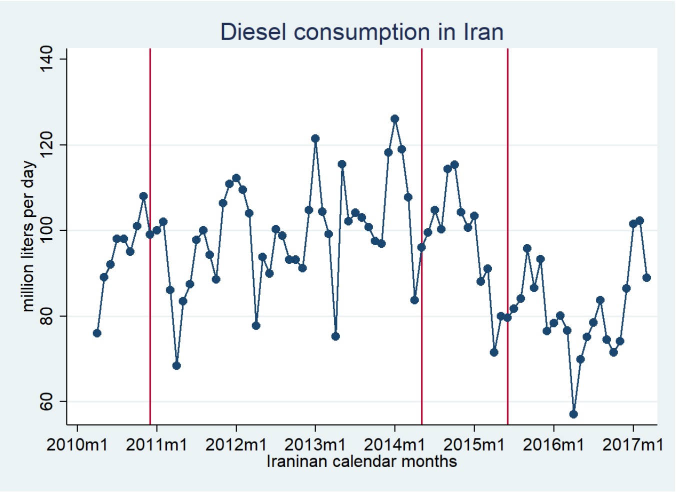
Data source: National Iranian Oil Refining and Distribution Company (2018)

Figure 3.3.A: Annual diesel consumption in Iran, 1978-2017



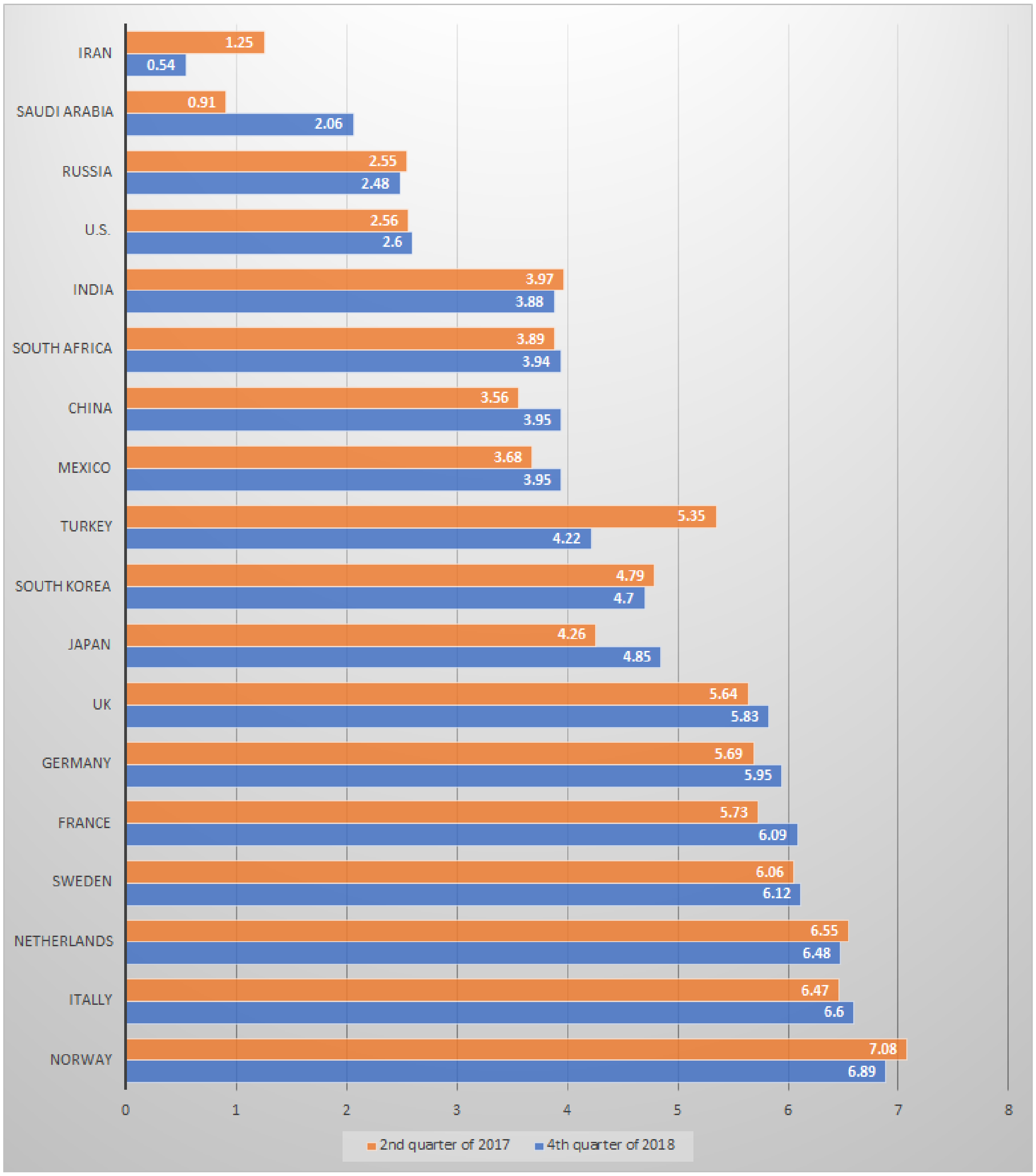
Data source: National Iranian Oil Refining and Distribution Company (2018)

Figure 3.3.B: Monthly diesel consumption in Iran



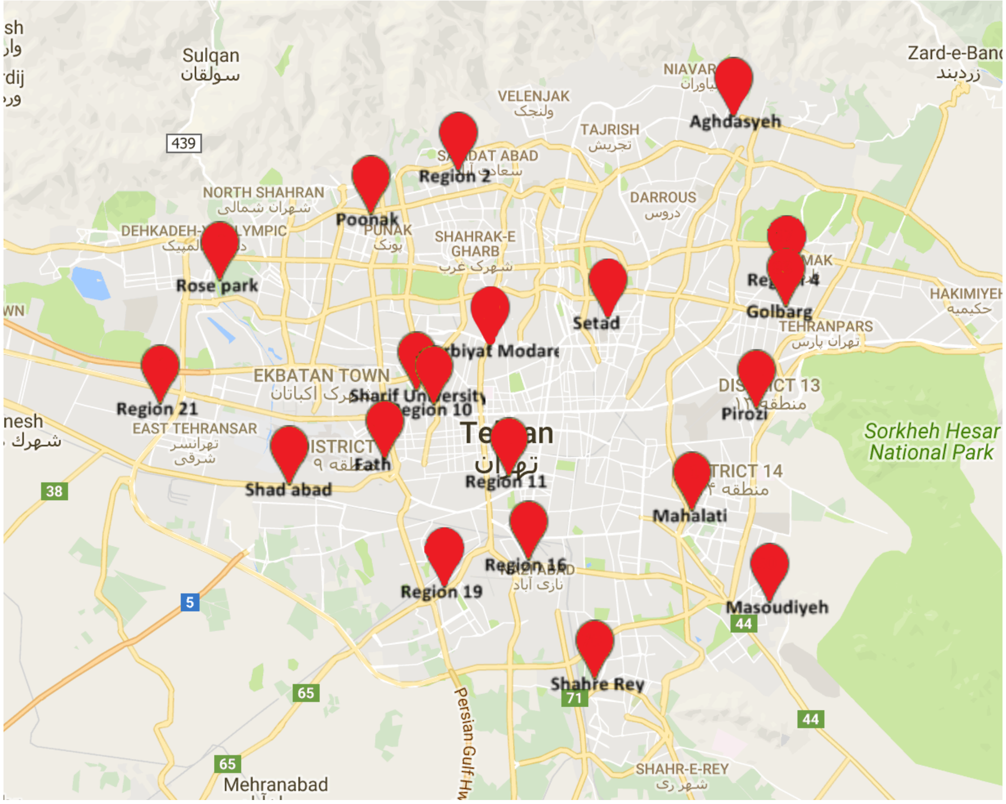
Data source: National Iranian Oil Refining and Distribution Company (2018)

Figure 3.4: Gasoline prices in selected countries worldwide (in U.S. dollars per gallon)



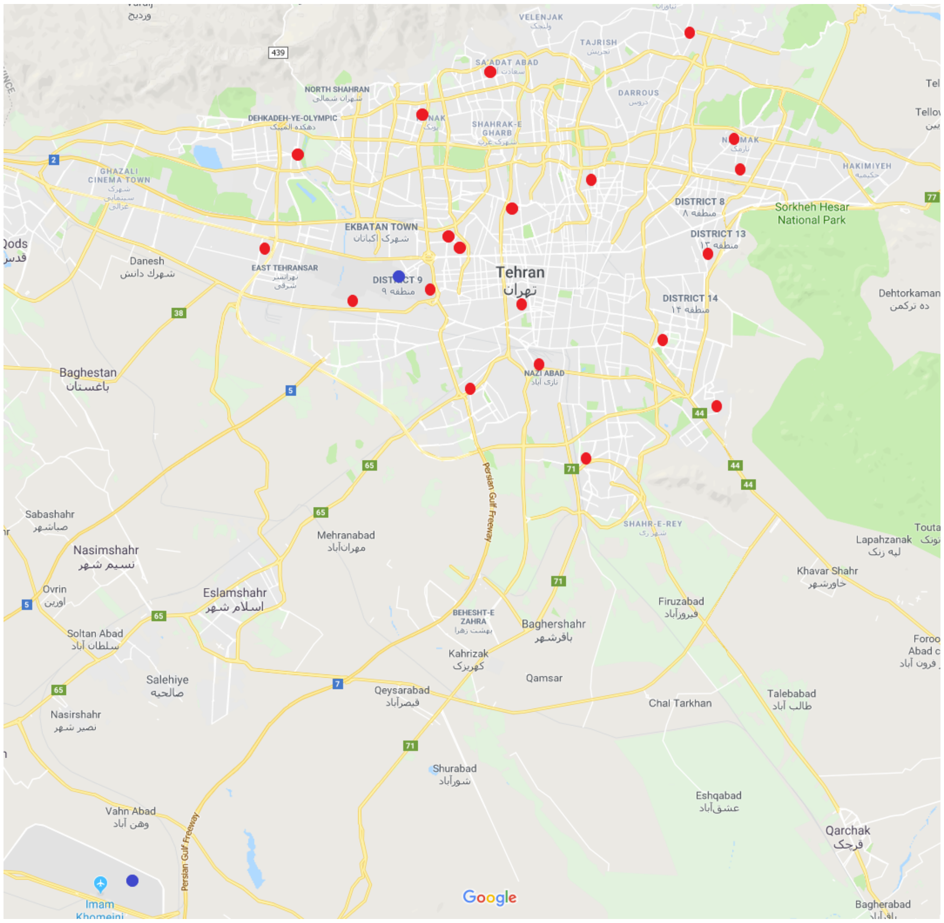
Data source: Statista (2018)

Figure 3.5: Local air quality monitoring stations across Tehran



Data source: Tehran Air Quality Control Company (`http://air.tehran.ir/`).

Figure 3.6: Local air quality monitoring and weather stations across Tehran



🔴 indicate air quality monitoring stations

🔵 indicate weather stations

Data sources: Tehran Air Quality Control Company (`http://air.tehran.ir/`); National Oceanic and Atmospheric Administration (NOAA) (2018).

Table 3.3: Summary statistics for air pollution concentration in Tehran, 2007-2017

Variable	**Mean**	**Std. Dev.**	**Min.**	**Max.**	**N**
Daily average pollution concentration averaged over all stations in Tehran					
O_3 (ppb)	22.998	11.393	1	100	3600
CO (ppm)	2.948	0.896	0.8	9	3606
NO_2 (ppb)	50.952	18.708	17.5	184	3606
SO_2 (ppb)	24.179	17.874	1	179.667	3600
PM_{10} ($\mu g/m^3$)	84.321	36.516	8	696.5	3606
Daily maximum pollution concentration averaged over all stations in Tehran					
O_3 (ppb)	48.452	25.416	1	191.333	3600
CO (ppm)	5.683	1.962	1.2	17.067	3606
NO_2 (ppb)	77.768	31.293	24	314.75	3606
SO_2 (ppb)	43.153	36.445	2	376	3600
PM_{10} ($\mu g/m^3$)	144.36	85.671	14.4	2136.923	3606

Data source: Tehran Air Quality Control Company (`http://air.tehran.ir/`).

Table 3.4: Summary statistics for daily weather data (averaged over two stations in Tehran), 2007-2017

Variable	**Mean**	**Std. Dev.**	**N**
Daily average temperature (°F)	64.593	18.308	3651
Maximum sustained wind speed (knots)	15.436	5.924	3651

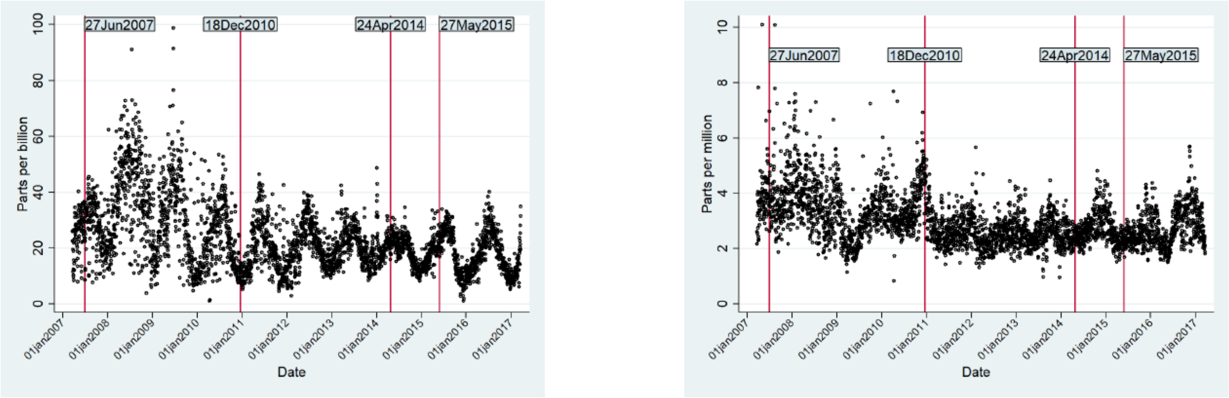
Data source: National Oceanic and Atmospheric Administration (NOAA) (2018)

Table 3.5: Summary statistics for daily weather data (Mehrabad Airport station), 2007-2017

Variable	**Mean**	**Std. Dev.**	**N**
Daily average temperature (°F)	65.145	18.132	3651
Maximum sustained wind speed (knots)(	13.95	6.511	3642

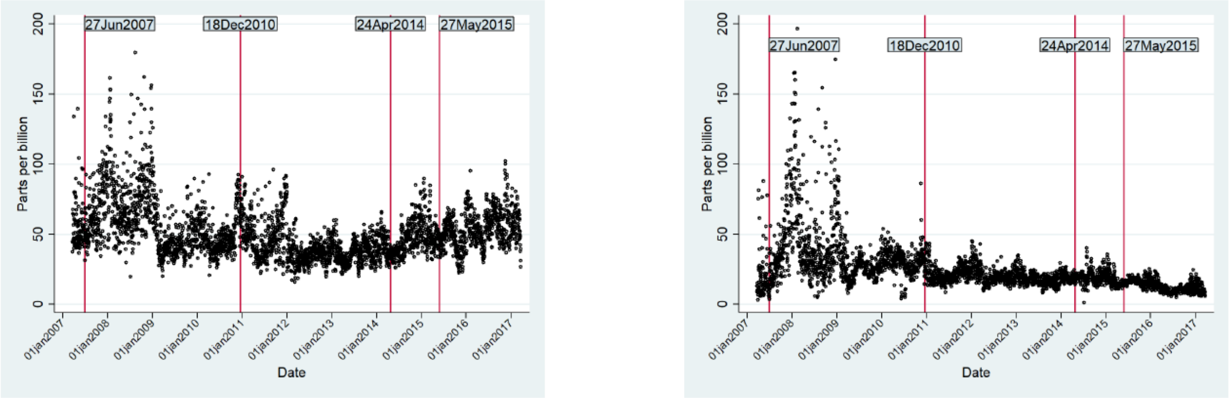
Data source: National Oceanic and Atmospheric Administration (NOAA) (2018)

Figure 3.7: Mean Daily Air Pollution Levels in Tehran, 2007-2017



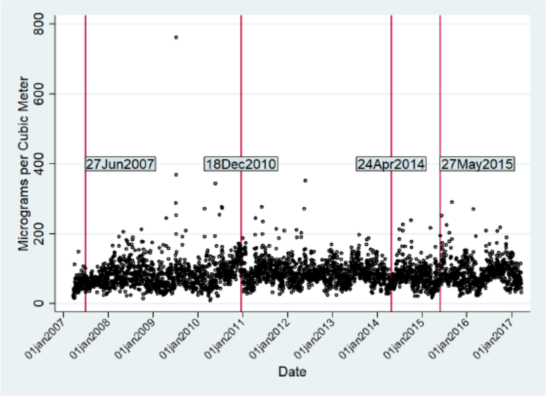
Ozone (O_3)

Carbon monoxide (CO)



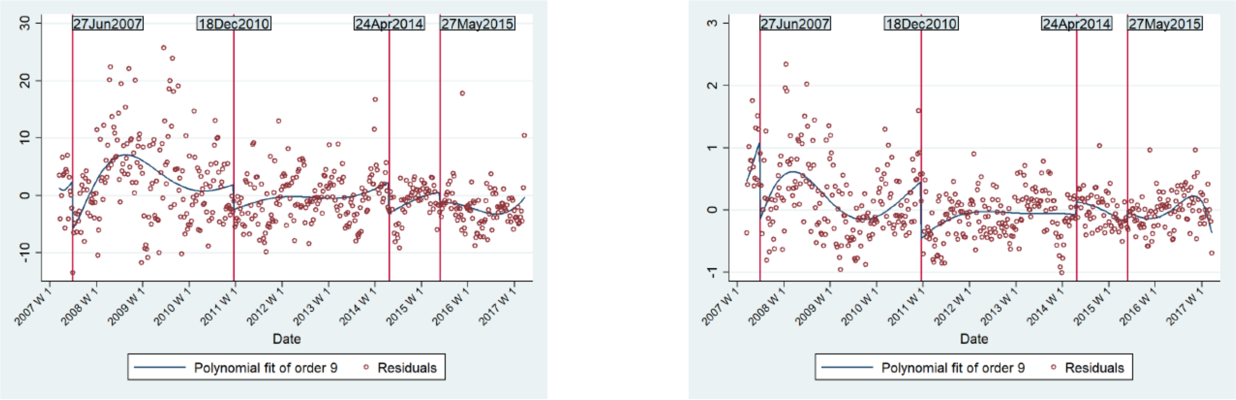
Nitrogen dioxide (NO_2)

Sulfur dioxide (SO_2)



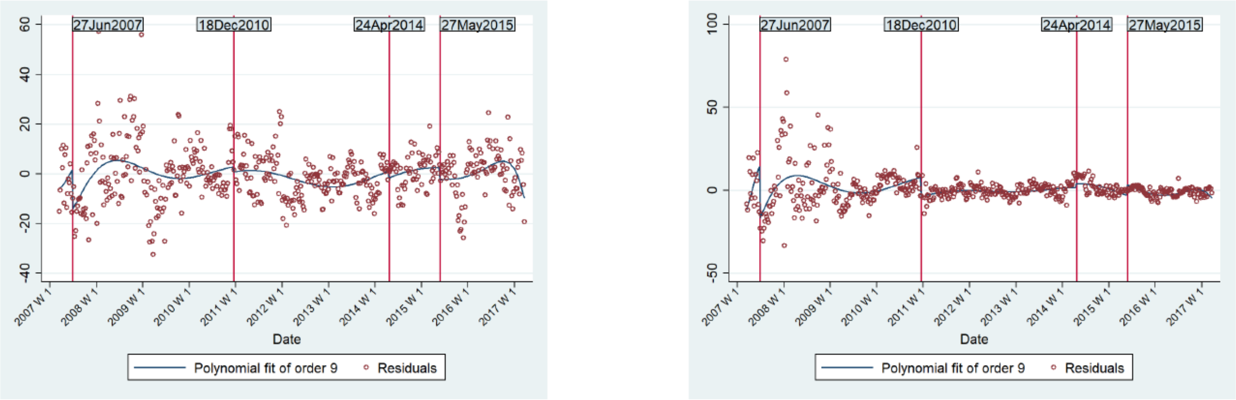
Particulate matter (PM_{10})

Figure 3.8: Air Pollution Levels in Tehran, Ninth-Order Polynomial Time Trend, 2007-2017 (Using daily average pollution levels)



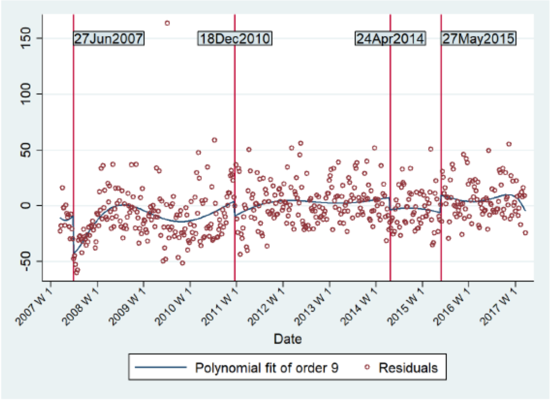
Ozone (O_3)

Carbon monoxide (CO)



Nitrogen dioxide (NO_2)

Sulfur dioxide (SO_2)



Particulate matter (PM_{10})

Table 3.6.A: The Effects of Removing Subsidies on Daily Average Pollution Levels in Tehran (using 9^{th}-order polynomial time trend)

	Dependent variable is log daily average pollution for:				
	O_3	CO	NO_2	SO_2	PM_{10}
Event 1: June 27, 2007	-0.2150*	-0.4669*	-0.6059*	-0.5479*	-0.7191*
	(0.0738)	(0.0473)	(0.0710)	(0.0740)	(0.0683)
Event 2: December 18, 2010	-0.3957*	-0.6935*	-0.5852*	-0.8471*	-0.7279*
	(0.0783)	(0.0506)	(0.0748)	(0.0785)	(0.0723)
Event 3: April 24, 2014	-0.5254*	-0.5319*	-0.5959*	-0.5715*	-0.8281*
	(0.0823)	(0.0528)	(0.0784)	(0.0851)	(0.0748)
Event 4: May 27, 2015	-0.5613*	-0.5372*	-0.7369*	-0.3748*	-0.7256*
	(0.0870)	(0.0562)	(0.0819)	(0.0918)	(0.0782)

Notes: This table reports estimates from five separate regression discontinuity specifications, one for each pollutant, each with a 9^{th}-order time trend, 4^{th} order polynomial on log daily average temperature and log daily max sustained wind speed, and station fixed effects. The unit of observation is a station-day; for each station, hourly pollution levels for were averaged over all hours of the day for that station. The reported coefficients correspond to indicator variables that equal to one for every day during the time periods of the respective subsidy reform phase. Standard errors, in parentheses, are robust to heteroskedasticity. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table 3.6.B: The Effects of Removing Subsidies on Daily Average Pollution Levels in Tehran (using 8^{th}-order polynomial time trend)

	Dependent variable is log daily average pollution for:				
	O_3	CO	NO_2	SO_2	PM_{10}
Event 1: June 27, 2007	-0.3104*	-0.1841*	-0.4709*	-0.3362*	-0.3577*
	(0.0670)	(0.0433)	(0.0645)	(0.0681)	(0.0622)
Event 2: December 18, 2010	-0.4802*	-0.4410*	-0.4601*	-0.6556*	-0.3961*
	(0.0734)	(0.0477)	(0.0695)	(0.0741)	(0.0676)
Event 3: April 24, 2014	-0.5933*	-0.3472*	-0.4915*	-0.4741*	-0.5621*
	(0.0793)	(0.0514)	(0.0750)	(0.0841)	(0.0719)
Event 4: May 27, 2015	-0.6032*	-0.4421*	-0.6671*	-0.3571*	-0.5520*
	(0.0860)	(0.0560)	(0.0805)	(0.0918)	(0.0771)

Notes: This table reports estimates from five separate regression discontinuity specifications, one for each pollutant, each with a 8^{th}-order time trend, 4^{th} order polynomial on log daily average temperature and log daily max sustained wind speed, and station fixed effects. The unit of observation is a station-day; for each station, hourly pollution levels for were averaged over all hours of the day for that station. The reported coefficients correspond to indicator variables that equal to one for every day during the time periods of the respective subsidy reform phase. Standard errors, in parentheses, are robust to heteroskedasticity. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table 3.6.C: The Effects of Removing Subsidies on Daily Average Pollution Levels in Tehran (using 10^{th}-order polynomial time trend)

	Dependent variable is log daily average pollution for:				
	O_3	CO	NO_2	SO_2	PM_{10}
Event 1: June 27, 2007	-0.2150*	-0.4669*	-0.6059*	-0.5479*	-0.7191*
	(0.0738)	(0.0473)	(0.0710)	(0.0740)	(0.0683)
Event 2: December 18, 2010	-0.3957*	-0.6935*	-0.5852*	-0.8471*	-0.7279*
	(0.0783)	(0.0506)	(0.0748)	(0.0785)	(0.0723)
Event 3: April 24, 2014	-0.5254*	-0.5319*	-0.5959*	-0.5715*	-0.8281*
	(0.0823)	(0.0528)	(0.0784)	(0.0851)	(0.0748)
Event 4: May 27, 2015	-0.5613*	-0.5372*	-0.7369*	-0.3748*	-0.7256*
	(0.0870)	(0.0562)	(0.0819)	(0.0918)	(0.0782)

Notes: This table reports estimates from five separate regression discontinuity specifications, one for each pollutant, each with a 10^{th}-order time trend, 4^{th} order polynomial on log daily average temperature and log daily max sustained wind speed, and station fixed effects. The unit of observation is a station-day; for each station, hourly pollution levels for were averaged over all hours of the day for that station. The reported coefficients correspond to indicator variables that equal to one for every day during the time periods of the respective subsidy reform phase. Standard errors, in parentheses, are robust to heteroskedasticity. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table 3.7.A: The Effects of Removing Subsidies on Daily Average Pollution Levels in Tehran (using 9^{th}-order polynomial time trend and Mehrabad only weather data)

	Dependent variable is log daily average pollution for:				
	O_3	CO	NO_2	SO_2	PM_{10}
Event 1: June 27, 2007	-0.2274*	-0.4510*	-0.5997*	-0.5521*	-0.7287*
	(0.0740)	(0.0473)	(0.0712)	(0.0741)	(0.0685)
Event 2: December 18, 2010	-0.4097*	-0.6795*	-0.5788*	-0.8483*	-0.7348*
	(0.0785)	(0.0506)	(0.0749)	(0.0787)	(0.0726)
Event 3: April 24, 2014	-0.5395*	-0.5199*	-0.5882*	-0.5750*	-0.8397*
	(0.0825)	(0.0528)	(0.0786)	(0.0853)	(0.0750)
Event 4: May 27, 2015	-0.5699*	-0.5299*	-0.7324*	-0.3747*	-0.7328*
	(0.0873)	(0.0562)	(0.0821)	(0.0920)	(0.0784)

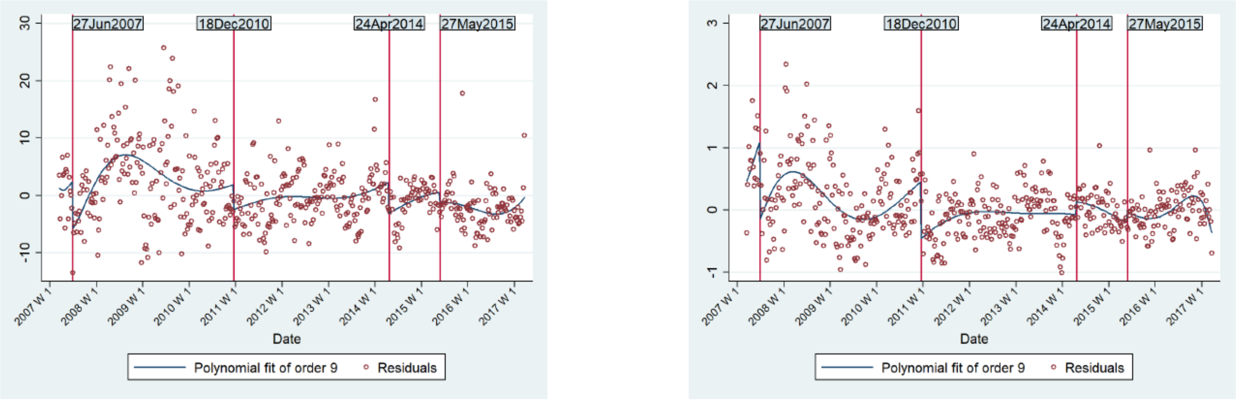
Notes: This table reports estimates from five separate regression discontinuity specifications, one for each pollutant, each with a 9^{th}-order time trend, 4^{th} order polynomial on log daily average temperature and log daily max sustained wind speed, and station fixed effects. The unit of observation is a station-day; for each station, hourly pollution levels for were averaged over all hours of the day for that station. The reported coefficients correspond to indicator variables that equal to one for every day during the time periods of the respective subsidy reform phase. Standard errors, in parentheses, are robust to heteroskedasticity. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table 3.7.B: The Effects of Removing Subsidies on Daily Average Pollution Levels in Tehran (using 8^{th}-order polynomial time trend and Mehrabad only weather data)

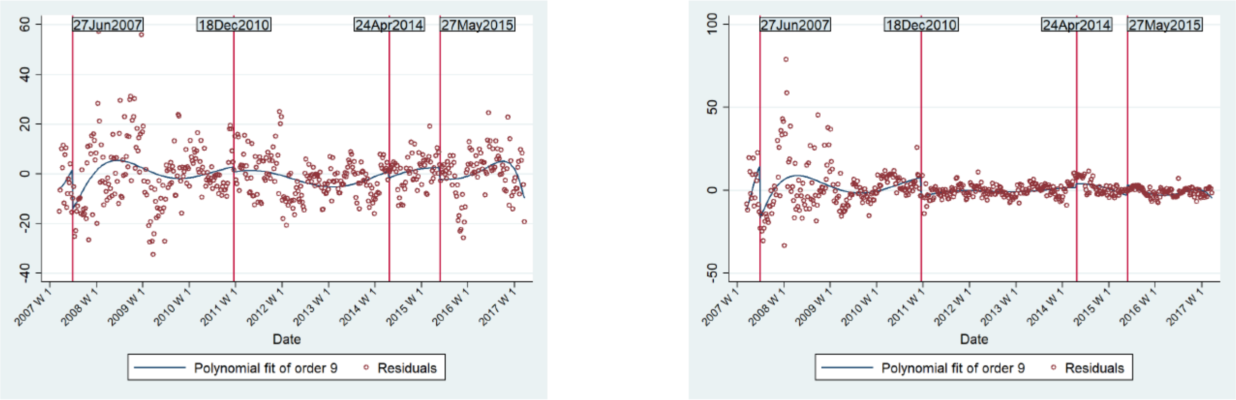
	Dependent variable is log daily average pollution for:				
	O_3	CO	NO_2	SO_2	PM_{10}
Event 1: June 27, 2007	-0.3155*	-0.1757*	-0.4731*	-0.3357*	-0.3690*
	(0.0673)	(0.0434)	(0.0647)	(0.0684)	(0.0625)
Event 2: December 18, 2010	-0.4877*	-0.4335*	-0.4613*	-0.6524*	-0.4041*
	(0.0736)	(0.0477)	(0.0697)	(0.0743)	(0.0678)
Event 3: April 24, 2014	-0.6022*	-0.3402*	-0.4901*	-0.4764*	-0.5748*
	(0.0796)	(0.0515)	(0.0752)	(0.0844)	(0.0722)
Event 4: May 27, 2015	-0.6085*	-0.4378*	-0.6670*	-0.3583*	-0.5600*
	(0.0862)	(0.0560)	(0.0807)	(0.0921)	(0.0774)

Notes: This table reports estimates from five separate regression discontinuity specifications, one for each pollutant, each with a 8^{th}-order time trend, 4^{th} order polynomial on log daily average temperature and log daily max sustained wind speed, and station fixed effects. The unit of observation is a station-day; for each station, hourly pollution levels for were averaged over all hours of the day for that station. The reported coefficients correspond to indicator variables that equal to one for every day during the time periods of the respective subsidy reform phase. Standard errors, in parentheses, are robust to heteroskedasticity. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

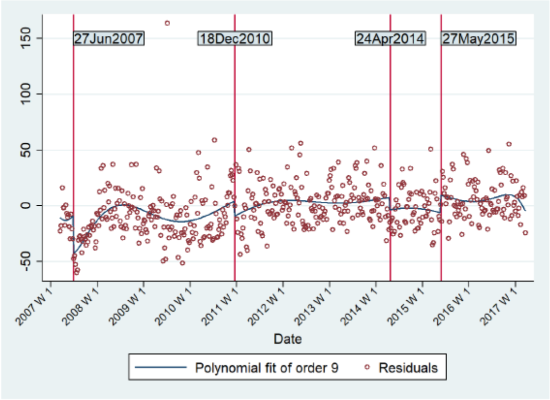
Figure 3.9: Air Pollution Levels in Tehran, Ninth-Order Polynomial Time Trend, 2007-2017 (Using daily maximum pollution levels)



Ozone (O_3) Carbon monoxide (CO)



Nitrogen dioxide (NO_2) Sulfur dioxide (SO_2)



Particulate matter (PM_{10})

Table 3.8.A: The Effects of Removing Subsidies on Daily Maximum Pollution Levels in Tehran (using 9^{th}-order polynomial time trend)

	Dependent variable is log daily max pollution for:				
	O_3	CO	NO_2	SO_2	PM_{10}
Event 1: June 27, 2007	-0.3239*	-0.5325*	-0.8041*	-0.7583*	-0.6963*
	(0.0837)	(0.0532)	(0.0724)	(0.0847)	(0.0752)
Event 2: December 18, 2010	-0.4965*	-0.7377*	-0.7706*	-1.0849*	-0.7354*
	(0.0888)	(0.0569)	(0.0763)	(0.0899)	(0.0796)
Event 3: April 24, 2014	-0.4697*	-0.5855*	-0.8076*	-0.7445*	-0.7712*
	(0.0934)	(0.0594)	(0.0800)	(0.0975)	(0.0823)
Event 4: May 27, 2015	-0.4421*	-0.5957*	-1.0328*	-0.6295*	-0.6263*
	(0.0988)	(0.0632)	(0.0835)	(0.1051)	(0.0860)

Notes: This table reports estimates from five separate regression discontinuity specifications, one for each pollutant, each with a 9^{th}-order time trend, 4^{th} order polynomial on log daily average temperature and log daily max sustained wind speed, and station fixed effects. The unit of observation is a station-day; for each station, hourly pollution levels for were averaged over all hours of the day for that station. The reported coefficients correspond to indicator variables that equal to one for every day during the time periods of the respective subsidy reform phase. Standard errors, in parentheses, are robust to heteroskedasticity. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table 3.8.B: The Effects of Removing Subsidies on Daily Maximum Pollution Levels in Tehran (using 8^{th}-order polynomial time trend)

	Dependent variable is log daily max pollution for:				
	O_3	CO	NO_2	SO_2	PM_{10}
Event 1: June 27, 2007	-0.4489*	-0.2968*	-0.6751*	-0.6378*	-0.3772*
	(0.0761)	(0.0486)	(0.0658)	(0.0780)	(0.0684)
Event 2: December 18, 2010	-0.6071*	-0.5272*	-0.6511*	-0.9759*	-0.4425*
	(0.0833)	(0.0536)	(0.0709)	(0.0848)	(0.0743)
Event 3: April 24, 2014	-0.5586*	-0.4315*	-0.7078*	-0.6890*	-0.5363*
	(0.0900)	(0.0578)	(0.0765)	(0.0963)	(0.0791)
Event 4: May 27, 2015	-0.4971*	-0.5164*	-0.9662*	-0.6195*	-0.4730*
	(0.0976)	(0.0629)	(0.0821)	(0.1051)	(0.0848)

Notes: This table reports estimates from five separate regression discontinuity specifications, one for each pollutant, each with a 8^{th}-order time trend, 4^{th} order polynomial on log daily average temperature and log daily max sustained wind speed, and station fixed effects. The unit of observation is a station-day; for each station, hourly pollution levels for were averaged over all hours of the day for that station. The reported coefficients correspond to indicator variables that equal to one for every day during the time periods of the respective subsidy reform phase. Standard errors, in parentheses, are robust to heteroskedasticity. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table 3.9.A: The Effects of Removing Subsidies on Daily Maximum Pollution Levels in Tehran (using 9^{th}-order polynomial time trend and Mehrabad only weather data)

	Dependent variable is log daily max pollution for:				
	O_3	CO	NO_2	SO_2	PM_{10}
Event 1: June 27, 2007	-0.3246*	-0.5129*	-0.8013*	-0.7723*	-0.7255*
	(0.0840)	(0.0531)	(0.0725)	(0.0850)	(0.0757)
Event 2: December 18, 2010	-0.4975*	-0.7192*	-0.7652*	-1.0972*	-0.7598*
	(0.0891)	(0.0567)	(0.0764)	(0.0902)	(0.0801)
Event 3: April 24, 2014	-0.4738*	-0.5698*	-0.8019*	-0.7576*	-0.7997*
	(0.0936)	(0.0593)	(0.0801)	(0.0978)	(0.0828)
Event 4: May 27, 2015	-0.4435*	-0.5852*	-1.0281*	-0.6385*	-0.6443*
	(0.0990)	(0.0631)	(0.0837)	(0.1055)	(0.0866)

Notes: This table reports estimates from five separate regression discontinuity specifications, one for each pollutant, each with a 9^{th}-order time trend, 4^{th} order polynomial on log daily average temperature and log daily max sustained wind speed, and station fixed effects. The unit of observation is a station-day; for each station, hourly pollution levels for were averaged over all hours of the day for that station. The reported coefficients correspond to indicator variables that equal to one for every day during the time periods of the respective subsidy reform phase. Standard errors, in parentheses, are robust to heteroskedasticity. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table 3.9.B: The Effects of Removing Subsidies on Daily Maximum Pollution Levels in Tehran (using 8^{th}-order polynomial time trend and Mehrabad only weather data)

	Dependent variable is log daily max pollution for:				
	O_3	CO	NO_2	SO_2	PM_{10}
Event 1: June 27, 2007	-0.4443*	-0.2870*	-0.6771*	-0.6471*	-0.3937*
	(0.0764)	(0.0486)	(0.0660)	(0.0784)	(0.0689)
Event 2: December 18, 2010	-0.6035*	-0.5173*	-0.6499*	-0.9838*	-0.4549*
	(0.0836)	(0.0535)	(0.0711)	(0.0852)	(0.0748)
Event 3: April 24, 2014	-0.5590*	-0.4224*	-0.7057*	-0.7005*	-0.5554*
	(0.0903)	(0.0577)	(0.0766)	(0.0967)	(0.0796)
Event 4: May 27, 2015	-0.4960*	-0.5097*	-0.9640*	-0.6291*	-0.4850*
	(0.0979)	(0.0628)	(0.0823)	(0.1055)	(0.0854)

Notes: This table reports estimates from five separate regression discontinuity specifications, one for each pollutant, each with a 8^{th}-order time trend, 4^{th} order polynomial on log daily average temperature and log daily max sustained wind speed, and station fixed effects. The unit of observation is a station-day; for each station, hourly pollution levels for were averaged over all hours of the day for that station. The reported coefficients correspond to indicator variables that equal to one for every day during the time periods of the respective subsidy reform phase. Standard errors, in parentheses, are robust to heteroskedasticity. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Figure 3.10: Number of observations per week for each pollutant around event 1

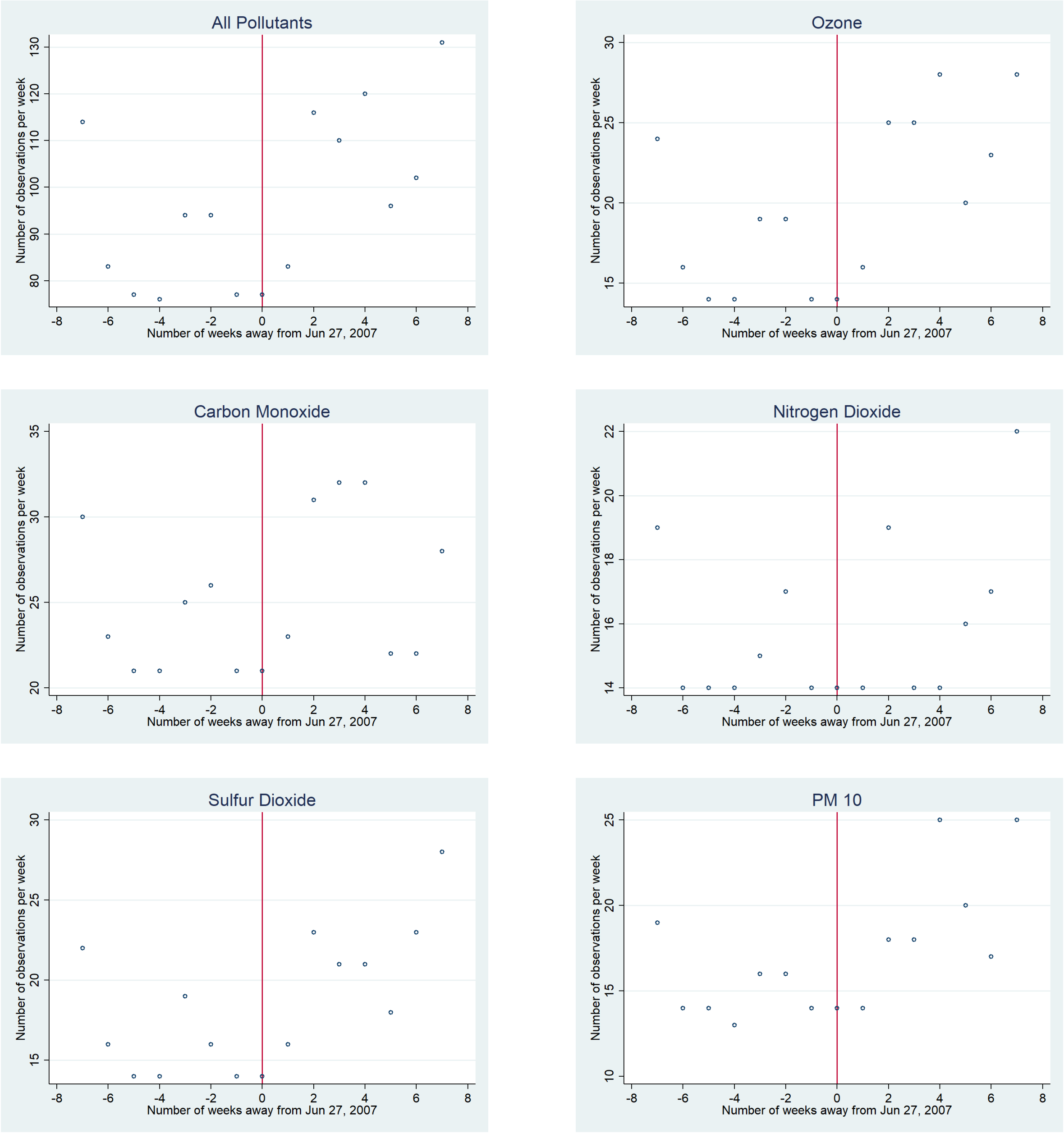


Figure 3.11: Number of observations per week for each pollutant around event 2

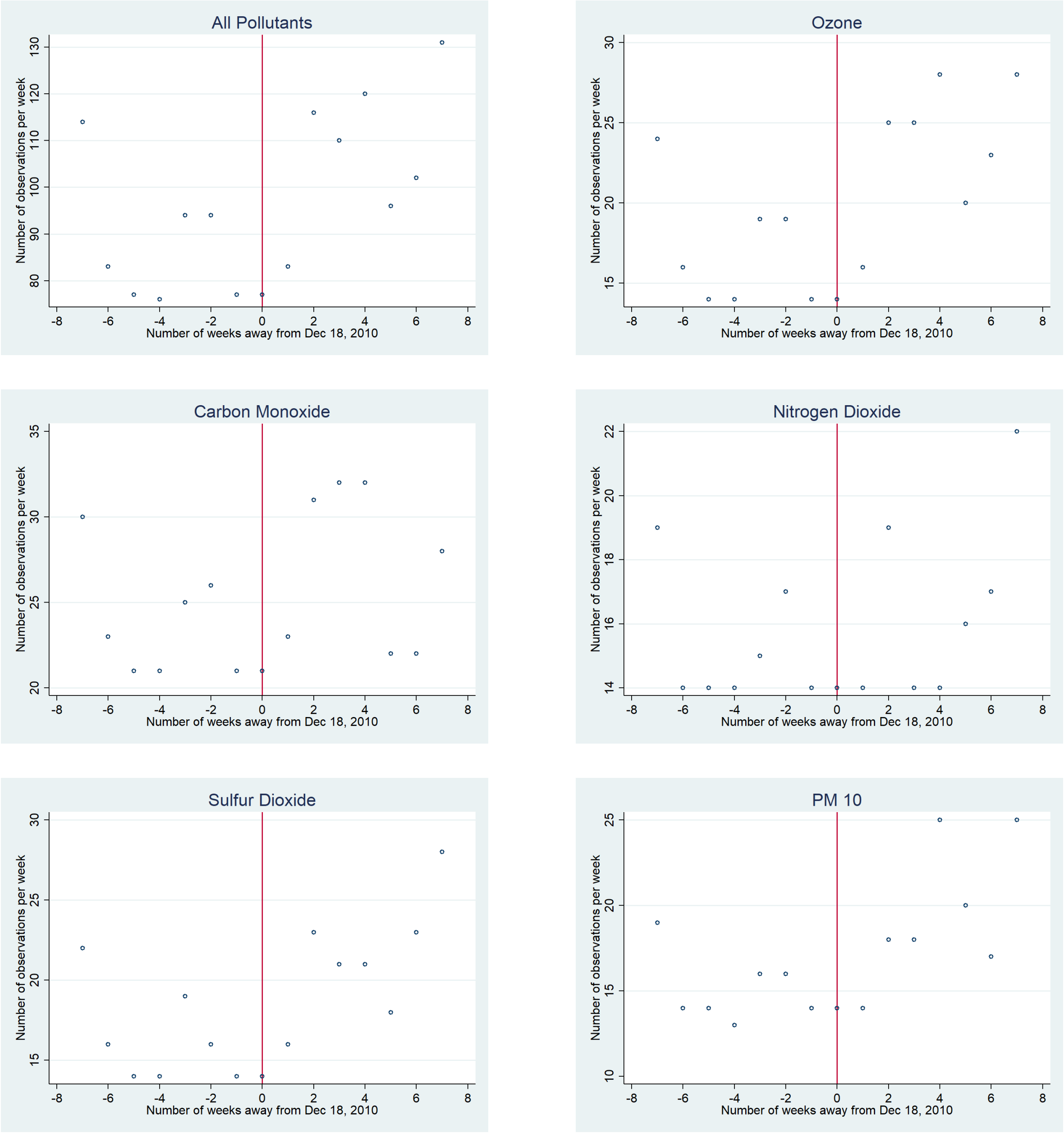


Figure 3.12: Number of observations per week for each pollutant around event 3

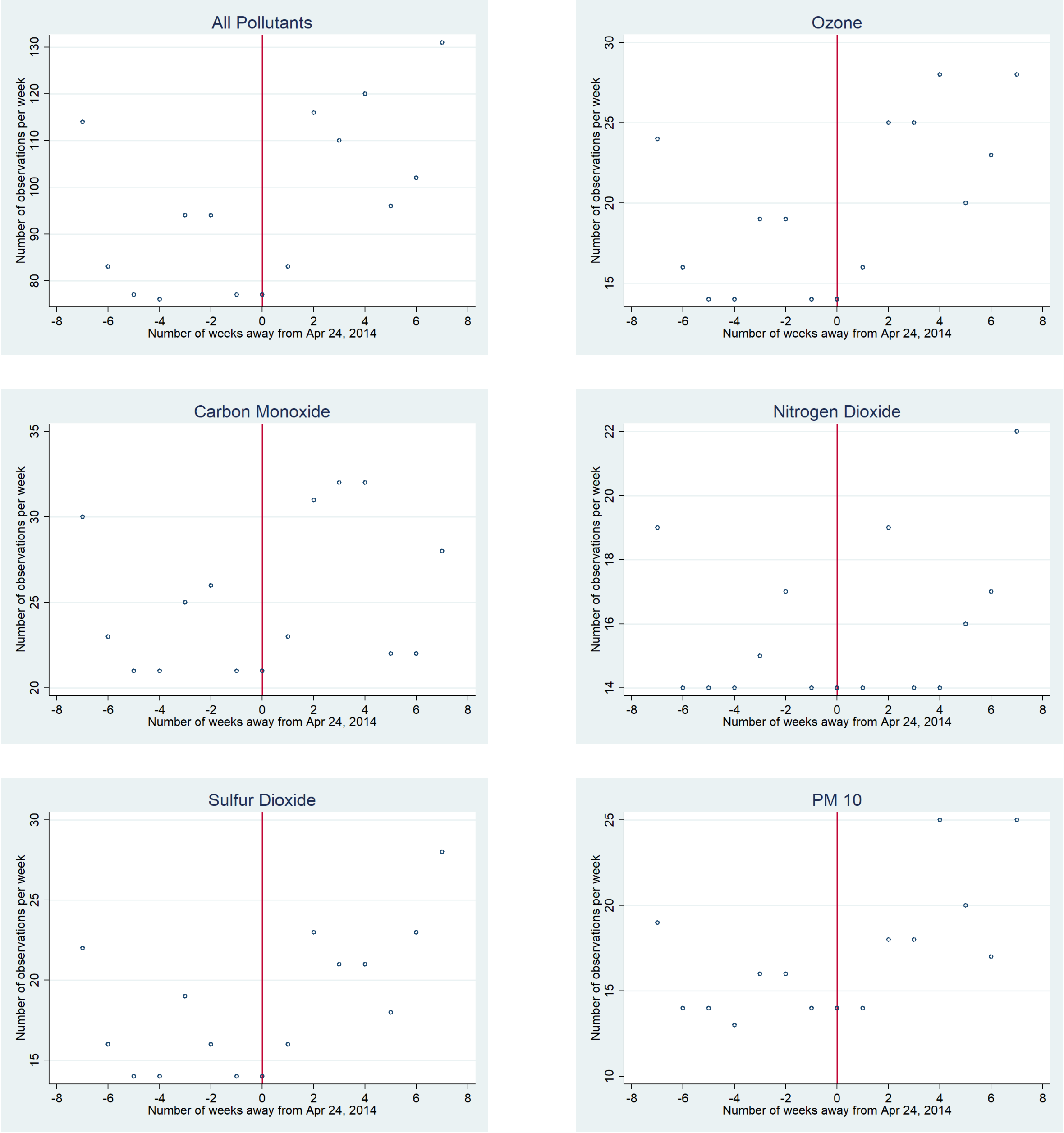


Figure 3.13: Number of observations per week for each pollutant around event 4

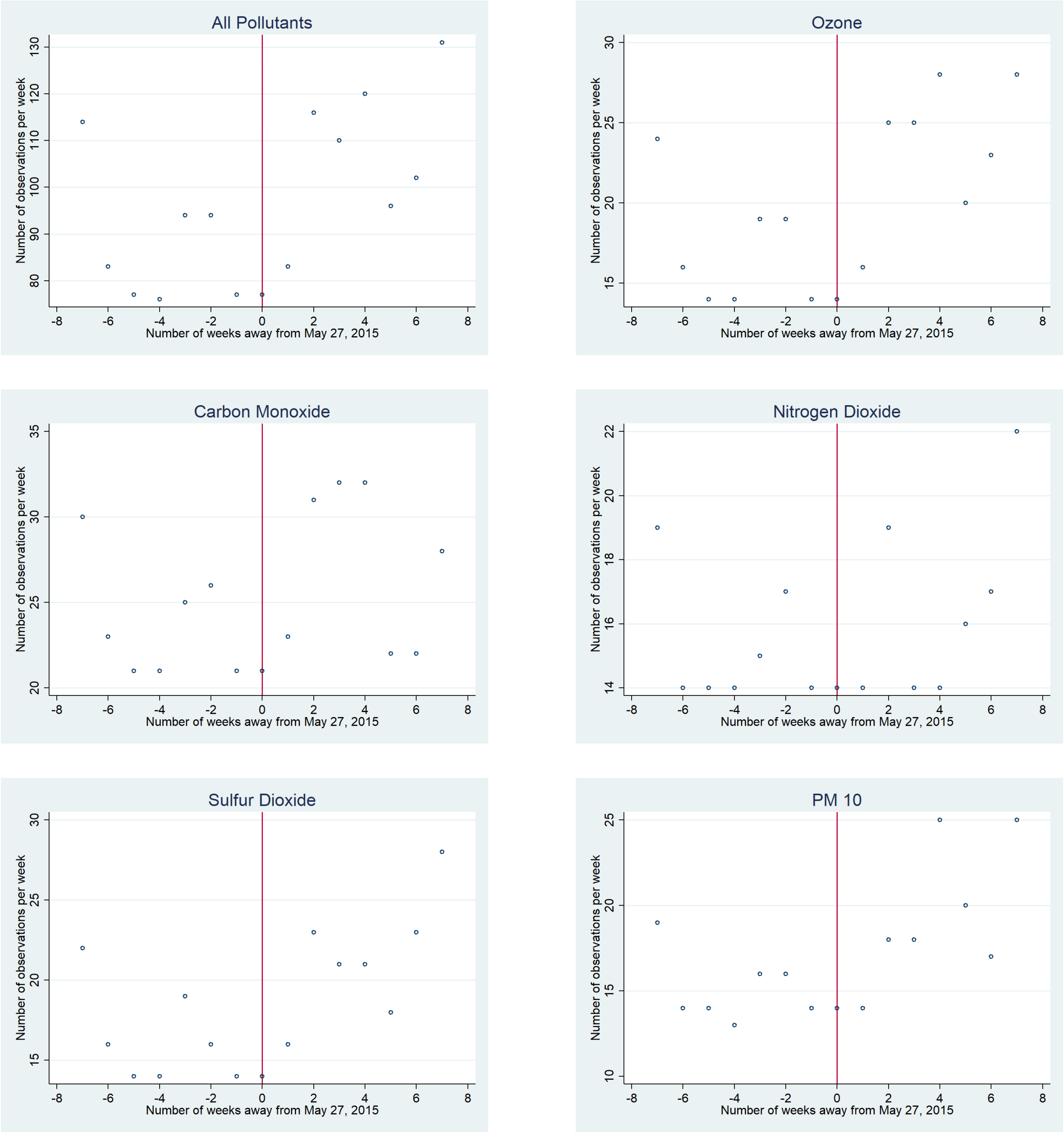


Table 3.10: The Effects of Removing Subsidies on Daily Mean Temperature in Tehran

Dependent variable is log daily average temperature					
N^{th} order time trend	10^{th} order	9^{th} order	8^{th} order	7^{th} order	6^{th} order
Event 1: June 27, 2007	0.0077	0.0077	-0.0017	-0.0017	-0.0034
	(0.0742)	(0.0742)	(0.0738)	(0.0738)	(0.0734)
Event 2: December 18, 2010	-0.0666	-0.0666	-0.0692	-0.0692	-0.0712
	(0.0762)	(0.0762)	(0.0762)	(0.0762)	(0.0756)
Event 3: April 24, 2014	-0.0303	-0.0303	-0.0321	-0.0321	-0.0353
	(0.0789)	(0.0789)	(0.0789)	(0.0789)	(0.0774)
Event 4: May 27, 2015	-0.0092	-0.0092	-0.0016	-0.0016	-0.0056
	(0.0851)	(0.0851)	(0.0848)	(0.0848)	(0.0826)

Notes: This table reports estimates from a regression discontinuity model with a N^{th}-order time trend. All models include day of the week, month of the year, and year dummies. The unit of observation is a station-day. The reported coefficients correspond to indicator variables that equal to one for every day during the time periods of the respective subsidy reform phase. Standard errors, in parentheses, are robust to heteroskedasticity. Significance code: * indicates significant at a 5% level.

Table 3.11: The Effects of Removing Subsidies on Daily Maximum Wind Speed in Tehran

Dependent variable is log daily maximum sustained wind speed					
N^{th} order time trend	10^{th} order	9^{th} order	8^{th} order	7^{th} order	6^{th} order
Event 1: June 27, 2007	-0.1304	-0.1304	-0.1052	-0.1052	-0.1180
	(0.1986)	(0.1986)	(0.1976)	(0.1976)	(0.1964)
Event 2: December 18, 2010	-0.0225	-0.0225	-0.0157	-0.0157	-0.0310
	(0.2040)	(0.2040)	(0.2040)	(0.2040)	(0.2023)
Event 3: April 24, 2014	0.0201	0.0201	0.0250	0.0250	0.0008
	(0.2112)	(0.2112)	(0.2112)	(0.2112)	(0.2072)
Event 4: May 27, 2015	0.1011	0.1011	0.0808	0.0808	0.0500
	(0.2277)	(0.2277)	(0.2271)	(0.2271)	(0.2210)

Notes: This table reports estimates from a regression discontinuity model with a N^{th}-order time trend. All models include day of the week, month of the year, and year dummies. The unit of observation is a station-day. The reported coefficients correspond to indicator variables that equal to one for every day during the time periods of the respective subsidy reform phase. Standard errors, in parentheses, are robust to heteroskedasticity. Significance code: * indicates significant at a 5% level.

Table 3.12.A: The Effects of Removing Subsidies on Daily Average Pollution Levels in Tehran (Post reform regression using 9^{th}-order polynomial time trend)

	Dependent variable is log daily average pollution for:				
	O_3	CO	NO_2	SO_2	PM_{10}
Event 1: June 27, 2007	-0.2846	-0.3604*	-0.5606*	-1.8997*	-0.7039*
	(0.1964)	(0.1160)	(0.1741)	(0.1888)	(0.1711)
Event 2: December 18, 2010	-0.2216*	-0.1923*	-0.0250	-0.3081*	-0.0657*
	(0.0234)	(0.0157)	(0.0196)	(0.0230)	(0.0199)
Event 3: April 24, 2014	-0.1823*	0.1113*	-0.0133	0.1308*	-0.1537*
	(0.0282)	(0.0180)	(0.0256)	(0.0446)	(0.0219)
Event 4: May 27, 2015	-0.0818	0.0549	-0.0591	0.1380*	0.2909*
	(0.0323)	(0.0218)	(0.0271)	(0.0321)	(0.0274)

Notes: This table reports estimates from five separate regression discontinuity specifications, one for each pollutant, each with a 9^{th}-order time trend, 4^{th} order polynomial on log daily average temperature and log daily max sustained wind speed, and station fixed effects, as well as month of the year, day of the week, and year fixed effects. The unit of observation is a station-day; for each station, hourly pollution levels for were averaged over all hours of the day for that station. The reported coefficients on "Post reform" correspond to indicator variable that equals to one after the first reform event on June 2007. The reported coefficients on other events correspond to indicator variables that equal to one for every day during the time periods of the respective subsidy reform phase. Standard errors, in parentheses, are robust to heteroskedasticity. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table 3.12.B: The Effects of Removing Subsidies on Daily Average Pollution Levels in Tehran (Post reform regression using 8^{th}-order polynomial time trend)

	Dependent variable is log daily average pollution for:				
	O_3	CO	NO_2	SO_2	PM_{10}
Event 1: June 27, 2007	-0.3854	-0.2890	-0.5471*	-1.7911*	-0.6770*
	(0.1954)	(0.1153)	(0.1730)	(0.1877)	(0.1701)
Event 2: December 18, 2010	-0.1967*	-0.2096*	-0.0273	-0.3314*	-0.0709*
	(0.0228)	(0.0154)	(0.0193)	(0.0226)	(0.0196)
Event 3: April 24, 2014	-0.1903*	0.1155*	-0.0121	0.1347*	-0.1522*
	(0.0281)	(0.0180)	(0.0255)	(0.0447)	(0.0219)
Event 4: May 27, 2015	-0.0409	0.0220	-0.0638	0.0925*	0.2809*
	(0.0312)	(0.0210)	(0.0262)	(0.0309)	(0.0265)

Notes: This table reports estimates from five separate regression discontinuity specifications, one for each pollutant, each with a 8^{th}-order time trend, 4^{th} order polynomial on log daily average temperature and log daily max sustained wind speed, and station fixed effects, as well as month of the year, day of the week, and year fixed effects. The unit of observation is a station-day; for each station, hourly pollution levels for were averaged over all hours of the day for that station. The reported coefficients on "Post reform" correspond to indicator variable that equals to one after the first reform event on June 2007. The reported coefficients on other events correspond to indicator variables that equal to one for every day during the time periods of the respective subsidy reform phase. Standard errors, in parentheses, are robust to heteroskedasticity. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table 3.13.A: The Effects of Removing Subsidies on Daily Max Pollution Levels in Tehran (Post reform regression using 9^{th}-order polynomial time trend)

	Dependent variable is log daily max pollution for:				
	O_3	CO	NO_2	SO_2	PM_{10}
Event 1: June 27, 2007	-0.3088	-0.4351*	-0.6027*	-1.9903*	-0.7772*
	(0.2227)	(0.1306)	(0.1773)	(0.2166)	(0.1884)
Event 2: December 18, 2010	-0.2217*	-0.1774*	-0.0438	-0.3461*	-0.1123*
	(0.0265)	(0.0177)	(0.0199)	(0.0264)	(0.0220)
Event 3: April 24, 2014	-0.0535	0.1027*	-0.0323	0.0215	-0.0741*
	(0.0319)	(0.0202)	(0.0261)	(0.0512)	(0.0242)
Event 4: May 27, 2015	0.0022	0.0428	-0.1000*	0.1202*	0.3337*
	(0.0367)	(0.0246)	(0.0276)	(0.0368)	(0.0302)

Notes: This table reports estimates from five separate regression discontinuity specifications, one for each pollutant, each with a 9^{th}-order time trend, 4^{th} order polynomial on log daily average temperature and log daily max sustained wind speed, and station fixed effects, as well as month of the year, day of the week, and year fixed effects. The unit of observation is a station-day; for each station, hourly pollution levels for were averaged over all hours of the day for that station. The reported coefficients on ”Post reform” correspond to indicator variable that equals to one after the first reform event on June 2007. The reported coefficients on other events correspond to indicator variables that equal to one for every day during the time periods of the respective subsidy reform phase. Standard errors, in parentheses, are robust to heteroskedasticity. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table 3.13.B: The Effects of Removing Subsidies on Daily Max Pollution Levels in Tehran (Post reform regression using 8^{th}-order polynomial time trend)

	Dependent variable is log daily max pollution for:				
	O_3	CO	NO_2	SO_2	PM_{10}
Event 1: June 27, 2007	-0.4177	-0.3630*	-0.6043*	-1.8837*	-0.7908*
	(0.2216)	(0.1299)	(0.1762)	(0.2153)	(0.1873)
Event 2: December 18, 2010	-0.1947*	-0.1949*	-0.0435	-0.3689*	-0.1096*
	(0.0258)	(0.0173)	(0.0196)	(0.0259)	(0.0216)
Event 3: April 24, 2014	-0.0621	0.1070*	-0.0325	0.0254	-0.0749*
	(0.0319)	(0.0202)	(0.0260)	(0.0512)	(0.0241)
Event 4: May 27, 2015	0.0464	0.0096	-0.0995*	0.0756	0.3388*
	(0.0354)	(0.0237)	(0.0267)	(0.0354)	(0.0292)

Notes: This table reports estimates from five separate regression discontinuity specifications, one for each pollutant, each with a 8^{th}-order time trend, 4^{th} order polynomial on log daily average temperature and log daily max sustained wind speed, and station fixed effects, as well as month of the year, day of the week, and year fixed effects. The unit of observation is a station-day; for each station, hourly pollution levels for were averaged over all hours of the day for that station. The reported coefficients on "Post reform" correspond to indicator variable that equals to one after the first reform event on June 2007. The reported coefficients on other events correspond to indicator variables that equal to one for every day during the time periods of the respective subsidy reform phase. Standard errors, in parentheses, are robust to heteroskedasticity. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table 3.14: Placebo tests for four subsidy reform events (Post reform regression using 9^{th}-order polynomial time trend)

	Dependent variable is log daily average pollution for:				
	O_3	CO	NO_2	SO_2	PM_{10}
Before event 1: March 28, 2007	0.2032	-0.0436	-0.1935	-0.1896	0.3052
	(0.1464)	(0.0872)	(0.1301)	(0.1419)	(0.1279)
Before event 2: June 21, 2008	-0.0099	0.0085	0.0389	-0.0220	-0.0784
	(0.0790)	(0.0581)	(0.0988)	(0.0845)	(0.0751)
Before event 3: June 27, 2013	-0.1582	-0.1323	0.2144	-0.1037	-0.1479
	(0.1001)	(0.0677)	(0.0840)	(0.0981)	(0.0721)
Before event 4: November 19, 2014	0.1188^*	-0.0116	0.0475	0.0173	0.0493
	(0.0281)	(0.0167)	(0.0215)	(0.0297)	(0.0206)

Notes: This table reports estimates from five separate regression discontinuity specifications, one for each pollutant, each with a 9^{th}-order time trend, 4^{th} order polynomial on log daily average temperature and log daily max sustained wind speed, and station fixed effects, as well as month of the year, day of the week, and year fixed effects. The unit of observation is a station-day; for each station, hourly pollution levels for were averaged over all hours of the day for that station. The reported coefficients on "Post reform" correspond to indicator variable that equals to one after the first reform event on June 2007. The reported coefficients on other events correspond to indicator variables that equal to one for every day during the time periods of the respective subsidy reform phase. Standard errors, in parentheses, are robust to heteroskedasticity. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table 3.15: Placebo tests for four subsidy reform events (Post reform regression using 9^{th}-order polynomial time trend using max pollution levels)

	Dependent variable is log daily maximum pollution for:				
	O_3	CO	NO_2	SO_2	PM_{10}
Before event 1: March 28, 2007	0.3067	0.0222	-0.3384	-0.1745	0.2060
	(0.1658)	(0.0981)	(0.1324)	(0.1626)	(0.1408)
Before event 2: June 21, 2008	-0.0412	-0.0420	0.0367	-0.0411	-0.1203
	(0.0895)	(0.0654)	(0.1006)	(0.0969)	(0.0826)
Before event 3: June 27, 2013	-0.1060	-0.1754	0.2056	-0.1566	-0.1916
	(0.1134)	(0.0762)	(0.0856)	(0.1124)	(0.0793)
Before event 4: November 19, 2014	0.0879^{*}	-0.0448	0.0113	0.0247	0.0334
	(0.0319)	(0.0188)	(0.0219)	(0.0340)	(0.0227)

Notes: This table reports estimates from five separate regression discontinuity specifications, one for each pollutant, each with a 9^{th}-order time trend, 4^{th} order polynomial on log daily average temperature and log daily max sustained wind speed, and station fixed effects, as well as month of the year, day of the week, and year fixed effects. The unit of observation is a station-day; for each station, hourly pollution levels for were averaged over all hours of the day for that station. The reported coefficients on ”Post reform” correspond to indicator variable that equals to one after the first reform event on June 2007. The reported coefficients on other events correspond to indicator variables that equal to one for every day during the time periods of the respective subsidy reform phase. Standard errors, in parentheses, are robust to heteroskedasticity. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table 3.16.A: The Effects of Removing Subsidies on Daily Average Pollution Levels in Tehran (Post reform regression controlling for SO_2 and using 9^{th}-order polynomial time trend)

	Dependent variable is log daily average pollution for:			
	O_3	CO	NO_2	PM_{10}
Event 1: June 27, 2007	-0.3890	-0.1873	-0.2846	-0.4297
	(0.1900)	(0.1371)	(0.1671)	(0.1725)
Event 2: December 18, 2010	-0.2981*	-0.1154*	-0.0438	0.0221
	(0.0258)	(0.0172)	(0.0213)	(0.0233)
Event 3: April 24, 2014	0.1383	0.0529	-0.2844*	-0.2864*
	(0.0560)	(0.0332)	(0.0435)	(0.0417)
Event 4: May 27, 2015	-0.0070	0.0031	-0.0355	0.3405*
	(0.0351)	(0.0240)	(0.0294)	(0.0317)

Notes: This table reports estimates from four separate regression discontinuity specifications, one for each pollutant, each with a 9^{th}-order time trend, 4^{th} order polynomial on log daily average temperature and log daily max sustained wind speed, and station fixed effects, as well as month of the year, day of the week, and year fixed effects. The unit of observation is a station-day; for each station, hourly pollution levels for were averaged over all hours of the day for that station. The reported coefficients on ”Post reform” correspond to indicator variable that equals to one after the first reform event on June 2007. The reported coefficients on other events correspond to indicator variables that equal to one for every day during the time periods of the respective subsidy reform phase. Standard errors, in parentheses, are robust to heteroskedasticity. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table 3.16.B: The Effects of Removing Subsidies on Daily Average Pollution Levels in Tehran (Post reform regression controlling for SO_2 and using 8^{th}-order polynomial time trend)

	Dependent variable is log daily average pollution for:			
	O_3	CO	NO_2	PM_{10}
Event 1: June 27, 2007	-0.4265	-0.1476	-0.3097	-0.3973
	(0.1889)	(0.1363)	(0.1660)	(0.1712)
Event 2: December 18, 2010	-0.2871*	-0.1244*	-0.0385	0.0142
	(0.0250)	(0.0169)	(0.0209)	(0.0228)
Event 3: April 24, 2014	0.1374	0.0530	-0.2850*	-0.2866*
	(0.0560)	(0.0332)	(0.0435)	(0.0417)
Event 4: May 27, 2015	0.0101	-0.0147	-0.0252	0.3268*
	(0.0338)	(0.0230)	(0.0283)	(0.0305)

Notes: This table reports estimates from four separate regression discontinuity specifications, one for each pollutant, each with a 8^{th}-order time trend, 4^{th} order polynomial on log daily average temperature and log daily max sustained wind speed, and station fixed effects, as well as month of the year, day of the week, and year fixed effects. The unit of observation is a station-day; for each station, hourly pollution levels for were averaged over all hours of the day for that station. The reported coefficients on ”Post reform” correspond to indicator variable that equals to one after the first reform event on June 2007. The reported coefficients on other events correspond to indicator variables that equal to one for every day during the time periods of the respective subsidy reform phase. Standard errors, in parentheses, are robust to heteroskedasticity. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table 3.17.A: The Effects of Removing Subsidies on Daily Max Pollution Levels in Tehran (Post reform regression controlling for SO_2 and using 9^{th}-order polynomial time trend)

	Dependent variable is log daily maximum pollution for:			
	O_3	CO	NO_2	PM_{10}
Event 1: June 27, 2007	-0.2727	-0.1559	-0.3396	-0.5193*
	(0.2176)	(0.1527)	(0.1712)	(0.1857)
Event 2: December 18, 2010	-0.2643*	-0.0862*	-0.0351	0.0517
	(0.0295)	(0.0192)	(0.0218)	(0.0251)
Event 3: April 24, 2014	0.1353	0.0590	-0.2810*	-0.2122*
	(0.0641)	(0.0369)	(0.0445)	(0.0449)
Event 4: May 27, 2015	0.0622	0.0127	-0.0877*	0.3770*
	(0.0402)	(0.0267)	(0.0301)	(0.0342)

Notes: This table reports estimates from four separate regression discontinuity specifications, one for each pollutant, each with a 9^{th}-order time trend, 4^{th} order polynomial on log daily average temperature and log daily max sustained wind speed, and station fixed effects, as well as month of the year, day of the week, and year fixed effects. The unit of observation is a station-day; for each station, hourly pollution levels for were averaged over all hours of the day for that station. The reported coefficients on ”Post reform” correspond to indicator variable that equals to one after the first reform event on June 2007. The reported coefficients on other events correspond to indicator variables that equal to one for every day during the time periods of the respective subsidy reform phase. Standard errors, in parentheses, are robust to heteroskedasticity. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table 3.17.B: The Effects of Removing Subsidies on Daily Max Pollution Levels in Tehran (Post reform regression controlling for SO_2 and using 8^{th}-order polynomial time trend)

	Dependent variable is log daily maximum pollution for:			
	O_3	CO	NO_2	PM_{10}
Event 1: June 27, 2007	-0.3220	-0.0631	-0.3829	-0.4993*
	(0.2163)	(0.1519)	(0.1700)	(0.1844)
Event 2: December 18, 2010	-0.2499*	-0.1071*	-0.0260	0.0468
	(0.0287)	(0.0188)	(0.0214)	(0.0246)
Event 3: April 24, 2014	0.1341	0.0593	-0.2819*	-0.2123*
	(0.0641)	(0.0370)	(0.0446)	(0.0449)
Event 4: May 27, 2015	0.0848	-0.0286	-0.0701	0.3686*
	(0.0387)	(0.0256)	(0.0290)	(0.0329)

Notes: This table reports estimates from four separate regression discontinuity specifications, one for each pollutant, each with a 8^{th}-order time trend, 4^{th} order polynomial on log daily average temperature and log daily max sustained wind speed, and station fixed effects, as well as month of the year, day of the week, and year fixed effects. The unit of observation is a station-day; for each station, hourly pollution levels for were averaged over all hours of the day for that station. The reported coefficients on "Post reform" correspond to indicator variable that equals to one after the first reform event on June 2007. The reported coefficients on other events correspond to indicator variables that equal to one for every day during the time periods of the respective subsidy reform phase. Standard errors, in parentheses, are robust to heteroskedasticity. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table 3.18.A: Effects of Removing Subsidies on Pollution Levels in Tehran (around event 1)

	Dependent variable is log avg daily pollution for:				
	O_3	CO	NO_2	SO_2	PM_{10}
8 weeks before and after event	-0.5173*	-0.1863	-0.2026	-0.2134	-0.6677*
	(0.1533)	(0.1337)	(0.1456)	(0.2734)	(0.1271)
10 weeks before and after event	-0.4461*	-0.1449	-0.1487	-0.1407	-0.5399*
	(0.1432)	(0.1321)	(0.1346)	(0.2500)	(0.1274)
20 weeks before and after event	-0.4236*	-0.2045	-0.0507	-0.4131	-0.4059*
	(0.1381)	(0.1199)	(0.1409)	(0.2431)	(0.1164)
26 weeks before and after event	-0.3296	-0.1930	-0.1344	-0.4632	-0.4099*
	(0.1549)	(0.1165)	(0.1425)	(0.2386)	(0.1253)
30 weeks before and after event	-0.3231	-0.2259	-0.1348	-0.4624	-0.4179*
	(0.1883)	(0.1183)	(0.1485)	(0.2395)	(0.1332)
40 weeks before and after event	-0.3006	-0.2072	-0.1475	-0.4752	-0.3611
	(0.2007)	(0.1203)	(0.1566)	(0.2624)	(0.1477)
50 weeks before and after event	-0.3551	-0.2615	-0.1745	-0.7661*	-0.3659
	(0.2161)	(0.1211)	(0.1538)	(0.2653)	(0.1639)
	Dependent variable is log max daily pollution for:				
	O_3	CO	NO_2	SO_2	PM_{10}
8 weeks before and after event	-0.8709*	-0.5687*	-0.2441	-0.3142	-0.7912*
	(0.2001)	(0.1593)	(0.1581)	(0.2958)	(0.1848)
10 weeks before and after event	-0.4236*	-0.2045	-0.0507	-0.4131	-0.4059*
	(0.1381)	(0.1199)	(0.1409)	(0.2431)	(0.1164)
20 weeks before and after event	-0.6404*	-0.3899*	-0.0869	-0.4207	-0.4857*
	(0.1786)	(0.1370)	(0.1662)	(0.2671)	(0.1429)
26 weeks before and after event	-0.5370*	-0.3371	-0.1396	-0.4479	-0.5020*
	(0.1834)	(0.1323)	(0.1649)	(0.2610)	(0.1456)
30 weeks before and after event	-0.5309	-0.3877*	-0.1435	-0.4330	-0.5248*
	(0.2088)	(0.1339)	(0.1740)	(0.2590)	(0.1530)
40 weeks before and after event	-0.5055	-0.3627*	-0.1470	-0.4630	-0.4518*
	(0.2257)	(0.1354)	(0.1852)	(0.2767)	(0.1644)
50 weeks before and after event	-0.5436	-0.4424*	-0.1917	-0.8279*	-0.4292
	(0.2382)	(0.1347)	(0.1814)	(0.2829)	(0.1779)

Notes: This table reports estimates from five separate regression using local polynomial. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table 3.18.B: Effects of Removing Subsidies on Pollution Levels in Tehran (around event 2)

	Dependent variable is log avg daily pollution for:				
	O_3	CO	NO_2	SO_2	PM_{10}
8 weeks before and after event	-0.1571	0.0743	0.0958	0.5508*	0.1548
	(0.0925)	(0.0613)	(0.0596)	(0.0940)	(0.0877)
10 weeks before and after event	-0.0229	-0.2432*	-0.1413*	0.0762	-0.0526
	(0.0629)	(0.0434)	(0.0386)	(0.0614)	(0.0571)
20 weeks before and after event	-0.0817	-0.2526*	-0.1655*	-0.0190	-0.1669*
	(0.0550)	(0.0360)	(0.0351)	(0.0577)	(0.0561)
26 weeks before and after event	-0.0786	-0.2279*	-0.0934*	0.0427	-0.0945
	(0.0586)	(0.0365)	(0.0358)	(0.0596)	(0.0555)
30 weeks before and after event	-0.0551	-0.2389*	-0.1224*	0.0162	-0.1114
	(0.0614)	(0.0371)	(0.0364)	(0.0605)	(0.0573)
40 weeks before and after event	-0.1139	-0.2085*	-0.0851	0.0350	-0.0629
	(0.0618)	(0.0363)	(0.0362)	(0.0579)	(0.0571)
50 weeks before and after event	-0.2205*	-0.1180*	0.0131	0.0839	0.0526
	(0.0577)	(0.0342)	(0.0375)	(0.0534)	(0.0534)
	Dependent variable is log max daily pollution for:				
	O_3	CO	NO_2	SO_2	PM_{10}
8 weeks before and after event	-0.0389	0.0523	0.0230	0.6565*	0.0049
	(0.1191)	(0.0667)	(0.0621)	(0.1109)	(0.1007)
10 weeks before and after event	-0.1063	-0.2983*	-0.1754*	0.0996	-0.0900
	(0.0788)	(0.0466)	(0.0403)	(0.0713)	(0.0658)
20 weeks before and after event	-0.1597	-0.2507*	-0.1680*	0.0042	-0.1753*
	(0.0650)	(0.0404)	(0.0382)	(0.0610)	(0.0624)
26 weeks before and after event	-0.1466	-0.2092*	-0.0825	0.0917	-0.1067
	(0.0681)	(0.0415)	(0.0388)	(0.0630)	(0.0628)
30 weeks before and after event	-0.1285	-0.2279*	-0.1176*	0.0533	-0.1206
	(0.0715)	(0.0426)	(0.0395)	(0.0642)	(0.0639)
40 weeks before and after event	-0.1952*	-0.1933*	-0.0745	0.0836	-0.0676
	(0.0733)	(0.0415)	(0.0391)	(0.0612)	(0.0626)
50 weeks before and after event	-0.3195*	-0.1152*	0.0009	0.1229	0.0363
	(0.0693)	(0.0389)	(0.0395)	(0.0566)	(0.0577)

Notes: This table reports estimates from five separate regression using local polynomial. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table 3.18.C: Effects of Removing Subsidies on Pollution Levels in Tehran (around event 3)

	Dependent variable is log avg daily pollution for:				
	O_3	CO	NO_2	SO_2	PM_{10}
8 weeks before and after event	0.0558	0.0904	0.0758	-0.0709	0.1295*
	(0.0473)	(0.0374)	(0.0495)	(0.0483)	(0.0452)
10 weeks before and after event	-0.0092	0.1108*	0.0340	-0.0269	0.1815*
	(0.0433)	(0.0354)	(0.0482)	(0.0499)	(0.0411)
20 weeks before and after event	-0.0691	0.1387*	-0.0540	-0.1306	0.0481
	(0.0560)	(0.0516)	(0.0686)	(0.0983)	(0.0551)
26 weeks before and after event	-0.0644	0.1081	0.0227	-0.0831	0.0524
	(0.0505)	(0.0431)	(0.0634)	(0.0746)	(0.0453)
30 weeks before and after event	-0.1148	0.0876	-0.0023	-0.0605	0.0541
	(0.0491)	(0.0438)	(0.0620)	(0.0766)	(0.0450)
40 weeks before and after event	-0.0933	0.0528	-0.0689	-0.1220	-0.0329
	(0.0479)	(0.0422)	(0.0619)	(0.0792)	(0.0439)
50 weeks before and after event	-0.1308*	0.0486	-0.0698	-0.0488	0.0413
	(0.0475)	(0.0407)	(0.0639)	(0.0781)	(0.0444)

	Dependent variable is log max daily pollution for:				
	O_3	CO	NO_2	SO_2	PM_{10}
8 weeks before and after event	0.1098	0.1474*	0.1075	-0.1290	0.1175
	(0.0527)	(0.0509)	(0.0553)	(0.0649)	(0.0601)
10 weeks before and after event	0.0506	0.1577*	0.0253	-0.0203	0.1968*
	(0.0483)	(0.0464)	(0.0523)	(0.0684)	(0.0546)
20 weeks before and after event	-0.0315	0.2169*	0.0168	-0.0190	0.1085
	(0.0563)	(0.0491)	(0.0637)	(0.0906)	(0.0556)
26 weeks before and after event	-0.0691	0.1387*	-0.0540	-0.1306	0.0481
	(0.0560)	(0.0516)	(0.0686)	(0.0983)	(0.0551)
30 weeks before and after event	-0.0988	0.1004	-0.0908	-0.0967	0.0438
	(0.0551)	(0.0520)	(0.0675)	(0.1034)	(0.0547)
40 weeks before and after event	-0.0635	0.0350	-0.1483	-0.1909	-0.0124
	(0.0563)	(0.0509)	(0.0675)	(0.1102)	(0.0522)
50 weeks before and after event	-0.0869	0.0236	-0.1532	-0.0940	0.0703
	(0.0552)	(0.0488)	(0.0684)	(0.1105)	(0.0527)

Notes: This table reports estimates from five separate regression using local polynomial. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table 3.18.D: Effects of Removing Subsidies on Pollution Levels in Tehran (around event 4)

	Dependent variable is log avg daily pollution for:				
	O_3	CO	NO_2	SO_2	PM_{10}
8 weeks before and after event	-0.2470*	-0.0714	-0.1726*	-0.0657	0.1900*
	(0.0496)	(0.0415)	(0.0396)	(0.0420)	(0.0635)
10 weeks before and after event	-0.1803*	-0.0734	-0.1597*	-0.0777	0.0792
	(0.0480)	(0.0392)	(0.0382)	(0.0404)	(0.0584)
20 weeks before and after event	-0.1870*	-0.0709	-0.1461*	-0.0142	0.3218*
	(0.0449)	(0.0374)	(0.0396)	(0.0467)	(0.0608)
26 weeks before and after event	-0.1693*	-0.0477	-0.0939	0.0087	0.4034*
	(0.0448)	(0.0380)	(0.0441)	(0.0483)	(0.0594)
30 weeks before and after event	-0.1501*	-0.0572	-0.0999	0.0281	0.4313*
	(0.0455)	(0.0391)	(0.0461)	(0.0500)	(0.0601)
40 weeks before and after event	-0.0706	-0.1073*	-0.1122	-0.0057	0.3476*
	(0.0455)	(0.0401)	(0.0487)	(0.0514)	(0.0585)
50 weeks before and after event	-0.0800	-0.0605	-0.0386	-0.0190	0.3531*
	(0.0478)	(0.0412)	(0.0506)	(0.0531)	(0.0572)
	Dependent variable is log max daily pollution for:				
	O_3	CO	NO_2	SO_2	PM_{10}
8 weeks before and after event	-0.3496*	-0.1509*	-0.2094*	-0.1638*	0.1770
	(0.0549)	(0.0541)	(0.0411)	(0.0609)	(0.0806)
10 weeks before and after event	-0.2997*	-0.1374*	-0.1635*	-0.1556*	0.0956
	(0.0529)	(0.0510)	(0.0392)	(0.0589)	(0.0743)
20 weeks before and after event	-0.2337*	-0.1337*	-0.1782*	-0.0741	0.3300*
	(0.0509)	(0.0470)	(0.0414)	(0.0650)	(0.0762)
26 weeks before and after event	-0.2151*	-0.1103	-0.1224*	-0.0513	0.4231*
	(0.0520)	(0.0471)	(0.0461)	(0.0671)	(0.0724)
30 weeks before and after event	-0.1884*	-0.1264*	-0.1267*	-0.0386	0.4520*
	(0.0526)	(0.0476)	(0.0487)	(0.0685)	(0.0720)
40 weeks before and after event	-0.0942	-0.1977*	-0.1435*	-0.0897	0.3896*
	(0.0523)	(0.0477)	(0.0509)	(0.0685)	(0.0694)
50 weeks before and after event	-0.0938	-0.1536*	-0.0782	-0.1041	0.3941*
	(0.0543)	(0.0486)	(0.0528)	(0.0699)	(0.0688)

Notes: This table reports estimates from five separate regression using local polynomial. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table 3.19.A: Effects of Removing Subsidies on Pollution Levels in Tehran (around event 1, using SO_2 as control)

	Dependent variable is log avg daily pollution for:			
	O_3	CO	NO_2	PM_{10}
8 weeks before and after event	-0.5674*	-0.1681	-0.1727	-0.6569*
	(0.1539)	(0.1786)	(0.1255)	(0.1284)
10 weeks before and after event	-0.5125*	-0.0949	-0.1369	-0.5192*
	(0.1394)	(0.1724)	(0.1177)	(0.1290)
20 weeks before and after event	-0.5407*	0.0011	-0.0142	-0.3465*
	(0.1344)	(0.1555)	(0.1332)	(0.1152)
26 weeks before and after event	-0.4705*	0.0247	-0.0988	-0.3148*
	(0.1539)	(0.1503)	(0.1343)	(0.1225)
30 weeks before and after event	-0.4540*	-0.0377	-0.0883	-0.3456*
	(0.1787)	(0.1530)	(0.1393)	(0.1301)
40 weeks before and after event	-0.4212	-0.0040	-0.1009	-0.2958
	(0.1893)	(0.1536)	(0.1494)	(0.1397)
50 weeks before and after event	-0.5237*	-0.0435	-0.0901	-0.3180
	(0.2061)	(0.1549)	(0.1485)	(0.1525)

	Dependent variable is log max daily pollution for:			
	O_3	CO	NO_2	PM_{10}
8 weeks before and after event	-0.9480*	-0.4928	-0.1847	-0.7603*
	(0.2013)	(0.1997)	(0.1414)	(0.1890)
10 weeks before and after event	-0.8876*	-0.3695	-0.1591	-0.6160*
	(0.1848)	(0.1906)	(0.1384)	(0.1737)
20 weeks before and after event	-0.7727*	-0.1531	-0.0699	-0.4195*
	(0.1778)	(0.1718)	(0.1646)	(0.1433)
26 weeks before and after event	-0.6727*	-0.0722	-0.1273	-0.4045*
	(0.1844)	(0.1635)	(0.1618)	(0.1443)
30 weeks before and after event	-0.6367*	-0.1594	-0.1130	-0.4462*
	(0.2069)	(0.1678)	(0.1697)	(0.1520)
40 weeks before and after event	-0.6247*	-0.1179	-0.1071	-0.3786
	(0.2171)	(0.1707)	(0.1811)	(0.1594)
50 weeks before and after event	-0.6859*	-0.1418	-0.0975	-0.3735
	(0.2292)	(0.1696)	(0.1794)	(0.1681)

Notes: This table reports estimates from four separate regression using local polynomial. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table 3.19.B: Effects of Removing Subsidies on Pollution Levels in Tehran (around event 2, using SO_2 as control)

	Dependent variable is log avg daily pollution for:			
	O_3	CO	NO_2	PM_{10}
8 weeks before and after event	-0.2602*	-0.0021	-0.0444	-0.0411
	(0.0936)	(0.0628)	(0.0592)	(0.0841)
10 weeks before and after event	-0.1140	-0.2327*	-0.2028*	-0.0548
	(0.0649)	(0.0423)	(0.0384)	(0.0536)
20 weeks before and after event	-0.1553*	-0.2741*	-0.2085*	-0.1549*
	(0.0570)	(0.0362)	(0.0368)	(0.0573)
26 weeks before and after event	-0.1608*	-0.2545*	-0.1479*	-0.0865
	(0.0587)	(0.0377)	(0.0365)	(0.0583)
30 weeks before and after event	-0.1504	-0.2600*	-0.1744*	-0.1015
	(0.0627)	(0.0385)	(0.0372)	(0.0599)
40 weeks before and after event	-0.2102*	-0.2357*	-0.1459*	-0.0754
	(0.0647)	(0.0382)	(0.0373)	(0.0607)
50 weeks before and after event	-0.2877*	-0.1261*	-0.0318	0.0100
	(0.0595)	(0.0363)	(0.0383)	(0.0569)
	Dependent variable is log max daily pollution for:			
	O_3	CO	NO_2	PM_{10}
8 weeks before and after event	-0.2078	-0.0565	-0.1535*	-0.1421
	(0.1180)	(0.0697)	(0.0604)	(0.0994)
10 weeks before and after event	-0.2575*	-0.2966*	-0.2427*	-0.0661
	(0.0792)	(0.0475)	(0.0397)	(0.0625)
20 weeks before and after event	-0.2743*	-0.2790*	-0.2030*	-0.1511
	(0.0670)	(0.0421)	(0.0398)	(0.0612)
26 weeks before and after event	-0.2718*	-0.2519*	-0.1384*	-0.0842
	(0.0704)	(0.0442)	(0.0397)	(0.0639)
30 weeks before and after event	-0.2655*	-0.2667*	-0.1677*	-0.0987
	(0.0749)	(0.0453)	(0.0406)	(0.0652)
40 weeks before and after event	-0.3348*	-0.2410*	-0.1357*	-0.0609
	(0.0785)	(0.0447)	(0.0403)	(0.0655)
50 weeks before and after event	-0.4352*	-0.1405*	-0.0511	0.0224
	(0.0731)	(0.0419)	(0.0402)	(0.0605)

Notes: This table reports estimates from four separate regression using local polynomial. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table 3.19.C: Effects of Removing Subsidies on Pollution Levels in Tehran (around event 3, using SO_2 as control)

	Dependent variable is log avg daily pollution for:			
	O_3	CO	NO_2	PM_{10}
8 weeks before and after event	0.1820	0.1330	0.1401	0.2521
	(0.0929)	(0.0815)	(0.1045)	(0.1023)
10 weeks before and after event	0.1704	0.1147	0.0569	0.2637^*
	(0.0777)	(0.0769)	(0.0912)	(0.0880)
20 weeks before and after event	-0.0323	0.1102	0.1104	0.2286^*
	(0.0970)	(0.0779)	(0.1060)	(0.0906)
26 weeks before and after event	-0.0611	0.0376	0.0528	0.1195
	(0.0940)	(0.0804)	(0.1061)	(0.0944)
30 weeks before and after event	-0.1166	0.0223	0.0163	0.1376
	(0.0904)	(0.0808)	(0.0999)	(0.0933)
40 weeks before and after event	-0.1200	0.0059	-0.0908	0.0146
	(0.0865)	(0.0778)	(0.0953)	(0.0901)
50 weeks before and after event	-0.1179	-0.0199	-0.2105	0.0405
	(0.0864)	(0.0733)	(0.1012)	(0.0913)

	Dependent variable is log max daily pollution for:			
	O_3	CO	NO_2	PM_{10}
8 weeks before and after event	0.1920	0.1972	0.1687	0.2838
	(0.0913)	(0.0989)	(0.1207)	(0.1174)
10 weeks before and after event	0.1831	0.1921	-0.0149	0.3008^*
	(0.0797)	(0.0878)	(0.1058)	(0.0990)
20 weeks before and after event	-0.1027	0.2609^*	-0.0147	0.3202^*
	(0.1132)	(0.0947)	(0.1204)	(0.1064)
26 weeks before and after event	-0.1711	0.1709	-0.0950	0.2036
	(0.1063)	(0.0973)	(0.1144)	(0.1101)
30 weeks before and after event	-0.1802	0.1240	-0.1255	0.2225
	(0.1039)	(0.0961)	(0.1080)	(0.1104)
40 weeks before and after event	-0.1970	0.0493	-0.2320	0.1174
	(0.1045)	(0.0926)	(0.1035)	(0.1032)
50 weeks before and after event	-0.1416	-0.0131	-0.3782^*	0.1619
	(0.1013)	(0.0857)	(0.1080)	(0.1056)

Notes: This table reports estimates from four separate regression using local polynomial. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

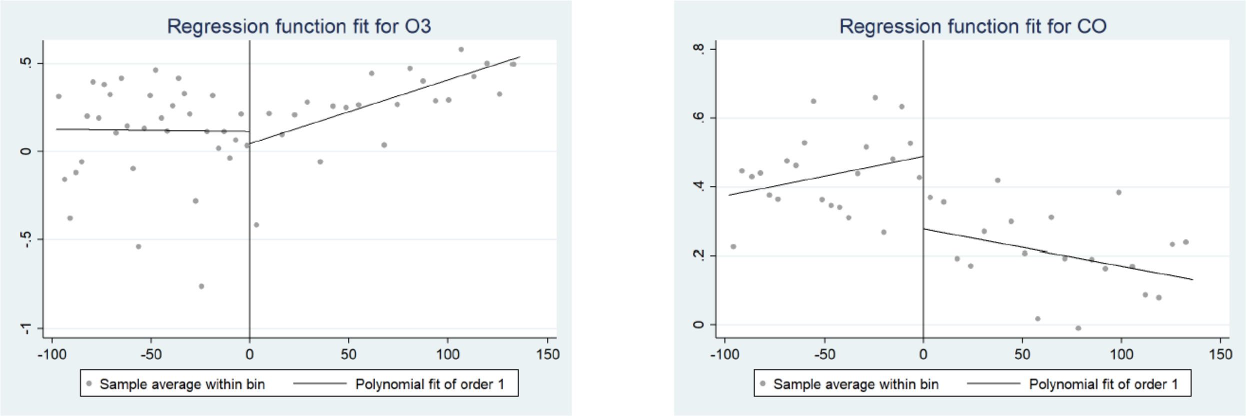
Table 3.19.D: Effects of Removing Subsidies on Pollution Levels in Tehran (around event 4, using SO_2 as control)

	Dependent variable is log avg daily pollution for:			
	O_3	CO	NO_2	PM_{10}
8 weeks before and after event	-0.2845*	-0.1032	-0.1458*	0.2727*
	(0.0562)	(0.0469)	(0.0450)	(0.0739)
10 weeks before and after event	-0.2219*	-0.1086	-0.1400*	0.1656
	(0.0551)	(0.0444)	(0.0430)	(0.0691)
20 weeks before and after event	-0.2149*	-0.1137*	-0.1218*	0.3806*
	(0.0509)	(0.0421)	(0.0435)	(0.0706)
26 weeks before and after event	-0.1962*	-0.0768	-0.0817	0.4327*
	(0.0512)	(0.0421)	(0.0468)	(0.0686)
30 weeks before and after event	-0.1792*	-0.0705	-0.0739	0.4574*
	(0.0522)	(0.0430)	(0.0476)	(0.0691)
40 weeks before and after event	-0.1103	-0.1085	-0.0751	0.4186*
	(0.0517)	(0.0435)	(0.0502)	(0.0677)
50 weeks before and after event	-0.1249	-0.0709	-0.0193	0.4227*
	(0.0530)	(0.0445)	(0.0521)	(0.0669)

	Dependent variable is log max daily pollution for:			
	O_3	CO	NO_2	PM_{10}
8 weeks before and after event	-0.3994*	-0.1636*	-0.1834*	0.2693*
	(0.0613)	(0.0603)	(0.0472)	(0.0929)
10 weeks before and after event	-0.3533*	-0.1554*	-0.1456*	0.1808
	(0.0604)	(0.0569)	(0.0442)	(0.0870)
20 weeks before and after event	-0.2819*	-0.1601*	-0.1434*	0.3803*
	(0.0585)	(0.0522)	(0.0456)	(0.0871)
26 weeks before and after event	-0.2642*	-0.1306*	-0.0934	0.4437*
	(0.0596)	(0.0516)	(0.0496)	(0.0833)
30 weeks before and after event	-0.2395*	-0.1255	-0.0844	0.4783*
	(0.0603)	(0.0520)	(0.0511)	(0.0826)
40 weeks before and after event	-0.1537*	-0.1722*	-0.0869	0.4518*
	(0.0591)	(0.0521)	(0.0533)	(0.0807)
50 weeks before and after event	-0.1501*	-0.1322*	-0.0363	0.4582*
	(0.0600)	(0.0527)	(0.0553)	(0.0805)

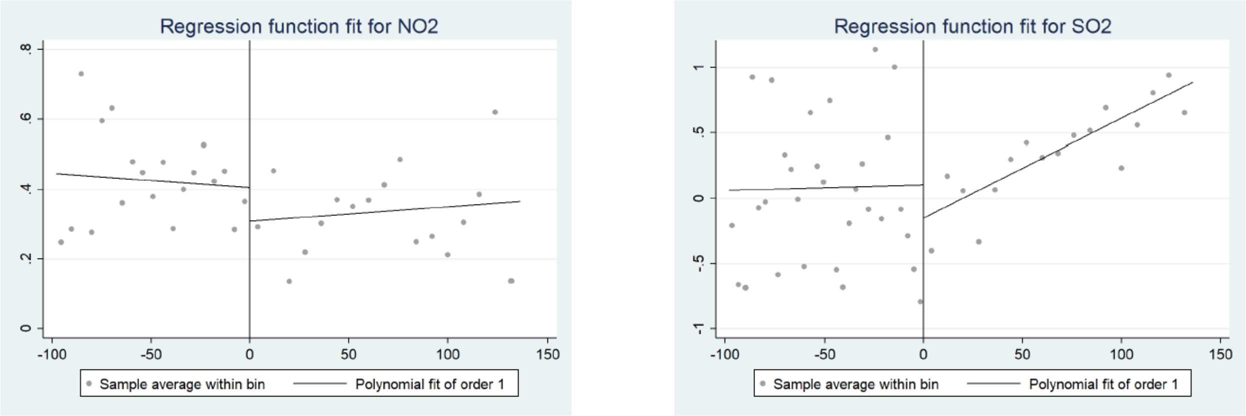
Notes: This table reports estimates from four separate regression using local polynomial. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Figure 3.14.A: Local linear residual plots 20 weeks before and after event 1 (daily average pollution)



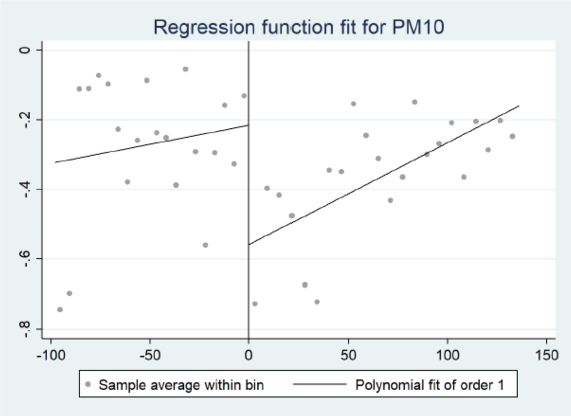
Ozone (O_3)

Carbon monoxide (CO)



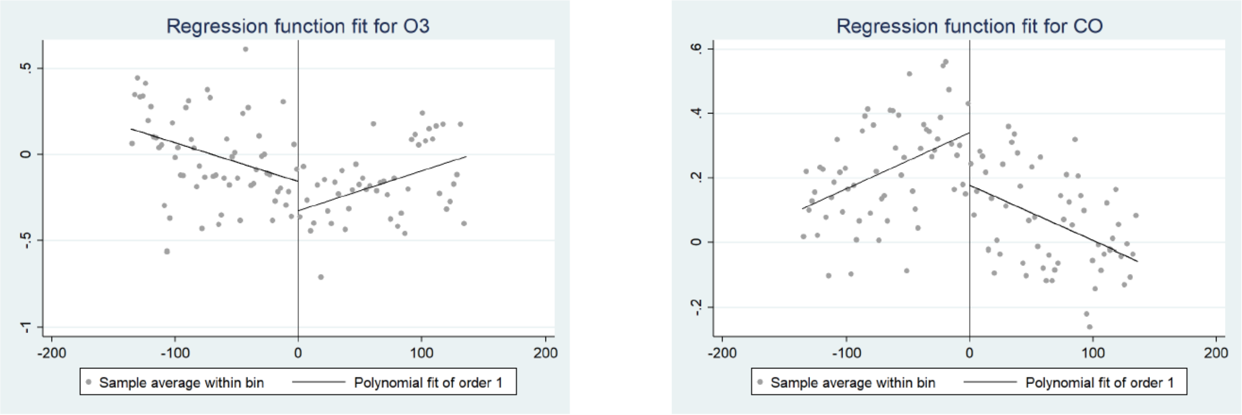
Nitrogen dioxide (NO_2)

Sulfur dioxide (SO_2)



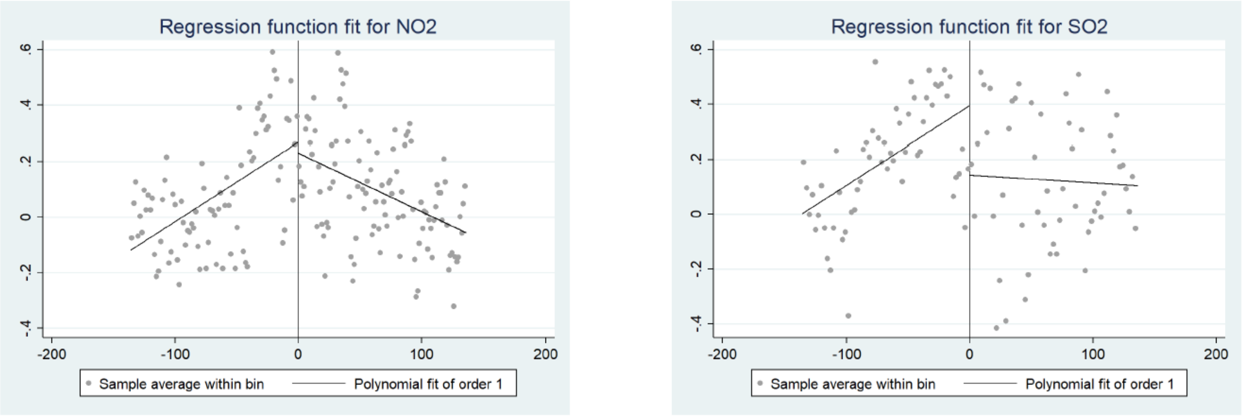
Particulate matter (PM_{10})

Figure 3.14.B: Local linear residual plots 20 weeks before and after event 2 (daily average pollution)



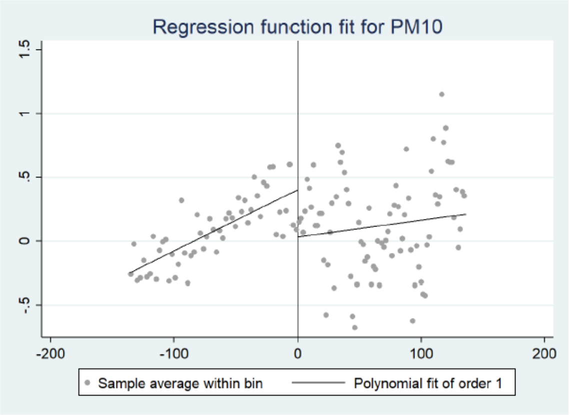
Ozone (O_3)

Carbon monoxide (CO)



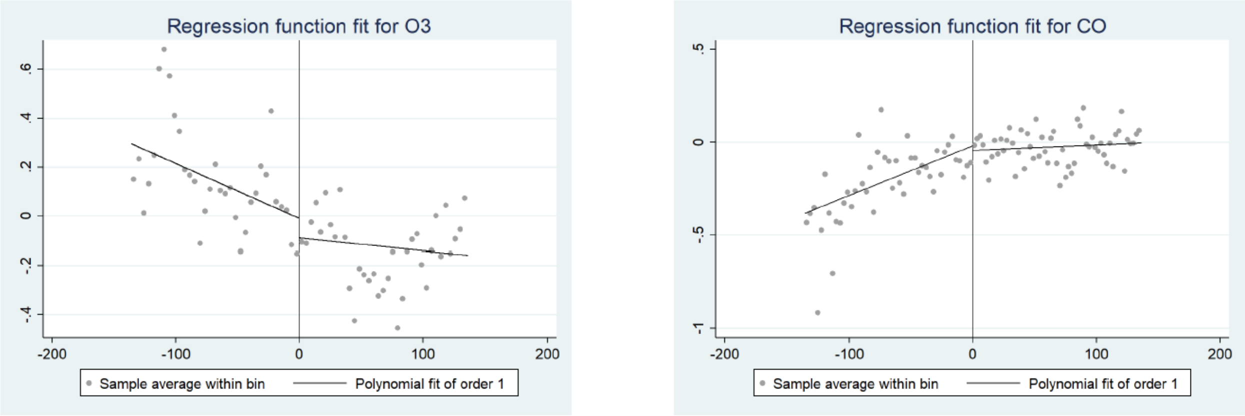
Nitrogen dioxide (NO_2)

Sulfur dioxide (SO_2)



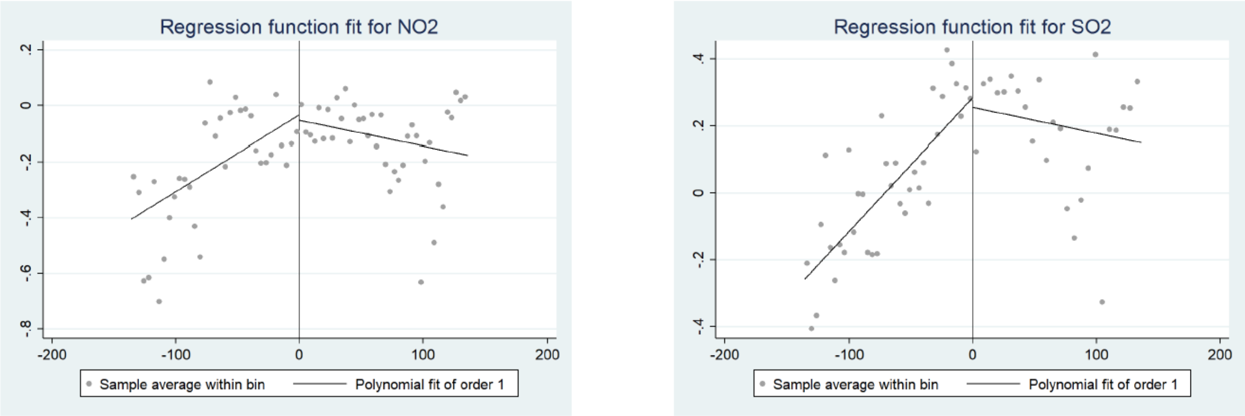
Particulate matter (PM_{10})

Figure 3.14.C: Local linear residual plots 20 weeks before and after event 3 (daily average pollution)



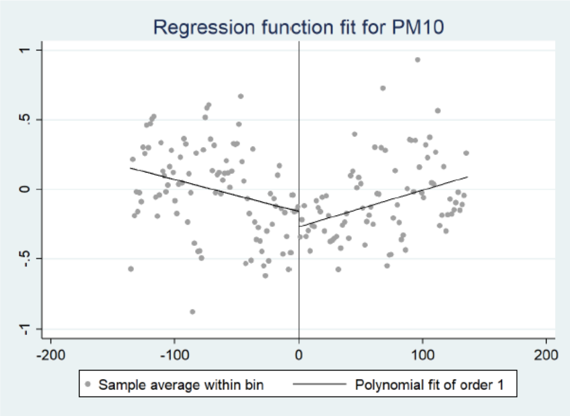
Ozone (O_3)

Carbon monoxide (CO)



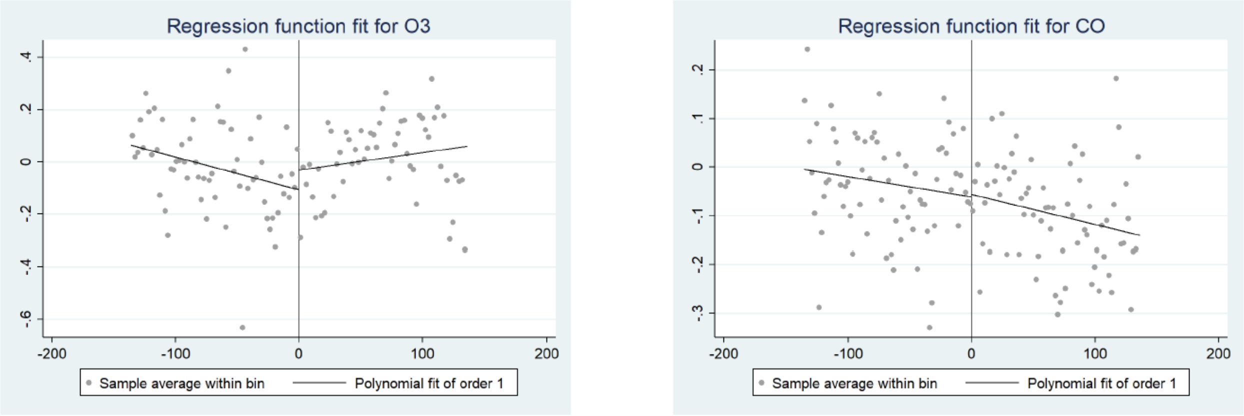
Nitrogen dioxide (NO_2)

Sulfur dioxide (SO_2)



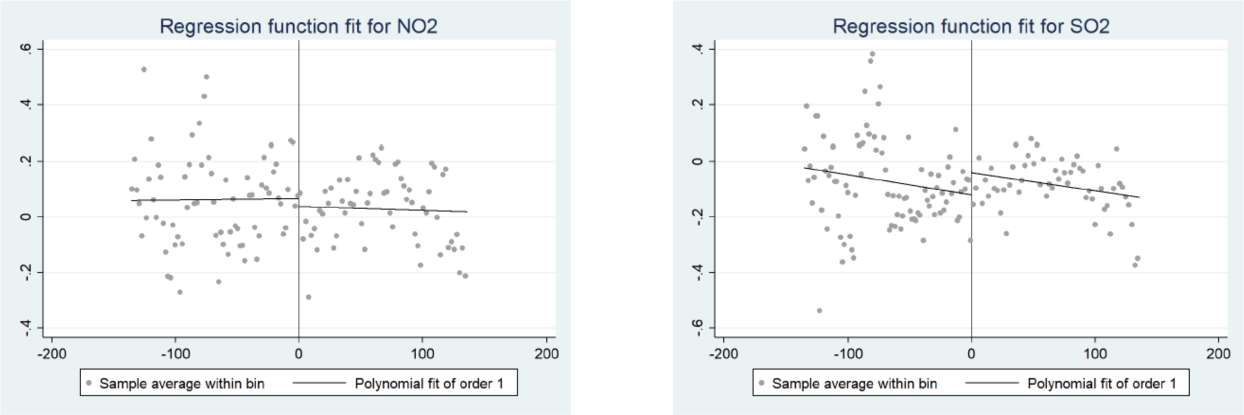
Particulate matter (PM_{10})

Figure 3.14.D: Local linear residual plots 20 weeks before and after event 4 (daily average pollution)



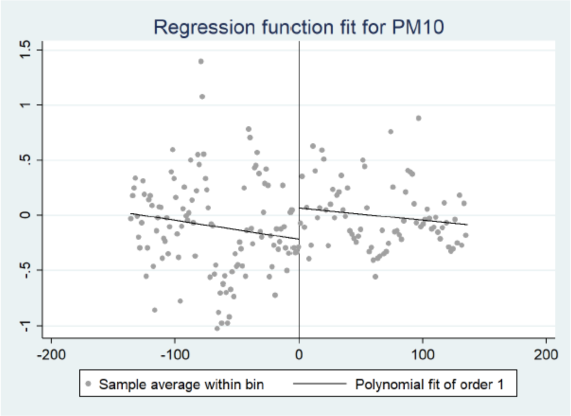
Ozone (O_3)

Carbon monoxide (CO)



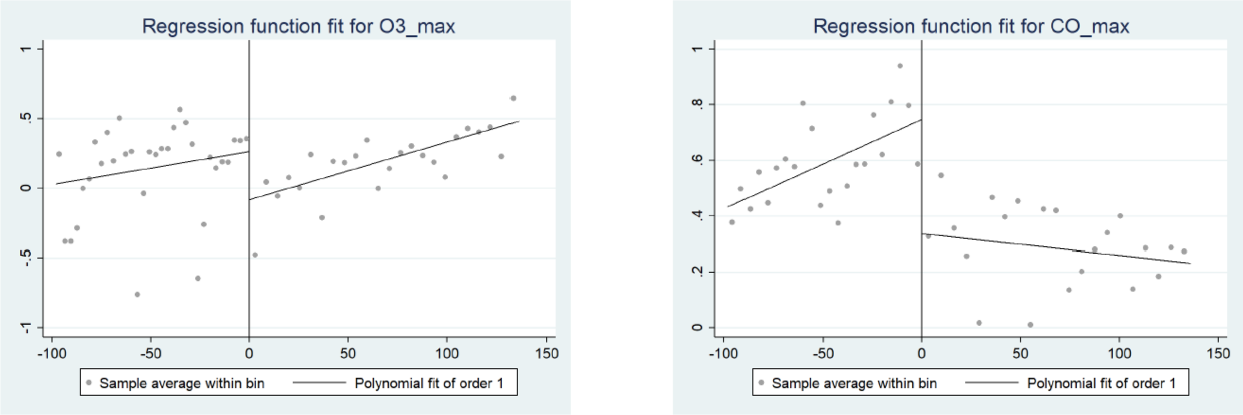
Nitrogen dioxide (NO_2)

Sulfur dioxide (SO_2)



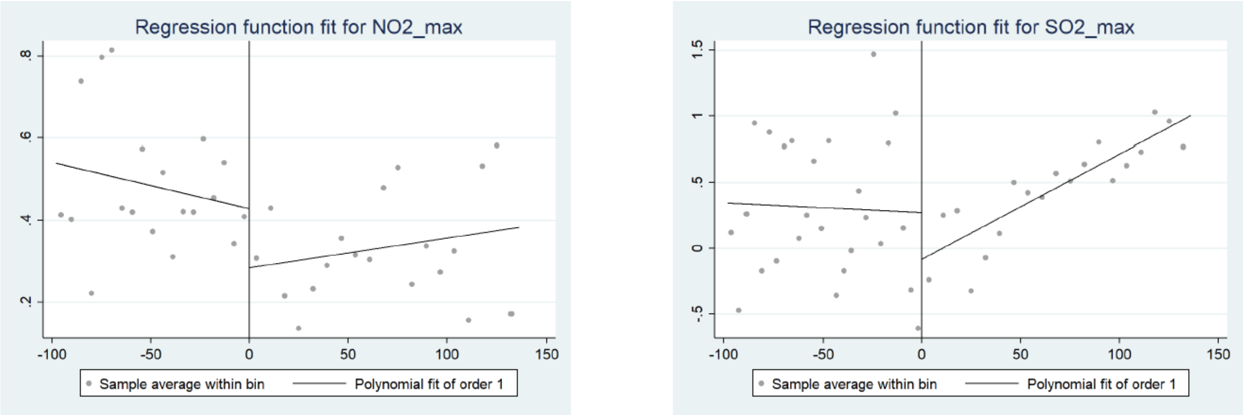
Particulate matter (PM_{10})

Figure 3.15.A: Local linear residual plots 20 weeks before and after event 1 (daily maximum pollution)



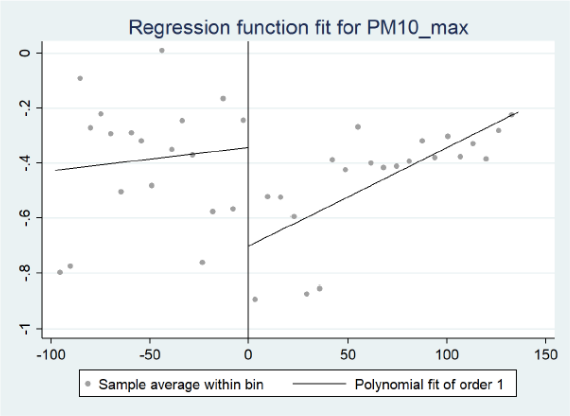
Ozone (O_3)

Carbon monoxide (CO)



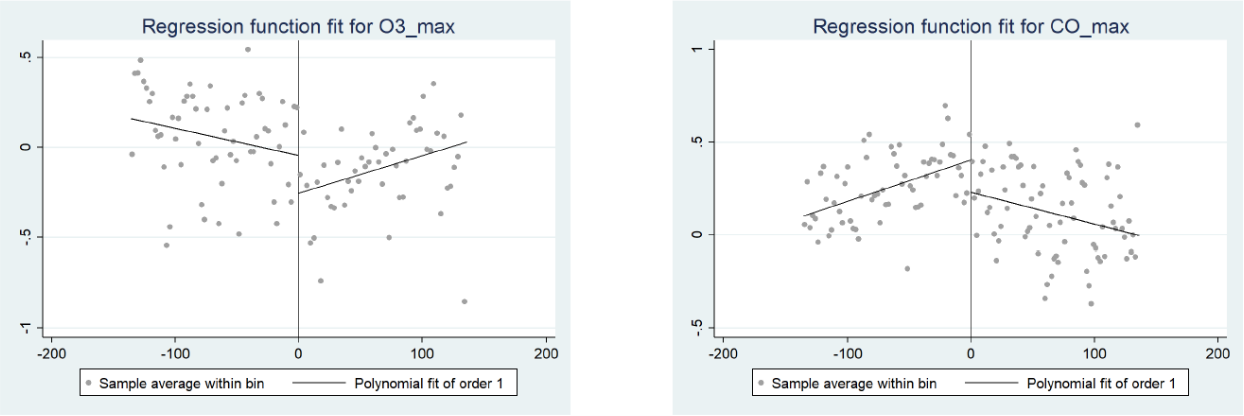
Nitrogen dioxide (NO_2)

Sulfur dioxide (SO_2)



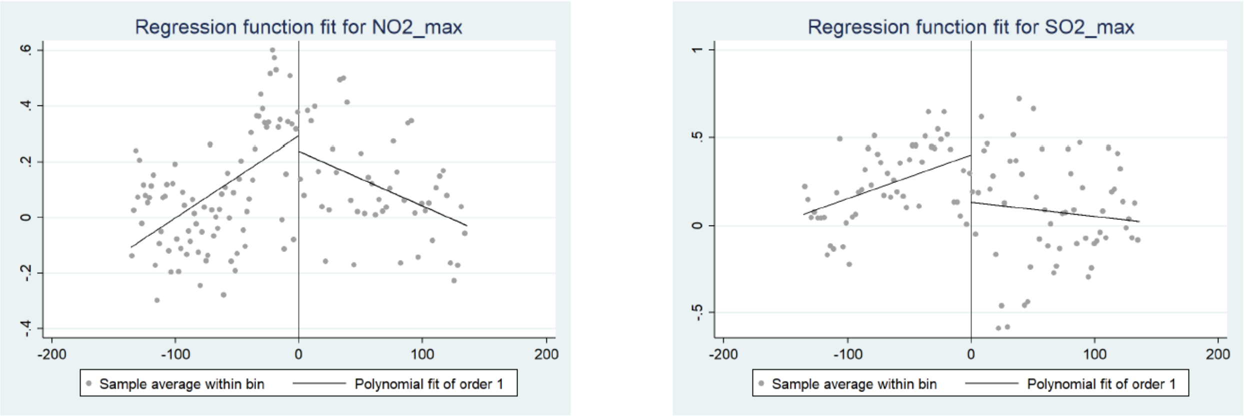
Particulate matter (PM_{10})

Figure 3.15.B: Local linear residual plots 20 weeks before and after event 2 (daily maximum pollution)



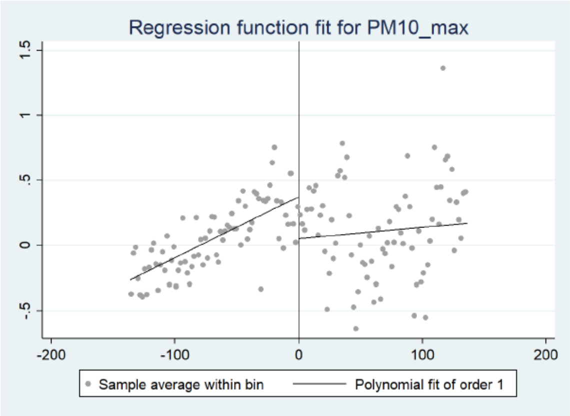
Ozone (O_3)

Carbon monoxide (CO)



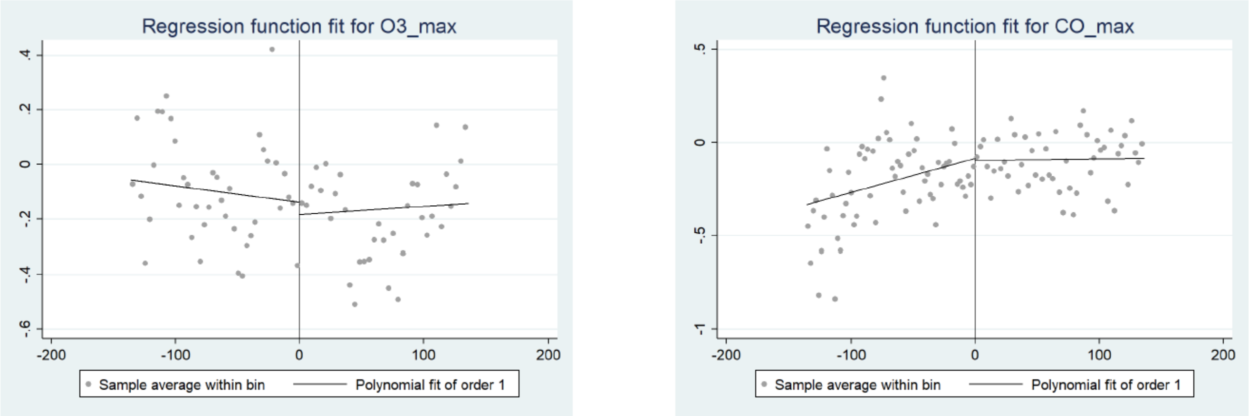
Nitrogen dioxide (NO_2)

Sulfur dioxide (SO_2)

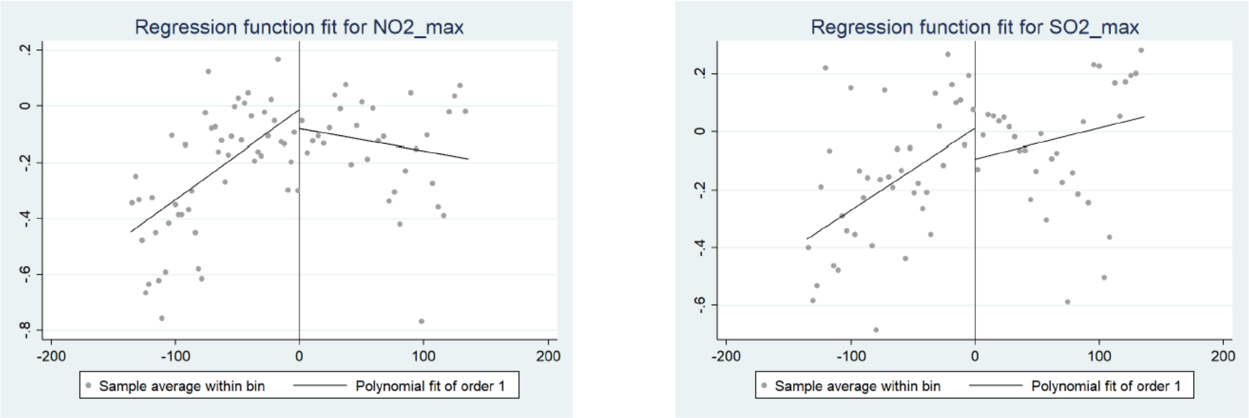


Particulate matter (PM_{10})

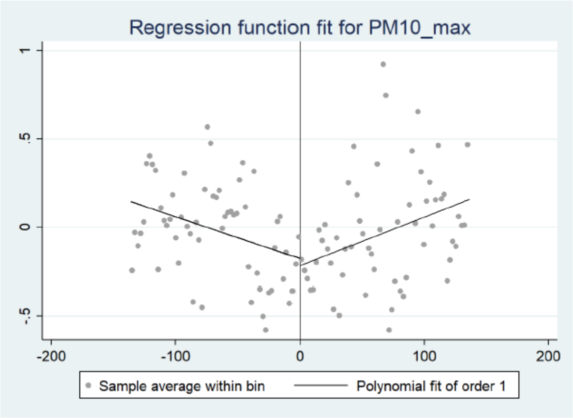
Figure 3.15.C: Local linear residual plots 20 weeks before and after event 3 (daily maximum pollution)



Ozone (O_3) Carbon monoxide (CO)

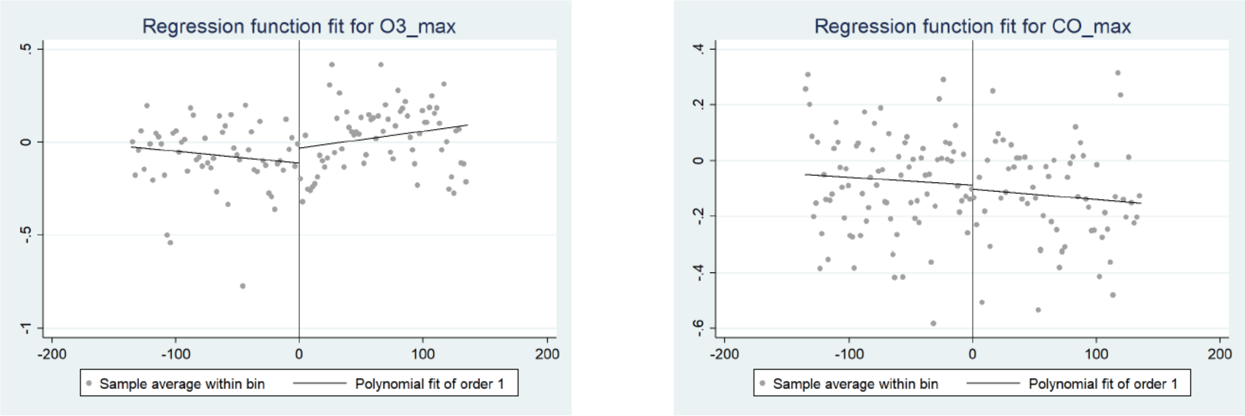


Nitrogen dioxide (NO_2) Sulfur dioxide (SO_2)



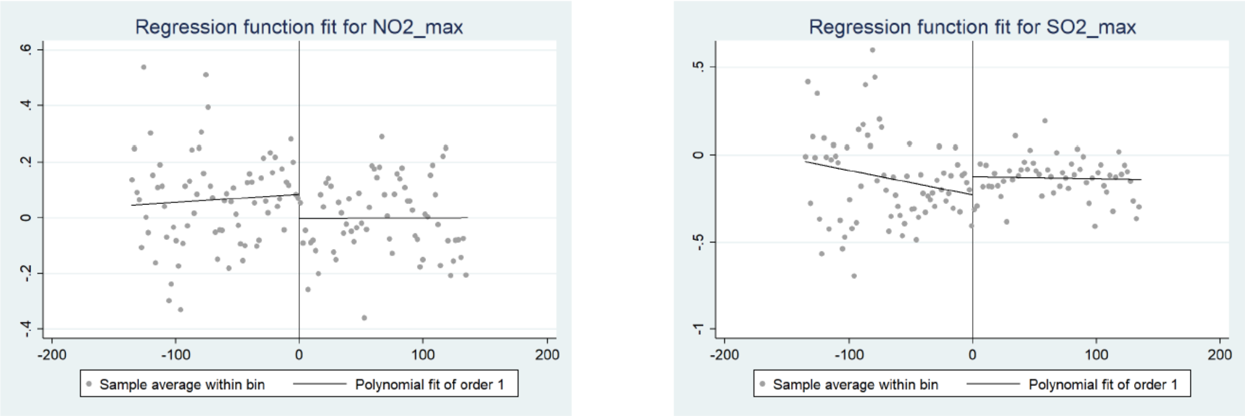
Particulate matter (PM_{10})

Figure 3.15.D: Local linear residual plots 20 weeks before and after event 4 (daily maximum pollution)



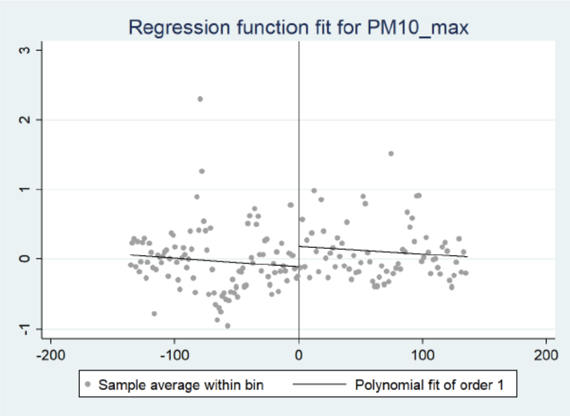
Ozone (O_3)

Carbon monoxide (CO)



Nitrogen dioxide (NO_2)

Sulfur dioxide (SO_2)



Particulate matter (PM_{10})

Table 3.20.A: Effects of Removing Subsidies on Pollution Levels in Tehran (local linear around event 1)

Dependent variable is predicted residuals from regression of log avg daily pollution for:					
	CO	O_3	NO_2	SO_2	PM_{10}
8 weeks before and after event	-0.0400	-0.4243	-0.2661*	0.2648	-0.5540*
	(0.2738)	(0.1864)	(0.0903)	(0.2968)	(0.2119)
10 weeks before and after event	-0.0102	-0.4790*	-0.2210	0.1090	-0.5456
	(0.2252)	(0.1627)	(0.0894)	(0.3163)	(0.2259)
20 weeks before and after event	-0.0504	-0.3942*	0.0213	0.3440	-0.2359
	(0.1515)	(0.1473)	(0.0832)	(0.2784)	(0.1196)
30 weeks before and after event	-0.0564	-0.3517	-0.0149	0.3153	-0.4396*
	(0.1576)	(0.1434)	(0.0869)	(0.2815)	(0.1560)
40 weeks before and after event	-0.0488	-0.3816	-0.0184	0.3344	-0.4868*
	(0.1735)	(0.1482)	(0.0880)	(0.2873)	(0.1670)
50 weeks before and after event	-0.0379	-0.3594*	-0.0480	0.3736	-0.5222
	(0.1854)	(0.1391)	(0.0919)	(0.2867)	(0.2029)
Dependent variable is predicted residuals from regression of log max daily pollution for:					
	CO	O_3	NO_2	SO_2	PM_{10}
8 weeks before and after event	-0.2804	-0.7085*	-0.2355	0.1214	-0.7877*
	(0.2038)	(0.2075)	(0.1666)	(0.3183)	(0.2225)
10 weeks before and after event	-0.2299	-0.7851*	-0.2060	-0.0878	-0.7365*
	(0.1839)	(0.2129)	(0.1626)	(0.3701)	(0.2245)
20 weeks before and after event	-0.1555	-0.6346*	0.0054	0.2779	-0.5550*
	(0.1356)	(0.1608)	(0.1030)	(0.2919)	(0.1705)
30 weeks before and after event	-0.1695	-0.6043*	-0.0389	0.2651	-0.6388*
	(0.1352)	(0.1588)	(0.1066)	(0.2931)	(0.1957)
40 weeks before and after event	-0.1621	-0.6903*	-0.0231	0.2816	-0.5407*
	(0.1387)	(0.1999)	(0.1055)	(0.3030)	(0.1549)
50 weeks before and after event	-0.1722	-0.6757*	-0.0569	0.3353	-0.4681*
	(0.1445)	(0.1828)	(0.1108)	(0.3046)	(0.1452)

Notes: This table reports estimates from five separate regression using local polynomial. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table 3.20.B: Effects of Removing Subsidies on Pollution Levels in Tehran (local linear around event 2)

Dependent variable is predicted residuals from regression of log avg daily pollution for:

	CO	O_3	NO_2	SO_2	PM_{10}
8 weeks before and after event	-0.1424	-0.3042	-0.1714	0.0585	0.1004
	(0.1135)	(0.1446)	(0.1094)	(0.1368)	(0.1835)
10 weeks before and after event	-0.1457	-0.0793	-0.1681	0.0426	-0.0477
	(0.1146)	(0.1180)	(0.1089)	(0.1265)	(0.1237)
20 weeks before and after event	-0.0420	-0.1486	-0.0893	0.1098	0.0777
	(0.0817)	(0.0806)	(0.0589)	(0.0901)	(0.1053)
30 weeks before and after event	-0.0973	-0.1584	-0.0494	0.1528	0.1912
	(0.0548)	(0.0728)	(0.0568)	(0.0868)	(0.0911)
40 weeks before and after event	-0.1554*	-0.1603*	-0.1242*	0.1934	0.1411
	(0.0462)	(0.0583)	(0.0391)	(0.0845)	(0.0766)
50 weeks before and after event	-0.1546*	-0.1893*	-0.1308*	0.1967	0.1737
	(0.0452)	(0.0540)	(0.0382)	(0.0843)	(0.0801)

Dependent variable is predicted residuals from regression of log max daily pollution for:

	CO	O_3	NO_2	SO_2	PM_{10}
8 weeks before and after event	-0.1710	-0.2160	-0.2403*	-0.1136	0.1065
	(0.1264)	(0.1393)	(0.0885)	(0.1861)	(0.1802)
10 weeks before and after event	-0.1804	-0.0819	-0.2488*	-0.1087	-0.0115
	(0.1313)	(0.1280)	(0.0893)	(0.1309)	(0.1398)
20 weeks before and after event	-0.0322	-0.1649	-0.1503*	0.1122	0.0842
	(0.0854)	(0.0914)	(0.0525)	(0.1093)	(0.1157)
30 weeks before and after event	-0.1290	-0.1589	-0.1079	0.1800	0.1841
	(0.0560)	(0.0835)	(0.0507)	(0.1060)	(0.0925)
40 weeks before and after event	-0.1684*	-0.1653	-0.1345*	0.2270	0.0377
	(0.0494)	(0.0819)	(0.0345)	(0.1035)	(0.0779)
50 weeks before and after event	-0.1451*	-0.2408*	-0.1295*	0.2595	0.0500
	(0.0448)	(0.0630)	(0.0352)	(0.1015)	(0.0793)

Notes: This table reports estimates from five separate regression using local polynomial. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table 3.20.C: Effects of Removing Subsidies on Pollution Levels in Tehran (local linear around event 3)

Dependent variable is predicted residuals from regression of log avg daily pollution for:

	CO	O$_3$	NO$_2$	SO$_2$	PM$_{10}$
8 weeks before and after event	0.0785	0.1393	0.1070	-0.1523	-0.2400
	(0.1195)	(0.1148)	(0.1266)	(0.0783)	(0.1381)
10 weeks before and after event	0.1574	0.1261	0.1169	-0.2162	-0.2487
	(0.0850)	(0.1097)	(0.1053)	(0.0998)	(0.1353)
20 weeks before and after event	0.0951	0.0882	0.1078	-0.1282	-0.0498
	(0.0600)	(0.0841)	(0.0989)	(0.0721)	(0.0798)
30 weeks before and after event	0.0690	0.1058	0.0509	-0.1319	-0.0684
	(0.0504)	(0.0677)	(0.0802)	(0.0632)	(0.0731)
40 weeks before and after event	0.0704	0.0251	0.0480	-0.1619*	-0.0027
	(0.0527)	(0.0528)	(0.0787)	(0.0528)	(0.0511)
50 weeks before and after event	0.0650	0.0145	0.0828	-0.1685*	0.0123
	(0.0464)	(0.0500)	(0.0602)	(0.0463)	(0.0493)

Dependent variable is predicted residuals from regression of log max daily pollution for:

	CO	O$_3$	NO$_2$	SO$_2$	PM$_{10}$
8 weeks before and after event	0.0384	0.2325	0.2229	-0.2822*	-0.2303
	(0.1446)	(0.1083)	(0.1314)	(0.1072)	(0.1411)
10 weeks before and after event	0.1767	0.2333	0.1957	-0.2559*	-0.1272
	(0.0963)	(0.1084)	(0.1175)	(0.0859)	(0.1150)
20 weeks before and after event	0.1136	0.1553	0.1915	-0.1848*	-0.0599
	(0.0683)	(0.0817)	(0.1048)	(0.0672)	(0.0856)
30 weeks before and after event	0.0974	0.1782	0.1108	-0.1811*	-0.0722
	(0.0585)	(0.0739)	(0.0799)	(0.0618)	(0.0772)
40 weeks before and after event	0.0939	0.0356	0.0673	-0.1967*	0.0309
	(0.0626)	(0.0495)	(0.0736)	(0.0571)	(0.0516)
50 weeks before and after event	0.1013	0.0415	0.0492	-0.2058*	0.0162
	(0.0537)	(0.0521)	(0.0581)	(0.0496)	(0.0544)

Notes: This table reports estimates from five separate regression using local polynomial. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table 3.20.D: Effects of Removing Subsidies on Pollution Levels in Tehran (local linear around event 4)

Dependent variable is predicted residuals from regression of log avg daily pollution for:

	CO	O_3	NO_2	SO_2	PM_{10}
8 weeks before and after event	0.1133	-0.2013	0.0353	0.0095	0.4661*
	(0.0830)	(0.1080)	(0.1591)	(0.0971)	(0.1222)
10 weeks before and after event	0.0011	-0.1854	-0.0958	0.0004	0.4871*
	(0.0606)	(0.0779)	(0.1373)	(0.0849)	(0.1218)
20 weeks before and after event	-0.0170	-0.2232*	-0.1249	-0.0167	0.3949*
	(0.0502)	(0.0718)	(0.0742)	(0.0439)	(0.0922)
30 weeks before and after event	-0.0605	-0.1905*	-0.1464	-0.0021	0.0846
	(0.0398)	(0.0551)	(0.0622)	(0.0428)	(0.0461)
40 weeks before and after event	-0.0644	-0.1419*	-0.1544*	-0.0134	0.1096
	(0.0370)	(0.0468)	(0.0595)	(0.0399)	(0.0469)
50 weeks before and after event	-0.0826	-0.0860	-0.1389	-0.0201	0.1299*
	(0.0383)	(0.0402)	(0.0755)	(0.0379)	(0.0344)

Dependent variable is predicted residuals from regression of log max daily pollution for:

	CO	O_3	NO_2	SO_2	PM_{10}
8 weeks before and after event	0.1572	-0.1297	-0.0449	-0.0057	0.3390
	(0.1048)	(0.0901)	(0.1351)	(0.1188)	(0.1526)
10 weeks before and after event	0.0660	-0.1291	-0.0741	-0.0330	0.0625
	(0.0830)	(0.1113)	(0.1293)	(0.1000)	(0.0805)
20 weeks before and after event	0.0130	-0.2921*	-0.1402	-0.0409	0.0966
	(0.0696)	(0.0600)	(0.0632)	(0.0697)	(0.0823)
30 weeks before and after event	-0.0782	-0.2254*	-0.1589*	-0.0409	0.1164
	(0.0481)	(0.0497)	(0.0560)	(0.0510)	(0.0728)
40 weeks before and after event	-0.0874	-0.2530*	-0.1603*	-0.0559	0.1135
	(0.0455)	(0.0525)	(0.0552)	(0.0488)	(0.0739)
50 weeks before and after event	-0.0998	-0.2280*	-0.1610	-0.0685	0.1102
	(0.0424)	(0.0524)	(0.0693)	(0.0428)	(0.0453)

Notes: This table reports estimates from five separate regression using local polynomial. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table 3.21.A: Effects of Removing Subsidies on Pollution Levels in Tehran (local linear around March 28, 2007 as placebo for event 1)

Dependent variable is predicted residuals from regression of log avg daily pollution for:					
	CO	O_3	NO_2	SO_2	PM_{10}
8 weeks before and after event	0.0391	0.1906	-0.0549	0.3610	-0.0434
	(0.1972)	(0.2187)	(0.3087)	(0.4724)	(0.3401)
10 weeks before and after event	-0.0498	0.2756	-0.1187	0.3585	-0.0851
	(0.1742)	(0.2213)	(0.2786)	(0.4032)	(0.3014)
20 weeks before and after event	-0.2343	0.3323	-0.2428	0.3994	-0.2437
	(0.1536)	(0.1856)	(0.2511)	(0.3652)	(0.2736)
30 weeks before and after event	-0.2349	0.3626	-0.2947	0.4082	-0.2259
	(0.1539)	(0.1761)	(0.2475)	(0.3558)	(0.2671)
40 weeks before and after event	-0.2352	0.2611	-0.3263	0.4952	-0.2129
	(0.1581)	(0.1967)	(0.2389)	(0.3432)	(0.2566)
50 weeks before and after event	-0.1312	0.2021	-0.1861	0.9885*	-0.0496
	(0.1583)	(0.2081)	(0.2359)	(0.3567)	(0.2661)
Dependent variable is predicted residuals from regression of log max daily pollution for:					
	CO	O_3	NO_2	SO_2	PM_{10}
8 weeks before and after event	0.2506	0.0166	0.0479	0.5355	-0.1141
	(0.2212)	(0.4022)	(0.3294)	(0.5902)	(0.3239)
10 weeks before and after event	0.0833	0.2110	-0.0200	0.5584	-0.1627
	(0.1959)	(0.3384)	(0.3001)	(0.5170)	(0.2919)
20 weeks before and after event	-0.3343	0.4222	-0.1355	0.6726	-0.4169
	(0.1495)	(0.2836)	(0.2767)	(0.4678)	(0.2592)
30 weeks before and after event	-0.2758	0.4499	-0.1561	0.6418	-0.3781
	(0.1484)	(0.2630)	(0.2767)	(0.4622)	(0.2528)
40 weeks before and after event	-0.4909*	0.2143	-0.2465	0.7406	-0.2946
	(0.1486)	(0.2871)	(0.2674)	(0.4503)	(0.2478)
50 weeks before and after event	-0.4538*	0.1538	-0.1458	1.2485*	-0.1357
	(0.1464)	(0.2949)	(0.2584)	(0.4394)	(0.2510)

Notes: This table reports estimates from five separate regression using local linear polynomial. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table 3.21.B: Effects of Removing Subsidies on Pollution Levels in Tehran (local linear around June 21, 2008 as placebo for event 2)

Dependent variable is predicted residuals from regression of log avg daily pollution for:

	CO	O_3	NO_2	SO_2	PM_{10}
8 weeks before and after event	-0.3626	0.0655	0.0593	0.0532	0.3397
	(0.1763)	(0.1672)	(0.1285)	(0.1742)	(0.1721)
10 weeks before and after event	-0.3727	0.0547	0.0468	0.0950	0.2120
	(0.1656)	(0.2102)	(0.1297)	(0.1578)	(0.1308)
20 weeks before and after event	0.0128	0.0269	0.0975	0.1111	-0.0527
	(0.1024)	(0.1270)	(0.0992)	(0.1335)	(0.0853)
30 weeks before and after event	0.0493	0.0271	0.1026	0.1278	-0.0309
	(0.0919)	(0.1071)	(0.0991)	(0.1203)	(0.0768)
40 weeks before and after event	0.0544	0.0276	0.0867	0.1372	-0.0388
	(0.0905)	(0.1068)	(0.0981)	(0.1185)	(0.0770)
50 weeks before and after event	0.0338	0.0259	0.0817	0.2225	-0.0432
	(0.0690)	(0.0790)	(0.0895)	(0.1184)	(0.0761)

Dependent variable is predicted residuals from regression of log max daily pollution for:

	CO	O_3	NO_2	SO_2	PM_{10}
8 weeks before and after event	-0.2260	0.0228	0.1192	-0.0517	0.1823
	(0.2032)	(0.2630)	(0.2068)	(0.2097)	(0.1867)
10 weeks before and after event	-0.2226	0.0153	0.0771	-0.0003	-0.0158
	(0.1719)	(0.2807)	(0.1823)	(0.1792)	(0.1274)
20 weeks before and after event	0.0213	0.0493	0.1075	0.0953	-0.0277
	(0.1089)	(0.1546)	(0.1181)	(0.1441)	(0.1025)
30 weeks before and after event	0.0338	0.0463	0.0714	0.0976	0.0202
	(0.0860)	(0.1311)	(0.1112)	(0.1329)	(0.0859)
40 weeks before and after event	0.0380	0.0265	0.1126	0.1136	0.0140
	(0.0840)	(0.1163)	(0.1152)	(0.1285)	(0.0867)
50 weeks before and after event	0.0017	0.0545	0.0907	0.1861	0.0675
	(0.0773)	(0.0918)	(0.1037)	(0.1286)	(0.0804)

Notes: This table reports estimates from five separate regression using local linear polynomial. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table 3.21.C: Effects of Removing Subsidies on Pollution Levels in Tehran (local linear around January 31, 2013 as placebo for event 3)

Dependent variable is predicted residuals from regression of log avg daily pollution for:	CO	O_3	NO_2	SO_2	PM_{10}
8 weeks before and after event	0.2663*	0.1274	0.2175	0.2027	0.4197*
	(0.0843)	(0.0973)	(0.0920)	(0.1119)	(0.0747)
10 weeks before and after event	0.2933*	0.1258	0.2294	0.2636	0.4145*
	(0.0813)	(0.0973)	(0.0944)	(0.1204)	(0.0732)
20 weeks before and after event	0.0338	0.1231	0.1378	0.2352	0.4462*
	(0.0365)	(0.0990)	(0.0836)	(0.1177)	(0.0676)
30 weeks before and after event	0.0726	0.0863	0.0632	0.0617	0.4560*
	(0.0406)	(0.0828)	(0.0728)	(0.0816)	(0.0685)
40 weeks before and after event	0.0343	0.0770	-0.0196	-0.0442	0.3952*
	(0.0356)	(0.0826)	(0.0486)	(0.0518)	(0.0574)
50 weeks before and after event	0.0266	-0.0553	-0.0012	-0.0142	0.0380
	(0.0289)	(0.0541)	(0.0540)	(0.0612)	(0.0329)

Dependent variable is predicted residuals from regression of log max daily pollution for:	CO	O_3	NO_2	SO_2	PM_{10}
8 weeks before and after event	0.2742*	0.1089	0.2857*	0.2998*	0.3769*
	(0.0840)	(0.1006)	(0.0942)	(0.1162)	(0.0812)
10 weeks before and after event	0.2795*	0.1061	0.3000*	0.3369*	0.3730*
	(0.0831)	(0.1006)	(0.0994)	(0.1212)	(0.0810)
20 weeks before and after event	0.3075*	0.1055	0.0394	0.3240*	0.3709*
	(0.0594)	(0.1017)	(0.0681)	(0.1201)	(0.0761)
30 weeks before and after event	0.1301*	0.0590	0.1446	0.1357	0.4033*
	(0.0457)	(0.0863)	(0.0783)	(0.0894)	(0.0810)
40 weeks before and after event	0.0793	0.0577	-0.0241	-0.0474	0.3400*
	(0.0368)	(0.0860)	(0.0529)	(0.0514)	(0.0600)
50 weeks before and after event	0.0723*	-0.0835	-0.0274	0.0810	0.0639
	(0.0262)	(0.0577)	(0.0544)	(0.0754)	(0.0388)

Notes: This table reports estimates from five separate regression using local linear polynomial. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table 3.21.D: Effects of Removing Subsidies on Pollution Levels in Tehran (local linear around July 16, 2014 as placebo for event 4)

Dependent variable is predicted residuals from regression of log avg daily pollution for:

	CO	O_3	NO_2	SO_2	PM_{10}
8 weeks before and after event	0.2829	0.2351	0.1102	0.0266	-0.1749
	(0.1210)	(0.1247)	(0.2588)	(0.2259)	(0.1600)
10 weeks before and after event	0.3336*	0.2086	0.2327	-0.0394	-0.2276
	(0.0942)	(0.1105)	(0.1975)	(0.2009)	(0.1482)
20 weeks before and after event	0.3601*	0.1736	0.1484	0.0637	-0.1417
	(0.0904)	(0.0859)	(0.1458)	(0.1440)	(0.1078)
30 weeks before and after event	0.3131*	0.0781	0.0239	0.0066	0.2366*
	(0.0717)	(0.0595)	(0.1015)	(0.1335)	(0.0632)
40 weeks before and after event	0.3386*	0.0863	-0.0017	-0.0453	0.2917*
	(0.0778)	(0.0668)	(0.0815)	(0.1204)	(0.0561)
50 weeks before and after event	0.2033*	0.1662*	-0.0458	-0.0056	0.2865*
	(0.0555)	(0.0591)	(0.0758)	(0.1217)	(0.0476)

Dependent variable is predicted residuals from regression of log max daily pollution for:

	CO	O_3	NO_2	SO_2	PM_{10}
8 weeks before and after event	0.3843	0.1287	0.2225	0.6160*	-0.0096
	(0.1622)	(0.1647)	(0.2771)	(0.2170)	(0.1688)
10 weeks before and after event	0.4097*	0.1285	0.3253	0.5703*	0.1006
	(0.1276)	(0.1549)	(0.2193)	(0.2161)	(0.2077)
20 weeks before and after event	0.4656*	0.2211	0.1961	0.6376*	0.2591*
	(0.1105)	(0.1009)	(0.1616)	(0.1990)	(0.0995)
30 weeks before and after event	0.4484*	0.1236	-0.0096	0.3082	0.2759*
	(0.0947)	(0.0677)	(0.0986)	(0.1391)	(0.0719)
40 weeks before and after event	0.4527*	0.1024	-0.0340	0.4000*	0.3043*
	(0.0986)	(0.0611)	(0.0875)	(0.1515)	(0.0687)
50 weeks before and after event	0.3611*	0.2091*	-0.0367	0.1792	0.2713*
	(0.0820)	(0.0667)	(0.0820)	(0.1191)	(0.0459)

Notes: This table reports estimates from five separate regression using local linear polynomial. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table 3.22.A: Effects of Removing Subsidies on Pollution Levels in Tehran (local linear with SO_2 as control around event 1)

Dependent variable is predicted residuals from regression of log avg daily pollution for:	CO	O_3	NO_2	PM_{10}
8 weeks before and after event	-0.0441	-0.3989	-0.2495	-0.5606*
	(0.2626)	(0.1969)	(0.1216)	(0.2097)
10 weeks before and after event	-0.0538	-0.4253	-0.2217	-0.5379
	(0.2148)	(0.1976)	(0.1164)	(0.2245)
20 weeks before and after event	-0.0046	-0.3589	-0.1027	-0.5281*
	(0.1713)	(0.1590)	(0.0893)	(0.1852)
30 weeks before and after event	-0.0450	-0.3121	-0.0614	-0.5714*
	(0.1751)	(0.1661)	(0.0829)	(0.2049)
40 weeks before and after event	-0.0138	-0.3641	-0.0653	-0.5712*
	(0.1684)	(0.1626)	(0.0845)	(0.1778)
50 weeks before and after event	0.0432	-0.3716	-0.0169	-0.5342*
	(0.1622)	(0.1542)	(0.0711)	(0.1614)

Dependent variable is predicted residuals from regression of log max daily pollution for:	CO	O_3	NO_2	PM_{10}
8 weeks before and after event	-0.2208	-0.6731*	-0.1910	-0.7015*
	(0.3146)	(0.1982)	(0.1891)	(0.2119)
10 weeks before and after event	-0.2551	-0.6931*	-0.1762	-0.6831*
	(0.2358)	(0.2411)	(0.1674)	(0.2205)
20 weeks before and after event	-0.1396	-0.6810*	-0.0129	-0.6182*
	(0.1737)	(0.1969)	(0.0911)	(0.1992)
30 weeks before and after event	-0.1360	-0.6577*	-0.0321	-0.6594*
	(0.1657)	(0.2015)	(0.0976)	(0.1987)
40 weeks before and after event	-0.0935	-0.7091*	-0.0296	-0.6703*
	(0.1590)	(0.2014)	(0.0899)	(0.1994)
50 weeks before and after event	-0.0652	-0.7246*	-0.0461	-0.6511*
	(0.1444)	(0.1908)	(0.1038)	(0.2005)

Notes: This table reports estimates from four separate regression using local polynomial. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table 3.22.B: Effects of Removing Subsidies on Pollution Levels in Tehran (local linear with SO_2 as control around event 2)

Dependent variable is predicted residuals from regression of log avg daily pollution for:	CO	O_3	NO_2	PM_{10}
8 weeks before and after event	-0.2207	-0.5050*	-0.0850	0.2613*
	(0.1476)	(0.1667)	(0.1061)	(0.0720)
10 weeks before and after event	-0.1679	-0.2921	-0.0785	0.1482
	(0.1212)	(0.1243)	(0.1019)	(0.0625)
20 weeks before and after event	-0.2071*	-0.3330*	-0.1041	0.0222
	(0.0644)	(0.0920)	(0.0676)	(0.0529)
30 weeks before and after event	-0.1990*	-0.3888*	-0.2137*	0.0368
	(0.0629)	(0.0784)	(0.0414)	(0.0440)
40 weeks before and after event	-0.1988*	-0.3093*	-0.2170*	-0.0361
	(0.0645)	(0.0623)	(0.0416)	(0.0422)
50 weeks before and after event	-0.1649*	-0.3353*	-0.2044*	0.0209
	(0.0434)	(0.0658)	(0.0405)	(0.0427)

Dependent variable is predicted residuals from regression of log max daily pollution for:	CO	O_3	NO_2	PM_{10}
8 weeks before and after event	-0.3006	-0.5244*	-0.1414	0.3379*
	(0.1640)	(0.1517)	(0.0924)	(0.0986)
10 weeks before and after event	-0.2130	-0.2770	-0.1339	0.0811
	(0.1357)	(0.1254)	(0.0904)	(0.0900)
20 weeks before and after event	-0.1674	-0.4287*	-0.1536	0.0665
	(0.0810)	(0.1015)	(0.0649)	(0.0741)
30 weeks before and after event	-0.2258*	-0.4610*	-0.2094*	0.1209
	(0.0682)	(0.0800)	(0.0387)	(0.0653)
40 weeks before and after event	-0.2248*	-0.4428*	-0.2162*	-0.0379
	(0.0700)	(0.0806)	(0.0382)	(0.0565)
50 weeks before and after event	-0.2204*	-0.4009*	-0.1993*	-0.0155
	(0.0616)	(0.0741)	(0.0364)	(0.0556)

Notes: This table reports estimates from four separate regression using local polynomial. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table 3.22.C: Effects of Removing Subsidies on Pollution Levels in Tehran (local linear with SO_2 as control around event 3)

Dependent variable is predicted residuals from regression of log avg daily pollution for:				
	CO	O_3	NO_2	PM_{10}
8 weeks before and after event	0.0918	0.1329	0.1860	-0.0941
	(0.1588)	(0.1002)	(0.2429)	(0.2386)
10 weeks before and after event	0.0185	0.1189	0.1850	-0.1112
	(0.1207)	(0.0975)	(0.2092)	(0.2335)
20 weeks before and after event	-0.0153	0.0607	0.1829	0.0242
	(0.1031)	(0.0987)	(0.1634)	(0.1669)
30 weeks before and after event	0.0137	-0.0190	0.1430	0.1803
	(0.0849)	(0.0678)	(0.1396)	(0.1123)
40 weeks before and after event	0.0220	-0.0288	0.1841	0.2040
	(0.0791)	(0.0691)	(0.1189)	(0.1037)
50 weeks before and after event	-0.0151	0.0574	0.3245*	0.0000
	(0.0792)	(0.0556)	(0.1054)	(0.0785)

Dependent variable is predicted residuals from regression of log max daily pollution for:				
	CO	O_3	NO_2	PM_{10}
8 weeks before and after event	0.0248	0.1190	0.2518	-0.0242
	(0.1878)	(0.0913)	(0.2205)	(0.1843)
10 weeks before and after event	0.0598	0.1045	0.2266	0.0247
	(0.1307)	(0.0914)	(0.1869)	(0.1699)
20 weeks before and after event	0.0417	0.0523	0.1419	0.0934
	(0.1151)	(0.0920)	(0.1290)	(0.1315)
30 weeks before and after event	0.0605	-0.0724	0.2052	0.1274
	(0.1016)	(0.0634)	(0.1470)	(0.1008)
40 weeks before and after event	0.0813	-0.0540	0.1104	0.1876
	(0.0859)	(0.0548)	(0.1160)	(0.0924)
50 weeks before and after event	0.1237	-0.0074	0.2420*	0.0308
	(0.0878)	(0.0550)	(0.0958)	(0.0607)

Notes: This table reports estimates from four separate regression using local polynomial. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table 3.22.D: Effects of Removing Subsidies on Pollution Levels in Tehran (local linear with SO_2 as control around event 4)

Dependent variable is predicted residuals from regression of log avg daily pollution for:	CO	O_3	NO_2	PM_{10}
8 weeks before and after event	0.0361	-0.1912	-0.1513	0.5497*
	(0.0780)	(0.1260)	(0.1518)	(0.1344)
10 weeks before and after event	-0.0427	-0.2043	-0.1695	0.5523*
	(0.0602)	(0.0875)	(0.1459)	(0.1371)
20 weeks before and after event	-0.0517	-0.2525*	-0.1061	0.3552*
	(0.0487)	(0.0798)	(0.0821)	(0.0985)
30 weeks before and after event	-0.0791	-0.2617*	-0.1160	0.1488*
	(0.0425)	(0.0666)	(0.0646)	(0.0586)
40 weeks before and after event	-0.0773	-0.1846*	-0.0972	0.2293*
	(0.0405)	(0.0521)	(0.0703)	(0.0615)
50 weeks before and after event	-0.0910	-0.1810*	-0.1214	0.1101
	(0.0387)	(0.0517)	(0.0744)	(0.0548)

Dependent variable is predicted residuals from regression of log max daily pollution for:	CO	O_3	NO_2	PM_{10}
8 weeks before and after event	0.1346	-0.2226*	-0.1694	0.3801
	(0.1140)	(0.0878)	(0.1226)	(0.1724)
10 weeks before and after event	0.0799	-0.1774	-0.1292	0.2156
	(0.0952)	(0.1292)	(0.1341)	(0.0993)
20 weeks before and after event	-0.0260	-0.3423*	-0.1116	0.1255
	(0.0736)	(0.0755)	(0.0764)	(0.0956)
30 weeks before and after event	-0.0895	-0.3714*	-0.1204	0.2195*
	(0.0547)	(0.0684)	(0.0597)	(0.0815)
40 weeks before and after event	-0.1022	-0.3328*	-0.0998	0.2106*
	(0.0503)	(0.0573)	(0.0657)	(0.0825)
50 weeks before and after event	-0.1156	-0.2868*	-0.1248	0.1353
	(0.0472)	(0.0518)	(0.0686)	(0.0649)

Notes: This table reports estimates from four separate regression using local polynomial. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table 3.23.A: Effects of Removing Subsidies on Pollution Levels in Tehran (local linear around event 1)

	Dependent variable is predicted residuals from regression of:			
	log avg daily pollution for:		log max daily pollution for:	
	CO	O_3	CO	O_3
10 weeks before and after	0.0906	-0.4516	-0.0233	-0.7891
	(0.1168)	(0.2792)	(0.2564)	(0.3711)
20 weeks before and after	0.0125	-0.5018*	-0.1521	-0.9236
	(0.5996)	(0.0931)	(0.1917)	(0.4596)
30 weeks before and after	0.0140	-0.5265*	-0.1508	-0.8935*
	(0.1179)	(0.1010)	(0.1865)	(0.1028)
40 weeks before and after	0.0175	-0.5313*	-0.1539	-0.9015*
	(0.1104)	(0.1104)	(0.1816)	(0.1063)
50 weeks before and after	0.0173	-0.5352*	-0.1540	-0.9035*
	(0.1230)	(0.1179)	(0.1785)	(0.1093)

Notes: This table reports estimates from two sets of two separate regression using local polynomial. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing. Standard errors are bootstrapped.

Table 3.23.B: Effects of Removing Subsidies on Pollution Levels in Tehran (augmented local linear around event 2)

	Dependent variable is predicted residuals from regression of:			
	log avg daily pollution for:		log max daily pollution for:	
	CO	O_3	CO	O_3
10 weeks before and after	-0.0540	-0.1297	-0.1012	-0.0158
	(0.0691)	(0.1049)	(0.1021)	(0.1401)
20 weeks before and after	-0.0766	-0.2776*	-0.1698	-0.1463
	(0.0851)	(0.1196)	(0.1405)	(0.0951)
30 weeks before and after	-0.2700*	-0.2693	-0.1732	-0.3207*
	(0.1196)	(0.1338)	(0.1926)	(0.0926)
40 weeks before and after	-0.2805*	-0.2753*	-0.1953	-0.4502*
	(0.0992)	(0.0849)	(0.1692)	(0.1059)
50 weeks before and after	-0.2818*	-0.2713*	-0.2001	-0.4234*
	(0.1187)	(0.0671)	(0.1472)	(0.0698)

Notes: This table reports estimates from two sets of two separate regression using local polynomial. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing. Standard errors are bootstrapped.

Table 3.23.C: Effects of Removing Subsidies on Pollution Levels in Tehran (local linear around event 3)

	Dependent variable is predicted residuals from regression of:			
	log avg daily pollution for:		log max daily pollution for:	
	CO	O_3	CO	O_3
10 weeks before and after	0.1071	-0.0666	-0.0100	0.1806
	(0.1273)	(0.2687)	(0.2151)	(0.0835)
20 weeks before and after	0.1081	-0.0341	0.1251	0.1926
	(0.0603)	(0.1936)	(0.1415)	(0.1752)
30 weeks before and after	0.1490*	0.0284	0.1395	0.0701
	(0.0502)	(0.1469)	(0.1140)	(0.1235)
40 weeks before and after	0.1361*	0.0129	0.1310	0.0796
	(0.0494)	(0.1439)	(0.1599)	(0.0742)
50 weeks before and after	0.1342*	0.2586*	0.1499	0.3367*
	(0.0471)	(0.0802)	(0.2882)	(0.1277)

Notes: This table reports estimates from two sets of two separate regression using local polynomial. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing. Standard errors are bootstrapped.

Table 3.23.D: Effects of Removing Subsidies on Pollution Levels in Tehran (local linear around event 4)

	Dependent variable is predicted residuals from regression of:			
	log avg daily pollution for:		log max daily pollution for:	
	CO	O_3	CO	O_3
10 weeks before and after	0.0436	-0.3381*	-0.0092	-0.3262*
	(0.0289)	(0.0703)	(0.0728)	(0.1048)
20 weeks before and after	0.0351	-0.0315	-0.0334	-0.2756*
	(0.0651)	(0.1255)	(0.0662)	(0.0725)
30 weeks before and after	-0.0199	-0.1067	-0.0410	-0.2999*
	(0.0824)	(0.1040)	(0.0942)	(0.0816)
40 weeks before and after	-0.0195	-0.0555	-0.0193	-0.2757*
	(0.0764)	(0.0895)	(0.0603)	(0.0490)
50 weeks before and after	-0.0140	-0.1350	-0.0216	-0.3083*
	(0.0606)	(0.0695)	(0.0504)	(0.0572)

Notes: This table reports estimates from two sets of two separate regression using local polynomial. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing. Standard errors are bootstrapped.

Table 3.24.A: Effects of Removing Subsidies on Pollution Levels in Tehran (local linear with SO_2 as control around event 1)

Dependent variable is predicted residuals from regression of:	log avg daily pollution for:		log max daily pollution for:	
	CO	O_3	CO	O_3
30 weeks before and after	0.0320		-0.1455	
	(0.0884)		(0.2416)	
40 weeks before and after	0.0321	-0.4723*	-0.1481	-0.8471*
	(0.0912)	(0.0668)	(0.2067)	(0.0696)
50 weeks before and after	0.0284	-0.4881*	-0.1314	-0.8094*
	(0.1160)	(0.0620)	(0.2003)	(0.0894)

Notes: This table reports estimates from two sets of two separate regression using local polynomial. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing. Standard errors are bootstrapped.

Table 3.24.B: Effects of Removing Subsidies on Pollution Levels in Tehran (local linear with SO_2 as control around event 2)

Dependent variable is predicted residuals from regression of:	log avg daily pollution for:		log max daily pollution for:	
	CO	O_3	CO	O_3
30 weeks before and after	-0.4201*		-0.4270*	
	(0.1787)		(0.1864)	
40 weeks before and after	-0.4150*	-0.4388*	-0.4271*	-0.6477*
	(0.1670)	(0.1358)	(0.1353)	(0.1501)
50 weeks before and after	-0.3594*	-0.4607 *	-0.2707	-0.6436*
	(0.1504)	(0.1548)	(0.1401)	(0.2317)

Notes: This table reports estimates from two sets of two separate regression using local polynomial. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing. Standard errors are bootstrapped.

Table 3.24.C: Effects of Removing Subsidies on Pollution Levels in Tehran (local linear with SO_2 as control around event 3)

	Dependent variable is predicted residuals from regression of:			
	log avg daily pollution for:		log max daily pollution for:	
	CO	O_3	CO	O_3
30 weeks before and after	0.1942		0.4186	
	(0.8389)		(0.2134)	
40 weeks before and after	0.2521	0.1920	0.5233	
	(0.2031)	(0.1666)	(0.2467)	
50 weeks before and after	0.2432	0.4233*	0.5439	0.5760
	(1.0932)	(0.1161)	(0.6290)	(0.8934)

Notes: This table reports estimates from two sets of two separate regression using local polynomial. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing. Standard errors are bootstrapped.

Table 3.24.D: Effects of Removing Subsidies on Pollution Levels in Tehran (local linear with SO_2 as control around event 4)

	Dependent variable is predicted residuals from regression of:			
	log avg daily pollution for:		log max daily pollution for:	
	CO	O_3	CO	O_3
30 weeks before and after	0.0313		-0.0431	
	(0.0730)		(0.0918)	
40 weeks before and after	0.0082	-0.0253	-0.0312	
	(0.0549)	(0.1044)	(0.0647)	
50 weeks before and after	0.0005	-0.0262	0.0126	-0.2592*
	(0.0386)	(0.1005)	(0.0602)	(0.0705)

Notes: This table reports estimates from two sets of two separate regression using local polynomial. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing. Standard errors are bootstrapped.

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