The Dissertation Committee for Ronald Joseph Briggs Certifies that this is the approved version of the following dissertation:

Essays on the Economics of Indoor and Outdoor Environments

Committee:

Roberton Williams III, Supervisor

Donald Fullerton

Richard Corsi

Daniel Slesnick

Jason Abrevaya

Essays on the Economics of Indoor and Outdoor Environments

by

Ronald Joseph Briggs, B.A.S.

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Dedication

To Javan, Aidan, and Merrick with love.

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Essays on the Economics of Indoor and Outdoor Environments

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Supervisor: Roberton C. Williams III

This dissertation consists of three chapters on questions in Environmental Economics, addressing policy and health issues in indoor and outdoor environments. In the first chapter, I explores price and quantity policy solutions to externalities that arise from private decisions made over time, focusing on resource extraction as a specific example. In the U.S., mining causes more pollution than any other single industry. I show how tax policy can optimally address a flow externality associated with resource extraction when the policymaker faces asymmetric information in the short run.

Chapter 2 investigates whether ordinary exposure to a common indoor air pollutant—Nitrogen Dioxide (NO_2)—affects respiratory health. About 40 percent of occupied homes in the U.S. use gas stoves for cooking, which produce NO_2 as a byproduct of combustion (US Census, 2006), and peak concentrations in homes may reach above 900 ppb when a gas stove is used for cooking (Dennekamp *et al.*, 2001). Permanent or fatal lung damage occurs at NO_2 concentrations greater than 1000 ppb

(Samet and Utell, 1990). Previous studies find mixed evidence of negative effects from indoor NO_2 (Basu and Samet, 1999), but exposure may be endogenous in these analyses. I address this problem by developing a physical model of indoor NO_2 concentrations that depends on ventilation decisions and housing characteristics and estimate it using data from the third wave of the National Health and Nutrition Examination Survey. In every model I consider, I find no significant effects of gas stoves on respiratory outcomes.

In the final chapter, I combine data on state and local tobacco control ordinances from Americans for Non-smokers Rights Tobacco US Tobacco Control Laws Database with a sample of 35 million births in the U.S. to examine the impact of smoking bans on birth weight and related outcomes. Using difference-in-difference techniques, I identify the effects of state bans net of local bans, as well as the effects of local bans net of state bans. The results suggest less restrictive bans do more to improve birth outcomes than "100% smokefree" bans do, particularly in urban settings.

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Chapter 1: Prices vs. Quantities in a Dynamic Problem: Externalities from Resource Extraction

Abstract: This paper shows how a Markovian tax policy can optimally address a flow externality associated with resource extraction when the policymaker faces asymmetric information. In the model I consider, the policymaker must set policy in each period before the realization of a price shock. Resource owners then learn the value of the shock, and the owners choose extraction quantities. The optimal policy responds to a positive shock to the current price by reducing next period's tax rate. Intuitively, a reduction in next period's tax rate makes extraction next period cheaper and thus dampens the resource owner's current response to a price increase. A quota policy cannot similarly attain the optimal path in this setting because quotas limit the resource owner's ability to respond to new information.

Keywords: pollution, externality, asymmetric information, non-renewable, resources, prices, quantities, taxes, quotas

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Metals mining often generates significant externalites. Groundwater pollution from chemicals like arsenic and cyanide used to leach metals from ore is one example; other examples include aquifer depletion, or air pollution from smelting byproducts like NO_x and mercury. While the National Income and Product Accounts show that the metals mining industry accounted for 1% of US National Income in 2004 [5] it accounted for 40% of all toxic material disposed or released during the same period—more than any other industry [6]. As mineral resources on this planet become more difficult to recover, and mining processes intensify, the external costs associated with mining are likely to continue to increase. A patchwork of standards and liability laws mitigates most of the worst outcomes in the U.S., but the inflexibility of standards and the option of bankruptcy make these policies less than optimal.

Incentive based instruments may offer welfare improvements over these policies. To compare how price instruments (taxes) and quantity instruments (quotas or tradable permits) perform in this setting, this paper employs a dynamic model where agents have information unavailable to policymakers in the short run and well defined property rights over a stock of a non-renewable resource. The solution to their private decision problem ties current and future decisions together because of opportunity costs: any quantity extracted in the current period cannot be extracted in the future. This link implies that current policy actions can affect the entire sequence of private decisions and social outcomes. For the same reason, credible threats to change future policy have an impact on current decisions. By using these threats as a policy instrument, I find that the policymaker can use a price instrument to attain the first-best.

Recent papers in the economics literature extend the original "prices vs. quantities" work of Weitzman [7] to dynamic social problems, but in each of these papers the economic problems private agents face remain static. Newell and Pizer [4] and Hoel and Karp [2], for example, use dynamic models to examine how the welfare implications of price and quantity policies change when the externality comes from a stock instead of a flow. Agents in these models make sequences of static decisions while the policymakers maximize welfare over the infinite horizon. In another paper, Weitzman [8] investigates the optimal regulation of a competitive fishery where the stock of fish evolves subject to uncertainty. This also amounts to a dynamic social problem over a sequence of static, private decisions. Private agents in this model do not link current and future fishing decisions because of the open access problem: since individual agents do not have property rights to the remaining fish, agents simply harvest fish up to the point where price equals marginal cost in each period.

Resource extraction, however, presents private agents with a fundamentally dynamic problem. The contribution of this paper relative to the prior literature is thus a comparison of price and quantity policies when both the private and social problems are dynamic. Analogous problems arise when Pigouvian taxes or quotas affect firms who face capital investment or research and development decisions. The results of this analysis may therefore inform policy comparisons for these problems as well.

The main result of this paper is that a stationary tax policy can induce resource owners to remain on the socially optimal extraction path despite informational asymmetry. The optimal tax policy under asymmetry works by making sure that future taxes adjust to account both for the present and future changes in marginal external damages (MED) that arise from private decisions. Since private agents care about profits over the infinite horizon, rather than just profits in a single period, changes in future tax policy can induce socially optimal choices in the present. Analysis here shows that the socially optimal policy requires that future tax rates fall in response to positive, current price shocks. Quantity instruments do not admit such a design, however, because no change to next period's quota can induce agents to respond to positive shocks with increases in current extraction, which social optimality requires.

I proceed to show these results in the next five sections. The first section begins by describing the economic environment and analyzing a representative non-renewable resource owner's extraction problem with future price uncertainty. Section II examines how the resource owner adjusts extraction to comply with a quantity policy, which the model generically represents as an extraction quota in each period. The optimal response condition for the quantity instrument translates easily into an analytic description of the owner's response to a price instrument, which the model takes to be a tax per unit of extraction. I make use of these response functions in Section III when I solve the social planner's problem. In Section IV, I analyze the policymaker's problem under asymmetric information. Assuming an economy with commitment, I construct the optimal tax policy and then prove quotas cannot attain the first-best. I provide further insight into the optimal policy with a comparative statics analysis. The paper concludes with a summary and questions for further research.

I. A MODEL OF NON-RENEWABLE RESOURCE EXTRACTION UNDER PRICE UNCERTAINTY

In keeping with the timing convention of Weitzman [7], I assume that the policymaker must announce policy before uncertainty is resolved in each period. I assume extraction yields a flow externality to represent pollution from private "production". Where Weitzman [7] focuses on additive shocks to the marginal costs of abatement, I choose to work with shocks to the resource price because natural resources like gold and oil have volatile price series. From an economic point of view, price shocks do represent shocks to marginal abatement costs in cases where reducing extraction is a form of abatement. In a static model, these assumptions would thus fit precisely into the framework Weitzman [7] considers.

To focus on how the dynamic component of the resource extraction problem affects the relative desirability of taxes and quotas, I limit my attention to an economic environment populated by a large number of homogeneous, price-taking resource owners. Each resource owner employs an extant extraction process to recover a known, fixed level of homogeneous reserves. This formulation of the owners' optimization problem puts distributional concerns aside and allows a single agent to represent a competitive non-renewable resource market.[1] By these assumptions, this paper ignores several important facets of non-renewable resource problems: human-made capital investment, resource exploration, ore quality, and backstop technologies. As long as policymakers and

[1] The results of the paper may generalize to cases of imperfect competition if the regulator knows the inverse demand function, but this second market failure changes the structure of the problem at hand. Since resource owners would exercise market power by supplying less than in a competitive market,

resource owners have the same information over these complicating factors, the main results of this paper remain intact. Additional sources of informational asymmetry, however, may affect the findings. At the conclusion of this paper, I return to these assumptions and consider their importance to future research.

To simplify the presentation of the model, I adopt a compact notation common to dynamic programming theory. At time t, for any parameter or variable a^t, suppress the superscript t and denote it simply as a. To distinguish the current value of a from next period's value, denote a^{t+1} by a'. This notation saves space and emphasizes the stationarity of the dynamic programming problems and their solutions.

Let the representative owner of the non-renewable resource be endowed with a known stock S of the resource at time t. The resource owner may choose to extract a non-negative quantity of the resource x and thereby reduce next period's stock to $S' = S - x$. By assumption, the resource owner faces a sequence of perfectly competitive markets for sale of the quantity extracted. To simplify exposition, assume that the expected price p is constant across all periods.[2] Suppose that the representative owner faces a zero-mean shock ε to the expected price p in each period, where $\{\varepsilon^t\}_{t=0}^{\infty}$ is independently and identically distributed.[3] Assume $p + \varepsilon > 0$ for all ε. Let the owner know the outcome of ε in the current period before choosing x.

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imperfect competition would itself reduce the level of pollution. The second-best policy in this setting requires careful analysis and lies outside the scope of this paper.

2 The results of this paper continue to hold if expected prices evolve according to some exogenous sequence $\{p^t\}_{t=0}^{\infty}$ known to both the policymaker and the resource owners.

On the cost side, assume extraction has costs given by the function $C(x)$, where $C(x)$ is increasing, continuous, twice differentiable, and strictly convex.[4] Let $C(0) = 0$ and $\frac{dc}{dx}(0) = 0$. Represent the value of any asset in the next period in current terms by applying the discount factor $\beta = (1 + r)^{-1}$, where $r > 0$ is the risk-free rate of return. The optimizing representative owner chooses the extraction path that will maximize the value of the non-renewable resource over the infinite horizon. Thus, the owner faces a standard "cake-eating" problem that can be described by the value function

(1) $$V(S,\varepsilon) = \max_{\substack{x\in[0,X]\\ X'=X-x}} (p+\varepsilon)\cdot x - C(x) + \beta \cdot E[V(S',\varepsilon')].$$

Given the Inada conditions above and $p + \varepsilon > 0$, it follows that

$\exists x \in (0,S) : p + \varepsilon - \frac{dc}{dx}(x) > 0$, and thus the optimal extraction policy $x:\ x \in (0,S)\ \ \forall t$.

The assumptions above imply that the current period profit function $(p+\varepsilon)\cdot x - C(x)$ is strictly concave; that the value function has a non-empty, compact-valued state-transition correspondence; and that β is less than one. Standard dynamic programming theory therefore shows that a solution to this problem exists, and that the value function V is twice differentiable and strictly concave. The following first order condition describes the optimal choice of x as the extraction quantity that equates the marginal net benefit and the marginal opportunity cost of extraction, which is the marginal

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[3] Shocks are chosen to have mean zero to reflect the absence of bias in agents' expectations. The assumption of independently and identically distributed shocks eases the exposition of the model, but is not necessary to the existence of an optimal sequence and does not otherwise change the results of the model.
[4] The results of this paper do not change when costs depend on the stock of the resource.

change in the value of the remaining resource stock:

$$(2) \qquad p+\varepsilon-\frac{dc}{dx}(x)=\beta\cdot E\left[\frac{\partial V}{\partial S}(S',\varepsilon')\right].$$

Because ε has mean zero, and the current realizations of ε do not give information on future realizations, the envelope theorem implies

$$(3) \qquad \frac{p-E\left[\frac{dc}{dx}(x')\right]}{p+\varepsilon-\frac{dc}{dx}(x)}=\frac{1}{\beta}$$

along the optimal extraction path. Equation (3) expresses a Hotelling rule [3], which states that the optimizing resource owner follows an extraction plan where the royalty—price less marginal cost—grows at the rate of interest.

When following this extraction path, the resource owner responds to positive price shocks by increasing extraction. Intuitively, a rise in prices implies a greater marginal benefit to extraction, justifying a greater marginal opportunity cost. To obtain this result mathematically, view the optimal extraction x as an implicit function of the state variables: $x = x(S, \varepsilon)$. Under the assumptions of this paper, dynamic programming theory shows that x is well-defined and continuous. The first order condition (2) is a level function of $x(S, \varepsilon)$ since it is always zero along the optimal path. Using the implicit function theorem, differentiate the first order condition (2) with respect to ε and solve for $\frac{\partial x}{\partial \varepsilon}$ to find that

(4) $$\frac{\partial x}{\partial \varepsilon} = \frac{1}{\frac{d^2C}{dx^2}(x) - \beta \cdot E\left[\frac{\partial^2 V}{\partial S^2}(S',\varepsilon')\right]}.$$

Since C is convex and V is concave, the denominator in (4) is strictly positive and therefore $\frac{\partial x}{\partial \varepsilon} > 0$.

The remainder of this paper builds on this model by analyzing its implications for optimal policy when extraction has an associated flow externality. In keeping with the "prices vs. quantities" literature, I represent quantity policies by a quota and price policies by a per-unit tax.[5] To lay the groundwork for the policy problem, the paper first addresses how the representative resource owner responds to policies that aim to curb pollution. I then specify a social planner's problem that takes these private responses into account when solving for optimal policy with symmetric information. The main problem this paper considers then comes into focus: can policymakers achieve this first-best when they must set policy before prices are realized, and when owners choose extraction levels?

II. Policy and Extraction Response

To begin, suppose that quantity and price policies depend on variables outside the control of any individual resource owner, such as the aggregate resource stock. From the perspective of an individual resource owner, given any such quota $q > 0$, the resource owner facing a series of price shocks as described in Section I now solves

(5) $$V(S,\varepsilon,q) = \max_{\substack{x\in[0,q] \\ S'=S-x}} (p+\varepsilon)\cdot x - C(x) + \lambda\cdot(q-x) + \beta\cdot E[V(S',\varepsilon',q')],$$

where $\lambda \geq 0$ is the shadow price of the quota—the marginal cost to the resource owner from not extracting the next unit of the resource in the current period.[6] The optimal extraction rule that solves (5) then has the form

(6) $$\frac{p - E\left[\frac{dC}{dx}(x') + \lambda'\right]}{p + \varepsilon - \frac{dC}{dx}(x) - \lambda} = \frac{1}{\beta}.$$

This rule again reflects the Hotelling logic, but includes the impact of the quota on royalties.

Consider the resource owner's extraction function $x_q(S, \varepsilon, q)$ under the quota q. When the resource owner does not expect the policy to bind in either period, $\lambda = E[\lambda'] = 0$ and the resource owner's behaves exactly as the unconstrained policy function $x(S, \varepsilon)$. Likewise, if the expected policy binds in both periods, $\lambda > 0$ and $E[\lambda'] > 0$ and the resource owner sets $x_q(S, \varepsilon, q) = q$. Finally, if the resource owner expects the policy to bind next period but not in the current period, the resource owner responds to higher costs in the future by increasing extraction in the present by choosing some extraction $x = x_q(S, \varepsilon, q)$: $x > x(S, \varepsilon)$.

In comparison, consider the resource owner's response to a per unit tax. From a

[5] These linear policies are general enough to approach the question at hand. It turns out that a sequence of either type of policy can attain the first-best under symmetric information. Under asymmetric information, no sequence of quotas can attain the first-best, but a sequence of per-unit tax functions can.

resource owner's perspective, given any tax τ per unit extracted the owner's problem has the form

(7) $$V(S,\varepsilon,\tau)=\max_{\substack{x\in[0,X]\\ X'=X-x}}(p+\varepsilon-\tau)\cdot x-C(x)+\beta\cdot E[V(S',\varepsilon',\tau')]\,.$$

To guarantee a non-zero optimal extraction choice, assume that the net price is always positive, i.e. $\forall\tau$ and ε , $p + \varepsilon - \tau > 0$. The optimal extraction rule for this problem grows the expected royalty $p+\varepsilon-\frac{dC}{dx}(x)-\tau$ according to the Hotelling rule:

(8) $$\frac{p-E\left[\frac{dC}{dx}(x')+\tau'\right]}{p+\varepsilon-\frac{dC}{dx}(x)-\tau}=\frac{1}{\beta}\,.$$

Under these assumptions, it is easy to show that the optimal extraction function under a per-unit tax, $x_\tau(S,\varepsilon,\tau)$, is positive, continuous, and increasing in S and ε .

III. THE SOCIAL PLANNER'S PROBLEM

If resource extraction yields an externality, the unconstrained private extraction policy of Section I is not socially efficient. To contrast the private resource owner's choices with the socially optimal policy, I now turn to the formulation and solution of a social planner's problem under symmetric information. I impose symmetry by supposing that both the planner and the representative owner know the value of ε in the current period, and that neither know the value of future realizations of ε . Thus, the planner still

[6] The marginal cost λ may also represent the cost of a permit in a tradable permit system. Under the assumption of resource owner homogeneity, however, no permit trading occurs if the regulators distribute the permits equally amongst the owners.

faces some uncertainty, but the representative owner faces that same uncertainty.[7]

Consider a partial equilibrium economy where a flow externality with damages $f(x)$ arises for x units of resource extracted by resource owners.[8] Assume $f(x)$ is twice differentiable and strictly convex with $f(0)=0$, $\frac{df}{dx}(0)=0$, and $\frac{df}{dx}(x)>0 \;\; \forall x>0$. Suppose that the private discount rate equals the social discount rate, and that the planner has perfect information on the representative owner's cost function.[9] By assumption, resource owners are homogenous and do not face a common pool problem, so the social problem may be written in terms of a representative agent.[10]

For parsimony, suppose that the resource owner can only abate pollution by reducing extraction. This modeling choice implies that taxes on extraction equate to taxes on pollution, and that the tax rate, in turn, impinges on a private dynamic choice variable. In more general settings, the results derived here hold as long as inputs into abatement are similarly dynamic. I discuss this assumption in light of my results at the end of the paper.

Taking into account the external damages from extraction, the planner maximizes welfare:

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[7] Weitzman [8] describes this kind of planner as "myopically omniscient", but since this planner both considers the infinite future and is plainly not omniscient, I eschew this term to avoid confusion. Throughout the paper, I simply refer to the planner's solution as the first-best or optimal path.

[8] This paper focuses on flow externalities, but Farzin [1] suggests that the conclusions here extend to stock externalities. Farzin shows that a pair of Pigouvian taxes can correct simultaneous flow and stock externalities if they are separable, but does not explore the effect of asymmetric information nor consider the prices vs. quantities question.

[9] The assumption of equal discount rates eases exposition, but is not necessary to the results. More generally, the policymaker must know the representative owner's discount rate.

(9) $$W(S_R,\varepsilon)=\max_{\substack{x_R\in[0,S_R]\\ S_R'=S_R-x_R}} N\cdot[(p+\varepsilon)\cdot x_R-C(x_R)]-f(N\cdot x_R)+\beta\cdot E[W(S_R',\varepsilon')],$$

where x_R and S_R respectively denote the representative agent's extraction and resource stock.

Assuming that marginal social royalty to extraction is always positive, i.e. $p+\varepsilon-\frac{dC}{dx}(x_R)-\frac{df}{dx}(N\cdot x_R)>0$, the optimal plan will always have $x_R>0$. The first order condition for this problem is

(10) $$N\cdot\left(p+\varepsilon-\frac{dC}{dx}(x_R)-\frac{df}{dx}(N\cdot x_R)\right)=\beta\cdot E\left[\frac{\partial W}{\partial S}(S_R',\varepsilon')\right].$$

Applying the envelope theorem to (10) yields the first-best policy rule:

(11) $$\frac{p-E\left[\frac{dC}{dx}(x_R')+\frac{df}{dx}(N\cdot x_R')\right]}{p+\varepsilon-\frac{dC}{dx}(x_R)-\frac{df}{dx}(N\cdot x_R)}=\frac{1}{\beta}.$$

Let x_{SO} and x_{SO}' denote the socially optimal extraction policies that satisfy (12). Note that $x_{SO}=x_{SO}(S_R,\varepsilon)$: the first-best depends on the representative agent's stock S_R and the realization of the price shock.

This extraction rule has the same form as the resource owner's, but it also takes into account the MED of extraction both in the current period and in the future. As in the resource owner's solution, unexpected price increases in the current period warrant increased extraction from the planner's perspective. The same intuition applies, as well:

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[10] This assumption holds for solid-phase non-renewables like precious metals but may be violated for liquid or gas phase resources like oil or natural gas.

because marginal benefits rise, the optimum must occur where marginal costs are also higher. The following comparative static result bears this logic out:

$$\text{(12)} \qquad \frac{\partial x_{SO}}{\partial \varepsilon} = \frac{N}{N \cdot \frac{d^2C}{dx^2}(x_{SO}) + N^2 \cdot \frac{d^2 f}{dx^2}(N \cdot x_{SO}) - \beta \cdot E\left[\frac{\partial^2 W}{\partial S_R{}^2}(S_R', \varepsilon')\right]},$$

which is strictly positive along the socially optimal path since the functions C and f are strictly convex and W is strictly concave in X. (See Appendix A. for the derivation of $\frac{\partial x_{SO}}{\partial \varepsilon}$). A quick comparison of (12) and (4) also shows that $\frac{\partial x_{SO}}{\partial \varepsilon} < \frac{\partial x}{\partial \varepsilon}$. Because of external damages, the social planner responds to a positive price shock with a smaller increase in extraction than a private resource owner would choose.

IV. ATTAINING THE FIRST-BEST UNDER ASYMMETRIC INFORMATION

Now consider a welfare-maximizing policymaker with asymmetric information: policy must be chosen before ε is realized. The first-best result that (11) describes suggests that such a policy cannot attain the optimum because the representative owner's allocation x_{SO} depends on ε. Nonetheless, in an economy with commitment, a stationary tax policy can attain the first-best. A similar quota policy, it turns out, cannot.

To see this result, consider a problem where the policymaker maximizes social welfare subject to the constraint that individual resource owners choose optimal extraction levels. The tax rate each period must be chosen before the realization of ε, but tax rates in the future may depend on past realizations. If a stationary tax policy exists that can induce the first-best, it must align the resource owner's optimal private extraction policy as described by (8) with the first-best as described by (11) so that the following must hold:

$$\text{(13)} \qquad \frac{p - E\left[\frac{dC}{dx}(x'_{SO}(S'_R, \varepsilon'))\right] - \tau'}{p + \varepsilon - \frac{dC}{dx}(x_{SO}(S_R, \varepsilon)) - \tau} = \frac{1}{\beta}.$$

In other words, individually optimizing resource owners facing the tax policy must choose the socially optimal path.

Solving this condition for τ and τ' yields a feasible, stationary policy rule that must induce the first-best by construction. Substituting for S'_R using the transition equation $S'_R = S_R - x_{SO}(S_R, \varepsilon)$, (13) implies

$$\text{(14)} \quad \tau' - \frac{\tau}{\beta} = p - E\left[\frac{dC}{dx}(x'_{SO}(S_R - x_{SO}(S_R, \varepsilon), \varepsilon'))\right] - \frac{1}{\beta} \cdot \left(p + \varepsilon - \frac{dC}{dx}(x_{SO}(S_R, \varepsilon)) \right).$$

This result shows that along the socially optimal path, it isn't the level of taxes that matters so much as the real difference between the current tax rate and next period's tax rate. In fact, this difference depends only on ε and the representative agent's resource stock. Since ε is exogenous and N is large, no individual resource owner can affect the right hand side of (14). Thus, for all τ, S_R, and ε there exists a τ' such that individually optimizing resource owners in this setting choose the socially optimal level of extraction.

Quotas cannot be similarly designed to achieve the first-best. In general, quotas fail to attain the optimal path because they do not allow private agents to make full use of information they have that the policymaker does not. A quota policy that adjusts next period's quota in response does not do any better. Suppose, for example, that the quota in the current period binds. If the realization of ε is greater than 0, then (12) shows that it must be socially optimal to increase extraction beyond the current quota. No change in next period's quota, however, can induce optimal behavior, because the current quota binds.

The formal proof of this idea turns on the same fact: quotas limit private choices. Consider a quota policy in the spirit of (14), where the shadow prices of the quotas are chosen so that individually optimizing resource owners choose the socially optimal extraction level. If such a policy exists, it must satisfy

$$(15)\quad \lambda' - \frac{\lambda}{\beta} = p - E\left[\frac{dC}{dx}(x'_{SO}(S_R - x_{SO}(S_R,\varepsilon),\varepsilon'))\right] - \frac{1}{\beta}\cdot\left(p + \varepsilon - \frac{dC}{dx}(x_{SO}(S_R,\varepsilon))\right)$$

The shadow prices λ and λ' arise from constraints on the private resource owners decision set. The question, then, is whether the socially optimal choice $x_{SO}(S_R,\varepsilon)$ lies within the resource owner's feasible set given the quota. If it does not, then the quota policy cannot induce the social optimum.

The only way that the policymaker can guarantee that the quota policy can permit the optimal choice in the current period, no matter what the realization of ε, is to set an initial quota level that does not limit resource owners at all in the present. Thus, it must be that $\lambda = 0$. Simple updating shows that this logic must hold in the next period as well: the only way to guarantee feasibility of the optimal choice next period is to set $\lambda' = 0$ as well. Yet, if $\lambda = 0$, then the policy condition given by (15) implies

(16) $\lambda'(S_R,\varepsilon) = p - E\left[\frac{dC}{dx}(x'_{SO}(S_R - x_{SO}(S_R,\varepsilon),\varepsilon'))\right] - \frac{1}{\beta}\cdot\left(p+\varepsilon-\frac{dC}{dx}(x_{SO}(S_R,\varepsilon))\right)$.

If $\frac{df}{dx} > 0$, as assumed, (16) implies $\lambda' > 0$, so next period's quota must bind—a contradiction. Therefore, no quota policy exists that can induce the first-best.

Returning to the optimal tax policy, a comparative statics analysis show that the optimal policy reduces next period's tax rate in response to positive price shocks in the current period. A positive price shock makes an extraction increase both privately and socially desirable, but the social planner would increase extraction less than the resource owner because of external costs. Reducing next period's tax rate makes extracting next period relatively more attractive to the private owner. The optimal policy thereby dampens private responses to price shocks to ensure the optimizing owner chooses the first-best path.

Mathematically, this result can be derived as follows. For any τ, S_R , and ε, differentiation of the optimal tax policy described by (15) yields:

(17) $$\frac{\partial\tau'}{\partial\varepsilon} = -N\cdot\frac{\partial x_{SO}}{\partial\varepsilon}\cdot\left(\frac{1}{\beta}\cdot\frac{\partial^2 f}{\partial x^2}(N\cdot x_{SO}) + E\left[\frac{\partial^2 f}{\partial x^2}(N\cdot x'_{SO})\right]\right).$$

(See Appendix B for proof). Since f is strictly convex and $\frac{\partial x_{SO}}{\partial\varepsilon} > 0$ by (12), it follows that $\frac{\partial\tau'}{\partial\varepsilon} < 0$. The intuition behind equation (17) is straightforward: as ε increases, MED increase beyond the current tax rate. To induce agents to respond correctly to the current rise in MED, the policy reduces next period's tax rate precisely by the change in the present value next period of MED along the optimal path.

V. CONCLUSIONS AND FURTHER QUESTIONS FOR RESEARCH

This paper shows how a stationary tax policy can optimally address a flow externality associated with resource extraction when the policymaker faces asymmetric information in the short run. Quotas cannot attain the optimum because they limit the resource owner's ability to respond to new information. The general idea in this paper is to employ a rule that uses future tax rates as a policy instrument to face private agents with the correct level of external costs. In this particular setting, the optimal policy reduces future taxes as prices rise. The tax rate reduction gives resource owners an incentive to save resources for later extraction, thereby reducing extraction in the current period.

This intuition points to a key assumption of this paper. The policy solution derived in this paper works precisely because changes in future taxes on extraction imply changes in opportunity costs and changes in the present discounted value of the resource stock. But this assumption does not hold in some important cases. Consider a model where resource owners could employ both dynamic and static factors, like capital and labor, to reduce pollution. In a nutshell, the policy described here does not attain the first best in such scenarios because, for purely static factors, current levels do not affect future levels. The future tax rates on such factors would therefore not appear in the resource owner's first-order conditions, because current levels would not represent an investment in future levels of these factors. The interesting question here then seems to be how the second best in such settings depends on not only the relative slopes of the marginal costs and marginal benefits of abatement but also the relative cost effectiveness of different types of inputs into abatement.

Another important assumption made in this paper is that the informational asymmetry in this model, though persistent, is short run in nature. The policymaker learns the value of the current shock at some point in the future and can therefore incorporate information on realizations of current uncertainty into future policy. If the asymmetry were instead permanent, so that policymakers *never* learned the value of the shock, a dynamic game might arise where policymakers would attempt to extract information from agents' observable decisions. If an equilibrium exists where the policymaker can identify past values of the shock, then a strategy that implements the first best via a price instrument may also exist.

It also seems worth considering how other forms of short run uncertainty affect this problem. For non-renewable resource extraction in particular, policymakers may face uncertainty over the resource owner's capital stock, the quality of ore extracted, and the price of the backstop technology. While an optimal tax sequence seems plausible for any one of these cases individually, how do prices and quantities compare when multiple sources of asymmetric information arise in a dynamic setting? Any source of uncertainty that implies a corner solution to the agents' problem may affect the optimality of taxes, but it may be possible to use such corner solutions in much the same way as Weitzman [8] makes use of the fishery's zero-profit condition.

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Chapter 2: Ventilation Choices and the Effects of Indoor NO_2 on Respiratory Health: Evidence from NHANES III

Abstract:

This paper investigates whether day-to-day exposure to a common indoor air pollutant—Nitrogen Dioxide (NO_2)—affects respiratory health. This oxidant gas causes permanent and sometimes fatal lung damage at concentrations greater than 1000 ppb (Samet and Utell, 1990). According to the 2005 American Housing Survey, about 40 percent of occupied homes in the US use gas stoves for cooking, which produce NO_2 as a byproduct of combustion (US Census, 2006). Peak concentrations in homes may reach above 900 ppb when a gas stove is used for cooking (Dennekamp *et al.*, 2001). Previous epidemiological studies find mixed evidence of negative effects from use of gas stoves (Basu and Samet, 1999). Economic theory suggests, however, that NO_2 exposure may be endogenous in these analyses. In this case, estimates of the effect of exposure in classic regression analyses will be biased.

I address this problem by developing a physical model of indoor NO_2 concentrations that depends on individual ventilation decisions and housing characteristics. I estimate this model using data from the third wave of the National Health and Nutrition Examination Survey (NHANES III), examining the effect of natural gas stoves on a set of objective measures of lung function (spirometry). County-level statistics on the observed housing stock act as instrumental variables, predicting the presence of gas stoves and ventilation use independently of health.

In every model I consider, I find no significant effects of gas stoves on the outcomes. The lower limits of the 95 percent confidence intervals for the coefficient estimates suggest only small potential negative effects on respiratory health from ordinary NO_2 exposure. In almost every case, the absolute value of the lower limit is less than one-third of a standard deviation of the outcome. Controlling for individual decisions yields insignificant but *positive* coefficients for the unadjusted and adjusted gas stove indicators for almost every outcome. The relatively small standard errors of these estimates suggest that in typical residential environments in the US, ordinary exposure to NO_2 from gas stoves does not pose a health risk. As homes become more energy efficient, however, risks of NO_2 exposure from gas stoves increase. Public policies that provide housing or encourage energy efficiency may consider complementary actions to mitigate these risks.

JEL Codes: I10, Q53, D10

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Indoor air pollutants like NO_2 have recently come to the attention of the scientific community because people in the US spend approximately 90% of their time indoors, where many air pollutant concentrations are higher than they are outdoors. (Klepeis *et al*., 2001; Wallace, 1991; Wallace *et al*. 1996). At the same time, rates of asthma morbidity and mortality in the US continue to rise despite dramatic improvements in outdoor air quality due to the clean air act (Mannino *et al*., 1999). Unlike outdoor air pollutants, however, indoor air pollutants do not impose an externality on society. Individuals can make decisions that directly affect their exposure to indoor air pollutants in their homes. This paper takes those decisions into account while examining whether day-to-day exposure to one indoor air pollutant—nitrogen dioxide—affects respiratory health.

Nitrogen Dioxide (NO_2) is one of several air pollutants found at much higher concentrations indoors than it is outdoors. According to the 2005 American Housing Survey, about 40 percent of occupied homes in the US use gas stoves for cooking, which produce NO_2 as a byproduct of combustion (US Census, 2006). While outdoor concentrations averaged below 20 ppb in the US in 2007 (US EPA, 2008a) and average indoor to outdoor concentration ratios of NO_2 in homes with gas stoves are only 1.19:1 (Levy *et al*., 1998), peak concentrations during cooking may reach above 900 ppb when gas is used for cooking (Dennekamp *et al*., 2001). At this concentration, NO_2 may pose risks to health: toxicological studies show that NO_2 causes permanent and sometimes fatal lung damage at concentrations of 1000 ppb and above (Samet and Utell, 1990).

I use data from the third wave of the National Health and Nutrition Examination Survey (NHANES III) to analyze the relationship between gas stoves and a set of objective measures of respiratory health derived from spirometry, which measures breathing flow rate and lung capacity. I focus on four spirometric outcomes in particular: forced expiratory volume at one second (FEV_1), forced vital capacity (FVC), the ratio of FEV_1 and FVC, and forced expiratory flow over the middle of the expiration ($FEF_{25\%-75\%}$) (US DHHS, 1996). I examine this relationship for adult lifetime non-smokers, controlling for individual characteristics using appropriate population reference values (Hankinson *et al*., 1999).

To identify variation in exposure to NO_2, I use a model of indoor air quality and individual choice. This structural model shows how housing characteristics and ventilation decisions affect NO_2 concentrations during cooking. These factors affect the volume of air indoors and the rate at which air from outdoors replaces the air indoors, referred to as the air exchange rate. Larger homes have more space for stove emissions to diffuse, yielding lower peak pollutant concentrations and. Homes with relatively higher air exchange rates also will tend to have lower pollutant concentrations from stove emissions because outdoor air replaces indoor air faster in these homes.

One way individuals can affect their air exchange rate is by using a mechanical vent hood. Ventilation use can dramatically reduce the concentration of NO_2 and other cooking emissions, reducing concentrations of pollutants by at least 40-70% depending on the size of the home and the power of the exhaust fan. More generally, individuals may reduce their exposure to NO_2 in a number of ways: by decreasing their cooking time, cooking with less intensity, or choosing an electric stove over a gas stove.

To the extent that individual health influences these choices, however, endogeneity bias enters regressions that attempt to measure the effects of exposure to NO_2. For sake of illustration, suppose that NO_2 exposure reduces health. If less-healthy individuals do relatively more to reduce their exposure, then classical regression analyses will bias the estimated effects of gas stoves on health upwards. On the other hand, if healthier individuals do relatively more to reduce exposure, the estimated effects will be biased downwards. Both cases seem plausible in the general population, more so than the case of no correlation. I address this problem with instrumental variables (IV) models, separately identifying the effect of exposure from gas stove by using county-level statistics from the observed housing as instruments.

I implement two IV models: one that does not adjust for the indoor environment and one that does. In the first stage of the IV analyses, I model exposure as a function of housing stock variables, including the percentage of homes with both a gas stove and a ventilation hood in the individual's home county, and statistics on the age of the housing stock in that county. The county-level variables affect the cost to an individual to obtain a home with both gas stove and a ventilation hood. At the same time, housing stock variables plausibly do not have direct effects on individual respiratory health because individuals spend most of their time in their own home, in transit, or at work (Klepeis *et al.*, 2001). Moreover, individuals cannot have easily selected where to locate their home as a function of high prevalence of kitchen ventilation because neither state nor county building codes specifying the need for range hoods existed during the data collection for NHANES III.

Previous epidemiological studies find mixed evidence of negative effects from exposure to NO_2 from gas stoves. Basu and Samet (1999) review 45 studies on the question and find that roughly half of these studies show significant negative effects on respiratory health outcomes while the other half do not. The authors conclude that:

> This failure to find consistent negative associations should not be interpreted as indicating safety, i.e. no effect of gas stoves. Methodological limitations of the studies blunt their sensitivity to detecting even modest associations. On the other hand, there are significant data to suggest that large effects of immediate public health concern have not been overlooked.

More recently, Eisner and Blanc (2003) analyze the health effects associated with gas stoves using NHANES III and find no effect for adults.

This paper makes two contributions relative to the prior literature. First, I account for the fact that human decisions will both affect the indoor environment and bias the results of classical regression analyses. Eisner and Blanc (2003) recognize this possibility in the conclusion of their work, but no prior studies control for the consequences of individual choices or the possibility of endogeneity. To capture the impact of individual decisions, I employ a physical model of the indoor environment where ventilation choices and home characteristics affect concentrations of NO_2. This model also sets this paper apart from prior studies. Past examinations of the effect of gas stoves on respiratory health use reduced form methods that do no explicitly model the indoor environment. A handful of small sample studies explicitly monitor indoor concentrations of NO_2, while most others simply use an indicator variable for the presence of a gas stove.

The results of this paper suggest that exposure to NO_2 from gas stoves in typical residential settings does not pose a substantial risk to adult health. Accounting for endogeneity bias does not reverse this finding. In every model I consider, the effect of a gas stove on respiratory health is small or zero. The lower limits of the 95 percent confidence intervals for the coefficient estimates suggest only small potential negative effects of ordinary NO_2 exposure on most of the outcomes I consider. In almost every case, the absolute value of the lower limit is less than a third of a standard deviation of the outcome. Controlling for endogeneity yields insignificant but *positive* coefficients for the unadjusted and adjusted gas stove indicators for almost every outcome. Under these results, the lower limits of the 95 percent confidence intervals again indicate negative impacts that are on the order of a third of a standard deviation of the outcomes for a typical home with a gas stove. If gas stoves do pose a risk to respiratory health, it is only to occupants of very small homes where kitchen ventilation is not used.

I proceed to show these results in six sections. The first section explains the overall research design of the paper, drawing out precisely what the presence of a gas stove in a home can indicate about NO_2 exposure. In Section II, I offer two theoretical models relevant to this research design. First, I set out a theoretical model of NO_2 concentrations indoors during stove use and show how housing characteristics and ventilation choices affect this concentration. I then turn to an economic model of ventilation choices to show how an individual's respiratory health may ultimately play a role in determining their

NO_2 exposure. I set forth an econometric model to estimate this relationship in Section III and describe the data I use to parameterize it in Section IV. use to analyze it. I report my the results of my analyses in Section V. The paper concludes with a summary of results and a short discussion of policy implications.

I. RESEARCH DESIGN

The construction of a controlled experiment aimed at identifying the effect of routine NO_2 exposure presents near insurmountable difficulties. Define total exposure to NO_2 as the sum of all NO_2 exposures in a lifetime, where each individual's exposure is the integral over time of an individual's breathing rate multiplied by the concentration of NO_2 in the air. This definition suggests that the ideal data set for examining the health effects of NO_2 would randomly assign exposure times and concentrations over individuals' lives and then examine respiratory health outcomes. An equally valid approach would use panel data to look at changes in respiratory health as a function of randomly assigned test exposures, comparing outcomes for exposed subjects to outcomes for control subjects.

Pure experiments are not practicable, and precisely measuring exposure concentrations—particularly with short time intervals—is cost-prohibitive, especially for large data sets. For this reason, more than 30 of the 45 reviewed studies by Basu and Samet (1999) measure exposure by comparing health outcomes between individuals who use gas stoves for cooking and those who do not. These types of studies provide information on the results of natural experiments where individuals are non-randomly exposed to some positive but unknown concentrations of NO_2 for unknown lengths of time throughout the observation period. In the absence of panel data, studies that make use of such data implicitly assume either that current indicators of NO_2 exposure are typical of an individual's lifetime exposure pattern or that health effects are dominated by current exposures. Statistically, these studies aim to identify effects of indoor NO_2 off of cross-sectional variation in exposure indicators. Assignment to exposure indicators is assumed to be random.

I extend this approach in two ways. First, I relax the assumption of random assignment of health outcomes to exposure indicators by allowing exposure to be endogenous to the estimated system. Second, I employ a physical model of the indoor environment to introduce variation in the exposure indicator. These two extensions are inter-related: the model of the indoor environment provides a window onto how individual decisions affect exposure.

In the model of the indoor environment that I use, home characteristics and ventilation choices affect the rate at which NO_2 emissions build up inside a home. For any given gas-cooking event, the concentration of NO_2 rises more slowly and attains a lower peak concentration in larger, draftier homes. Because larger homes have a greater volume of indoor air, diffusion of NO_2 into the air in these homes drives the concentration down. Draftier homes likewise have lower peak concentrations of NO_2 because air from the outdoors replaces the air indoors at a relatively faster rate. For the same reason, using a kitchen vent hood will also drive down NO_2 levels. I develop this model in detain in the next section.

II. THEORETICAL MODEL OF THE INDOOR ENVIRONMENT

In any indoor environment, the concentration of a pollutant over time depends on the rate at which sources add the pollutant to the indoor space and the rate at which the pollutant is removed from that space. I identify typical sources and means of removal, referred to as "sinks", for NO_2 and derive a differential equation that characterizes the concentration of NO_2 indoors. This "mass balance" equation describes the change in the mass of NO_2 as a function of the emission and removal rates and characteristics of the home. I find the closed form solution for this differential equation, which is the indoor concentration of NO_2 as a function of time when a source is in use. I analyze this equation and discuss its implications for NO_2 concentrations indoors. Since the use of kitchen ventilation has a substantial effect on the mass balance, I suggest a simple economic model for the individual decision to ventilate. This model illustrates how an individual's health may affect the decision to ventilate or reduce exposure generally.

Sources of NO_2 indoors include NO_2 from the outdoors and unvented indoor gas appliances, namely gas stoves or kerosene heaters. Between kerosene heaters and gas stoves, gas stoves are the more important source. Gas stoves are more prevalent in homes and are used on a near-daily basis. In contrast, the use of kerosene heaters is largely seasonal. Other appliances like water heaters or gas furnaces typically add only negligible amounts of NO_2 to indoor air because they are directly vented to the outdoors. Therefore, gas stoves are the only source of NO_2 indoors that I consider in this analysis.

Sinks for NO_2 indoors include air exchange, chemical reactions on surfaces ("heterogeneous reactions"), and chemical reactions in the indoor air. Of these three sinks, air exchange and heterogeneous reactions dominate. Measurements of the speed at which NO_2 reacts with surfaces in homes—its deposition velocity—show that air exchange and heterogeneous reactions reduce NO_2 at similar rates (*e.g*. Yamanaka, 1984). Based on these characteristics, the concentration of NO_2 in a well-mixed indoor environment when a gas stove is on evolves according to the following mass balance equation:

$$(18) \quad V \cdot \frac{dC}{dt} = (\lambda + \delta \cdot \lambda_{hood}) \cdot V \cdot C_{out} + E - (\lambda + \delta \cdot \lambda_{hood}) \cdot V \cdot C(t) - v_d \cdot A \cdot C(t),$$

where the boundary condition is $C(0) = C_0$. In this equation, V is the volume of the indoor space and $C(t)$ represents the concentration of NO_2 at time t, λ is the air exchange rate of the indoor space, δ is an indicator variable taking the value 1 when a ventilation hood is on, λ_{hood} is the increase in air exchange due to the ventilation hood, C_{out} is the concentration of NO_2 outdoors, E is the mass per unit time of NO_2 emitted by the gas stove, v_d is the average rate at which NO_2 reacts with surfaces in the home and A is the surface are in the home. Thus, the rate of change in mass of NO_2 is equal to the rate at which outdoor air and indoor emissions add NO_2 to the indoor space net of the loss of indoor NO_2 to outdoor air due to air exchange.

Equation (18) is separable after one substitution and has the following, closed-form solution:

$$(19) \quad C(t) = e^{-\left(\lambda + \delta \cdot \lambda_{hood} + \frac{v_d \cdot A}{V}\right) \cdot t} \cdot C_0 + \left[1 - e^{-\left(\lambda + \delta \cdot \lambda_{hood} + \frac{v_d \cdot A}{V}\right) \cdot t}\right] \cdot \left[\frac{(\lambda + \delta \cdot \lambda_{hood}) \cdot C_{out} + \frac{E}{V}}{\lambda + \delta \cdot \lambda_{hood} + \frac{v_d \cdot A}{V}}\right].$$

In theory, total exposure to NO_2 is the integral over time of $C(t)$ multiplied by an individual's breathing rate, but analysis of the function $C(t)$ alone leads to several inferences. First, in the absence of indoor sources of NO_2, the concentration of NO_2 indoors should tend towards the outdoor concentration. Next, the volume of the indoor space and air exchange dilute the concentration of indoor NO_2 as the mass emitted spreads throughout the home and outdoors as it flows down the concentration gradient. Thus, the use of kitchen ventilation reduces indoor NO_2 by facilitating dilution. Finally, homes with relatively higher surface area to volume ratios will tend to have relatively lower concentrations of NO_2 because of removal of the pollutant to surfaces. Little data on indoor, residential surface-area-to-volume ratios exist, but a recent study suggests that typical ratios are about 3:1 (Hodgson *et al.*, 2004). Because of the lack of data on this term, however, I ignore the effects of surface deposition for the remainder of this paper. Equation (19) demonstrates, however, that for any given emission rate E, variation in air exchange rates and ventilation use will still lead to variation in indoor NO_2 concentrations, independent of surface deposition.

While the effects of air exchange on indoor pollutant concentrations are well known, the impact of kitchen ventilation has received little attention in the empirical literature. In an experimental setting, Traynor *et al.* (1982) show how variation in ventilation hood speed can be used to calculate the NO_2 emission rate from a gas stove. In the course of their work, the authors measure the concentration of NO_2 emitted from an oven set to 180°C in a 27m^3 experimental chamber. The vent hood increases the air exchange rate from the natural rate of 0.24-0.42 hr^{-1} to up to 7.0 hr^{-1}. The difference in air exchange rates has a dramatic impact on the observed concentration of NO_2. With no mechanical ventilation, the concentration of NO_2 reaches 1 ppm in less than 20 minutes and peaks at above 1.5 ppm. With the vent hood on, the concentration of NO_2 reaches a peak of about 0.1 ppm within the first few minutes of the experiment—90% less than the peak concentration reached with the vent hood off.

Equation (19) implies, however, that the effect of a ventilation hood on the indoor concentration of NO_2 will depend on the strength of the ventilation fan, the volume of the indoor space, and the natural air exchange rate. Calculation shows that in a typical 600 m^3 home (roughly 2150 sq ft, with 9ft ceilings) and a median natural air exchange rate of 0.5 hr^{-1}, a vent hood with a speed of between 100 and 400 CFM will increase the air exchange rate of the home by 0.28-1.13 hr^{-1}.[11] If the air in the home is well mixed, the use of kitchen ventilation will reduce the impact a gas stove will have on the indoor concentration of NO_2 by about 56-126%. But since emissions from a gas stove typically flow upwards in the heat plume, directly towards ventilation hood, the well-mixed assumption fails. These calculations may therefore be seen as lower bounds for the effects of kitchen ventilation in a typical home.

This physical model of indoor air quality explains how the concentration of NO_2 changes given that an individual cooks with a gas stove or uses their ventilation hood, but it does not provide insight into how individuals make these choices. To address how individuals make decisions that affect their indoor environment, I offer a simple

[11] The relevant conversion factor for this calculation is: 1 CFM = 1.699 m^3h^{-1}. The typical range for most residential vent hoods is 100-400 CFM according to the Home Ventilating Institute (2008)

economic model. Although this model lacks the precision of physical models, it illustrates how individuals may balance the costs and benefits of improved air quality. The key hypothesis that this model generates is that individuals who benefit more from cleaner air will do more to keep their indoor air clean. For parsimony, I confine this model to one decision: the decision whether or not to use kitchen ventilation. Decisions over how much time to spend cooking, cooking intensity, whether to purchase a vent hood, or which type of stove to buy could be included in the model, but the basic intuition remains the same.

For the ventilation choice problem, suppose that people gain utility from health and disutility from noise. If individuals know that ventilation improves their air quality when cooking, then the following maximization problem economically characterizes how often individuals who own a vent hood will use it:

(20) $$\max_{\theta \in [0,1]} U(h, n \cdot \theta) : h = H(A(\theta), X) .$$

In equation (20), $n > 0$ represents noise from running the ventilation hood, θ is the proportion of time the vent hood is turned on during, or equivalently, the probability that $\delta = 1$ in equations (18) and (19) ; U is a differentiable, concave utility function; h is an individual's health, H is a differentiable function that gives the health of individual ; A is a differentiable function representing air quality, and X is a vector of individual characteristics which are fixed at the time of the decision. Suppose that utility is increasing and strictly concave in health ($\frac{\partial U}{\partial h} > 0$, $\frac{\partial^2 U}{\partial h^2} < 0$) while decreasing and strictly convex in noise ($\frac{\partial U}{\partial(n\cdot\theta)}<0$, $\frac{\partial^2 U}{\partial(n\cdot\theta)^2}>0$). To complete the model, assume that health is increasing and concave with respect to air quality increases ($\frac{\partial H}{\partial A}>0$, $\frac{\partial^2 H}{\partial A^2}<0$), and that air quality is increasing and concave in vent hood use ($\frac{dA}{d\theta}>0$, $\frac{\partial^2 A}{\partial\theta^2}<0$).[12]

With these assumptions, standard economic theory guarantees that the first order conditions of (20) completely characterize its solution. These first order conditions are:

(21a) $\frac{\partial U}{\partial h}\cdot\frac{\partial h}{\partial A}\cdot\frac{dA}{d\theta}+n\cdot\frac{\partial U}{\partial(n\cdot\theta)}+\mu-\rho=0$

(21b) $\mu\cdot\theta=0$

(21c) $\rho\cdot(1-\theta)=0$,

where $\mu\geq 0$ and $\rho\geq 0$ are the Lagrangian multipliers for the respective corner solutions. Intuitively, these first order conditions say that individuals choose the θ that balances the marginal costs of vent hood use (noise) against the marginal benefits of use (improved air quality, which in turn yields greater health).

This simple model yields a sensible implication for individuals located along different iso-characteristic curves on the surface traced out by the health function: individuals

[12] These conditions simply insure that the marginal costs of vent use are increasing while the marginal costs are declining. It is perhaps worth noting that the functional assumptions of for the air quality function A are consistent with the model described by (2) when initial concentrations of indoor NO_2 (C_0) and the outdoor concentration of NO_2 (C_{out}) are relatively small.

whose health is relatively more sensitive to changes in air quality will use their vent hood at least as much as those who are not sensitive. I express this result in Proposition 1.

Proposition 1: Consider two distinct individuals x_1 and x_2 with characteristics X_1 and X_2 respectively, each facing the optimization problem (20). Suppose that x_1 benefits more from improved air quality than x_2, which can be written as:

$$(22) \qquad \frac{\partial H(A(\theta), X_1)}{\partial A} > \frac{\partial H(A(\theta), X_2)}{\partial A}.$$

Under this assumption, $\theta_1 \geq \theta_2$, with equality only at corner solutions.

Proof: See Appendix C.

This result holds because "sensitive" individuals in this model derive relatively higher marginal benefits from air quality than others do at every point while the marginal cost curves remains the same for both types of individuals.

These theoretical predictions have a practical implication. Insofar as prior health is a component of the vector of characteristics that determines current health, health may correlate with vent hood use. In the terms of the model, suppose $X \in \mathbb{R}^k = (x_1, ..., x_k)$ with x_h representing prior health. Suppose that:

$$(23) \qquad \frac{\partial}{\partial x_h} \frac{\partial H(A(\theta), X)}{\partial A} \neq 0.$$

According to the analysis above, the model now predicts that for any two otherwise identical individuals, different levels of prior health imply different ventilation choices. Health may influence ventilation choices in either direction, depending on the sign of this derivative. When the derivative is negative, for example, lower prior health implies greater "sensitivity" as described by (22), and thus greater marginal returns of air quality to health.

While this simple economic model analyzes only an individual's decision to use ventilation, a more complete model that includes individual cooking time and intensity decisions would show similar results. To the extent that individuals think that exposure to stove emissions have an impact on their indoor air quality and thus their respiratory health, they may reduce their exposure by operating on a variety of intensive or extensive margins. Depending on their preferences, relatively more sensitive individuals may reduce the time they spend cooking, cook on lower heats, cook using less burners or their microwave, grill outdoors, eat out more often, or simply choose to own an electric stove instead of a gas stove. In all cases, economic theory predicts that, all else being equal, those who benefit more from clean air will do more to keep their air clean.

III. ECONOMETRIC METHODS

I now apply these models to an econometric analysis. The standard cross-sectional model for this problem is a simple linear system:

(24) $\mathbf{y}_i = \mathbf{X}_i\boldsymbol{\beta}_i + \mathbf{Z}_i\gamma_i + \boldsymbol{\varepsilon}_i, \; i = 1, \ldots, M.$

In this equation, $\mathbf{y}_i$ is a vector of data on respiratory health outcome i for the sample, $\mathbf{X}_i$ are data on relevant demographic and individual characteristics in explaining respiratory health outcome i, $\boldsymbol{\beta}_i$ are the coefficients to be estimated for $\mathbf{X}_i$, $\mathbf{Z}_i$ are data on the environmental factors of interest for i, γ_i is the vector of coefficients to be estimated for $\mathbf{Z}_i$, $\boldsymbol{\varepsilon}_i$ is the mean zero residual for the equation i, and M is the number of respiratory outcomes considered. In the literature and in this paper, regressors are identical across equations: $\mathbf{X}_i = \mathbf{X}_j = \mathbf{X}$ and $\mathbf{Z}_i = \mathbf{Z}_j = \mathbf{Z}$ for all i, j. The interdependence of the equations is not always considered in the literature, but seems appropriate in this application given that factors affecting one measure of respiratory health will affect other measures. The base model thus fits into the seemingly-unrelated regressions (SUR) framework.

The variables $\mathbf{y_i}$ I investigate are three respiratory health outcomes derived from spirometry done as part of NHANES III. Spirometry directly assesses respiratory health by measuring the amount of air inhaled and exhaled and the speed at which an individual breathes. Analytically, these outcomes have at least two advantages over other health outcomes. First, spirometry provides a high quality, empirical measure of respiratory health. Examinations for NHANES III implemented the 1987 American Thoracic Society's recommendations for performing spirometry, and all results were later reviewed for reliability.

Second, the spirometry of asymptomatic, lifelong non-smokers in NHANES III has already received careful study. Hankinson *et al*. (1999) develop reference values and predictive equations for normal spirometric outcomes using piecewise polynomial functions of individual age, sex, height, and ethnicity. In accordance with the guidelines of the American Thoracic Society and the European Respiratory Society (Pellegrino *et al.* 2005), I take these reference values into account in my analysis by using the residual between these predicted outcomes and actual spirometric results as my dependent variables. Further details on the specific outcomes I analyze appear in Section IV.

I treat asthma as an independent variable in the $\mathbf{X}$ matrix. According to the National Heart Lung and Blood Institute, asthma and its persistence begin early in life (NHLBI, 2007). Thus, while features of the indoor environment may aggravate their condition, adult asthmatics develop their condition in earlier, unobserved circumstances. For that reason, it makes little sense to include asthma status as a dependent variable. Asthma status cannot, however, be excluded from the list of independent variables: asthmatics have significantly lower spirometry scores than the general population, with large differences in FEV_1 and $FEF_{25\%\text{-}75\%}$ in particular.[13]

I also use the matrix $\mathbf{X}$ to control for regional and seasonal variations by including indicator variables for the geographic region of the observation (Northeast, South, Midwest, or West), and the month that the NHANES medical exam occurred. I also control for relevant socio-demographic variables in some analyses, including years of

13 According to the National Heart Blood and Lung Institute, "Asthma is a common chronic disorder of the airways that involves a complex interaction of airflow obstruction, bronchial hyperresponsiveness and an underlying inflammation. This interaction can be highly variable among patients and within patients over time" (NHLBI, 2007). Asthma is thus not defined by spirometric results, but asthmatics in NHANES III do have significantly lower FEV_1 and $FEF_{25\%\text{-}75\%}$ scores than similar individuals. Low FEV_1 scores with no concomitant reduction in FVC typically identifies obstructive conditions like asthma. Reductions in $FEF_{25\%\text{-}75\%}$ may also suggest the onset of obstructive conditions (Pellegrino *et al.*, 2005).

education, family income, and the presence of smokers in the home. Because of the poor quality of income data (family incomes are reported only up to $50,000) and because a substantial number of observations are missing for income and years of education, I do not include these variables in the main results of the paper. Their inclusion does not alter the result.

The analysis in this paper fundamentally consists of four different models of $\mathbf{Z}$ and its relationship to the errors $\boldsymbol{\varepsilon}_i$: a base model, an extended model that structurally accounts for the indoor environment, and two instrumental variables (IV) models (one for the base model and one for the extended model) that account for the possible co-determination of health outcomes and indoor air quality. I conduct this analysis over all non-smoking adults in NHANES III who have location information, reliable spirometry, and for whom the national reference equations are valid.

The base model follows the prior literature and uses an indicator variable for the presence of a gas stove in the home to control for exposure to NO_2. The extended model uses a more refined measure of NO_2 exposure based on the mass balance model in Section II. Since respiratory health itself may affect NO_2 exposure, the IV models attempts to independently identify the effect of exposure by using county-level data on the housing stock. The idea behind this identification strategy is that housing stock characteristics will affect the relative costs of obtaining a home with a gas stove and the cost of obtaining a home with a ventilation hood.

In the extended model, NO_2 in indoor air is assumed to come only from gas stoves. To keep the sample as large as possible, I do not include statistics on outdoor NO_2 levels as regressors in the analysis. In each of the four models, analysis shows that county-level statistics on outdoor NO_2 do not significantly affect respiratory outcomes nor alter the fundamental result of the paper. Thus, from equation (19), the extended model focuses only on the term

$$(25) \qquad \frac{E}{(\lambda + \delta \cdot \lambda_{hood}) \cdot V} \ .$$

In the absence of precise data on the variables, I approximate this term as best as possible by making use of available data on home characteristics and individual decisions. As other authors implicitly do, I replace E with an indicator variable for the presence of a gas stove. For each individual home, I impute the average air exchange by climatic region from Murray and Burmaster (1995).

As a robustness check, I run a separate set of regressions with λ set equal to the national residential median of 0.5 hr^{-1}, but this change does not affect the results. I use the number of rooms as reported in NHANES III in place of home volume with the idea that larger homes will tend to have more rooms. Calculations suggest λ_{hood} lies between 0.28 and 1.13 in a typical home. In the absence of data, I normalize λ_{hood} = 1 hr^{-1}, which is within its expected limits.

Some direct data on ventilation hood use are available. For NHANES III who report using a gas stove or oven for cooking in their residence, the survey asks: "Is there an exhaust fan near this stove that sends fumes outside the house?" If the respondent answers in the affirmative then the survey further asks, "When the stove or oven is being used, how often is this exhaust fan used? Would you say it is used always, sometimes, rarely, or never?" Since very few observations report "never" and the semantic difference between "sometimes" and "rarely" may vary between individuals, I focus on individuals who report "always" using their ventilation hood by using an indicator variable for this choice.

In total, these compromises transform (8) into the calculable term

$$\text{(25a)} \quad \frac{\delta^{gas}}{(\bar{\lambda}^{r} + \delta^{hood}) \cdot rooms},$$

where δ^{gas} is an indicator variable for the presence of a gas stove, $\bar{\lambda}^{r}$ is the mean air exchange rate for the climatic region, δ^{hood} is an indicator variable for "always" using a ventilation hood, and $rooms$ is the number of rooms in the home.[14] I refer to this term as the IAQ-adjusted gas stove indicator. Intuitively, this term captures the essence of the physical model of indoor air quality by inversely weighting the presence of a gas stove by factors that dilute the concentration of NO_2 in the home.

For robustness, I interact available data on home age with the IAQ-adjusted indicator. Respondents to NHANES III report whether their home was built before 1946. These interactions provide a means to account for differences in emissions and air exchange rates by home age. Older natural gas stoves may use pilot lights, which constantly emit low levels of NO_2 into indoor air. On the other hand, older homes tend to have relatively

[14] For any given flow rate, the effect that vent hood use will have on a home's air exchange rate will decline as home size increases. This model does not capture this fact: the use of a vent hood is simply treated as having the same additional effect on air exchange across homes.

higher air exchange rates compared to newer homes. These interactions do not change the results of the analysis.

For the first two models, I assume that the outcomes are not correlated with the regressors, *i.e.* $E[\boldsymbol{\varepsilon}_i \mid \mathbf{X}, \mathbf{Z}] = \mathbf{0}$. I estimate this system using a standard two-step Zellner estimate of the coefficients for the system. Standard errors are corrected for the clustering of observations within homes by bootstrapping. To generate reliable standard errors and confidence intervals, I use 1,000 bootstrap iterations per model.

Because the theoretical model suggests that the use of kitchen ventilation and other decisions that affect indoor air quality may be endogenous, the assumption $E[\boldsymbol{\varepsilon}_i \mid \mathbf{X}, \mathbf{Z}] = \mathbf{0}$ may fail. I address this possibility in the third and fourth regressions by using instrumental variables (IV) models. In these models, I separately identify ventilation fan use off of variables that affect the cost of owning a home with a gas stove and ventilation hood. Explicitly, I include a first-stage equation that sets the gas stove term in each model equal to a linear function of the county-level percentage of homes with gas stoves, the county-level percentage of homes with both gas stoves and ventilation hoods, the county-level percentage of homes built before 1946, and the county-level percentage of homes built after 1973. I include an indicator for asthma status regional and seasonal controls in these models as well. I estimate these systems using three stage least-squares, bootstrapping standard errors as in the first two models.

IV. Data and Descriptive Statistics

The data for this study principally come from the US Third National Health and Nutrition Examination Survey (NHANES III) (NCHS, 1997). As in Eisner and Blanc (2003), I focus on lifetime non-smokers for whom predicted spirometric values can be calculated from the population reference equations of Hankinson *et al.* (1999). I merge the NHANES III data with regional statistics on residential air exchange rates from Murray and Burmaster (1995) and with ambient NO_2 statistics from the US EPA'S AirData database. This procedure requires I restrict the NHANES sample to individuals for whom location data is available. These individuals live in counties of 500,000 or more at the time of the survey. In this section, I provide brief details on each of these datasets followed by descriptive statistics on the data used in the analysis.

The NHANES III uses a stratified, multi-stage probability design to select a representative sample of the non-institutionalized, civilian population of the US from 1988 to 1994 (NCHS, 1996). Observations were gathered in two waves: October 1988-September 1991 and October 1991-1994. Participants in NHANES III answer lengthy surveys about their individual characteristics, homes, habits, and history. They also receive a complete medical examination, including spirometry.

The four spirometric results I analyze in this paper are forced expiratory volume at 1 second (FEV_1), forced vital capacity (FVC), the ratio of FEV_1 to FVC, and forced expiratory flow over the middle 25-75% of expiration ($FEF_{25\%-75\%}$). Forced expiratory volume at 1 second is the total amount of air in liters a person can forcibly blow out of their lungs after one second. Similarly, FVC is the total volume of air in liters that a person can forcibly exhale after taking a full breath. The secondary measure $FEF_{25\%-75\%}$ captures an individual's speed of exhalation over the middle of the spirometric test in liters per second.

Following Eisner and Blanc (2003), I focus on absolute deviations from predicted values.[15] Of these four measurements, FEV_1/FVC is the primary measurement used to diagnose respiratory problems. On its own, FEV1 is the most indicative of overall lung health. According to the American Thoracic Society, deficiencies in FEV_1 from normal predicted values generically describe the severity of any pulmonary abnormality (Pellegrino *et al.*, 2005). In conjunction with FEV_1/FVC, FVC is used to help identify obstructive versus restrictive lung disorders (Pellegrino *et al.*, 2005). A low FVC score relative to normal with no concomitant problem in FEV_1/FVC indicates a restrictive lung disease, which may be a result of damage to functional lung tissue or of disease of the surrounding tissues responsible for helping the lungs draw breath. Last, deficiencies in $FEF_{25\%-75\%}$ can help identify the early stages of an obstructive abnormality (Pellegrino *et al.*, 2005).

Based on the results of NHANES III, Hankinson *et al.* (1999) develop spirometric reference equations for the US population that describe normal pulmonary function. The reference equations for FEV_1, FVC, and $FEF_{25\%-75\%}$ are piecewise polynomials whose parameters vary by age, sex, and ethnicity (non-hispanic white, non-hispanic black, and

[15] Alternatively, I conduct an analysis of percent deviations from normal predicted spirometric values as well. The results are robust to either specification.

Mexican American). The predicted values are valid for adults aged 80 years and younger in these race/ethnicity categories. Each reference equation has the form:

(26) $\mathbf{y}_{predicted} = \mathbf{b}_0 + \mathbf{b}_1\, age + \mathbf{b}_2\, age^2 + \mathbf{b}_3\, height^2.$

The reference equation for FEV_1/FVC is similar but depends only on age, with different parameter values for each sex and race ethnicity categories. Using the parameter values published in Hankinson *et al.*, I calculate predicted values for each of the spirometric measures I use.

I use location data to connect NHANES observations to data on residential air exchange rates. Murray and Burmaster (1995) analyze air exchange rate data for a non-random sample of 2,844 homes compiled by the Brookhaven National Laboratory from 1982-1987. The US EPA identifies this data as "the most extensive air exchange rate database for US residences" (US EPA 2008c). Air exchange rates in the data are measured by the perflourocarbon tracer gas method, which follows the decay of a known concentration of an inert gas injected into a home. Since differences in outdoor temperature affect both air exchange and home ventilation design, the authors divide the data into four climatic regions based on the average number of heating degree days a given location experiences per year. I geographically match the climatic regions in their analysis to counties in the NHANES III and assign individuals the mean annual air exchange rate for their climatic region.

Table 1 presents counts and the sum of weights for observations in NHANES III to show how criteria for sample selection affect the number of observations available for analysis. I focus on lifelong non-smokers aged 80 years or less who have location

Table 1
NHANES III Sample Derivation

Criteria	**N**	**Sum of Weights**
Adults in NHANES	20050	187.5×10^6
…with reliable spirometry	16300	177.3×10^6
…and who are life-long non-smokers	8006	79.4×10^6
…and for who reference equations are valid	7114	68.3×10^6
…and who have location data available	3294	28.9×10^6

Note: 17 individuals in the final sample do not report the number of rooms in their home. The IAQ-adjusted gas stove indicator cannot be calculated for these individuals, which reduces the total N to 3277 for that model. Further requiring data on individual education levels and income data reduces the sample to 2912. Requiring outdoor NO_2 data reduces the primary sample to N = 2955.

information available and identify themselves as belonging to one the three major race/ethnicity categories. This sample derivation is similar to Eisner and Blanc (2003) up to the location criterion, which reduces the size of the sample by more than half. The criterion cannot be relaxed for the IV analysis because the instruments vary by location. It can, however, be relaxed for the first model to generate the results similar to Eisner and Blanc. The requirement of location can also be suspended for the second model by assigning individuals the national median residential air exchange rate of 0.5. As a robustness check, I conduct the first two stages of my analysis over the sample with location information as well as the larger sample without location information. The overall results do not differ, so I simply present analysis for the sample with location information in the next section. This choice allows a comparison between the results for each of the four models. I present means and standard deviations for the weighted

Table 2 Descriptive Statistics		
	Mean	**Std. Dev.**
Characteristics and Demographics		
Female	0.61	0.47
White	0.73	0.41
Black	0.17	0.35
Mexican American	0.10	0.26
Height (cm)	167.77	9.84
Age	38.94	18.13
Asthmatic	0.05	0.22
Spirometry residuals		
FEV_1 (L)	-0.05	0.50
FVC (L)	0.03	0.51
FEV_1/FVC	-0.01	0.07
$FEF_{25\%-75\%}$ (L/s)	-0.03	0.93
Home Characteristics		
Smoker lives in the home	0.14	0.30
Cooks with a gas stove	0.52	0.50
…and has an exhaust	0.29	0.44
…and always uses exhaust	0.11	0.29
Rooms in home	6.01	2.33
Instrumental Variables		
Percent pre-1946 homes in county	0.23	0.17
Percent 1946-1973 homes in county	0.42	0.14
Percent homes with gas stove and exhaust in county	0.29	0.16
Statistics for Secondary Samples		
Years of education (*N=2912*)	13.28	2.86
Family income (*N = 2912*)	33902.66	16311.41
County NO_2 mean (ppb) (*N=2955*)	0.02	0.01
County NO_2 max (ppb) (*N=2955*)	0.01	0.10
County NO_2 standard deviation (ppb) (*N=2955*)	0.21	0.00

sample with location data in Table 2.[16] For completeness, I also include descriptive statistics for the sub-samples of note. While individual characteristics and demographics (*e.g*. sex, age, and ethnicity) do not explicitly appear in this paper's analysis, they do drive the calculation of the spirometry residuals. Therefore, I include means and standard errors for these variables as well.

The descriptive statistics in this table reveal that the sample has a relatively high number of women. The selection criteria favor women because they are less likely to have tried smoking in their lifetime. Summary statistics from the 2006 American Time Use Survey show that women spend nearly twice as much time as men doing food preparation and cleanup (US Department of Labor, 2007). Because of this fact, women may be more exposed to NO_2 and therefore more likely to demonstrate relatively poorer respiratory health as a result. I do not find support for this hypothesis, however: interactions between the female indicator variable and the NO_2 exposure terms do not yield any significant results. This feature of the sample thus does not drive the findings.

Table 2 shows that approximately 52% of the sample cooks with a gas stove. In comparison, the 2005 American Housing Survey shows that 40 percent of homes use gas stoves. While this figure is not weighted for the number of people who live in each home, it suggests that homes in the sample are more likely to have gas stoves relative to the general housing stock. A direct comparison confirms this idea: 61% of the unique households in the sample use gas stoves for cooking. This slight over-sampling increases

[16] Due to the large size of the weighted sample, standard errors for these means are all near zero.

Degree Days	0-2499	2500-5499	5500-7000
States in sample	CA, AZ, TX, FL	AZ, CA, MO, OH, TX, WA	IL, MA, MI, NY, OH, RI
Best-fit mean air exchange rate (h^{-1})[*]	0.687	0.439	0.430
N	619	351	370
Sum of weights	4.6×10^6	3.5×10^6	5.4×10^6

Table 3
Imputed Air Exchange Rates by Climatic Region

[*] Murray and Burmaster, 1995

the chance of finding an effect of gas stoves on health by presenting a relatively higher number of test cases to examine.

I use geographic variation in the sample in an attempt to identify differences in air exchange rates and thus identify some variation in exposure to NO_2. I use the best-fit mean air exchange rates for climatic regions defined by Murray and Burmaster (1996). These climatic regions are defined by annual average heating degree days.[17] Table 3 reports the air exchange rates I use for these regions and shows how the NHANES III sample falls into these regions, indicating the states that each region represents, the number of individual observations per region, and the sum of weights for those observations.[18]

The sample of NHANES III participants I analyze is spread relatively evenly across three climatic regions. Murray and Burmaster consider a fourth region that encompasses

[17] One heating degree day is counted for each day and for every degree that the mean outdoor temperature is below 65 degrees Fahrenheit. For example, a day with a mean outdoor temperature of 55 degrees would be 10 heating degree days.
[18] Air exchange rates also vary by season, but I focus on geographic variation rather than temporal variation to emphasize differences in average NO_2 exposure.

the US's northern states, but none of these appear in the sample. The absence of observations from these states is likely due to the fact that relatively few counties in these

Table 4
IAQ-adjusted Gas Stove Indicator Values by Climatic Region, Home Size, and Vent Use

	Degree Days	**0-2499**		**2500-5499**		**5500-7000**	
	Use a Vent Hood?	*Yes*	*No*	*Yes*	*No*	*Yes*	*No*
Rooms	**1**	0.593	1.455	0.695	2.277	0.699	2.326
	2	0.296	0.727	0.347	1.139	0.350	1.163
	3	0.198	0.485	0.232	0.759	0.233	0.775
	4	0.148	0.364	0.174	0.569	0.175	0.581
	5	0.119	0.291	0.139	0.455	0.140	0.465
	6	0.099	0.242	0.116	0.380	0.117	0.388
	7	0.085	0.208	0.099	0.325	0.100	0.332
	8	0.074	0.182	0.087	0.285	0.087	0.291
	9	0.066	0.162	0.077	0.253	0.078	0.258
	10	0.059	0.145	0.069	0.228	0.070	0.233

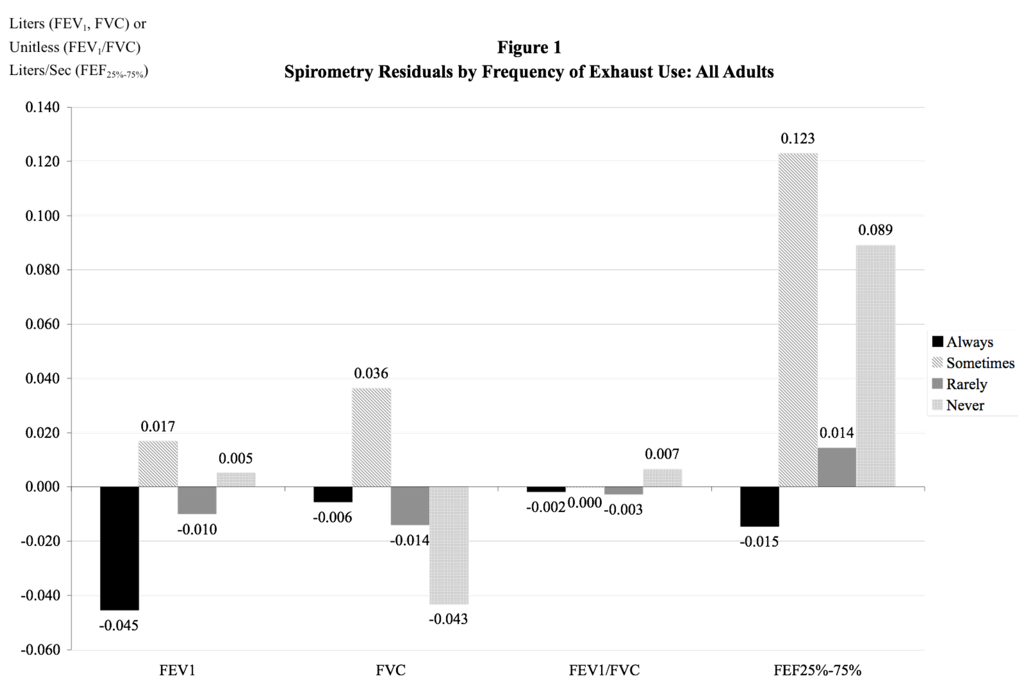

Figure 1
Spirometry Residuals by Frequency of Exhaust Use: All Adults

states have populations in excess of 500,000 people. Thus, any observation from these states in the NHANES III will not have location data associated with it.

Table 3 shows that the main difference between regions in terms of mean air exchange lies between the southern areas of the US and the rest of the country. In the warmest region, the mean annual air exchange rate is 0.69 h^{-1} compared to 0.43 or 0.44 for the rest of the country. This relatively small, coarse difference between two sub-samples does not yield much variation by itself, but it does help generate differences between homes when applied to the model of indoor air quality in Section II.

The implications of this model are drawn out in Table 4. For each region, I calculate the IAQ-adjusted gas stove indicator by vent hood use for homes with between 2 and 10 rooms. The calculations in this table show that differences between the regions are more important for smaller homes when individuals do not use ventilation. As the number of rooms increases, the model assumes that the volume of the home increases. The weight on the gas stove indicator therefore decreases to reflect the fact that the diffusion of NO_2 in a larger space will result in a lower indoor concentration. Likewise, if an individual reports that they always use the vent hood, the model assumes that for any given home size, the effective air exchange rate in the home increases when the stove is in use. The model reflects this increase by decreasing the IAQ-weighted gas indicator.

The economic model in Section II suggests that if individuals know cooking emissions may affect their health, exposure itself may be endogenous. This proposition cannot be completely explored because of insufficient data, but some analysis of the relationship between health and ventilation decisions is possible. Descriptive statistics for the sample reveal a small relationship between spirometry and vent use in the general sample. Figure 1 reports the means for each of the four spirometric residuals by self-reported vent use for the final sample. The differences Figure 1 point out are not large. In terms of normal predicted values for each of the outcomes, the mean differences represent deviations of approximately two percent from normal at most.

Differences are more pronounced, however, for asthmatics. Of the 22% of asthmatics in the sample who own both a gas stove and a ventilation hood, 88% report "always" or "sometimes" using their vent hood, while less than one percent "never" use it. Individuals who "always" use their vent have FEV_1 scores that are 83% of normal and $FEF_{25\%-75\%}$ scores that are 66% of normal on average. In comparison, asthmatics who "never" use their vent have significantly higher FEV_1 and $FEF_{25\%-75\%}$ scores: 89% and 74% on average, respectively. These findings give some credence to the theory that health status can influence individual actions, which can in turn influence the indoor environment. Based on these findings, I include asthma status as an independent variable in the first-stage equation in the IV models.

For instruments, the IV models in this paper use county-level housing stock data calculated from the sample. Table 5 summarizes the relationship between home age, the presence of a gas stove, and the presence of a vent hood. These statistics show that older

Table 5 Home Age and Gas Stove Use				
Era built	**Percent of sample individuals in homes this age**	**Use a Gas Stove**	**Use a Gas Stove and Have a Vent**	**Percent of Gas Stove Homes w/ a Vent**
pre-1946	23.46%	74.38%	30.94%	41.59%
1946-1973	44.23%	52.43%	31.98%	61.00%
1974-	26.02%	31.52%	23.43%	74.33%
Unknown	6.29%	54.71%	26.09%	47.69%

homes are more likely to have gas stoves than newer homes: 74% of homes built before 1946 have a gas stove, compared to to 32% of homes built after 1974. Newer homes with gas stoves, however, are more likely to have a vent hood: less than half of the homes with gas stoves built before 1946 have these devices, compared to almost three-quarters of such homes built after 1974. These tabulations suggest that, relative to homes built after 1974, homes built in the two earlier eras are more likely to both have a gas stove and *not* use a vent hood. In a first-stage analysis that uses the percentage of homes built before 1946 and built between 1946 and 1973 as instruments, it thus seems likely that both terms will be positive relative to the omitted category.

V. ANALYSIS

As described in Section III, I analyze a set of four models: a base model that uses a simple indicator for gas stoves, an IAQ-adjusted model that inversely weights the gas stove indicator by the number of rooms and an imputed air exchange rate, and IV specifications for both of these models. To maximize the number of observations available and maintain parsimony, I present a set of representative results based on regressions using the least restrictive set of independent variables. This set includes indicators for the presence of a smoker in the household, asthma status, month of test, and geographic region. In the three-stage least squares regressions, I regress the gas stove indicators against asthma status, the county-level percent of homes built before 1946, the county-level percent of homes built between 1946 and 1973, the county-level percent of homes with both a gas stove and a vent hood, geographic region indicators, and month of test. For each of these models, I bootstrap coefficient standard errors to account for clustering within households.

Table 6 presents the results of this analysis in terms of the estimated coefficients for the gas stove indicators. In addition to the coefficient estimate for each outcome in each model, I report the standard error of the estimate, the normal z-score, the normal probability associated with scores greater than the absolute value of z, and the 95 percent confidence interval associated with the coefficient. The results uniformly show no significant effect of gas stoves on any of the spirometry outcomes. I find similar results across other specifications: interactions of home age, sex, or asthma status with the gas stove indicators do not yield significant or substantial changes in coefficient values. The results are also robust to changes in the imputed air exchange rate; inclusion of education, income, or outdoor NO_2 data; or specifying outcomes in terms of percent deviations from predicted normal values rather than absolute deviations. Using first-stage models that include the four spirometric outcomes as independent variables or that do not include the regional and month indicators also produces similar results.

Table 6
Regression Results: Gas Stove Effects for Adults in NHANES III*

Model	Estimate	SE	z	P > |z|	Normal 95% CI	
Base						
FEV_1	-0.001	0.032	-0.050	0.964	-0.064	0.061
FVC	-0.054	0.030	-1.780	0.076	-0.113	0.006
FEV_1/FVC	0.003	0.004	0.770	0.444	-0.005	0.011
$FEF_{25\%-75\%}$	0.019	0.059	0.330	0.742	-0.097	0.136
IAQ-adjusted						
FEV_1	-0.002	0.041	-0.040	0.967	-0.082	0.079
FVC	-0.054	0.047	-1.170	0.243	-0.146	0.037
FEV_1/FVC	-0.004	0.008	-0.500	0.614	-0.019	0.011
$FEF_{25\%-75\%}$	-0.088	0.114	-0.770	0.438	-0.311	0.135
3SLS unadjusted						
FEV_1	0.054	0.081	0.670	0.506	-0.104	0.212
FVC	-0.015	0.083	-0.180	0.859	-0.176	0.147
FEV_1/FVC	-0.001	0.012	-0.070	0.942	-0.024	0.022
$FEF_{25\%-75\%}$	0.104	0.172	0.610	0.543	-0.232	0.441
3SLS, IAQ-adjusted						
FEV_1	0.010	0.139	0.070	0.940	-0.262	0.283
FVC	-0.190	0.150	-1.270	0.204	-0.484	0.103
FEV_1/FVC	0.003	0.004	0.670	0.504	-0.005	0.010
$FEF_{25\%-75\%}$	0.114	0.236	0.480	0.629	-0.348	0.577

*This table reports the coefficients and related statistics for the unadjusted and IAQ-adjusted gas stove coefficients and related statistics. Standard errors and confidence intervals are based on bootstrapping to account for clustering of observations within households. These regressions use absolute deviations from normal spirometry outcomes as dependent variables and do not include additional regressors such as individual education, family income, or outdoor NO_2 statistics. Similar results obtain for models that include these regressors and models that regress the independent variables on percent deviations from normal outcomes. Likewise, interacting data on home age or sex with the unadjusted and IAQ-adjusted gas stove terms does not produce any significant results.

The results for the base model compare well with Eisner and Blanc's (2003) findings. For a similar model estimated over a larger sample, Eisner and Blanc find no significant effects of gas stoves. For FEV_1, FVC, FEV_1/FVC, and $FEF_{25\%-75\%}$, they report coefficient estimates of 0.021, 0.008, 0.0052, and 0.086, respectively. These previous estimates are nearly spot-on with my results. All of them lie well within the 95 percent confidence interval for the base model estimated here.

The coefficients for the IAQ-adjusted model are uniformly negative in sign and look deceptively larger in absolute value than the coefficients of the base model. In fact, they indicate a slightly weaker effect on FEV_1 and FVC for individuals in most homes because the IAQ-adjusted indicator usually takes a value of less than one. After accounting for the fact that the mean value of the adjusted indicator is 0.36 (standard error: 8.07×10^{-5}) in homes with gas stoves, the central estimates of the coefficients in this model are not significantly different from the estimates in the unadjusted model.[19] In homes with few rooms or low air exchange rates, however, the adjusted indicator can be greater than 2.0. At the 95 percent confidence level, the largest potential negative impact on occupants of such homes nonetheless remains substantially less than a standard deviation of any of the outcomes.

The bottom-half of Table 6 shows the coefficient estimates for the IV models.[20] In both of these models, the estimated effects of gas stoves remain insignificant. The

[19] A mean adjusted indicator of 0.36 is approximately consistent with living in a six room home with the median national residential air exchange rate of 0.5.

[20] The R^2 statistics of these regressions do not suggest weak instrument issues (Staiger and Stock, 1997). The first-stage estimated equation for the unadjusted gas stove indicator has R^2 =0.23. The third stage

confidence intervals for these estimates are small. Comparing the lower limits of the 95 percent confidence intervals to the standard deviations of the spirometric outcomes in Table 2, the results for the unadjusted model suggest that the potential negative impact of a gas stove are on the order of one-third of a standard deviation of the outcomes or less.

Somewhat similar inferences can be drawn from the IAQ-adjusted model, but the interpretation of the effect of a gas stove in this model depends on the characteristics of the home and ventilation decisions. At the conditional mean of 0.36, the lower limit of the 95 percent CI implies that the negative impacts of a gas stove on health outcomes are again on the order of one-third of a standard deviation of the outcomes or less. Solving for the critical values where the IAQ indicator would imply a negative impact on respiratory health greater than one standard deviation of the outcome reveals that gas stoves pose are not likely to pose any risk to FEV_1/FVC or $FEF_{25\%-75\%}$. This level of damage would require the IAQ-adjusted indicator to take values outside the range shown in Table 4. For FEV_1 and FVC, however, these critical values are 1.9 and 1.1, respectively. For one and two room homes where ventilation is not used, the adjusted indicator does exceed these values. At the largest indicator values in the data (2.326), the central estimate of the effect of FVC implies a decrease of approximately 0.9 standard deviations as well. These results thus suggest that if NO_2 exposure does pose a risk,

estimates The percent of homes in the county built before 1946 and the percent of homes with gas stoves and vent hoods are both positive and significant at the 99.9% level. The remaining instrument, the percent of homes built between 1946 and 1973, is positive with a z-score of 1.92. For the IAQ-adjusted indicator, $R^2 = 0.17$ and the significance of the instruments follows the same pattern.

individuals living in very small homes without adequate ventilation are more likely to be affected than others.

VI. CONCLUSIONS

The results of this paper show that NO_2 from gas stoves is unlikely to pose a risk to health in typical residential environments. Central estimates of the effect of gas stoves are not significantly different from zero for any of the outcomes I examine. The lower limits of the confidence intervals for these estimates suggest that gas stoves have only small impacts on respiratory health in typical homes. This result is robust across all four models I consider in this paper and across several specifications of these models. Results from the final model indicate that occupants of small homes (two rooms or less) where kitchen ventilation is not used may be at some risk. Gas stoves may have more of an impact in these settings because NO_2 will build up faster and dissipate more slowly in smaller homes with lower air exchange rates. Future research on the effects of indoor NO_2 might therefore target occupants of small, energy-efficient dwellings as a population of interest.

Since gas stoves do not seem to pose a significant risk to health in typical residential settings, the findings here do not support any policy actions aimed at the existing housing stock. Indeed, standard economic theory argues against such policy generally insofar as individuals are well-informed of the potential risks of NO_2 exposure and the costs of avoiding it. But to the extent that housing or other related goods are publicly provided, policymakers might consider that increases in home energy efficiency may lead to increased risks of gas stove use. Energy efficiency is often improved by reducing a home's air exchange rate. Lower air exchange rates, however, imply NO_2 from a gas stove will reach higher peak concentrations and remain in the home's air for a longer time.

The coarse IAQ-adjusted stove indicator developed in this paper suggests that occupants of a four room home with a gas stove may face risks to their health from exposure to NO_2 when air exchange rates of $0.2hr^{-1}$ or less, which are not atypical for energy-efficient homes. The adjusted indicator reaches a level of 1.25 or greater in such homes, which exceeds the critical value calculated for a gas stove to imply a negative impact greater than one standard deviation of FVC at the lower limit of the 95 percent confidence interval. Thus, increases in home energy efficiency may lead to increased health risks from indoor NO_2 .

If the expected marginal benefits outweigh the marginal costs, providers of public housing with gas stoves may mitigate this risk by either designing adequate natural ventilation into the structure or by simply including a vent hood and providing occupants with information about its benefits. By the same token, public initiatives that encourage or subsidize increased energy efficiency might improve welfare by providing individuals with information about the potential risks of NO_2 exposure, why those risks increase with energy efficiency, and what steps they can take to reduce risk if they so choose. Indoor air quality policies that complement existing policies in the housing market make sense from an economic standpoint because they reduce the chances that a publicly provided good imposes inadvertent costs on society.

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CHAPTER 3: THE IMPACT OF SMOKING BANS ON BIRTH WEIGHT: IS LESS MORE?

Abstract: I combine data on state and local tobacco control ordinances from Americans for Non-smokers Rights Tobacco US Tobacco Control Laws Database with a sample of 35 million births from national natality data files to examine the impact of smoking bans on birth weight, the probability of low birth weight, and weeks of gestation. Using difference-in-difference techniques, I identify the effects of state bans net of local bans, as well as the effects of local bans net of state bans. If ban choice is endogenous, then these effects will be biased in opposite directions. Estimated effects may therefore be viewed as lower bounds of central estimates for state ban effects, or upper bounds of central estimates for local ban effects. Applying this logic to the analysis of results suggests that less restrictive bans do more to improve birth outcomes than "100% smokefree" bans do, particularly in urban settings.

JEL Codes: I18, Q53

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Forty-eight states and 2,960 cities and counties in the US currently enforce one or more forms of no-smoking ordinances, usually termed "smoking bans." Smoking bans aim to protect public health from environmental tobacco smoke (ETS) by restricting or eliminating the right to smoking in public or semi-public venues. The direct health benefits of smoking bans, however, remain poorly understood. Contrary to popular belief, smoking bans may not uniformly benefit public health.

A handful of studies analyze the effects of smoking bans on the incidence of acute myocardial infarctions (AMI) in specific counties or municipalities. Overall, these studies find support for the hypothesis that smoking bans decrease the risk of AMI but cannot separate the effects of bans on smokers versus non-smokers, nor track effects over a constant population (Meyer and Neuberger 2008). Markowitz (2008) improves over these studies by using individual-level data to examine the effect of bans on Sudden Infant Death Syndrome (SIDS), but this study finds only mixed support for the hypothesis that smoking bans reduce SIDS cases. Likewise, Adda and Cornaglia (2006) examine individual non-smoker exposure to ETS, as measured by blood sera cotinine, and find that bans have no effect on average cotinine levels in the US. The authors suggest that this zero-net effect occurs because bans shift smoking into private environments where non-smoking family members are still exposed.[21]

[21] Adda and Cornaglia's result raises the question of whether secondhand or "third hand" smoke drives the observed exposure to nicotine because the chemical profile of these two sources of nicotine are different. Secondhand smoke contains hundreds of volatile organic compounds (VOCs) and high concentrations of particulate matter at elevated temperatures. Third hand smoke, which arises from the desorption of cigarette tar from indoor surfaces, contains many of the same VOCs at room temperature and very little of the particulate matter. Both are dangerous to health, but because of the presence of PM in secondhand

The purpose of this paper is to investigate separately the impact of state and local smoking bans on birth weight and related outcomes. According to the US Surgeon General, ETS exposure increases the risk of low birth weight (defined as less than 2500 g or 5.5 pounds) and "represents an avoidable contribution to birth weight reductions" (US Department of Health and Human Services, 2006).[22] Lower birth weight possibly occurs in part because ETS may cause children to be born earlier than they otherwise would, but evidence from the Surgeon General considers evidence on this link only "suggestive" at this point (*ibid*). In turn, birth weight significantly affects the probability of infant death and a variety of individual outcomes later in life.[23] Any increases in mean birth weight due to smoking bans may therefore be viewed as a direct benefit of the ban.

Beyond its first-order implications, birth weight also provides an interesting, continuous measure of the effects of environment on human health, both because of the relatively short period of fetal gestation and because of the likelihood of increased risk aversion during pregnancy. Although mothers are mobile over their lives and may in fact choose where to live or work based on local amenities like smoking bans, nine months is a relatively small interval in their lifetime. Thus, individuals observed in the data as living in a given location are likely to have spent their pregnancy in that location.

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smoke, secondhand smoke is more likely to cause damage to the lungs in the near term. See Singer *et al.* (2003) for an investigation of the contribution of third hand smoke to exposure profiles.

[22] The meta-analysis of Windham *et al.* (1999), which contributes to the Surgeon General's finding, estimates a mean reduction of 28 g (about 1 ounce) in birth weight due to ETS exposure. In an updated meta-analysis over a larger set of studies, Leonardi-Bee *et al.* (2008) estimate a mean decrease of 33 g in birth weight due to ETS exposure, a figure similar in magnitude albeit somewhat larger. Both studies estimate that maternal exposure to ETS increases the risk of low birth weight by about 20%.

[23] See Royer (2009); Almond, Chay, and Lee (2007); or Black, Devereux, and Salvanes (2007) for the most recent work in the area.

Research can thus reasonably connect the policies of an individual's location to their infant's birth outcomes.

Further, to the extent that pregnancy increases a woman's aversion to environmental risks, the measured effects of environmental variables on fetuses will be biased downwards. If pregnant women do not spend a lot of time in bars, for instance, bans on smoking in bars may have little effect on their infant's birth weight. Labor supply decisions may have a similar impact on the estimated effects of workplace bans on birth outcomes: if women decrease their labor supply during pregnancy, work-place smoking bans may have a less pronounced effect on their infant's birth outcomes.

On the other hand, it may be the case that bans reduce the health costs of some behaviors, such as working or spending time in bars, which in turn negatively affect birth outcomes. While work does not appear to negatively affect birth outcomes (Baum, 2005), increased time in bars may reduce birth weight if it is positively correlated with alcohol consumption. Smoking bans may also negatively affect birth outcomes by crowding more smoking into private environments. For pregnant women who live or socialize with smokers, a ban on smoking in any kind of public or semi-public space may lead their partner or friends to smoke more in shared private environments. In the reduced-form analysis I present here, I cannot separately identify the contributions of these factors to the estimated effects. Instead, I aim simply to estimate a lower bound for the effect of state-level smoking bans by differencing between infants who were covered by local smoking bans while *in utero* and those who were not.

City and county governments have a longer history of smoking bans than states do, beginning in 1974 in Sacramento County, California. Before state-level bans, local bans covered highly populated areas such as Los Angeles County and New York City, which began restricting smoking in 1985 and 1988 respectively. In contrast, statewide bans begin in 1979 (Nebraska) with the bulk occurring after the EPA declared ETS a Class A carcinogen in 1993. Thus, if state smoking bans have a true positive effect on a given outcome, then estimations of their effect derived from analyses that do not account for the local bans may be biased downward. In essence, the impact of local bans may dilute the measured effect of state bans.

At the same time, the presence of a ban at either the state or local level indicates that the median voter in that jurisdiction prefers a ban. If stronger preferences for smoking bans correlate with relatively stronger preferences for health goods in general, the measured effect of smoking bans on health outcomes will be biased upward. A simple story for this endogeneity problem is that the people who vote for a smoking ban may be the same health conscious people who consider the impact of their activities and environments on their unborn child's health. Thus, observed birth weights in jurisdictions with smoking bans may be higher because people in those areas do more in general to promote healthy birth weight.

The ideal instrument for this problem would identify individuals with a taste for health goods independently of people who live in an area subject to a smoking ban. In this paper, I settle for a second-best: I eschew precise estimation of local smoking bans for a conservative estimate of state-level bans by using the presence of a local ban to identify observations in my data who may be more likely to have a relatively stronger preferences for health goods. If local bans correlate better with individual preferences than state bans, then the effects of statewide bans on jurisdictions that did not put a local ban in place will be underestimated.

This paper thus contributes to the research on the effects of state-level smoking bans by providing estimates of their impact that accounts for both the dilution of state ban effects and the endogeneity of ban choice. To obtain these estimates, I connect birth weight data from the National Vital Statistics System (NCHS, 1989-2004) to state and local policy data compiled by Americans for Non-smokers Rights (ANR, 2008), controlling for differences in cigarette prices across states and years using standard data from Orzechowski and Walker (2007). I then use difference-in-difference techniques within local-level fixed effects models to measure the impact of state-level bans on populations that did not previously have a local ban in place.

If people choose where to live based on preferences for health-related goods, and smoking bans reveal local preferences for those goods, then estimates of the effects of state-level smoking on locations that did not previously ban smoking will be biased downwards. At the same time, estimates of the effects of local bans in jurisdictions not covered by state bans will be biased upwards. Thus, the estimates reported here may be viewed as lower bounds for the effects of state bans and upper bounds for the effects of local bans. To the extent that local and state bans are comparable, both estimates taken together may inform policymakers about the consequences of smoking bans in general.

Using this approach, I estimate the impact of bans on birth weight and the probability of low birth weight. I also analyze their effect on weeks of gestation. Exposure to ETS has known negative effects on the first two outcomes, but the link between ETS and weeks of gestation is less well established. I therefore consider the analysis of the impact of smoking bans on gestation as a contribution to the exploration of this link. For each of these outcomes, I estimate the effects of smoking bans using two samples: one with 34.8 million births linked to county and state policy, and a sub-sample of 9.8 million births linked to the municipal level as well.

I estimate two sets of models for each sample, using one of two distinct sets of policy controls to account for smoking bans. The data on bans identify the type of venues the ban covers (workplaces, restaurants, or bars), the level of government responsible for the ban, and ANR's rating of the ban's strength. Strength ratings fall into three categories: "100% smokefree", "qualified", or "some coverage". Bans that are "100% smokefree" essentially prohibit smoking with almost no exceptions, "qualified" bans allow for smoking in separately ventilated spaces, and bans that provide "some coverage" restrict smoking in a way that does not meet the standard of "qualified. In the first set of models, I simply use indicator variables to control for the presence of the various types of smoking bans at the time of birth.

In the second model, each policy control counts the number of months that a fetus was covered by various types of smoking bans while *in utero*. This continuous set of control variables provides a more precise measure of policy coverage than the indicators used in the first set of models and in prior studies and therefore a better way to test ban effectiveness. While I prefer this set of controls, it has at least one limitation: its semi-functional dependency on weeks of gestation makes it ill suited to analyze the impact of bans on gestation itself. Thus, for weeks of gestation, I report results only for models that use indicator variables to control for smoking bans.

Estimates of the impact of smoking bans using the county-within-state policy sample show that strong state level bans covering restaurants have positive and significant effects on infant birth weight across both models, although "100% smokefree" bans may not outperform slightly weaker bans, which appear to increase birth weight by at least 4.4 g *for every month covered while in utero* in this sample. Only the weakest workplace bans show positive and significant impacts on birth weight and reduced chances of low birth weight, and these effects are somewhat small: an increase of approximately 0.8 g in birth weight and approximately an 0.1% point reduction in the probability of low birth weight for every month covered. None of the estimates of the effects of county level bans on birth weight or the probability of low birth weight contravene these results. Bar bans have little significant impact relevant to this analysis, and gestation does appear to be significantly and positively related to smoking bans in this sample.

The municipality-within-county-within-state sample affords a better-specified model, but uses a smaller number of observations drawn from more urban environments. In this sample, weaker workplace and restaurant bans imposed by states appear to significantly improve birth outcomes in the policy month control models, increasing birth weight by at least 3.5 g and 14.5 g for every month of coverage, respectively. On the other hand, the estimated effects at the local level in this model suggest that "100% smokefree" bans may worsen birth outcomes. In both the indicator and policy month models, "100% smokefree" bans are associated with significant *decreases* in birth weight and increases in the probability of low birth weight. Under the assumption of endogeneity, these are upper bounds for the effects of 100% bans, which would suggest that their true impact is more negative. Bar bans again have little relevant impact, and gestation does not appear to be as tightly linked to policy in this sample.

Overall, these results suggest that bans that are less than "100% smokefree" may do a better job at improving birth outcomes. This finding has at least two implications. First, the impact of bans likely differs between urban and non-urban settings. Significant problems with "100% smokefree" bans only appear in the more urban sub-sample. State-level policy may therefore do more to improve public health by imposing less restrictive smoking bans and allowing communities to self-determine stricter "100% smokefree" coverage. Second, less may be more for smoking bans because prohibiting smoking in public places entirely shifts more smoking into private spaces where non-smokers are exposed. Given that people are going to smoke, public health might be improved by providing designated space for smokers where no non-smokers will be exposed to their emissions rather than prohibiting smoking entirely.

I proceed to show these results in five sections. In the first section, I describe the research design of the paper in more detail and provide the econometric framework for my analysis. Information on the natality and smoking policy data that I use appear in Section II. I report descriptive statistics for the sample I analyze in Section III. In Section IV, I present and discuss the results of the regression analyses, focusing on the estimates of the policy control variables by model and outcome. I conclude the paper by summarizing my results, considering their limitations, and offering questions for further research.

I. Research Design and Econometric Methods

In this paper, I use a reduced-form, difference-in-difference approach to identify the treatment effect of state level smoking bans on birth outcomes. Riechman *et al*. (2006) investigate the use of reduced-form analyses of infant birth weight and consider how estimations of effects might be affected by typically-unobserved-but-theoretically-important variables (TUV), other non-standard covariates (NSC), and input reporting. While the authors find that self-reporting of some inputs—like tobacco use—can lead to overestimates of their effects and that both TUV and NSC have significant effects on birth outcomes, they conclude that neither the use of self-reported variables nor the exclusion of TUVs or NSCs appreciably affects other input estimates. In the context of this paper, if the presence of a smoking ban results in increased under-reporting of tobacco use, the estimated effect of the smoking ban would be biased downwards. The reduced-form approach is thus in keeping with the aim to provide a conservative estimate of the effects of bans.

To investigate the effect of smoking bans on birth outcomes, I estimate a set of regressions based on the following fixed-effects model:

$$y_{icst} = \gamma_1 b_{st} + \gamma_2 b_{ct} + \gamma_3 b_{st} b_{ct} + \gamma_4 P_{st} + \beta_1 X_i + \alpha_c + \varepsilon_{ist} \quad . \tag{27}$$

In equation (27), y_{ilst} denotes the birth outcome of individual i whose mother resides in location l within state s at the time of birth t, b_{st} denotes a vector of state- and time-varying policy controls, b_{ct} is a vector of county- and time-varying controls, P_{st} is the average real price of cigarettes in state s and time t, X_i is a vector of maternal, infant, and birth characteristics, α_c is a time-invariant fixed effect for county c, and ε_{ist} is a mean zero random error. The vector $b_{st}b_{ct}$ captures the values of state and county policy controls when both state and local policy are controls non-zero, taking on the value (b_{st}, b_{lt}). The vectors of parameters γ_1-γ_4 and β_1 are to be estimated. I use ordinary least squares (OLS) to estimate the model.

Since the vector $b_{st}b_{ct}$ takes on the values of both state and county bans when both are present, the vector of parameters γ_1 represents the effects of state bans on individuals in counties where no county ban is in place. Likewise, γ_2 represents the effects of county level bans on individuals living in counties that have ban within a state that does not. Thus, the presence of a county level ban does not dilute the estimate of the effect of state bans given by γ_1. Further, if the presence of county bans indicates relatively stronger individual preferences for health related goods, γ_2 is biased upwards and γ_1 is biased downwards. In this case, γ_1 represents a set of lower bound estimates for the effects of state bans.

I extend this approach to the municipal level where data is available by using the following model:

$$(28)\quad y_{iscmt} = \gamma_1 b_{st} + \gamma_2 b_{ct} + \gamma_3 b_{mt} + \gamma_4 b_{st} b_{ct} + \gamma_5 b_{ct} b_{mt} + \gamma_6 b_{st} b_{mt} + \gamma_7 b_{st} b_{ct} b_{mt} + \gamma_8 P_{st} + \beta_1 X_i + \alpha_m + \varepsilon_{isct}\,.$$

The definitions of the data and parameter variables in (28) are similar to the model described by (27) with some additions. I use the subscript m to denote variables that depend on municipal characteristics. In particular, the vector b_{mt} represents bans present in municipality m at time t and the fixed effects α_m are set at the municipal level. As in (27), this model uses interaction terms to capture when an observation in the data is simultaneously covered by policy at any combination of the state, county, or municipal levels. Specifically, the vector $b_{st}b_{ct}$ gets the values (b_{st}, b_{ct}) when both state and county policy are present $b_{ct}b_{mt}$ takes the value (b_{ct}, b_{mt}) when both county and municipal policy are present, $b_{st}b_{mt}$ takes the value (b_{st}, b_{mt}) when both state and municipal policy are present, and $b_{st}b_{ct}b_{mt}$ takes the value (b_{st}, b_{ct}, b_{mt}) when an observation is covered by policy at all three levels. I again use OLS to estimate the model parameters.

Model (28) has both advantages and disadvantages relative to model (27). As in the first model, the interaction terms imply that the vector of parameters γ_1 represents the effects of state bans on birth outcomes for infants not covered by county or local policy. Thus, the estimate γ_1 represents the undiluted effect of state bans. Likewise, γ_1 is again biased downwards if the presence of county or municipal bans indicates relatively stronger individual preferences for health related goods. The second model does a better job than the first, however, in controlling for dilution of state policy by local policy and in controlling for idiosyncratic local effects that may be correlated with outcomes. On the other hand, because the data requirements for the second model constrain the sample, the analysis may be less broadly applicable. I turn to this and other issues in the next section.

II. DATA

For this paper, I integrate data on smoking bans, cigarette prices, and births. In this section, I report on the granularity of each data set, the length of time that it covers, the time intervals of observations, and any limiting factors that lead to notable lacunae in the samples I use in my analyses. After describing each data set in turn, I discuss the samples of interest and how I construct the policy control variables for analysis.

Smoking Bans

State and Local tobacco control ordinance data were provided by the American Nonsmoker's Rights (ANR) Foundation U.S. Tobacco Control Laws Database© (2008).[24] This database provides information on smoking bans put into effect at the state, county, and municipal levels of government. At the county level, the data set provides information on whether the ban covers incorporated areas as well as unincorporated areas in the county. For each ban, the database reports what type of venue it covers (workplaces, restaurants, or bars), the effective date for the ban by venue; the state, county, or place FIPS code that the ban covers; and the "strength" of the ban coverage. The three characterizations of ban strength are defined by ANR (2008) as follows:

> ***Workplaces***
>
> 100% Smokefree: All workplaces must be completely smokefree, with some minor exceptions: A) Workplaces with only one employee are exempt. B) Family-owned businesses and businesses run by self-employed persons, in which all the employees are related to the owner or the self-employed person and which are not open to the public are exempt. C) With respect to public workplaces, jails or interrogation rooms are exempt.
>
> Qualified: Workplaces must be smokefree with two possible general exceptions: A) Workplaces with a specified number of employees or fewer (but more than one employee) are exempt. If the

[24] Abstracts based on this data are available online at ANR's website, www.no-smoke.org.

exemption in a law is for one employee only (whether or not the employer), this field will be marked "Yes." B) Smoking is permitted in enclosed, separately ventilated smoking rooms.

Some Coverage: There is some coverage for workplaces, but less than either of the above two categories.

Restaurants

100% Smokefree: All restaurants, including attached bars, must be completely smokefree, *without exception*. If, *by law*, there are no bars in the community, this field will be marked "Yes" even though the law does not specifically address attached bars.

Qualified: Restaurants must be smokefree with three possible exceptions: A) Smoking is permitted in enclosed, separately ventilated dining rooms. B) Restaurants with a specified number of seats or fewer. C) Smoking is permitted in attached bars that are separately ventilated.

Some Coverage: There is some coverage for restaurants, but less than either of the above two categories.

Bars

100% Smokefree: All freestanding bars must be completely smokefree, *without exception.*

Qualified: Freestanding bars must be smokefree with one possible exception: Smoking is permitted in enclosed, separately ventilated rooms.

Some Coverage: There is some coverage for bars, but less than either of the above two categories.

The data also provide information on when a ban was weakened, partially repealed, or repealed. In total, the ANR U.S. Tobacco Control Laws Database represents a historical record of tobacco ordinances in the US from 1974 to present. To my knowledge, no key observations are missing from this data. With respect to data on smoking bans, this data set is ideal for addressing the research question in this paper.

Cigarette Prices

To account for variation in the after-tax price of cigarette, I use data from the annual *Tax Burden on Tobacco* (Orzechowski and Walker, 2007). This data set gives average after-tax prices for a pack of 20 cigarettes by state and year, from 1970 to present. I deflate these prices using the US Bureau of Labor Statistics National Consumer Price

Index (1982–1984 = 100). While these data provide some control for variation in cigarette prices, they fall short of ideal data in that they do not account for variation within states or within years. To my knowledge, however, this is the best available national data series on cigarette prices. I link these data to births by year and state.

Birth data

The US National Center for Health Statistics provides data on all births in the US in each month from 1968 to present. Variables that connect mothers to their place of residence by FIPS county codes first appear in the national birth data in 1982. To protect privacy, these data are only available for births to mothers living in counties with 100,000 or more people. Data that connect births to municipal place of residence by FIPS codes are available from 1994 forward. As with counties, this information is also restricted to births to mothers living in cities with greater than 100,000 people as of the most recent census. Beginning in 2005, the natality files no longer contain location in publicly available data above the state level due to privacy concerns.

The birth data include a wide variety of maternal and infant controls. I use a small set of these in this study. The controls I use include mother's age, race/ethnicity, education, marital status, total number of prior live births, self-reported smoking during pregnancy, infant's sex, weeks of gestation, and plurality of birth (singleton, twin, etc). Self-reported risk factors, including maternal tobacco use, are first reported in the data beginning in 1989. These factors directly affect birth weight and are likely affected by tobacco policy.[25] Maternal tobacco use is not reported for births occurring in California. Before 1999, maternal tobacco use was also not reported for the states of Indiana; the state of New York, excluding of New York City; and South Dakota.[26]

Samples of interest and ban controls

These data constraints suggest two samples of interest. The larger, primary sample uses data from 1989 to 2004, when county location and the full set of appropriate controls are available. Analyses of this sample can provide estimates of the effects of statewide smoking bans on counties that do not have bans in place. Because of a lack of data, births to mothers living in counties of less than 100,000 cannot be connected to policy and therefore are not included in the sample. Interpretation of the results thus may not extend to more rural counties. Indeed, it is plausible that smoking bans may have less impact on more rural counties because rural counties tend to be less densely populated. Estimated effects based on this sample can therefore be interpreted as the effect of a statewide smoking ban on birth outcomes for people living in a county of population 100,000 or more that did not previously have a ban in place.

Estimated effects based on the primary sample do not account for dilution of effects due to municipal smoking bans. The ideal data set would thus control for municipal policy as well. I construct a sub-sample of observations from the birth data that meet this requirement for a supplementary analysis. This sub-sample runs from 1994 to 2004 and

[25] See for example Evans *et al*. (1999).

[26] New York City, however, reports maternal tobacco use from 1989 forward.

contains data on all births in the US in municipalities with populations greater than 100,000. The greater population density of these areas suggests that results from these analyses apply only to larger cities. The results from analyses on this sample can be interpreted as the effects of state-level bans on births to people living in cities of greater than 100,000 people that did not previously have a ban in place.

For observations in each of these two samples, I construct two sets of controls for smoking bans. Each set of controls identifies smoking bans that cover the mother's area of residence by the level of government responsible for the ban, the type of place it covers, and the strength of the bans. The first set of controls are simple indicator variables which take a value of one if the area of residence was covered by the ban it represents during the year and month of the infant's birth. Because similar controls appear in other smoking ban studies, the results I offer based on can be compared to findings in other research.

The data, however, allow for a more precise measurement of policy coverage. I construct a second set of controls that count the number of months that the infant was covered by a ban during its gestation. I calculate the number of months of ban coverage based on the ban's effective date, the infant's total number of weeks of gestation at the time of birth, and the month and year of birth.[27] For example, if a smoking ban were passed in January and the infant were born in March, then the infant would have been covered by the ban for two months while *in utero*. Because this measure relies in part on

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[27] Because only the month and year of birth are reported, I convert weeks of gestation to months by using an average of $365.25/12*7 \approx 4.35$ weeks per month.

weeks of gestation, however, it cannot be used to analyze the impacts of ban coverage on weeks of gestation itself.

III. DESCRIPTIVE STATISTICS

In this section, I present descriptive statistics for the samples of interest to provide adequate background for the interpretation of regression analyses in the next section. I focus on the basic means and standard deviations of the maternal and infant birth controls for the two samples of interest. I also provide some basic tabulations of the policy control variables. For the price data, I only report overall mean and standard deviations for observations within the sample—see Orzechowski and Walker (2007) for further information on these data.

Table 7 presents sample means and standard deviations of outcomes and select controls for the county-within-state sample. This sample contains 34.8 million of the 64.3 million births that occurred from January 1989 through December 2004. Observations within the sample come from 530 different counties spread across every state in the US except Wyoming. Because California does not report maternal tobacco use, only a scant 6,000 births in this data are to California residents. The summary statistics reflect the fact that the births within this sample are drawn from more urban settings, where the percentages of minority populations are relatively higher. The percentage of self-reported smokers in this sample appears to underestimate the true percentage of smokers: 12% of mothers report smoking at some time during their

Table 7
Summary Statistics: County-within-State Sample
N=34817843

	Mean	*Std. Dev.*
Birth Weight (g)	3311.14	608.32
Percent with low birth weight	0.08	0.27
Infant controls		
Weeks of Gestation	38.84	2.63
Plural birth	0.03	0.17
Female	0.49	0.50
Maternal controls		
Smoked during pregnancy	0.12	0.33
Age	27.25	6.08
Number of prior living births	2.03	1.22
Years of education	12.94	2.72
Married	0.68	0.47
Hispanic	0.16	0.37
White, non-Hispanic	0.60	0.49
Black, non-Hispanic	0.19	0.39
Other	0.05	0.22
Price and policy controls		
Real price of cigarettes (pack of 20), 1982-84 = 100	1.56	0.45
Covered by at least one county smoking ban	0.26	0.44
Covered by at least one state smoking ban	0.23	0.42

pregnancy, while national estimates suggest that the true figure is closer to 19% (SAMSHA, 2000). Twenty-six percent of births in this sample were to mothers who lived in an area covered by at least one smoking ban, and 23% were covered by at least one state ban.

Similar sample characteristics appear in the summary statistics of the municipality-within-county-within-state sub-sample shown in Table 8. This sub-sample contains data on 9.8 million births that occurred from 1994-2004. Observations come from 235

Table 8
Summary Statistics: Municipality-within-County-within-State Sub-sample
N=9781176

	Mean	***Std. Dev.***
Birth Weight (g)	3254.2741	615.4404
Percent with low birth weight	0.09	0.28
Infant controls		
Weeks of Gestation	-1.32	2.74
Plural birth	0.03	0.17
Female	0.49	0.50
Maternal controls		
Smoked during pregnancy	0.10	0.30
Age	26.55	6.23
Number of prior living births	2.08	1.31
Years of education	12.46	2.86
Married	0.56	0.50
Hispanic	0.27	0.44
White, non-Hispanic	0.39	0.49
Black, non-Hispanic	0.28	0.45
Other	0.06	0.24
Price and policy controls		
Real price of cigarettes (pack of 20), 1982-84 = 100	1.74	0.50
Covered by at least one municipal ban	0.69	0.46
Covered by at least one county smoking ban	0.33	0.47
Covered by at least one state smoking ban	0.18	0.39

different municipalities within 201 different counties across 44 states.[28] Relative to the larger sample, mothers in the sub-sample tend to be slightly younger, slightly less educated, and much more likely to be minority. A large share of the births in this sample—69%—belongs to mothers who live in areas covered by a municipal smoking ban. Thirty-three percent are covered by a county ban, and only 18% are covered by state bans.

[28] Delaware, Maine, Montana, North Dakota, Vermont, West Virginia, and Wyoming are not represented.

Table 9
Summary Statistics for Policy Controls: County-within-State Sample

	Ban type	***Indicators*** Mean	Std. Dev.	***Policy Months*** Mean	Std. Dev.
State	**Workplaces**				
	Some Coverage	0.189	0.391	1.646	3.453
	Qualified	0.004	0.066	0.033	0.522
	100% Smokefree	0.009	0.096	0.051	0.593
	Restaurants				
	Some Coverage	0.128	0.334	1.122	2.957
	Qualified	0.0004	0.021	0.004	0.186
	100% Smokefree	0.021	0.144	0.149	1.089
	Bars				
	Some Coverage	0.008	0.090	0.070	0.786
	Qualified	*NA*			
	100% Smokefree	0.007	0.086	0.045	0.580
County	**Workplaces**				
	Some Coverage	0.233	0.423	2.039	3.738
	Qualified	0.006	0.079	0.053	0.682
	100% Smokefree	0.004	0.066	0.031	0.499
	Restaurants				
	Some Coverage	0.089	0.285	0.789	2.533
	Qualified	0.012	0.107	0.098	0.925
	100% Smokefree	0.005	0.072	0.038	0.556
	Bars				
	Some Coverage	0.008	0.090	0.072	0.797
	Qualified	*NA*			
	100% Smokefree	0.005	0.068	0.035	0.532

Table 10
Summary Statistics for Policy Controls:
Municipality-within-County-within-State Sub-sample

	Ban type	***Indicators*** Mean	Std. Dev.	***Policy Months*** Mean	Std. Dev.
State	**Workplaces**				
	Some Coverage	0.153	0.360	1.342	3.184
	Qualified	0.005	0.071	0.039	0.569
	100% Smokefree	0.006	0.080	0.031	0.443
	Restaurants				
	Some Coverage	0.093	0.290	0.819	2.577
	Qualified	*NA*			
	100% Smokefree	0.015	0.120	0.098	0.878
	Bars				
	Some Coverage	0.014	0.119	0.125	1.045
	Qualified	*NA*			
	100% Smokefree	0.003	0.059	0.020	0.373
Municipal	**Workplaces**				
	Some Coverage	0.601	0.490	5.335	4.381
	Qualified	0.014	0.118	0.117	1.005
	100% Smokefree	0.017	0.131	0.128	1.022
	Restaurants				
	Some Coverage	0.533	0.499	4.729	4.460
	Qualified	0.030	0.170	0.242	1.424
	100% Smokefree	0.013	0.115	0.095	0.874
	Bars				
	Some Coverage	0.041	0.199	0.346	1.707
	Qualified	0.001	0.024	0.003	0.142
	100% Smokefree	0.008	0.090	0.057	0.677

Tables 9 and 10 contain descriptive statistics for the policy control variables I analyze. For each ban type, I report the mean and standard deviations for the policy indicator and months of coverage variables. For the county-within-state sample, these statistics appear in Table 9. Table 10 reports this summary for the municipality-within-county-within state sub-sample. These means reveal that bans offering "some coverage" are the most common for observations in these samples. Bans rated "qualified" or "100% smokefree" cover relatively few infants born in these samples from a proportional perspective, but the raw numbers covered are still large. For example, in the main sample over 200,000 births are covered by "qualified" workplace bans and more than 150,00 are covered by "100% smokefree" bans. Similar calculations show that bar bans, while relatively uncommon, nonetheless covered hundreds of thousands of births. "Qualified" bans covering bars are completely absent from both samples, and "qualified" restaurant bans at the state level are absent in the sub-sample. Last, policy month variables are not simply equal to nine times indicator variables, due to variation in weeks of gestation and bans taking effect in the middle of some pregnancies.

IV. Regression Analyses

In this section, I report the parameter estimates and standard errors for policy control variables using the county-within-state sample. I also report the effects of price on outcomes in each model, but the effects of price are likely attenuated because of the lack of variation in tobacco prices within years and within states. I briefly discuss the precise implementations of my models and the general interpretation of estimates for this analysis before reporting results.

For both the county-within-state sample and the municipality-within-county-within-state sub-sample, I separately regress birth weight, probability of low birth weight, and weeks of gestation against the policy control variables at both the state and county level as well as a set of interactions as described in Section I. I report these results in Tables 11 and 12, respectively. The first three columns in each table represent estimates of ban impacts based on indicator control variables. The last two columns represent estimates based on policy month controls.

I do not report estimates of the impact of policy month controls on weeks of gestation. Other control variables not reported include the maternal and infant characteristics tabulated in Section III, as well as sets of dummy variables for each year (2004 omitted), a separate set of dummies for each month (January omitted), and a set of county-level fixed effects. I do not include weeks of gestation as an explanatory variable in models where it is a dependent variable. County policy effects are estimated in the models for the municipality-within-county-within-state sample, but I do not report them because they lack clear interpretation in this context. Each model is estimated via ordinary least squares, with linear probability models used for the probability of low birth weight.

The estimates in the upper-half of Tables 11 and 12 represent the effects of state-level smoking bans on birth outcomes to mothers living in areas with no local ban coverage in place. Under the assumption of endogeneity, estimates in this half of the table are biased downwards and estimates in the lower half are biased upwards. Estimated negative effects of state policy controls on birth weight or weeks of gestation, as well as positive

Table 11
Effects of Smoking Bans on Birth Outcomes: County-within-State Sample

	Indicator Controls			*Policy Month Controls*	
Policy Controls	**Birth Weight (g)**	**Low Birth Weight (*P*)**	**Gestation (weeks)**	**Birth Weight (g)**	**Low Birth Weight (*P*)**
State Bans					
Workplaces					
Some Coverage	-1.105	-0.001 **	-0.018 **	0.802 ***	-0.001 ***
	(0.761)	(0.0004)	(0.004)	(0.085)	(0.0000)
Qualified	-9.375 **	0.001	0.044 **	-0.542	0.000
	(2.875)	(0.0013)	(0.015)	(0.389)	(0.0002)
100% Smokefree	-13.093 ***	0.000	0.032 **	-1.182 **	0.000
	(2.056)	(0.0010)	(0.011)	(0.367)	(0.0002)
Restaurants					
Some Coverage	-23.027 ***	0.003 ***	-0.020 **	-1.578 ***	0.000 ***
	(1.262)	(0.0006)	(0.007)	(0.130)	(0.0001)
Qualified	35.192 ***	0.003	0.079 **	4.435 ***	0.000
	(5.770)	(0.0027)	(0.031)	(0.646)	(0.0003)
100% Smokefree	5.613 ***	0.001	-0.011	0.473 **	0.000 *
	(1.513)	(0.0007)	(0.008)	(0.174)	(0.0001)
Bars					
Some Coverage	3.275	-0.002	-0.095 ***	0.187	-0.001 ***
	(3.565)	(0.0017)	(0.019)	(0.457)	(0.0002)
100% Smokefree	-1.822	0.000	-0.035 ***	-0.076	0.000 **
	(2.005)	(0.0009)	(0.011)	(0.389)	(0.0002)
County Bans					
Workplaces					
Some Coverage	-0.039	0.000	0.013 ***	0.223 ***	-0.001 ***
	(0.520)	(0.0002)	(0.003)	(0.058)	(0.0000)
Qualified	3.209	-0.002	-0.049	4.007 ***	-0.003 ***
	(4.775)	(0.0023)	(0.025)	(0.533)	(0.0002)
100% Smokefree	3.058	-0.002	-0.027 *	0.368	-0.001 ***
	(2.582)	(0.0012)	(0.014)	(0.345)	(0.0002)
Restaurants					
Some Coverage	5.076 ***	-0.002 ***	-0.006	1.320 ***	-0.001 ***
	(1.056)	(0.0005)	(0.006)	(0.118)	(0.0001)
Qualified	7.759 ***	0.001	0.039 ***	1.574 ***	-0.001 ***
	(1.920)	(0.0012)	(0.010)	(0.226)	(0.0001)
100% Smokefree	-8.106	0.002	0.105 ***	-2.361 ***	0.001
	(4.433)	(0.0022)	(0.023)	(0.718)	(0.0003)
Bars					
Some Coverage	3.922	-0.002	-0.315 ***	-2.723	-0.010 *
	(15.598)	(0.007)	(0.083)	(2.099)	(0.001)
100% Smokefree	-4.744	-0.001	-0.160 ***	0.893	0.000
	(5.177)	(0.002)	(0.027)	(0.794)	(0.000)
Average Price	-0.021	0.003 ***	0.110 ***	-0.826	0.003 ***
	(0.633)	(0.000)	(0.003)	(0.633)	(0.000)

*** Significant at $\alpha = 0.001$
** Significant at $\alpha = 0.01$
* Significant at $\alpha = 0.05$

Table 12
Effects of Smoking Bans on Birth Outcomes: Municipality-within-County-within-State Sub-sample

	Indicator Controls			*Policy Months Controls*	
Policy Controls	**Birth Weight (g)**	**Low Birth Weight (*P*)**	**Gestation (weeks)**	**Birth Weight (g)**	**Low Birth Weight (*P*)**
State Bans					
Workplaces					
Some Coverage	-20.825 ***	-0.001	-0.099 *	2.911 ***	-0.006 ***
	(5.556)	(0.0027)	(0.031)	(0.676)	(0.0003)
Qualified	-27.196 *	0.001	-0.035	3.528 *	-0.006 ***
	(10.748)	(0.0053)	(0.059)	(1.555)	(0.0008)
100% Smokefree	-38.256 ***	0.008	0.046	-1.443	-0.004 ***
	(8.489)	(0.0042)	(0.047)	(1.206)	(0.0006)
Restaurants					
Some Coverage	-46.624	-0.033	-1.601	14.472 ***	-0.025 ***
	(164.362)	(0.0810)	(0.903)	(1.349)	(0.0007)
100% Smokefree	19.938 *	-0.002	0.046	-2.273 *	0.004 ***
	(7.957)	(0.0039)	(0.044)	(0.952)	(0.0005)
Bars					
Some Coverage	13.640	-0.003	-0.023	-5.302 **	0.005 ***
	(12.649)	(0.0062)	(0.069)	(1.746)	(0.0009)
100% Smokefree	2.711	0.004	0.094	-1.962	0.002
	(8.977)	(0.0044)	(0.049)	(1.956)	(0.0010)
Municipal Bans					
Workplaces					
Some Coverage	-5.255	-0.005	-0.038	2.421 ***	-0.018 ***
	(6.166)	(0.0030)	(0.034)	(0.433)	(0.0002)
Qualified	4.633	0.001	0.009	0.953	-0.002 ***
	(6.094)	(0.0030)	(0.033)	(0.846)	(0.0004)
100% Smokefree	-11.164 ***	0.002 *	-0.098 ***	-1.491 ***	0.000
	(2.403)	(0.0012)	(0.013)	(0.330)	(0.0002)
Restaurants					
Some Coverage	-5.145	0.005 ***	0.040 *	-1.793 ***	-0.002 ***
	(2.893)	(0.0014)	(0.016)	(0.297)	(0.0001)
Qualified	1.750	0.000	0.009	0.510	0.000 **
	(2.280)	(0.0011)	(0.013)	(0.268)	(0.0001)
100% Smokefree	-15.647 **	0.004	0.111 *	-1.916 *	0.000
	(5.722)	(0.0028)	(0.031)	(0.774)	(0.0004)
Bars					
Some Coverage	-7.944	0.001	-0.053 *	-1.151	0.000
	(4.433)	(0.0022)	(0.024)	(0.642)	(0.0003)
Qualified	-11.286	0.004	-0.046	-4.431	-0.004 *
	(14.378)	(0.0071)	(0.079)	(3.850)	(0.0019)
100% Smokefree	15.941 *	-0.003	-0.110 **	1.999 *	0.000
	(6.309)	(0.0031)	(0.035)	(0.834)	(0.0004)
Average Price	2.568 *	0.0028 ***	0.138 *	3.321 **	0.0015 *
	(1.246)	(0.001)	(0.007)	(1.249)	(0.001)

*** Significant at $\alpha = 0.001$
** Significant at $\alpha = 0.01$
* Significant at $\alpha = 0.05$

marginal effects on the probability of low birth weight may therefore be explained by endogeneity: poor outcomes may be due to location selection based on preferences for health related goods. For the same reason, however, positive impacts of state policy on birth weight or weeks of gestation, or reductions in the probability of low birth weight, are likely underestimated. Therefore, significant results in this analysis that show state bans improve outcomes are credible even under the assumption of endogeneity.

The lower half of the tables may be read in the opposite fashion. Estimates in this half of the table represent the impact of local bans in areas without state bans. Under the assumption of endogeneity, estimates in this half of the table are biased upwards. Estimated positive effects of local policy on birth weight or weeks of gestation, or reductions in probability of low birth weight, may be due to stronger local preferences for health related goods. On the other hand, if estimates suggest that local bans worsen outcomes despite an upward bias, unbiased estimates would still suggest bans have a negative impact. Thus, in this half of the table, significant results that show local bans worsen outcomes are credible even under the assumption of endogeneity.

Results in the top half of Table 11 suggest that weaker state-level bans on smoking in restaurants and workplaces do more to improve birth weight than 100% smokefree bans, and that bar bans have small but significant impacts on the probability of low birth weight. This disparity in the effects, as well as the general lack of positive and significant results for 100% smokefree bans, may be due to a true difference in relative ban impacts or due to endogeneity bias. . At a minimum, however, the results show that state bans on smoking in restaurants rated “qualified” are associated with birth weight increases of 35.2

g, or 1.2 oz, in the indicator model and 4.4 g per month of coverage in the policy month model. One hundred percent smokefree restaurant bans at the state-level are significantly associated with an increase of 5.6 g in birth weight or 0.47 g increase per month of coverage. State-enforced workplace bans that provide "some coverage" per ANR's ratings are also associated with small but significant reductions in the probability of low birth weight in both types of models, and birth weight increases of 0.8 g per month of coverage in the policy month models.

The bottom half of Table 11 offers no contrary evidence on the impacts of bans on birth weight in this sample. They do suggest, however, that county-level workplace bans that are "100% smokefree" decrease weeks of gestation. The estimated effect is small (equivalent to less than a fraction of a day), but may be biased upwards. Local bar bans also significantly reduce weeks of gestation by at least one to two days.

Average cigarette prices have little beneficial impact on birth outcomes in this sample. While an increase of $1 in the real price of cigarettes increases gestation by approximately 0.8 days, it paradoxically increases the probability of low birth weight by 0.3 percentage points. The available data do not permit a thorough investigation of this result.

Analysis of the municipality-within-county-within-state sub-sample shown in Table 12 yields some similar results, but offers more caveats. Weaker state bans on smoking in workplaces again appear to significantly improve birth outcomes: bans that offer "some coverage" increase birth weight by at least 2.9 g per month and reduce the probability of low birth weight by more than ½ a percentage point for each month they are in place.

Estimates of the effects of "qualified" state-level workplace bans are similar. Restaurant bans that offer "some coverage" have dramatic effects on birth weight: at a minimum, the results suggest that for every month of coverage, these bans increase birth weight by 14.5 g and decrease the probability of low birth weight by 2.46 percentage points for births in this sample. Unfortunately, no states in this sample offer "qualified" restaurant bans, so their impact in this sample cannot be analyzed.

State bans that are "100% smokefree" are associated with some positive impacts in this sample, but estimates of their effects at the local level give cause for some concern. In the indicator control model, "100% smokefree" restaurant bans increase birth weight by 19.9 g, but this result is only weakly significant ($\alpha = 0.05$). No similar results for "100% smokefree" restaurant bans appear in other models. Likewise, "100% smokefree" state bans on smoking in workplaces significantly reduce the probability of low birth weight in the policy indicator model, but similar effects do not appear in other models or for other outcomes.

At the same time, however, municipal workplace and restaurant bans that are "100% smokefree" are associated with significantly worse birth outcomes in several models. In particular, workplace bans of this type appear to reduce birth weight by at least 11.2 g or 1.5 g per month of coverage while increasing the probability of low birth weight by 0.25 percentage points. They also have a significant and negative marginal effect on weeks of gestation. Similarly, municipal "100%-smokefree" restaurant bans reduce birth weight by at least 15.6 g or 1.9 g per month of coverage in this sample. It is worth noting that municipal restaurant bans that meet the "some coverage" and "qualified" criteria also appear to significantly worsen birth outcomes. While the estimated marginal effects for these policies are not as large in magnitude, the small estimates may again be due to a true difference in relative policy impacts or due to endogeneity bias. Municipal bans rated "qualified," however, appear to cause no problems in workplaces.

Moving beyond birth weight, bans do not appear to have a significant positive effect on weeks of gestation in this sample. In fact, municipal "100% smokefree" workplace bans and bar bans rated "some coverage" and "100% smokefree" have significant and negative impacts on weeks of gestation. These negative impacts are consistent across both samples.

Last, increases in average real cigarette prices significantly improve birth weight outcomes in this sample. They are also again associated with an increase in weeks of gestation. However, the paradoxical result that higher cigarette prices lead to greater chances of low birth weight persist in this sample as well.

V. Conclusions and Further Questions for Research

The results of this analysis suggest that less-restrictive bans may do more to improve birth outcomes than "100% smokefree" bans. In both samples, workplace and restaurant bans with "some coverage" or "qualified" ratings appear to outperform "100% smokefree bans", although the difference in these effects cannot conclusively be attributed to superior effectiveness for less restrictive bans. At the municipal level, however, "100% smokefree" bans in restaurants and workplaces appear to significantly worsen birth weight outcomes.

Overall, state bans that meet ANR's "qualified" rating seem to perform best: looking across the results from both samples, bans at this level of coverage show the strongest positive results when implemented at the state level and the fewest significant problems at the municipal level. While summary statistics reveal that only a small proportion of births were covered by these kinds of bans, the total number of births that this proportion represents are nonetheless large and estimated effects tend to be highly significant.

In general, the results in this paper suggest some small but significant impacts of smoking bans on weeks of gestation. These results, however, are not consistent across both samples. In the main sample, the effects of bans work in the expected direction: bans appear to increase weeks of gestation. In the sub-sample, however, no significant positive effects of state bans on weeks of gestation appear. On the contrary, municipal bans that offer "100% smokefree" coverage of workplace or coverage of bars significantly reduce weeks of gestation.

While the data used in this paper are not well suited to analyze the effectiveness of cigarette prices as policy instruments to protect health, the findings here show that increases in cigarette prices significantly *increase* the probability of low birth weight. This unexpected finding may be due to any number of factors that may be illuminated by an analysis of cigarette prices. Greater expenditures on healthcare or access to better neo-natal care in states with higher cigarette taxes may explain this finding. Investigation of this relationship may provide insight into determinants of maternal smoking, maternal ETS exposure, or the effectiveness of public health spending on birth outcomes.

This analysis cannot determine why less restrictive bans appear to perform better or why bans may cause harm. One explanation is that more restrictive bans crowd smoking into private environments where non-smokers are exposed. Another explanation may be that bans reduce the costs to pregnant women of spending time in workplaces, restaurants, or bars. In turn, time spent in these places may correlate with activities or consumption that reduces infant health. I do not find this explanation plausible for the effects of workplace bans (Baum, 2005), but it may well explain the effect of bar bans on weeks of gestation. A careful analysis over a smaller sample with more information on maternal choices may be able to provide more insight into this issue.

Finally, while birth outcomes do have long-run implications, they provide information only on the short-run effects of smoking bans. More strict smoking bans may reduce the probability that someone begins smoking, increase the probability that they will quit smoking, or reduce their smoking habit. Evans *et al*. (1999) shows support for the idea that workplace bans will reduce cigarettes smoked (by 10%) and decrease smoking prevalence (by 5%), but I know of no research that investigates whether these effects vary by ban strength and if so, by how much. In any case, however, bans do not target these outcomes well. Supplementing less restrictive bans with continued support for cessation and education programs may be the best approach.

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APPENDIX A.

Equation (12) in Chapter 1 arises from invoking the implicit function theorem and differentiating the social planner's first order condition (11) on the optimal path with respect to ε. Beginning with that differentiation,

(A1) $$\frac{\partial}{\partial \varepsilon}\left[N\cdot\left(p+\varepsilon-\frac{dC}{dx}(x_{SO}(S_R,\varepsilon))-\frac{df}{dx}(N\cdot x_{SO}(S_R,\varepsilon))\right)\right]=\frac{\partial}{\partial \varepsilon}\left[\beta\cdot E\left[\frac{\partial W}{\partial S_R}(S_R',\varepsilon')\right]\right].$$

This operation yields

(A2)

$$N\cdot\left(1-\frac{\partial}{\partial \varepsilon}\left[\frac{dC}{dx}(x_{SO}(S_R,\varepsilon))\right]-\frac{\partial}{\partial \varepsilon}\left[\frac{df}{dx}(N\cdot x_{SO}(S_R,\varepsilon))\right]\right)=\beta\cdot E\left[\frac{\partial}{\partial \varepsilon}\left[\frac{\partial W}{\partial S_R}(S_R',\varepsilon')\right]\right]$$

, which simplifies via the chain rule to

(A3)

$$N\cdot\left(1-\frac{d^2C}{dx^2}(x_{SO}(S_R,\varepsilon))\cdot\frac{\partial x_{SO}}{\partial \varepsilon}-N\cdot\frac{d^2C}{dx^2}(N\cdot x_{SO}(S_R,\varepsilon))\cdot\frac{\partial x_{SO}}{\partial \varepsilon}\right)=\beta\cdot E\left[\frac{\partial}{\partial \varepsilon}\left[\frac{\partial W}{\partial S_R}(S_R',\varepsilon')\right]\right].$$

The right-hand side of (A3) can be re-written in terms of the transition equation $S_R'=S_R-x_{SO}(S_R,\varepsilon)$ to find

(A4)

$$N\cdot\left(1-\frac{d^2C}{dx^2}(x_{SO}(S_R,\varepsilon))\cdot\frac{\partial x_{SO}}{\partial \varepsilon}-N\cdot\frac{d^2f}{dx^2}(N\cdot x_{SO}(S_R,\varepsilon))\cdot\frac{\partial x_{SO}}{\partial \varepsilon}\right)=\beta\cdot E\left[\frac{\partial}{\partial \varepsilon}\left[\frac{\partial W}{\partial S_R}(S_R-x_{SO}(S_R,\varepsilon),\varepsilon')\right]\right],$$

which reduces via the chain rule to

(A5)

$$N \cdot \left(1 - \frac{d^2C}{dx^2}(x_{SO}(S_R,\varepsilon)) \cdot \frac{\partial x_{SO}}{\partial \varepsilon} - N \cdot \frac{d^2 f}{dx^2}(N \cdot x_{SO}(S_R,\varepsilon)) \cdot \frac{\partial x_{SO}}{\partial \varepsilon} \right) = \beta \cdot E\left[-\frac{\partial^2 W}{\partial {S_R}^2}(S_R - x_{SO}(S_R,\varepsilon),\varepsilon') \cdot \frac{\partial x_{SO}}{\partial \varepsilon} \right].$$

After using the transition equation once more and noting that the expectation is over ε' and not ε, (A5) may be simplified to

(A6)

$$N \cdot \left(1 - \frac{d^2C}{dx^2}(x_{SO}(S_R,\varepsilon)) \cdot \frac{\partial x_{SO}}{\partial \varepsilon} - N \cdot \frac{d^2 f}{dx^2}(N \cdot x_{SO}(S_R,\varepsilon)) \cdot \frac{\partial x_{SO}}{\partial \varepsilon} \right) = -\beta \cdot \frac{\partial x_{SO}}{\partial \varepsilon} \cdot E\left[\frac{\partial^2 W}{\partial {S_R}^2}(S_R',\varepsilon') \right].$$

Solving for $\frac{\partial x_{SO}}{\partial \varepsilon}$ algebraically now yields

(A7) $$\frac{\partial x_{SO}}{\partial \varepsilon} = \frac{N}{N \cdot \frac{d^2C}{dx^2}(x_{SO}) + N^2 \cdot \frac{d^2 f}{dx^2}(N \cdot x_{SO}) - \beta \cdot E\left[\frac{\partial^2 W}{\partial {S_R}^2}(S_R',\varepsilon') \right]}$$

which is equation (12) .

APPENDIX B.

The proof for equation (17) in Chapter 1 goes as follows. Begin with equation (15), and let τ, S_R, and ε be given. Solving for τ'

$$\text{(B1)}\ \tau'(\tau,S_R,\varepsilon)=p-E\left[\frac{dC}{dx}(x'_{SO}(S_R-x_{SO}(S_R,\varepsilon),\varepsilon'))\right]-\frac{1}{\beta}\cdot\left(p+\varepsilon-\frac{dC}{dx}(x_{SO}(S_R,\varepsilon))-\tau\right),$$

and differentiate with respect to ε. This procedure yields

$$\text{(B2)}\ \frac{\partial\tau'}{\partial\varepsilon}=-E\left[-\frac{\partial x_{SO}}{\partial\varepsilon}\cdot\frac{d^2C}{dx^2}(x'_{SO}(S_R-x_{SO}(S_R,\varepsilon),\varepsilon'))\right]-\frac{1}{\beta}\cdot\left(1-\frac{d^2C}{dx^2}(x_{SO}(S_R,\varepsilon))\cdot\frac{\partial x_{SO}}{\partial\varepsilon}\right).$$

After applying the transition equation $X'_R=X_R-x_{SO}(X_R,\varepsilon)$ to express terms more simply, basic arithmetic yields

$$\text{(B3)}\qquad \frac{\partial\tau'}{\partial\varepsilon}=\frac{1}{\beta}\cdot\left[\frac{\partial x_{SO}}{\partial\varepsilon}\cdot\frac{d^2C}{dx^2}(x_{SO})-1\right]+E\left[\frac{\partial x_{SO}}{\partial\varepsilon}\cdot\frac{d^2C}{dx^2}(x'_{SO})\right].$$

The expectation operator in (iii) is over ε' , not ε , so the derivative $\frac{\partial x_{SO}}{\partial\varepsilon}$ may be moved outside the expectation to obtain

$$\text{(B4)}\qquad \frac{\partial\tau'}{\partial\varepsilon}=\frac{1}{\beta}\cdot\left[\frac{\partial x_{SO}}{\partial\varepsilon}\cdot\frac{d^2C}{dx^2}(x_{SO})-1\right]+\frac{\partial x_{SO}}{\partial\varepsilon}\cdot E\left[\frac{d^2C}{dx^2}(x'_{SO})\right].$$

Substitution for $\frac{\partial x_{SO}}{\partial\varepsilon}$ using into (12) yields

(B5)

$$\frac{\partial\tau'}{\partial\varepsilon}=\frac{1}{\beta}\cdot\left[\left(\frac{N\cdot\frac{d^2C}{dx^2}(x_{SO})}{N\cdot\frac{d^2C}{dx^2}(x_{SO})+N^2\cdot\frac{d^2f}{dx^2}(N\cdot x_{SO})-\beta\cdot E\left[\frac{\partial^2W}{\partial {S_R}^2}(S'_R,\varepsilon')\right]}\right)-1\right]+\frac{N\cdot E\left[\frac{d^2C}{dx^2}(x'_{SO})\right]}{N\cdot\frac{d^2C}{dx^2}(x_{SO})+N^2\cdot\frac{d^2f}{dx^2}(N\cdot x_{SO})-\beta\cdot E\left[\frac{\partial^2W}{\partial {S_R}^2}(S'_R,\varepsilon')\right]}$$

.

After obtaining a common denominator for all terms, (B5) can be rewritten as

(B6)

$$\frac{\partial\tau'}{\partial\varepsilon}=\frac{\frac{1}{\beta}\cdot\left(N\cdot\frac{d^2C}{dx^2}(x_{SO})-\left(N\cdot\frac{d^2C}{dx^2}(x_{SO})+N^2\cdot\frac{d^2f}{dx^2}(N\cdot x_{SO})-\beta\cdot E\left[\frac{\partial^2W}{\partial {S_R}^2}(S_R',\varepsilon')\right]\right)\right)+N\cdot E\left[\frac{d^2C}{dx^2}(x_{SO}')\right]}{N\cdot\frac{d^2C}{dx^2}(x_{SO})+N^2\cdot\frac{d^2f}{dx^2}(N\cdot x_{SO})-\beta\cdot E\left[\frac{\partial^2W}{\partial {S_R}^2}\right](S_R',\varepsilon')}.$$

Arithmetic simplification of (B6) yields:

(B7) $$\frac{\partial\tau'}{\partial\varepsilon}=\frac{-\frac{N^2}{\beta}\cdot\frac{d^2f}{dx^2}(N\cdot x_{SO})+E\left[\frac{\partial^2W}{\partial {S_R}^2}(S_R',\varepsilon')\right]+N\cdot E\left[\frac{d^2C}{dx^2}(x_{SO}')\right]}{N\cdot\frac{d^2C}{dx^2}(x_{SO})+N^2\cdot\frac{d^2f}{dx^2}(N\cdot x_{SO})-\beta\cdot E\left[\frac{\partial^2W}{\partial {S_R}^2}(S_R',\varepsilon')\right]},$$

which can be further simplified by applying the identity for $\frac{\partial x_{SO}}{\partial\varepsilon}$ given in (13). This procedure gives:

(B8) $$\frac{\partial\tau'}{\partial\varepsilon}=\frac{\partial x_{SO}}{\partial\varepsilon}\cdot\left(-\frac{N}{\beta}\cdot\frac{d^2f}{dx^2}(N\cdot x_{SO})+\frac{1}{N}\cdot E\left[\frac{\partial^2W}{\partial {S_R}^2}(S_R',\varepsilon')\right]+E\left[\frac{d^2C}{dx^2}(x_{SO}')\right]\right)$$

Equation (B8) yields (17) after the application of the envelope theorem to find

$E\left[\frac{\partial^2W}{\partial {S_R}^2}(S_R',\varepsilon')\right]$.

***Lemma*:** $E\left[\frac{\partial^2W}{\partial {S_R}^2}(S_R',\varepsilon')\right]=-N\cdot E\left[\frac{\partial^2C}{\partial x^2}(x_{SO}')+N\cdot\frac{\partial^2f}{\partial x^2}(N\cdot x_{SO}')\right].$

First, note that

(B9) $$\frac{\partial}{\partial x_R}E\left[W(S_R',\varepsilon')\right]=\frac{\partial}{\partial x_R}E\left[W(S_R-x_R,\varepsilon')\right]=-E\left[\frac{\partial W}{\partial S_R}(S_R-x_R,\varepsilon')\right].$$

Differentiating once more and substituting using the transition equation, (B9) implies

$$\text{(B10)}\quad \frac{\partial^2}{\partial x_R^2} E\left[W(X_R', \varepsilon')\right] = \frac{\partial}{\partial x_R^2} E\left[W(S_R - x_R, \varepsilon')\right] = E\left[\frac{\partial^2 W}{\partial S_R^2}(S_R - x_R, \varepsilon')\right] = E\left[\frac{\partial^2 W}{\partial S_R^2}(S_R', \varepsilon')\right].$$

But note that by the envelope theorem (twice applied) that:

$$\text{(B11)}\quad \frac{\partial^2}{\partial x_R^2} E\left[W(X_R', \varepsilon')]\right] = N \cdot E\left[-\frac{\partial^2 C}{\partial x^2}(x_{SO}') - N \cdot \frac{\partial^2 f}{\partial x^2}(N \cdot x_{SO}')\right].$$

Thus, from (B10) and (B11), it follows that

$$\text{(B12)}\quad E\left[\frac{\partial^2 W}{\partial S_R^2}(S_R', \varepsilon')\right] = -N \cdot E\left[\frac{\partial^2 C}{\partial x^2}(x_{SO}') + N \cdot \frac{\partial^2 f}{\partial x^2}(N \cdot x_{SO}')\right],$$

which completes the lemma.

Returning to the derivation of $\dfrac{\partial \tau'}{\partial \varepsilon}$, substitute (B12) into (B8) to find

$$\text{(B13)}\quad \frac{\partial \tau'}{\partial \varepsilon} = \frac{\partial x_{SO}}{\partial \varepsilon} \cdot \left(-\frac{N}{\beta} \cdot \frac{d^2 f}{dx^2}(N \cdot x_{SO}) - E\left[\frac{d^2 C}{dx^2}(x_{SO}') + N \cdot \frac{d^2 f}{dx^2}(N \cdot x_{SO}')\right] + E\left[\frac{d^2 C}{dx^2}(x_{SO}')\right]\right),$$

which reduces to

$$\text{(B14)}\quad \frac{\partial \tau'}{\partial \varepsilon} = -N \cdot \frac{\partial x_{SO}}{\partial \varepsilon} \cdot \left(\frac{1}{\beta} \cdot \frac{d^2 f}{dx^2}(N \cdot x_{SO}) + E\left[\frac{d^2 f}{dx^2}(N \cdot x_{SO}')\right]\right).$$

Equation (B14) is equation (17), which was to be shown.

APPENDIX C.

Proposition 1 of Chapter 3 may be proved as follows. Consider the interior case first, and suppose that $\theta_2 > \theta_1$. Assumption (22) implies that:

$$\text{(C1)}\quad \left.\frac{\partial U}{\partial h}\cdot\frac{dA}{d\theta}\cdot\frac{\partial H(A(\theta),X_1)}{\partial A}\right|_{\theta=\theta_2} > \left.\frac{\partial U}{\partial h}\cdot\frac{dA}{d\theta}\cdot\frac{\partial H(A(\theta),X_2)}{\partial A}\right|_{\theta=\theta_2}$$

Equation (C1) simply shows that the marginal benefits of x_1 at the optimal choice for x_2 are greater than the marginal benefits x_2 receives at that choice of θ_2. This observation leads to a contradiction. Since the first order condition for x_2 holds, (C1) may be appended to read:

$$\text{(C2)}\quad \left.\frac{\partial U}{\partial h}\cdot\frac{dA}{d\theta}\cdot\frac{\partial H(A(\theta),X_1)}{\partial A}\right|_{\theta=\theta_2} > \left.\frac{\partial U}{\partial h}\cdot\frac{dA}{d\theta}\cdot\frac{\partial H(A(\theta),X_2)}{\partial A}\right|_{\theta=\theta_2} = -n\cdot\left.\frac{\partial U}{\partial(n\cdot\theta)}\right|_{\theta=\theta_2}.$$

At the same time, however, the first order condition for x_1 and the functional assumptions imply

$$\text{(C3)}\quad -n\cdot\left.\frac{\partial U}{\partial(n\cdot\theta)}\right|_{\theta=\theta_2} > \left.\frac{\partial U}{\partial h}\cdot\frac{dA}{d\theta}\cdot\frac{\partial H(A(\theta),X_1)}{\partial A}\right|_{\theta=\theta_2}.$$

In words, (C3) states that marginal costs at θ_2 exceed marginal benefits for x_1. This relationship holds because as θ increases from θ_1, marginal benefits decrease and marginal costs increase. The result (C3) directly contradicts (C2), which depends on the assumption $\theta_2 > \theta_1$. Therefore, at an interior solution, $\theta_1 > \theta_2$.

For the corner solutions, the proof is identical. Consider the case where $\theta_1 = 0$ and $\theta_2 > 0$. Assumption (22) and the first order condition for x_2 imply (C2). At the same time, the first order condition for x_1 implies

(C4) $-n \cdot \left.\frac{\partial U}{\partial (n \cdot \theta)}\right|_{\theta=0} > \frac{\partial U}{\partial h} \cdot \frac{dA}{d\theta} \cdot \left.\frac{\partial H(A(\theta), X_1)}{\partial A}\right|_{\theta=0}$.

Since $\theta_2 > 0$, marginal costs are even higher at for x_1 at θ_2, so the functional assumptions again imply (C3) holds, which again contradicts (C2). Thus $\theta_1 = 0$ and $\theta_2 > 0$ cannot hold. If $\theta_1 = 0$ and $\theta_2 = 0$, however, the first order conditions and assumption (5) imply

(C5) $$-n \cdot \left.\frac{\partial U}{\partial (n \cdot \theta)}\right|_{\theta=0} > \frac{\partial U}{\partial h} \cdot \frac{dA}{d\theta} \cdot \left.\frac{\partial H(A(\theta), X_1)}{\partial A}\right|_{\theta=0} > \frac{\partial U}{\partial h} \cdot \frac{dA}{d\theta} \cdot \left.\frac{\partial H(A(\theta), X_2)}{\partial A}\right|_{\theta=0},$$

which does not contradict any assumptions. The final corner solution is easily proved by the same arguments.

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Vita

Ronald Joseph Briggs graduated from El Dorado High School in Placerville, California. He briefly attended St. John's College in Santa Fe and American River College in Sacramento before completing a Bachelor's of Arts and Sciences degree in Economics and Mathematics at the University of California, Davis. After graduation in March of 2000, Mr. Briggs took a position at the Rand Corporation, supporting research on education policy, national security, and defense. During his time at Rand, he co-authored several books on education, including Examining gaps in mathematics achievement among racial-ethnic groups (with Mark Berends and Sam Lucas). In 2003, Mr. Briggs left Rand to pursue doctoral studies in Economics at The University of Texas at Austin as a Donald D. Harrington Doctoral Fellow. His studies focused on the fields of Environmental and Resource Economics and Public Economics, and he has experience teaching in both of these areas. In addition to his studies in Economics, Mr. Briggs was awarded a National Science Foundation Integrative Graduate Education and Research Traineeship in Indoor Environmental Science and Engineering. In this two-year program, Mr. Briggs developed expertise in Indoor Air Quality and interned at the US Department of Energy's Lawrence Berkeley National Labs. Mr. Briggs will begin as a Professor of Energy and Environmental Economics at the Pennsylvania State University in State College, PA in the fall of 2009.

Permanent address: 901 Red River St, Apt 1304, Austin, TX 78701

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