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ABSTRACT:

This paper explains how the increasingly popular quasi-experimental approach to hedonic estimation relates to Rosen's (1974) concept of market equilibrium. We demonstrate that the conventional approach to hedonic estimation and the quasi-experimental approach to estimation attempt to measure different phenomena. In a theoretical setting where omitted variables are not an issue, conventional hedonic estimates of the MWTP for an amenity will generally differ from quasi-experimental estimates for the rate at which changes in that amenity are capitalized into property values. Thus, comparisons between the two sets of estimates are generally invalid. Recent work in microeconometrics has sought to bridge the gap between structural and quasi-experimental methods by identifying special situations where treatment effects serve as "sufficient statistics" for welfare measurement (Chetty [2008]). We extend this logic to the hedonic property value framework by formalizing the specific assumptions on household preferences and the data that make it possible, in special cases, to interpret a quasi-experimental estimate for a capitalization rate as a measure of MWTP.

KEY WORDS: capitalization, hedonic, quasi-experimental, policy, preferences, welfare

JEL CODES: C33, Q21, R21, H41

1. Introduction

Hedonic property value models are frequently used to evaluate what people are willing to pay for a wide range of public goods, from school quality to air quality to cleanup of hazardous waste sites. The conceptual basis for this strategy was developed by Rosen (1974). He demonstrated conditions under which regressing product prices on their attributes can reveal consumers' willingness-to-pay for a marginal change in a continuous attribute of a differentiated product (MWTP). Over the past 35 years, Rosen's logic has been transformed into a practical tool for property value assessment, litigation of externalities, and public policy evaluation. Because of these capabilities, the hedonic model is generally viewed as one of the success stories of applied microeconomics (Palmquist and Smith [2002]). Yet there is increasing concern about the appropriate use of the method (Smith [2007a]).

Due to concern about the potential for omitted variables to bias estimates for MWTP, recent studies have sought to nest the hedonic model in a quasi-experimental framework that uses panel data to purge time-constant omitted variables. This strategy has been used to investigate how housing prices react to shocks in leukemia risk (Davis [2004]), air quality (Chay and Greenstone [2005]), and exposure to hazardous waste sites (Greenstone and Gallagher [2008]) to name only a few. These studies provide compelling evidence that observed changes in housing prices are *caused* by observed shocks in the amenity of interest. However, the ability to address omitted variables comes at a cost.

Time-differencing the data changes the conceptual logic that underlies hedonic estimation. Rosen's theoretical model describes market equilibrium at a single point in time. The quasi-experimental approach to estimating that model measures the rate at which amenities are capitalized into property values over time. In the context of hedonic theory, these studies track the movement between different equilibria. Additional assumptions about preferences and/or the data are needed to interpret the corresponding capitalization rate as a measure of MWTP. The relationship between these "new" assumptions and the underlying concept of a hedonic equilibrium has not been investigated in the literature. It is especially important to understand this relationship given the growing enthusiasm for using the quasi-experimental hedonic model to inform public policy.

This paper explains how the quasi-experimental approach to hedonic estimation relates to Rosen's (1974) concept of market equilibrium. We demonstrate that the conventional approach to hedonic estimation and the newer quasi-experimental approach to estimation attempt to measure different phenomena. In a theoretical setting where omitted variables are not an issue, conventional hedonic estimates of the MWTP for an amenity will generally differ from quasi-experimental estimates for the rate at which changes in that amenity are capitalized into property values. Thus, comparisons between the two sets of estimates are generally invalid. This finding is consistent with the broader microeconometric literature on the difference between treatment effects and structural parameters (Heckman [2001]; Todd and Wolpin [2003]; Keane [forthcoming]).

Recent work in microeconometrics has sought to bridge the gap between structural and quasi-experimental methods by identifying situations where treatment effects serve as "sufficient statistics" for welfare measurement (Chetty [2008]). We bring this logic to the hedonic model by formalizing specific assumptions on household preferences and the data that are jointly sufficient for quasi-experimental estimates for the capitalization rate to identify MWTP. Consider a large shock to an amenity that serves as the basis for a quasi-experiment. We demonstrate that identifying a household's MWTP in the pre-shock equilibrium requires that their demand curves for the amenity are perfectly elastic over the range of the shock and constant over the duration of the quasi-experiment. If this assumption does not hold, one can still identify MWTP in the post-shock equilibrium if the shock is uncorrelated with all other variables. If this assumption is also violated, welfare measures based on the capitalization rate can fall outside the range defined by the true MWTP in the pre-shock and post-shock equilibria.

The remainder of the paper proceeds as follows. Section 2 begins by reviewing the key features of the conventional hedonic model. Then we summarize how the model has actually been used for evaluating public policies and litigating private property externalities. This summary helps to motivate our discussion of the current uncertainty in the hedonic literature about econometric methodology. In section 3 we attempt to resolve some of this uncertainty by providing a theoretical foundation for the quasi-experimental model. Section 4 considers the econometric implications and outlines the assumptions needed to interpret capitalization rates as measures of MWTP. Key points in sections 3 and 4 are illustrated using Tinbergen's (1959) linear-quadratic-normal model. Finally, section 5 discusses some empirical implications of our results and section 6 concludes.

2. The Hedonic Property Value Model in Theory and Practice

Hedonic models express the price of a differentiated product as a function of its characteristics. While the conceptual basis for this approach dates back to the 1920s, the method was popularized by Griliches's (1971) work on using a hedonic price function to make quality adjustments to price indices for automobiles. Rosen (1974) strengthened the economic foundations of the method by demonstrating that the hedonic price function can be interpreted as an equilibrium relationship resulting from interactions between all the buyers and sellers in a market. He also suggested that the hedonic price function could be used to infer the demand for product characteristics, inspiring a line of research that continues today.

One of the main applications of the hedonic method has been to derive implicit prices for public goods. Consider air quality. While a household does not pay anyone directly for the air its members breathe, the household purchases the right to have access to this air on a regular basis through the price of its home. Regressing housing prices on air quality, while controlling for other housing and location-specific characteristics, offers the potential for revealing the marginal price that households implicitly pay for improvements in air quality. The possibility of using this information to infer the demand for air quality (and other public goods) has intrigued economists since Rosen's (1974) paper.

Over the past 35 years, Rosen's theoretical model has evolved into a practical tool for property value assessment, private litigation, and policy evaluation. Because of these capabilities, the hedonic model is generally viewed as one of the success stories of applied microeconomics. However, recent studies have argued that quasi-experimental designs present a number of advantages over the conventional (cross-section) approach to hedonic estimation. This has led to a lively debate on the appropriate use of the method.

In the remainder of this section we summarize the current state of knowledge on conventional and quasi-experimental approaches to hedonic estimation. We begin by briefly reviewing the theoretical properties of the hedonic property value model. Then we discuss how conventional and quasi-experimental approaches to estimating that model have been used to evaluate public policy and to settle lawsuits. We conclude by presenting the key questions that have characterized the recent debate on hedonic methodology.

2.1. Hedonic Theory for the Measurement of Marginal Values

Rosen (1974) defined conditions under which the hedonic price function will identify consumers' willingness-to-pay for a marginal change in a continuous attribute of a differentiated product. Suppose we seek to measure consumers' willingness-to-pay for a marginal change in a single public good, *g*, which is conveyed through the location of a home. Let the annualized price of housing be expressed as $P = P(g, X)$, where *X* is a vector of structural housing characteristics and other spatially delineated public goods. Partially differentiating this price function with respect to *g* provides an estimate of the marginal price function for *g:*

(1) $$P_g = \frac{\partial P(g, X)}{\partial g}.$$

P_g is the marginal contribution of *g* to the price of housing given the current level of *g* and levels of the other characteristics. In other words, equation (1) depicts an implicit price function that describes the marginal price for each unit of *g* relevant for every household in the market described by $P(g, X)$. The assumptions of Rosen's (1974) model guarantee the existence of an equilibrium price function where consumers choose a level of *g* that sets their willingness-to-pay for a marginal change in *g* equal to its marginal implicit price.

Hedonic property value models typically assume that households are price-takers who face a continuum of choices—they can choose a home with any combination of structural characteristics and public goods.[1] Thus, the household's utility maximization problem can be written as (2).

$$\text{(2)} \qquad \max_{g,X,b} \; U(g,X,b;\alpha) \;\; \textit{subject to} \;\; y = b + P(g,X).$$

Each household chooses the combination of structural characteristics, public goods, and the numeraire composite commodity (*b*) that maximize its utility, given its preferences (α) and income (y). The first order conditions to this problem produce one of the key results of the model:

$$\text{(3a)} \qquad \frac{\partial P(g,X)}{\partial g} = \frac{\partial U/\partial g}{\partial U/\partial b} \equiv D(g;X,\alpha,y).$$

$$\text{(3b)} \qquad \frac{\partial P(g,X)}{\partial X} = \frac{\partial U/\partial X}{\partial U/\partial b} \equiv S(X;g,\alpha,y).$$

The first equality in (3a) implies that consumers will maximize their utility by choosing a house that provides them with a level for *g* at which their marginal willingness-to-pay for an additional unit exactly equals its marginal implicit price. Assuming the marginal utility of income is constant for each consumer, the second equality simply observes that as *g* varies the marginal rate of substitution defines its inverse demand curve, conditional on *X*. Equation (3b) defines analogous first order conditions for *X*.

Figures 1 and 2 illustrate the first order condition for *g*. Figure 1 shows bid functions for housing in the *g* dimension for two different households. The bid functions

[1] If households are unable to choose continuous quantities of every attribute, it is not possible to point-identify their MWTP for housing attributes from the hedonic price function. However, it is still possible to identify bounds on MWTP if one is willing to make a parametric assumption about the functional form for utility (Bajari and Benkard [2005]; Kuminoff, [forthcoming]).

express each household's willingness-to-pay for housing as a function of *g*, given the household's preferences and income, and given levels of all the other housing characteristics and public goods. Each household will select the quantity of *g* where its bid function is tangent to the hedonic price function. In the figure, the two households purchase homes that are identical except in their provision of the public good. Household 1 spends $\$_1$ on a house that provides g_1 units of the public good and household 2 spends $\$_2$ on a house with g_2.

The first order condition implies that, if markets are in equilibrium, evaluating P_g at a household's chosen level of *g* will return that household's marginal willingness-to-pay (MWTP) for *g*. Combining this information with the level of *g* at a household's location identifies exactly one point on that household's inverse demand curve. In figure 2, household 1's inverse demand (D_1) intersects P_g at the point where its MWTP exactly equals the marginal price for an extra unit of *g*. While MWTP is identified by the gradient of the price function, inverse demand curves are not. An infinite number of demand curves could pass through the points defined by $(MWTP_1, g_1)$ and $(MWTP_2, g_2)$. Thus, without additional assumptions about the nature of consumer preferences, the hedonic price function does not identify a household's demand for *g* or its willingness-to-pay for non-marginal changes.[2] Because of this limitation, hedonic practitioners have primarily used the model to assess the willingness-to-pay for marginal changes in

[2] This limitation has motivated considerable research on microeconometric strategies that seek to identify the demand for a public good by adding information about consumer preferences. The additional information may consist of: (1) a parametric representation for the utility function (e.g. Bayer et al. [2007]); (2) separability restrictions on marginal utility (e.g. Ekeland et al. 2004); or (3) an assumption that consumers in different housing markets share a common distribution of preferences (e.g. Boyle et al. [1999]). While this is an active research area, these methods have not been widely used for litigation or policy evaluation.

spatially delineated amenities. Or they have used the model to predict how residential property values would be affected by a change in *g*.

2.2. Applications of the Hedonic Method: Litigation and Policy Evaluation

Over the past 35 years, the hedonic property value model has evolved into a practical tool for property value assessment, litigation, and policy evaluation. The model is frequently used by property appraisers (e.g. Schultz and Schmitz [2008]) and the methodology is widely accepted by the legal community (e.g. Malani [2008]). Hedonic estimates for the property value impacts of transportation noise, air pollution, water pollution, hazardous waste, and other disamenities have been used to determine damages in civil lawsuits and have helped to shape environmental policy. For these reasons, the hedonic model is generally viewed as one of the success stories of applied microeconomics (Palmquist and Smith [2002]). Providing some quick background and examples of how hedonic modeling is used for private litigation and public policy will help to motivate our main points about the important differences between the conventional and quasi-experimental approaches to hedonic estimation.

<u>Policy Evaluation</u>

When hedonic models are used for policy evaluation, welfare measurement is the main objective. By providing a theoretically consistent measure of MWTP, hedonic estimates can be used to develop a crude approximation to the partial equilibrium welfare effects from the environmental improvements that are expected to follow a new regulation. It is easy to demonstrate that this line of work has served as an input to the policymaking process, but difficult to document where it has affected specific policy outcomes. We are unable to find a single case where the passage of a federal regulation clearly hinged on the estimates from a hedonic model. Yet it is readily apparent that policymakers take hedonic estimates seriously.

The Environmental Protection Agency (EPA), the Department of Agriculture (USDA), and other federal agencies routinely sponsor research that uses conventional hedonic methods to assess the importance of agricultural and environmental issues. Table 1 reports the results from a systematic search through the EPA and USDA databases of funded research.[3] During the past 10 years, EPA and USDA spent more than two million dollars sponsoring applied research that sought to use the hedonic model to assess the value of a wide range of amenities including air quality, water quality, ecosystem health, hazardous waste, open space, water rights, and recreation opportunities.

Palmquist and Smith (2002) provide the most detailed analysis of how the hedonic property value model has actually affected public policy. Based on a series of case studies at EPA, they suggest that hedonic modeling has influenced the policymaking process in two ways. First, hedonic estimates of the MWTP for reduced air pollution, water pollution, and hazardous waste have helped to convince policymakers that the public is willing to pay for regulation of these pollutants. Second, hedonic estimates have

[3] This information was collected by searching the EPA/NSF Research Funding data at the National Center for Environmental Economics and USDA's Current Research Information System. Searches were conducted using the keywords "hedonic", "property value" and "housing prices." If the resulting abstract indicated that hedonic modeling was a major component of the research, we included the study in our sample. This approach provides a lower bound on the magnitude of sponsored research using hedonic methods..

been used to determine the validity of welfare measures used in benefit-cost analyses of environmental regulations.

To see how hedonic models have been used to validate benefit estimates, consider EPA's standards for ambient levels of criteria air pollutants. In the early 1980s EPA hired *Mathtech* to estimate the non-health benefits from proposed secondary standards for sulfur dioxide and total suspended particulates.[4] To do this, *Mathtech* used a linear expenditure system to predict how households would adjust their consumption of private goods in response to changes in air pollution. The resulting benefit estimates were compared with 11 hedonic studies. It was believed that the hedonic estimates for MWTP would reflect households' valuation of all the benefits from reduced air pollution (both health and non-health). In this case, the hedonic estimates would exceed the marginal non-health benefits. Upon evaluating the two sets of results, the hedonic estimates did in fact provide an upper bound on the marginal benefits implied by their expenditure model. Thus, the hedonic results were interpreted as reinforcing the validity of *Mathtech's* estimates for the non-health increase in consumer welfare from decreased air pollution.[5]

<u>Private Litigation</u>

When hedonic models are used for private litigation, welfare measurement is not the main objective. The objective is to measure the decrease in property values induced by the introduction of an externality. Homeowners often use the court system to seek

[4] EPA believed that health benefits were already addressed by the primary standards for the criteria pollutants. Therefore, they sought to isolate the additional benefits from reduced expenditures on goods and services not related to health outcomes. Mathtech focused on four categories of expenditures: shelter, home operations, furnishing and equipment, and transportation.
[5] See Palmquist and Smith (2002) for a more thorough description of this example and other case studies describing how hedonic modeling has influenced decision-making at EPA.

compensation for private property externalities. To win their case, a plaintiff must convince the court of two things: (i) the value of their property decreased and (ii) the decrease was *caused* by the externality. To accomplish these tasks, the plaintiff typically hires an expert—either a real estate appraiser or an economist—to establish causation and measure the decrease in property values. Hedonic modeling is the primary technique that is used, and it usually succeeds in persuading judges and juries.[6] In his comprehensive review of litigation over environmental contamination of private property, Simons (2006) concludes that the hedonic property value model "is one of the few techniques that can stand alone in determining the effects of contamination of property value, provided sufficient accurate data are available."[7]

Given the importance of a homeowner's property in their wealth portfolio, it is not surprising that litigation is extensive. Table 2 provides a sense of the diversity of environmental externalities that have led to lawsuits. This summary is compiled from Simons's (2006) database of property-related toxic tort cases and awards between 1991 and 2004.[8] The wide range of per/plaintiff awards reflects variation in the severity of contamination and in the type of damages awarded. In some cases, the award is simply meant to compensate property owners for a decrease in the value of their homes. In other cases, punitive damages have been added.

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[6] The defense will often ask the court to throw out testimony by an expert witness based on the "Daubert" ruling that outlines four key factors which determine whether scientific evidence can be admitted: (1) the employment of scientific methodology; (2) peer review and publication of the methodology; (3) the potential rate of error; and (4) general acceptance. An economist using the hedonic method typically passes this hurdle.

[7] When there is not "sufficient accurate data available," other techniques have been used such as real estate trends analysis, contingent valuation, case studies, and matched appraisal pairs.

[8] This database is a collection of cases found to be of interest by MEALEYS' staff writers for practicing lawyers. See Simons (2006) for additional details about the 79 cases in the table.

To see how hedonic modeling can simultaneously establish causation and measure the damages to private property, consider the recent case of residents v. PEPCO. After a pipeline rupture in April, 2000 spilled 40,000 gallons of oil into Maryland's Patuxent river estuary, a group of 400 waterfront property owners sued PEPCO. To determine the impact on property values, an expert witness for the plaintiffs estimated a hedonic model using data on property sales *inside* and *outside* the contaminated area, *before* and *after* the pipeline rupture. This setup mimics a controlled experiment. Waterfront properties inside the contaminated area are the "treatment" group and comparable properties outside the contaminated area are the "control" group. Houses located in the contaminated area unexpectedly received the oil spill "treatment". Comparing the change in resale value for the treated properties with the change in resale value for the control properties isolates the change in property values that was *caused* by the oil spill. By using this "quasi-experimental" approach to hedonic modeling, the expert witness was able to provide compelling evidence that the oil spill caused the resale value of contaminated properties to decline by 10% to 12%.

Legal use of the quasi-experimental hedonic design dates back at least to Mendelsohn's analysis of PCB contamination in New Bedford Harbor (Mendelsohn et al. [1992], Palmquist and Smith [2002]). The distinguishing feature of the methodology is that the availability of panel data on property sales allows the expert witness to simultaneously demonstrate causality and measure the property value impacts of the externality. When the lack of panel data precludes a quasi-experimental design, establishing causality and measuring damages tend to become separate tasks. For example, causality may be established through site visits or anecdotal evidence, and damages may be assessed using a cross-section property value model or estimates from previous hedonic studies (Simons [2006]).

Summary

The difference in the way hedonic modeling has been used in private litigation and public policy previews the methodological issues at the heart of this paper. To summarize our main points in this subsection: (1) the hedonic model has had a real impact on public policy and private litigation; (2) the model is used differently in litigation and policy; (3) policy evaluation hinges on welfare measurement; (4) private litigation hinges on demonstrating causation and measuring damages; and (5) a quasi-experimental design is particularly well suited to litigation because it can simultaneously establish causation and measure damages.

Because the quasi-experimental design has a clear advantage in demonstrating causality, recent studies have sought to extend the methodology to estimate welfare measures and evaluate public policies. Is this approach valid? The extensive use of hedonic models for policy evaluation underscores the importance of considering the question.

2.3. New Questions about the Appropriate Use of Hedonic Models

Until recently, the leading strand of research on the hedonic property value model has mostly ignored time. The typical theoretical exposition of the model takes a short run perspective in the sense that the supply of housing is assumed to be fixed and markets are assumed to be in equilibrium (Palmquist [2005]). These assumptions are convenient because they allow us to treat the equilibrium hedonic price function as given which, in turn, allows us to interpret its partial derivatives as measures of the MWTP. Our theoretical model in section 2.1 is representative of this literature.

A short-run perspective on hedonic theory translates into a cross-sectional approach to econometric estimation of the hedonic price function. The key requirement for this econometric approach to be valid is that omitted variables must be uncorrelated with observed variables. Over the past few years, there has been increasing debate about the empirical plausibility of this condition and about the severity of the bias that results from violating it.

The debate has revolved around two microeconometric questions. Are conventional hedonic estimates for welfare measures plagued by omitted variable bias? If so, will the bias be purged through quasi-experimental application of panel data and instrumental variables? To date, there has been no resolution of either issue. For example, in a recent EPA-sponsored workshop on methods for estimating the social benefits of federal land cleanup and reuse programs, a major area of disagreement among participating economists was on the "limitations in the available hedonic models using data based on individual housing (or commercial/industrial) transactions to adequately separate the effects of hazardous waste sites from other spatial and temporal confounders" (Smith [2007b] p.17).

Advocates of the quasi-experimental approach argue that the conventional literature is plagued by omitted variable bias. Greenstone and Gayer (forthcoming) summarize this perspective. Greenstone and Gallagher (2008, p.997) are more specific about the implications for the hedonic model. They conclude that their study of whether hazardous waste matters for property values "contributes to a growing body of research…demonstrating that it is possible to identify research designs that mitigate the confounding that has historically undermined the credibility of conventional hedonic approaches to valuing nonmarket goods". Smith (2007a) makes the counterargument that much of the conventional hedonic literature *is* based on a valid research design despite the fact that quasi-experimental terminology has rarely been used to describe how confounding influences are addressed. He also observes that "experimentalists replace the assumptions of the older literature with new ones (p.302)".[9]

There is a long history of using repeat sales of individual homes to investigate how externalities are capitalized into residential property values (e.g. Brookshire et al. [1985] and Mendelsohn et al. [1992]).[10] Since these early applications, the literature has evolved to adopt the quasi-experimental language popularized by labor economists. More importantly, the literature has evolved to exploit temporal and spatial discontinuities in order to address omitted variable bias with greater precision. For example, in her work on the property value impact of school quality, Black (1999) exploits the discreteness in school district boundaries by comparing the prices of similar properties on opposite sides of a boundary. Pope (2008) combines this logic with a temporal discontinuity in real estate disclosure laws to measure the impact of new information on property values. Davis (2004) and Greenstone and Gallagher (2008) provide additional examples of how discontinuities in time and space can be used to

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[9] The "new" assumptions that he cites include the maintained assumption that there exists an integrated national market for housing, reliance on self-reported property values as opposed to data on homes that were actually sold, and the aggregation of these self-reported values over census tracts.

[10] The idea for using panel data to measure how changes in quality characteristics influence housing prices dates back at least to Bailey, Muth, and Nourse (1963). The economic applications begin with Palmquist (1982).

measure capitalization rates. Overall, this new empirical capitalization literature provides the strongest evidence to date that changes in amenities *cause* housing prices to change.

In the new empirical capitalization literature there is a tendency to interpret a carefully identified capitalization rate as a measure of MWTP. For example, Chay and Greenstone (2005, p.418) conclude that their study of whether air quality matters for property values demonstrates how “quasi-experimental approaches can be effective in estimating parameters derived from economic models (e.g., MWTP)”. Other recent quasi-experimental studies that have interpreted capitalization rates as a measure of welfare include Davis (2004), Greenstone and Gallagher (2008), and Linden and Rockoff (2008).

Equality between capitalization rates and welfare measures does not follow from Rosen (1974) or from the subsequent theoretical development of the hedonic property value model (Palmquist [2005]). To the best of our knowledge, there is no theoretical model that would imply capitalization rates can be interpreted as welfare measures. On the contrary, the capitalization literature is clear that, in general, capitalization rates do not identify welfare measures (Starrett [1981], Scotchmer [1986]). Thus, the relationship between capitalization rates and welfare measures needs clarification. To begin to formalize the connections between these two concepts, we return to our theoretical model of property values and extend it to consider how an exogenous shock to the hedonic equilibrium induces movement to a new equilibrium.

3. Hedonic Theory for the Capitalization of Market Shocks

Quasi-experimental studies measure how changes in public goods are capitalized into housing prices. In the context of hedonic theory, they track the movement from an initial equilibrium to a new equilibrium following some exogenous shock. To understand how the resulting capitalization rates relate to welfare measures we must consider the demand and supply conditions that govern how the equilibrium price function changes over time in response to shocks. The demand conditions are already defined by equations (2)-(3), leaving us to consider supply.

3.1. Using all the Economics of the Model to Track the Movement between Equilibria

In a housing market, the "producers" may include some combination of developers, contractors, and individuals interested in selling their homes. To formalize ideas let $C(M, X; \beta)$ denote a producer's cost function, where *M* is the number of type-*X* homes they sell and β is a vector of parameters describing each producer. For a developer or contractor, the cost function will reflect the physical, labor, and regulatory costs of building a particular home. For a homeowner, the cost function will reflect their psychological attachment to the home as well as the cost of making renovations. Variation in β captures differences in costs faced by different types of producers as well as all other sources of producer heterogeneity. We follow Rosen (1974) in treating each producer as a price taker who may be free to vary the number of units they sell as well as a subset of the characteristics of each unit. For notational simplicity, we assume that g is exogenously determined but that producers are free to vary the individual elements of X.[11] In this case, the profit maximization problem can be defined as (4).

[11] The main results of this section are not altered by allowing firms to choose *g* or by restricting their ability to choose *X*. The key restriction needed to relate our model to the new empirical capitalization literature is that *g* is at least partly determined by forces that are exogenous to our model.

(4) $$\max_{X,M} \ \pi = M \cdot P(g, X) - C(M, X; \beta).$$

Each producer chooses the X, M combination that maximizes their profits, given β. Equation (5) defines the corresponding pair of first order conditions.

(5) $$P(g, X) = \frac{\partial C(M, X; \beta)}{\partial M}, \qquad \frac{\partial P(g, X)}{\partial X} = \left(\frac{1}{M}\right)\frac{\partial C(M, X; \beta)}{\partial X}.$$

Producers choose *M* to set the sale price of the marginal home equal to its production costs, and they choose *X* to set the marginal per unit cost of each attribute equal to its marginal implicit price.

Equilibrium occurs when the first order conditions in (3) and (5) are simultaneously satisfied for all households and producers. This system of differential equations determines how the equilibrium hedonic price function arises from interactions between all the buyers and sellers in the market. Equation (6) rewrites the equilibrium price function in a way that acknowledges its dependence on the underlying distributions of household and producer characteristics.

(6) $$P(g, X) \equiv P\{\ g, X[g, F(y, \alpha), V(\beta)]\ , F(y, \alpha)\}.$$

Equilibrium levels of the endogenous housing characteristics, *X*, are determined by the following exogenous variables: *g* the public good of interest, $F(y, \alpha)$ the joint distribution of household income and preferences, and $V(\beta)$ the distribution of producer characteristics.[12] In other words, the endogenous features of the housing stock and the distribution of prices are simultaneously determined as equilibrium outcomes of the "sorting" process that clears the market for housing. At a single point in time all of the

[12] *M* is excluded from (6) for notational simplicity. In general, *X* may depend on *M*. However, since the equilibrium level of *M* can be written as a function of all the model primitives, *M* can be dropped from the expression for *X*. That is: $X\{g, F(y, \alpha), V(\beta), M[g, F(y, \alpha), V(\beta)]\} \equiv X[g, F(y, \alpha), V(\beta)]$.

arguments of the hedonic price function are fixed and we can use the left side of equation (6) as the basis for estimating the reduced-form equilibrium price function. The expression to the right of the equality illustrates the ways in which changes in the structural parameters change the shape of the price function over time.

The quasi-experimental capitalization literature aims to measure the rate at which exogenous shocks to *g* are capitalized into housing prices. Equation (7) illustrates the basic idea, using 0 and 1 subscripts to denote the arguments of the equilibrium price function in the pre-shock and post-shock equilibria.

$$(7) \qquad \frac{P_1\{\ g_1, X_1[g_1, F_1(y,\alpha), V_1(\beta)]\ , F_1(y,\alpha)\} - P_0\{\ g_0, X_0[g_0, F_0(y,\alpha), V_0(\beta)]\ , F_0(y,\alpha)\}}{g_1 - g_0}.$$

The rate at which the change in the public good is capitalized into housing prices is simply the difference quotient defined by the difference in the price function divided by the difference in *g*. In the special case when producer and household characteristics are constant and the change in the public good is infinitesimal, the difference quotient in (7) simplifies to the partial derivative in (3a). That is, the capitalization rate for *g* equals MWTP. In general, however, this equality does not hold.

In general, the reduced-form equilibrium price function is nonlinear with no closed-form solution.[13] The curvature of $P_0\{\cdot\}$ and $P_1\{\cdot\}$ depends on the level of each housing characteristic and on the distribution of household and producer characteristics in the pre-shock and post-shock equilibria. A non-marginal change in *g* may change the equilibrium levels of *X*, and any non-marginal change in *g* or *X* may change the shape of the equilibrium price function. For example, consider a large shock to *g* such as an

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[13] Ekeland et al. (2004) prove that nonlinearity is a generic property of the hedonic price function.

unexpected cancer cluster or a major flood. This would change the shape of the hedonic price function through the direct effect of g on $P\{\cdot\}$. A less dramatic shock could also change the shape of $P\{\cdot\}$ through the indirect effect of g on *X*.[14] Deteriorating air quality may induce households to install better air conditioning equipment; persistent drought conditions may decrease the share of new homes with pools. Finally, exogenous shocks to *X* may also change the curvature of $P\{\cdot\}$. A decrease in crime may increase the marginal value of proximity to parks in urban neighborhoods, for example.

Over time, changes in $F(y,\alpha)$ and $V(\beta)$ will also change the shape of the hedonic price function, whether or not these changes are related to g. For example, the environmental movement in the 1970s may have represented a fundamental change in household preferences for environmental amenities. Increasing incomes in the 1980s and 1990s may have driven the increasing supply of suburban "McMansions". The enactment of stricter zoning regulations in some parts of the U.S. over the past decade has increased development costs and led to higher development densities, which has influenced the structural features of new homes being built. All of these types of changes have the potential to confound our ability to interpret the capitalization rate for g as a measure of MWTP by driving a wedge between the partial derivatives of $P_0\{\cdot\}$ and $P_1\{\cdot\}$.

3.2. A Parametric Example

A parametric example may help to clarify the mechanisms that have the potential

[14] Scotchmer (1986) makes a similar point. Her theoretical model envisions households adjusting the size of their lot in response to changing environmental quality.

to confound the equality of capitalization rates and MWTP. Consider the special case where the supply of housing is fixed, utility is quadratic in housing characteristics, and preferences and housing characteristics are normally distributed. The advantage of this setup is that it produces a closed-form expression for the equilibrium price function.[15] Tinbergen (1959) first used this "linear-quadratic-normal" example to illustrate the properties of equilibria in labor markets with heterogeneous workers. Epple (1987) adapted the model to illustrate the consumer side of a hedonic equilibrium.

Let the consumer's utility from consuming *b* units of the numeraire and occupying a home defined by a vector of attributes $k = [g, X]$ be parameterized as follows:

$$(8) \qquad U = -(k-\alpha)' \frac{\Omega}{2}(k-\alpha) + b \, .$$

In the equation, α is a vector of individual-specific preferences and Ω is a positive definite diagonal scaling matrix. When k and α are both normally distributed such that $k \sim N(\mu_k, \Sigma_k)$ and $\alpha \sim N(\mu_\alpha, \Sigma_\alpha)$, the hedonic price function takes the following closed-form:

$$(9) \qquad P(k) = \Psi' k + k' \frac{\Gamma}{2} k \, , \quad \text{where } \Psi = \Omega\left(\mu_\alpha - \Sigma_\alpha^{0.5}\Sigma_k^{0.5}\mu_k\right) \text{ and } \Gamma = -\Omega\left(I - \Sigma_\alpha^{0.5}\Sigma_k^{0.5}\right).$$

All else constant, a non-marginal change in g will change each consumer's MWTP and will also change the shape of the equilibrium price function. In other words, the reduced-form parameters which describe the shape of the hedonic price function (Ψ, Γ) are themselves a function of the structural preference parameters $(\mu_\alpha, \Sigma_\alpha)$ and the parameters

[15] See Sattinger (1980) for closed form expressions for the hedonic price function under alternative sets of assumptions about market primitives.

which describe the distribution of characteristics that are conveyed through the choice of a home (μ_k, Σ_k).

In the pre-shock equilibrium, MWTP is defined by $\Psi_0 + \Gamma_0 k$. A non-marginal shock to *g* will change Ψ and Γ so that MWTP in the post-shock equilibrium equals $\Psi_1 + \Gamma_1 k$, where $\Psi_0 \neq \Psi_1$ and $\Gamma_0 \neq \Gamma_1$. Thus, the capitalization rate can be expressed as (10):

$$(10) \qquad \frac{P_1\{\cdot\} - P_0\{\cdot\}}{g_1 - g_0} = \frac{\Psi_1' k_1 + k_1' \frac{\Gamma_1}{2} k_1 - \Psi_0' k_0 + k_0' \frac{\Gamma_0}{2} k_0}{g_1 - g_0}.$$

As $(g_1 - g_0) \to 0$, $\Psi_1 \to \Psi_0$, $\Gamma_1 \to \Gamma_0$, and $(10) \to \partial P / \partial g$. In words: for an infinitesimal change in *g*, MWTP in the pre-shock equilibrium will equal MWTP in the post-shock equilibrium which will equal the capitalization rate. In contrast, for a non-marginal change in *g*, a non-marginal change in $(\mu_\alpha, \Sigma_\alpha)$, or a non-marginal change in (μ_k, Σ_k), the capitalization rate will not necessarily equal $MWTP_0$ or $MWTP_1$. Variation in the reduced-form hedonic parameters over time drives a wedge between capitalization rates and MWTP. Consider a shock that increases the amount of *g* for all homes. If demand curves are downward sloping, this will increase the price of housing, but decrease each household's MWTP for an additional improvement. In figures 1 and 2, this situation would describe the adjustment from the initial equilibrium at (g_1, g_2) to a new equilibrium at (g_1', g_2').

There is a growing movement in microeconometrics to bridge the gap between structural and quasi-experimental methods by searching for situations where treatment effects estimated from quasi-experimental models can serve as "sufficient statistics" for welfare measurement (Chetty [2008]). In the next section, we apply this logic to the hedonic model by formalizing restrictions on preferences and the data generating process that are needed for econometric estimates for capitalization rates to identify MWTP.

4. Sufficient Statistics for Quasi-Experimental Welfare Measurement

Hedonic models are estimated using data on housing prices and characteristics from individual real estate transactions. Unfortunately, it is typically impossible for the econometrician to observe every relevant characteristic. To acknowledge this limitation, we partition X into two components: H which represents characteristics observed by both households and the econometrician, and ξ which represents characteristics observed by households but not by the econometrician. Using the new notation, the hedonic price function can be rewritten as $P(g, H, \xi) = P(g, X)$.

The conventional cross-section approach to estimation and the more recent quasi-experimental studies all begin by selecting a parameterization for the equilibrium price function at a single point in time. While theory suggests that nonlinearity is a generic property of the equilibrium price function, empirical studies usually treat linearity as a maintained assumption.[16] To focus attention on the difference between capitalization rates and welfare measures we abstract from functional form issues and simply assume price is a linear function of housing characteristics. This simplification does not represent a loss of generality; our main results in this section can be applied to both linear and nonlinear functional forms.

Equation (11) depicts our parametric specification for the reduced-form

[16] In a Monte Carlo analysis, Cropper et al (1988) demonstrate that simple linear models often outperform more general specifications in a cross-section setting Monte Carlo analysis of how the accuracy in predicting MWTP varies across competing functional form assumptions.

equilibrium price function.

(11) $P_1 = g_1\theta_1 + H_1\eta_1 + \varepsilon_1(\xi_1)$.

In the equation θ is the marginal implicit price of the public good, η is a vector measuring the marginal contributions of the control variables, $\varepsilon = \varepsilon(\xi)$ is an error term that captures the composite effect of the unobserved variables, and the subscripts indicate the time period. The H_1 matrix of control variables may also include a vector of ones so that η includes an intercept.

Assuming (11) depicts the true equilibrium price function, the first order condition in (3a) implies θ_1 equals the average MWTP for *g* in period 1. In order for OLS estimation of (11) to provide an unbiased estimate of θ_1, the usual zero conditional mean assumption must hold: $E[\varepsilon_1(\xi_1) | g_1, H_1] = 0$. The perception that this condition is consistently violated in empirical applications is what motivates the quasi-experimental approach to estimation.

Suppose the same housing market can be observed in a new equilibrium following a shock to *g* that serves as a quasi-experiment:

(12) $P_2 = g_2\theta_2 + H_2\eta_2 + \varepsilon_2(\xi_2)$.

The reduced-form parameters of the new equilibrium price function have new temporal subscripts to acknowledge that its shape may have been altered by the shock to *g* or by other changes between the two time periods.[17] Subtracting the old price function from the new one yields the following expression:

[17] It is assumed that the new price function can be adequately represented by changing the parameters of the model as opposed to changing the functional form. This assumption is most appropriate for flexible functional forms. While we could rewrite the equations in this section using higher order polynomial functions of the covariates, for example, doing so does not change our basic results.

(13) $\Delta P = (g_2\theta_2 - g_1\theta_1) + (H_2\eta_2 - H_1\eta_1) + \Delta\varepsilon$.

In the special case where $\theta_1 = \theta_2$ and $\eta_1 = \eta_2$, the expression reduces to a more familiar version of the time-differenced model where the parameters lack temporal subscripts (e.g. Chay and Greenstone [2005]).

(14) $\Delta P = \Delta g\theta + \Delta H\eta + \Delta\varepsilon$.

Here, θ measures the rate at which changes in *g* are capitalized into the price of housing. In order for OLS estimation of (14) to provide an unbiased estimate of θ, $\Delta\varepsilon$ must be uncorrelated with Δg and ΔH .

Quasi-experimental studies argue that changes in the observed variables will be uncorrelated with changes in the unobserved variables such that $E[\Delta\varepsilon \mid \Delta g, \Delta H] = 0$.[18] However, this condition is insufficient to identify MWTP if the hedonic price function is altered by the shock to *g* that defines the quasi-experiment. This can be seen from equation (15), which expresses the expected value of θ from the first-differenced regression in terms of the parameters of the equilibrium price functions that precede and follow the shock.

(15) $$E[\hat{\theta}] = \theta_2 + \frac{r'g_1}{r'r}(\theta_2 - \theta_1) + \frac{r'H_1}{r'r}(\eta_2 - \eta_1),$$

where $r = \Delta g - \Delta H(\Delta H'\Delta H)^{-1}\Delta H'\Delta g$.

Put differently, equation (15) reports what we can expect to learn from estimating (14) when (13) is the true model and $E[\Delta\varepsilon \mid \Delta g, \Delta H] = 0$.

[18] There is reason for concern about this assumption. If unobserved features of the urban landscape are endogenously determined through households' location choices, the zero conditional mean assumption may be systematically violated (Kahn [2006]). For example, if a large improvement to air quality attracts better educated households then (unobserved) public school quality may improve. In this example, the capitalization of public school quality into property values would be incorrectly attributed to air quality.

The expected capitalization rate in (15) is a function of ex-ante MWTP, ex-post MWTP, and correlations between the various housing characteristics. The second term to the right of the equality is a "price effect" that arises from a change in the implicit price of *g* between the initial equilibrium and the new equilibrium. The third term is a "substitution effect" that arises from changes in the implicit prices of other housing characteristics that affect utility and, in some sense, serve as substitutes for *g*.

Clearly, some additional restrictions on preferences and/or the data generating process are needed to give the estimated capitalization rate a welfare theoretic interpretation. Three special cases have important implications.

<u>Case 1: No Restrictions</u>

If the demand for *g* is less than perfectly elastic, a non-marginal shock may change MWTP such that $\theta_2 \neq \theta_1$. In this case, the expected value of $\hat{\theta}$ may lie outside the interval defined by (θ_2, θ_1). For example, consider a quality improvement when demand is downward sloping but there is no change in the control variables or in their marginal implicit prices; i.e. $\theta_1 > \theta_2$, and $\Delta H = \beta_2 - \beta_1 = 0$. In this situation, (15) implies that $E[\hat{\theta}] < \theta_2$ if $\text{cov}(\Delta g, g_1) > 0$. Alternatively, $E[\hat{\theta}] > \theta_1$ if $\text{var}(\Delta g) < -\text{cov}(\Delta g, g_1)$. Thus, the relationship between the average capitalization rate and the average MWTP cannot be determined without imposing some additional restrictions on preferences and/or the data.

<u>Case 2: Restrictions on the Data Generating Process</u>

If the shock to *g* is not correlated with its initial level, or with the initial levels of the control variables, or with changes in those variables, the capitalization rate provides a theoretically consistent measure of average MWTP in the new equilibrium, even if the shape of the hedonic price function changes. More formally, it can be seen from (15) that $E[\hat{\theta}] = \theta_2$ if $E[\Delta H'\Delta g] = E[H_1 \Delta g] = E[g_1' \Delta g] = 0$. These three restrictions are testable. If they hold, $\hat{\theta}$ provides a consistent measure of average MWTP in the post-shock equilibrium. If they do not hold, the econometrician must impose additional restrictions on household preferences in order to draw conclusions about MWTP.

Case 3: Restrictions on Preferences

If every household's demand curve for every housing characteristic is perfectly elastic over the range of the changes in g and H and their demand curves are unaffected by other changes that occur between the two time periods that serve as reference points for measuring hedonic equilibria, then MWTP for each housing characteristic must be constant such that $\theta_1 = \theta_2$ and $\eta_1 = \eta_2$. In this case, equation (15) reduces to $E[\hat{\theta}] = \theta_1 = \theta_2$. Thus, the capitalization model in (14) provides an unbiased estimator of average ex ante MWTP which equals average ex post MWTP. This constant MWTP assumption is testable. In principle, equation (13) could be used to conduct a joint test of the null hypothesis that $\theta_1 = \theta_2$ and $\eta_1 = \eta_2$.

Numerical Examples

We return to the linear-quadratic-normal model from (8)-(9) to provide a brief Monte Carlo demonstration of how the correlation between g_1, Δg, H_1, and ΔH influences what can be learned about MWTP from observed capitalization rates. We assume there are three housing characteristics, $x = [g, h, \xi]$, the first two of which are observed by the econometrician. The data generating process is defined by the following parameters:

$$\alpha \sim N(\mu_\alpha, \Sigma_\alpha), \qquad \mu_\alpha = [20 \quad 50 \quad 25], \quad \Sigma_\alpha = \begin{bmatrix} 2 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 3 \end{bmatrix},$$

$$\text{(16)} \qquad x \sim N(\mu_x, \Sigma_x), \qquad \mu_x = [5 \quad 10 \quad 0], \qquad \Sigma_x = \begin{bmatrix} 2 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix},$$

$$\text{and} \qquad \Omega = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 3 \end{bmatrix}.$$

Under these assumptions, all three housing characteristics are normal goods, the demand for each is downward sloping, and the equilibrium hedonic price function is linear. Thus, the estimating equations in (11) and (12) are correctly specified.

We begin the Monte Carlo simulation by taking 1000 draws from the multivariate normal distributions in (16) and using them to calculate the initial equilibrium price function in (9). Then we generate a non-marginal shock to g_1 such that $\Delta g \sim N(3{,}0.25)$ and $\text{cov}(\Delta g, h_1) = \text{cov}(\Delta g, \xi_1) = \text{cov}(\Delta g, \Delta h) = \text{cov}(\Delta g, \Delta \xi) = 0$. Restricting the correlation between Δg and ($h_1, \Delta h, \xi_1, \Delta \xi$) allows us to focus on the wedge between capitalization rates and welfare measures that is driven by the price effect in (15). After solving for the new equilibrium price function, we measure the "capitalization bias" conveyed by interpreting the first-differenced estimates for θ from (14) as a measure of average MWTP. Repeating this process 1000 times allows us to calculate the expected capitalization bias.

Figures 3, 4, and 5 report our simulation results for three different values of

$\text{cov}(\Delta g, g_1)$. Each figure shows the implicit price function for g in the initial hedonic equilibrium and in the new hedonic equilibrium, as well as demand curves for two particular households. In all three figures, the increase in g increases the price of housing but decreases MWTP because the demand for g is downward sloping. These figures provide numerical examples of the conceptual illustration of hedonic equilibrium from figure 2.

In figure 3, g_1 and Δg are negatively correlated so that the areas with the lowest baseline levels of g receive the largest improvements. The covariance is defined such that $\text{var}(\Delta g) < -\text{cov}(\Delta g, g_1)$. These conditions place a sufficiently large upward bias on the first-differenced estimate for MWTP that its average value ($18.12) exceeds average MWTP in the initial equilibrium ($15). This effect could be interpreted as gentrification. Households with the highest MWTP for g drive up housing prices in the improved areas by more than the average resident would be willing to pay for the improvement.

Figure 4 demonstrates the opposite case where the areas with the highest baseline levels of g receive the largest improvements and $\text{var}(\Delta g) < \text{cov}(\Delta g, g_1)$. In this case, the first-differenced estimate for MWTP is biased downward such that its average value ($6.03) underestimates average MWTP in the new equilibrium ($11.85). This is consistent with Starrett's (1981) observation that in a sorting equilibrium (such as the hedonic model) there is little upward pressure on housing prices when the highest quality neighborhood experiences a further improvement. Intuitively, households who have previously chosen to live in lower quality areas have done so because they have a lower MWTP for g. These households are simply not in the market for homes in the highest quality areas.

Finally, figure 5 reports results from the special case where $\text{cov}(\Delta g, g_1) = 0$. This setup depicts a truly natural experiment in the sense that the Δg "treatment" is orthogonal to changes in all other variables and to the initial levels of each variable. In this case, equation (15) simplifies to $E[\hat{\theta}] = \theta_2$ so that the first-differenced estimate for θ provides an unbiased measure for MWTP in the new equilibrium. As expected, there is almost no difference between the average capitalization rate ($12.08) and average MWTP in the new equilibrium ($11.92).

5. Discussion

In a true experiment, the researcher could measure ex post MWTP by holding the control variables constant while randomly varying the amenity of interest. Unfortunately, few applications meet this requirement. The catastrophic events that have been exploited as natural experiments in the past, including earthquakes, hurricanes, and floods, tend to impact continuous geographic regions, which may induce correlation between the event and spatially correlated control variables such as local public goods or environmental amenities. This would imply $E[H_1' \Delta g] \neq 0$. Meanwhile, the public policies that tend to serve as the basis for quasi-experimental studies, such as the Clean Air Act and the Superfund program, have been explicitly targeted on the basis of existing environmental quality, so that $E[g_1' \Delta g] \neq 0$ by design.

Since few hedonic applications are truly natural experiments, the new empirical capitalization literature typically invokes the "perfectly elastic demand" or "constant MWTP" assumption in order to interpret capitalization rates as welfare measures. For example, in order to estimate MWTP for the large air quality improvements in the United

States during the 1970s, Chay and Greenstone (2005) explicitly assume MWTP is constant throughout the decade. Davis (2004) assumes the MWTP to reduce the risk of pediatric leukemia is unaffected by a six-fold increase in that risk. Greenstone and Gallagher (2008) assume that households' MWTP for Superfund-sponsored cleanup of hazardous waste sites was unchanged between 1980 and 2000.

The constant MWTP assumption may provide a reasonable approximation for small changes that occur over short time periods. However, it is natural for quasi-experimental applications to focus on large shocks and/or shocks that occur over long time periods. It takes a large shock to justify the assumption of re-equilibration of the housing market, especially if we acknowledge moving costs, imperfect information, and other sources of friction that limit households' willingness to move in response to small changes. Furthermore, it can take many years for markets to re-equilibrate following a shock. Over a longer time period a household's MWTP may change in response to changes in its wealth, information, or preferences.

Costa and Kahn (2003) provide preliminary evidence that MWTP does change over time. They use national housing and wage data from 1970 to 1999 to assess the degree of temporal variation in the marginal implicit price of living in a metropolitan area with a temperate climate. Their results imply that the implicit price doubled between 1970 and 1980, and then doubled again between 1980 and 1990. Thus, over a ten-year period when climate itself is relatively stable, Costa and Kahn observe a large change in its implicit price. It seems reasonable to expect similar trends for other public goods and environmental amenities which are conveyed through the location of a home.

6. Conclusion

We have argued that, in theory, the conventional approach to hedonic estimation and the newer quasi-experimental approach measure phenomena that are fundamentally different. It is well known that the conventional approach offers the potential to measure consumer welfare from a marginal change in an amenity. The quasi-experimental approach offers the potential to measure the rate at which changes in that amenity are capitalized into property values. Only under special circumstances will these two measures be equal. This is the main point of our paper and it deserves repeating. Under the general conditions of Rosen's (1974) theoretical model, we would not expect capitalization rates to equal MWTP. Thus, comparisons between conventional hedonic estimates and quasi-experimental hedonic estimates are generally invalid.

The fact that capitalization rates do not, in general, equal MWTP does not imply capitalization rates are uninteresting, unimportant, or irrelevant for public policy. Capitalization rates are certainly important to property owners and to the beneficiaries of public programs funded by property taxes. We have also argued that the quasi-experimental approach to hedonic modeling is uniquely suited to the task of private litigation. By simultaneously demonstrating causality and measuring damages, a quasi-experimental hedonic model can provide convincing evidence for judges and juries that urban and environmental externalities do impact residential property values.

Moving from theory to practice, we have good reason to believe that the conventional hedonic model and the quasi-experimental model *both* generate biased estimates for MWTP. In the conventional model, the bias stems from omitted variables. While the quasi-experimental model can purge omitted variable bias, we have argued that consumers' MWTP may change over the duration of the quasi-experiment. In some cases, the shock that forms the basis for the experiment may also shock MWTP. In other cases, MWTP may adjust to changes in other exogenous factors. In either case, the quasi-experimental "cure" to omitted variable bias may be worse than the conventional "symptoms".

The relative importance of omitted variable bias and capitalization bias is an important empirical question that deserves further research. Spatial dummies provide one way to control for omitted variables without the need for data from multiple hedonic equilibria. Likewise, it may be possible to avoid capitalization bias by controlling for changes in the hedonic price surface within a quasi-experimental design. One approach would be a "differences-in-differences" type estimator that interacts an ex-post dummy variable with every other independent variable. This would make it possible to simultaneously estimate ex-ante MWTP and ex-post MWTP. Dual estimates for MWTP from a single market could also serve as an input to "second-stage" models of the demand for an amenity.

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FIGURE 1.—Equilibrium Bid Functions for Housing as a Function of *g*

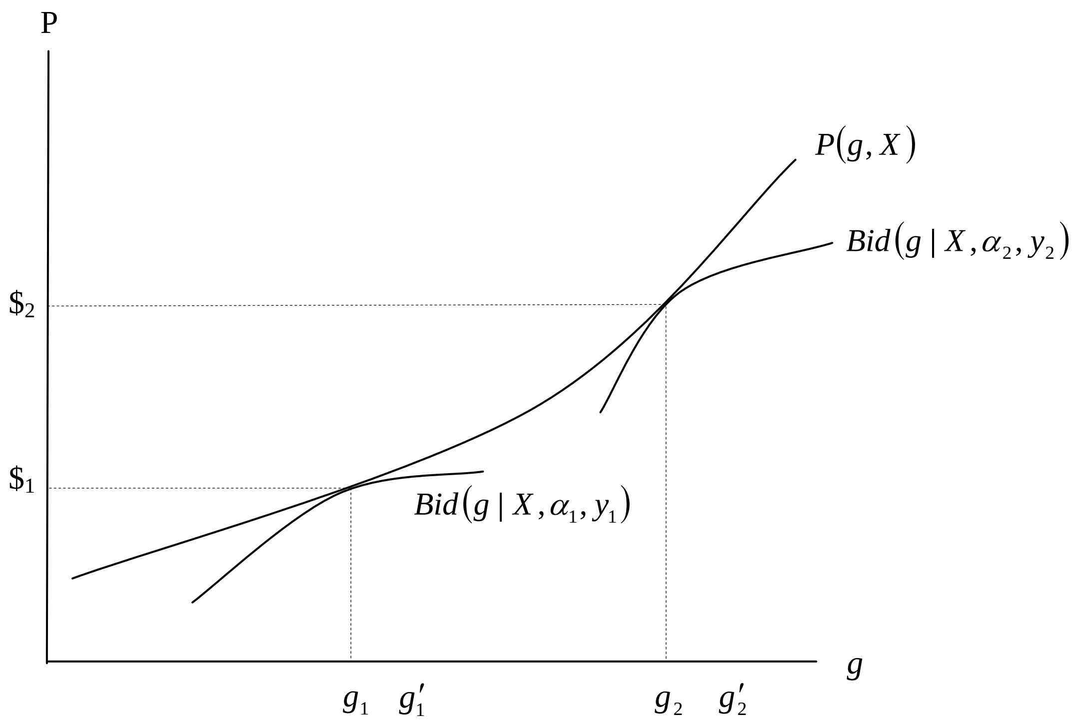


FIGURE 2.—Implicit Price Function for *g* and Demand Curves for Two Households

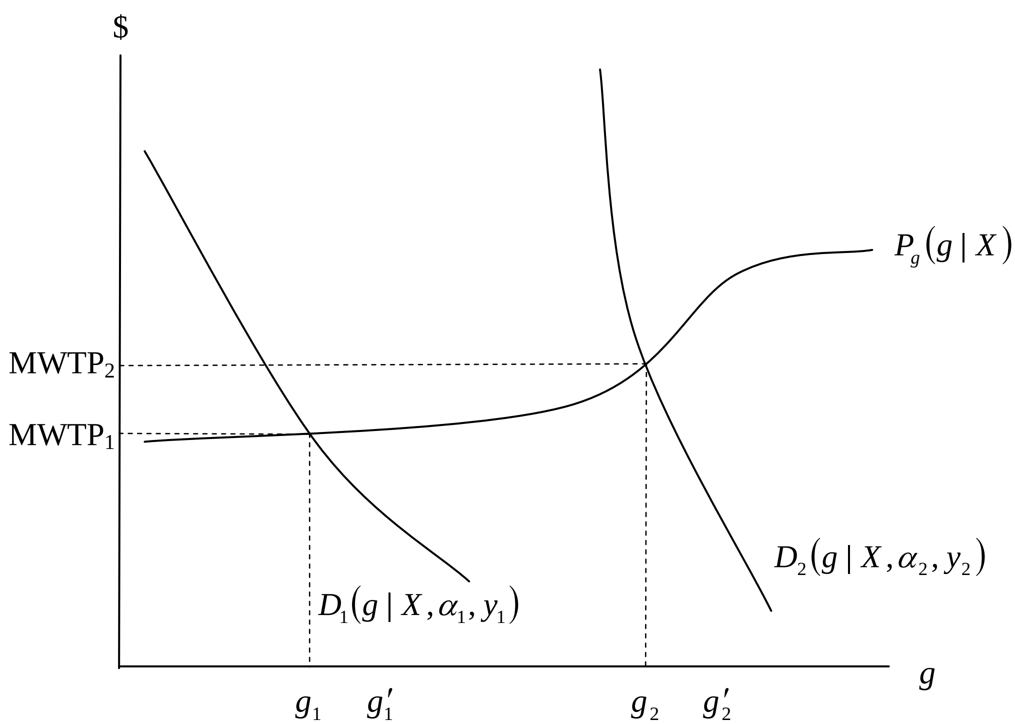
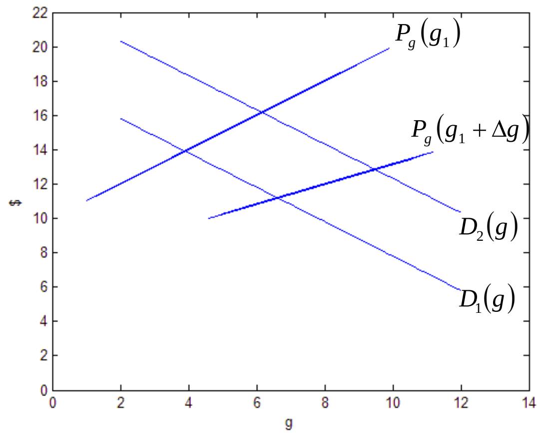


FIGURE 3: $\text{cov}(\Delta g, g_1) = -0.5$

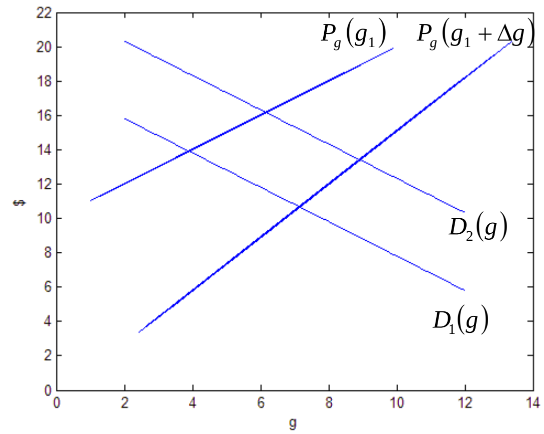


$\theta_1 = 15.0$

$mean(\theta_2) = 11.97$

$mean(\hat{\theta}_{FD}) = 18.12$

FIGURE 4: $\text{cov}(\Delta g, g_1) = 0.5$

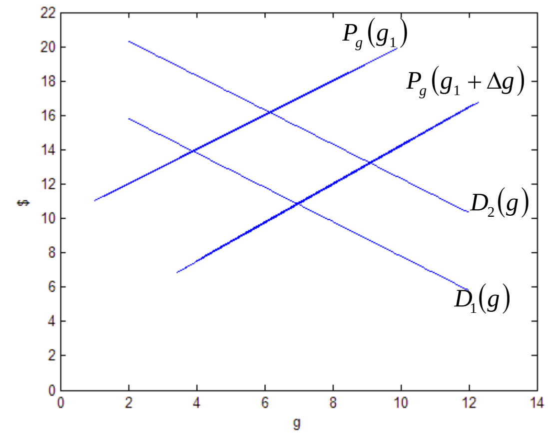


$\theta_1 = 15.0$

$mean(\theta_2) = 11.85$

$mean(\hat{\theta}_{FD}) = 6.03$

FIGURE 5: $\text{cov}(\Delta g, g_1) = 0.0$



$\theta_1 = 15.0$

$mean(\theta_2) = 11.92$

$mean(\hat{\theta}_{FD}) = 12.08$

<u>Note</u>: Each of these figures is showing a numerical example of figure 2 derived from the linear-quadratic hedonic model. All characteristics other than g are held constant as g changes. D_1 and D_2 are the demand curves for two individual consumers, $P_g(g_1)$ is the marginal implicit price function for g in the initial equilibrium and $P_g(g_1 + \Delta g)$ is the implicit price function in the new equilibrium after g changes. The means are based on 1000 Monte Carlo replications.

Table 1: EPA and USDA Sponsored Research Involving Hedonic Applications over the Last 10 Years

Investigators	Ending Year of Grant	Grant Title	Primary Amenity/Disamenity	Total Grant Amount
Examples of EPA/NSF Funding				
Mark Thayer, James C. Murdoch, and Kurt Beron	1998	Improving Air Quality Benefit Estimates from Hedonic Methods	Air Quality	165,553
V. Kerry Smith, and Holger Sieg	2004	The Role of Locational Equilibria and Collective Behavior in Measuring the Benefits of Air Pollution Policies	Air Quality	228,512
Jacqueline Geoghegan	1998	Ecosystem Valuation: Policy Applications for the Patuxent Watershed Ecological Model	Ecosystem Health	138,724
Gordon C. Rausser	1998	Stigma of Environmental Damage on Residential Property Values	Hazardous Waste Sites	56,001
V. Kerry Smith, Raymond B. Palmquist, and Daniel J. Phaneuf	2004	Measuring Economics Benefits for Amenity Consequences of Land Cover Changes	Water Quality	342,691
James Boyd, and David R. Simpson	2001	Indicators of Ecosystem Value: Deriving Units of Exchange for Habitat Trades, Banking and Preservation Priorities	Wetlands	333,153
Examples of USDA/NRI Funding				
D. McLeod, K. Inman, and R. Coupal	2001	The Impacts of Amenity Values on Agricultural Lands Conservation: Community Preferences and Property Values in the Rocky Region	Agricultural Lands	158,644
M. Espey, and L.R. Gering	2005	Forces of Change in the Rural/Urban Interface: Residential Land Use	Urban Fringe Landscape	132,923
D.M. Theobald, S.A. Wiler, R.W. Kling, and G.N. Wallace	2005	Maximizing Protection of Ecological, Agricultural, and Community Values at the Rural-Urban Fringe	Urban Fringe Landscape	201,600
B. Golden	2009	Evaluation of Policy Options Aimed at Achieving a Reduction in Groundwater Consumption in Western Kansas	water rights	83,500
G. W. Brester	2009	Quantifying Recreational Amenities as a Means of Ecologically Sustaining Small and Medium-Sized Farm and Ranch Profitability	recreation amenities	295,100
			Total:	**2,136,401**

Note: This information was collected by searching the EPA/NSF Research Funding data at the National Center for Environmental Economics (NCEE) and the Current Research Information System (CRIS) at the United States Department of Agriculture (USDA) websites. Searches were conducted using the keywords "hedonic", "property value" and "housing prices." Each grant's abstract that was returned in these searches was then read to determine if hedonic property value estimates appeared to be a major component of the grant's activities. However, there may be other relevant grants by these two funding agencies that we did not discover using our search criteria. The "Total Grant Amount" reported in the table was converted to 2008 constant dollar amounts using the CPI.

Table 2: Property-related toxic tort cases and Awards between 1991 and 2004

Environmental and Urban Disamenities / Contaminants	Legal Cases (Verdicts and Settlements)	Per Plaintiff Median Net Award
Toxic mold	6	20,422
Landfill	7	23,687
Trichloroethylenes (TCEs)	4	9,928
Polychlorinated biphenyls (PCBs)	5	48,727
Water	6	520,328
Air Pollution	3	17,087
Insecticide / pesticide / herbicide	4	5,627,383
Oil spill	13	36,538
Leaking underground storage tank	8	32,468
Asbestos	4	127,273
Arsenic / mercury / uranium / lead	5	7,707
Other / nuisance / EMFs	10	35,248
Superfund / hazardous waste	4	1,020
TOTAL / AVERAGE	79	500,601

Note: Adapted from Tables 13-1 and 13-3 in Simons (2006). "Legal Cases" include both verdicts and settlements. "Per Plaintiff Median Net Award" is an average of the median net award per plaintiff for verdicts and the median net award per plaintiff for settlements. The term "net" is used because expenses for expert witnesses and legal fees have been deducted.