Welfare Measurement and Policy Evaluation in a Dual-Market Locational Equilibrium

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Abstract: This paper uses a model of sorting behavior across housing and labor markets in the San Francisco and Sacramento Consolidated Metropolitan Statistical Areas to evaluate the distributional welfare implications of California’s new standard for ambient ozone concentrations. The model depicts working households who differ in their job skills and in their relative preferences for multiple public goods making a joint job-house choice among housing communities and labor markets that differ in the job opportunities and public goods they provide. Households reveal features of their preferences through the locations they choose, and these choices determine spatial variation in the demand for housing and the supply of labor. A companion paper develops a structural estimator which recovers preferences for public goods from the observed sorting behavior of working and retired households (Kuminoff [2007]). After combining information about preferences with information about the supply of housing and the demand for labor, the model of sorting behavior is used to simulate how wage rates, housing prices, and people’s location choices would adjust to the air quality improvements needed to meet California’s new standard. Converting these results into welfare measures suggests annualized benefits range from $292 to $346 per household. These estimates are less than half the size of approximations based on the standard practice of multiplying the average marginal willingness-to-pay by the size of the ozone reduction.

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I. Introduction

More than 50 years ago, Charles Tiebout (1956) suggested that people sort themselves across space according to their preferences for the public goods that differentiate urban neighborhoods. This simple proposition underlies the traditional hedonic approach to estimating the benefits from changes in public goods. More recently, advances in sorting research have produced a new framework for policy evaluation which combines the information provided by an equilibrium hedonic price function with a formal description of the choice process that explains how heterogeneous households sort themselves across differentiated neighborhoods (Epple and Sieg [1999]; Bayer et al. [2007]). These “equilibrium sorting” models directly manifest Tiebout’s logic. They use the properties of market equilibria, together with information on households and their location choices, to estimate structural parameters which characterize heterogeneity in preferences for local public goods. The results can be used to develop theoretically consistent predictions for the distributional welfare implications of future policy changes. Analysis is not limited to marginal effects or a partial equilibrium setting. By characterizing the sorting process, the analyst can predict how households would adjust their behavior in response to large-scale changes in public goods or other amenities (Sieg et al. [2004]).

Understanding how people differ in their preferences is important for designing new policies and evaluating their impacts. For example, Blinder and Rosen (1985) demonstrate how information about preference heterogeneity can, in principle, be used to design more efficient taxes on private goods. Equilibrium sorting models provide the means to implement their idea and extend it to consider policies which target public goods or environmental amenities that affect people differently. Likewise, to evaluate the welfare implications of a new policy which affects people differently, the analyst must understand how people differ in their willingness-to-pay for the associated change in public goods.

Equally important for policy evaluation is the need to recognize that people may adjust their behavior in response to large-scale changes. For example, Banzhaf and Walsh (forthcoming) find that when industrial facilities which emit toxic chemicals move into a neighborhood, some residents move out. When these facilities move out, new residents move in. The price adjustments needed to clear the housing market following these shocks will affect the welfare of homeowners and renters. Recent studies have demonstrated that shocks to spatially
delineated amenities such as cancer risk (Davis [2004]), air quality (Chay and Greenstone [2005]), flood risk (Pope [forthcoming]), and the presence of registered sex offenders (Linden and Rockoff [forthcoming]) can produce economically significant changes in property values.

The objective of this paper is to use a model of equilibrium sorting in Northern California’s two largest population centers, the San Francisco and Sacramento Consolidated Metropolitan Statistical Areas, to evaluate the benefits from the state’s new standard on ambient ozone concentrations. In May of 2006, California reduced its 8-hour ozone standard to 0.070 parts per million. Meeting this standard would require a large change in the spatial distribution of air quality in the study region. Natural weather patterns limit ozone accumulation in the San Francisco Bay Area so that many of its communities already meet the new standard. Meanwhile, Sacramento is located in one of the four most polluted air basins in the United States, and would require ozone reductions of up to 28%. This change is sufficiently large to expect that, if met, it may influence where some households decide to live.

While the San Francisco and Sacramento metropolitan areas are adjacent, their major business districts are 80 to 120 miles apart—far enough to limit commuting. Thus, for working households, moving to a new home may require finding a new job or adjusting to a different commute. More generally, it is important to consider how labor markets influence the way households adjust to large-scale changes because historical evidence on sorting behavior and recent survey data both suggest that job opportunities may be the dominant factor in determining where households choose to live (Rhode and Strumpf [2003]). For example, the annual American Housing Survey consistently reports “proximity to employment” as the reason most frequently cited by households for choosing to live in their current neighborhood.

The model developed in this paper extends the equilibrium sorting framework from Epple and Sieg (1999) and Sieg et al. (2004) to recognize that working households make a joint job-house choice. In this new “dual-market” framework, a location conveys a set of job opportunities together with local public goods, while working households differ in their job skills and in their relative preferences for those public goods. A companion paper, Kuminoff (2007), develops a structural estimator which recovers information on job skill and preferences for public goods from data on the characteristics of working households and their location choices in both markets. The results from estimating the model for the San Francisco-Sacramento region
are used here to simulate how households, prices, and wages would adjust to the large-scale improvements to air quality required to meet California’s new ozone standard.

The dual-market framework and Epple and Sieg’s model are both used to evaluate the distribution of benefits from California’s new ozone standard. Moving to the dual-market framework increases benefit estimates by 55% for the average household. However, this figure aggregates over order-of-magnitude differences for households in the communities which experience the largest reductions. The results also indicate that approximations to welfare measures based on the standard practice of multiplying average marginal willingness-to-pay by the size of the change would overstate benefits by up to 336%.

The remainder of the paper is organized as follows. Section II develops a model of sorting behavior in the spirit of Tiebout’s original model, and then generalizes it to recognize that working households make a joint job-house choice. After formalizing the conditions for a dual-market locational equilibrium, this concept is compared to alternative equilibrium concepts from the hedonic and sorting literatures. Section III develops a parametric version of the model and uses it to illustrate how assumptions about heterogeneity in preferences and job opportunities influence estimated welfare measures. Section IV summarizes the data and results from estimating the model for Northern California and discusses the parameter estimates used to calibrate the policy simulation. Section V translates California’s new ozone standard into a spatial distribution of air quality for the policy simulation, and section VI develops the general equilibrium model and interprets the results. Finally, section VII summarizes the policy implications and provides some concluding remarks.

II. Characterizing a Dual-Market Locational Equilibrium

To begin, divide the urban landscape into a finite set of $J$ housing communities, each of which differs in its price of housing ($p_j$) and in its provision of a vector of local public goods, ($g_j$).

Public goods are defined broadly to include services produced from local taxes, such as school quality and police and fire protection, as well as environmental amenities such as air quality and access to open space. Households may differ in the relative importance they assign to each of these public goods. To reflect this heterogeneity, let $\gamma$ represent relative preferences, and $\bar{g}_j(\gamma)$ represent the composite provision of public goods in community $j$ as perceived by a $\gamma$–type
household. All households are assumed to be price-takers, to have perfect information, and to be freely mobile. Each one will choose the community that maximizes its utility, given its income \( y \) and its preferences \( \alpha \) for public goods relative to private goods.

Utility maximization can be represented as a two-stage problem, where each household first determines the optimal quantities of housing and numeraire in every community and then chooses the community that maximizes its utility. The first stage is shown as equation (1).

\[
\max_{(h,b)} U \left[ g(y), h, b, \alpha \right] \text{ subject to } ph = y - b. \tag{1}
\]

Conditional on a community, a household will choose quantities of housing \( h \) and a composite private good \( b \) to maximize its utility subject to the budget constraint. Assuming households are free to purchase continuous quantities of housing at the market price in each community, preferences can be restated using the indirect utility function in (2).

\[
V[g(y), p, \alpha, y] = U \left[ g(y), h(g(y), p, \alpha, y), y - ph(g(y), p, \alpha, y), \alpha \right]. \tag{2}
\]

Each household will choose the community that provides its preferred bundle of public goods, given its (exogenous) income and prices. This is “Tiebout sorting”.

To recognize that working households face differentiated job opportunities, divide the urban landscape along a second dimension into \( K \) labor markets that differ in the wage paid to workers of each job skill. With \( J \) housing communities and \( K \) labor markets, each \( (j,k) \) pair represents a unique job-house combination, which will be described as a “location”. Each location requires a specific commute. For a household that commutes between \( j \) and \( k \), let \( w_{j,k}(\theta) \) represent wage earnings less the value of time spent commuting, where \( \theta \) is a vector describing the worker’s job skill and their shadow value of time.\(^1\) Therefore, a working household’s total income can be represented by \( nw + w_{j,k}(\theta) \), its exogenous non-wage income \( (nw) \) plus its “virtual wage income”. Holding their job location and nominal wage fixed, a household can vary their virtual wage income by changing their house location, which changes their commute time.

\(^1\) The \( k \) subscript on the wage function recognizes that, conditional on skill, a worker may be compensated differently in different labor markets due to variation in technology, regulation, agglomeration, or other factors which affect labor demand.
Utility maximization is similar to (2) except that households now choose both a home and a job. Equation (3) formalizes this problem for household $i$.

$$\max_{jk} V\left[\bar{g}_j(y_i, p_j, \alpha, y_{ijk})\right], \quad \text{where} \quad y_{ijk} = nw_i + w_{jk}(\theta). \quad (3)$$

A working household will choose the job-house combination that maximizes its utility, recognizing that its wage income will be determined by that choice. For a retired household, $y_i = nw_i$, and the location choice problem reduces to the more familiar one of selecting a housing community.

Utility maximization is a necessary, but not sufficient, condition for the existence of a locational equilibrium. A dual-market locational equilibrium must also be characterized by vectors of housing prices and wage rates such that all markets clear and no household could improve its utility by moving. These conditions are formalized in (4).

$$V\left[\bar{g}_j(y_i, p_j, \alpha, y_{ijk}(\theta))\right] \geq V\left[\bar{g}_l(y_i, p_l, \alpha, y_{ilk}(\theta))\right] \quad \forall \ i, l, m \quad (4.A)$$

$$H_j^p[p_j] = H_j^D[p, g, f(\alpha, \gamma, \theta, nw)] \quad \forall \ j \quad (4.B)$$

$$L_k^w[w, p, g, f(\alpha, \gamma, \theta, nw)] = L_k^D[w_k(\theta)] \quad \forall \ k \quad (4.C)$$

Equation (4.A) simply says that every household chooses the location which maximizes its utility. These choices, in turn, determine spatial variation in the demand for housing and the supply of labor. Equation (4.B) provides the market clearing condition for housing in community $j$. Supply equals demand, and of course both depend on the price of housing. In general, the demand for housing will also depend on the characteristics of communities and job opportunities which influence where households choose to locate. Thus, the demand for housing depends on wages, local public goods, and $f(\alpha, \gamma, \theta, nw)$, the joint density of non-wage income, preferences, and job skills in the population of households. Equation (4.C) provides a parallel equilibrium condition for labor market $k$. The supply of labor depends on the wages offered to workers, on the characteristics of households, and on the characteristics of communities.

The dual-market locational equilibrium in (4) combines features of the equilibrium
concepts that underlie models of Tiebout sorting and interregional models of hedonic equilibria. As in the sorting literature, households choose from a discrete set of communities according to their heterogeneous preferences for local public goods (e.g. Epple and Seig [1999]; Bayer and Timmins [2007]). As in the interregional hedonic literature, workers may be compensated differently if they move between labor markets (e.g. Rosen [1979]; Roback [1982]). In addition to integrating these features, the equilibrium summarized in (4) generalizes both literatures to recognize that households may choose to live in one labor market and work in another. Importantly, the ability to commute expands the ways in which households can adjust to a shock. They can move to a different community, as in the sorting literature. They can change their job and their house simultaneously by moving to a different labor market, as in the interregional hedonic literature. Or they can choose to remain in the same community (labor market) and commute to a different labor market (community). Figure 1 illustrates how this spatial landscape (panel D) differs from hedonic property value models (panel A), interregional hedonic models (panel B), and models of Tiebout sorting (panel C).

The theoretical properties of a dual-market locational equilibrium do not provide clear predictions for what we can expect to learn about the willingness-to-pay for public goods from hedonic rent and wage functions. This is because the model relaxes two key assumptions of the hedonic framework. First, households are not free to choose continuous quantities of every public good. School quality may vary discretely from school district to school district, for example. Without continuity we cannot invoke the first-order conditions from Rosen’s (1974) model to interpret a partial derivative of a hedonic rent function as a measure of the willingness-to-pay for a marginal change in a public good. Second, the key result from Roback’s (1982) interregional hedonic model—that the full implicit price of a public good is measured by combining rent and wage differentials—relies on the assumption that people live and work in the same place. Commuting breaks the connection between changes in public goods, rents, and wages at a point in space. For example, consider households who live in community A and work in community B. An exogenous shock to A’s air quality may be partly capitalized into B’s wages.

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2 Bajari and Benkard (2005) provide a general discussion of the implications of discrete and continuous choice sets in hedonic models of differentiated product markets and Bayer et al. (2007) provide additional intuition for the connection to structural models of sorting behavior.
Is commuting empirically important? Interregional hedonic applications typically define a location as a county (Blomquist et al. [1988]; Chay and Greenstone [2005]) or as a metropolitan area (Roback [1982]; Bayer et al. [2006]). According to year 2000 Census worker flow files, 27% of U.S. workers live in one county and work in another, and 10% of workers commute between primary metropolitan statistical areas (PMSA). These national shares seem sufficiently large to warrant further investigation. Moreover, national shares will tend to underestimate commuting rates in highly urbanized areas such as Boston, Los Angeles, and San Francisco, which have provided the setting for empirical studies of Tiebout sorting (Epple and Seig [1999]; Seig et al. [2004]; Bayer et al. [2007]). For example, 19% of the workers who live in the San Francisco consolidated metropolitan statistical area commute between PMSAs in the region. On average, these workers spend 106 minutes commuting to and from work every day. If wage income were exogenous to job location, one would expect these workers to work closer to home.

When households choose among a discrete set of communities and some households choose to commute between communities, we cannot exploit the results from Rosen (1974) and Roback (1982) to interpret the partial derivatives of hedonic rent and wage functions as exact welfare measures for marginal changes in public goods. Nevertheless, households’ behavior can reveal features of their preferences which make it possible to estimate the demand for public goods, the demand for housing, and the supply of labor. To exploit this information, we must be willing to impose some parametric restrictions on the shape of a household’s utility function.

III. A Parametric Representation of Dual-Market Sorting

A. Utility Maximization by Working Households

We will assume that an individual household’s utility can be represented by the following CES function:

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3 Technically, Roback (1982) uses data from 98 U.S. cities. However, these “cities” are often defined in a way that effectively aggregates over primary metropolitan areas, such as the “city” of San Francisco-Oakland, or they tend to be the central city of a metropolitan area, such as Washington D.C.
\[ V_{jk} = \left\{ \alpha_i \left( G_j \right)^\rho + \left[ \exp \left( \frac{y_{jk} - 1}{1 - \nu} \right) \exp \left( - \frac{\beta P_{jk}^{\eta+1} - 1}{1 + \eta} \right) \right]^{\rho} \right\}^{\frac{1}{\rho}}, \]

where \( G_j = \gamma_1 g_{1j} + \ldots + \gamma_{N-1} g_{N-1j} + \gamma_N \xi_j \), and \( y_{jk} = n w_i + \theta_{i} w_{zk} \left( 1 - \theta_{i} t_{jk} \right) \).

The first term in the function represents utility from public goods, and the second represents utility from the private good component of housing. All households are assumed to share the same elasticity of substitution between public and private goods (\( \rho \)), and the same housing demand parameters: price elasticity (\( \eta \)), income elasticity (\( \nu \)), and demand intercept (\( \beta \)).

Households differ in their relative preferences for a linear index of public goods provided by each community. They differ in the weights they place on each public good in the index \( \left( \gamma_1, \ldots, \gamma_N \right) \) and in their overall preferences for public goods relative to private goods (\( \alpha_i \)). The index weights are normalized to sum to 1, which allows \( \alpha_i \) to be identified separately as a scaling parameter on the strength of preferences.\(^4\) Of the \( N \) public goods in the index, \( N-1 \) are observable. The \( N^{th} \) public good (\( g_{Nj} = \xi_j \)) is observed by households but not by the analyst.\(^5\)

A household’s income is defined by the sum of its exogenous non-wage income and wage income, less the value of time spent commuting. The primary earner of each household is assumed to possess skills that qualify them for a certain occupation (e.g. accountant, construction worker). This observable component of job skill is indexed by \( z \). In labor market \( k \), the average wage for that occupation is \( w_{zk} \). However, a worker’s ability to collect that wage if they were to move from their current job depends on features of their job skill, such as education, experience, and ability. These features are reflected in a single heterogeneous parameter, \( \theta_{ik} \), that represents each worker’s labor market mobility within their occupation. For example, if \( \theta_{ik} \) is greater (less) than 1, the worker would earn more (less) than the average wage for their occupation if they were to move to a new labor market. The wage in each job location is also adjusted for required

\(^4\) \( \alpha_i \) is extraneous in the sense that it is only identified by a normalization to the weights in the public goods index. Nevertheless there are two reasons for including it in the model. First, it helps to illustrate the connection to Epple and Seig (1999). Second, normalizing the weights in the public good index simplifies estimation.

\(^5\) One can interpret \( \xi \) as a theoretically consistent index of \( M \) unobserved attributes as long as households share the same index weights. Since \( \xi \) is the only structural error, equation (5) exemplifies the “pure characteristics” approach to modeling the demand for a differentiated product (Berry and Pakes [2007]).
commute time. $t_{jk}$ is the ratio of commute time to work time, and $\theta_{i2}$ represents the worker’s shadow value of time as a share of the wage rate. If $\theta_{i2} = 0$, effective wage income equals actual wage income. At the other extreme, if $\theta_{i2} = 1$, the worker’s shadow value of time equals their wage rate.

The demand for housing and the supply of labor depend on all the parameters of the indirect utility function. For each community, the residual demand for housing is calculated by aggregating over the individual demands of all the households who maximize their utility by choosing to live there.\(^6\) Applying Roy’s Identity to (5) produces the following expression for an individual household’s demand:

$$h_i = \beta p_j^y y_i^r.$$ \hspace{2cm} (6)

To develop an expression for market demand, let $\Omega_{jk}$ denote the set of values for the heterogeneous parameters such that location $jk$ maximizes utility, given values for the housing demand parameters and the elasticity of substitution,

$$\Omega_{jk} = \{ (\alpha, \gamma, \theta) : V_{ik}(\cdot | \beta, \eta, v, \rho) \geq V_{ik}(\cdot | \beta, \eta, v, \rho) \quad \forall \quad l, m \} , \hspace{1cm} (7)$$

and let $I_{ijk}$ be an indicator function which equals 1 if household $i$’s preferences and skills belong to the $\Omega_{jk}$ set. Then the aggregate demand for housing in community $j$ can be written as (8).

$$H^D_j = \sum_{k} \sum_{i} I_{ijk} \beta p_j^y [n w_i + \theta_{i1} w_{ik} (1 - \theta_{i2} t_{jk})]. \hspace{2cm} (8)$$

The supply of labor can be defined analogously. Assuming workers each work 40-hour weeks, we can measure the labor supply in terms of the number of workers:

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\(^6\) In this model, housing is treated as a homogeneous commodity. Of course, housing is not homogenous. Its structural characteristics (e.g. bedrooms, bathrooms, sqft.) vary within communities, and these differences will be reflected in observable sale prices. This can be addressed if structural characteristics enter the direct utility function through a separable sub-function that is HOD 1. Under this restriction, Sieg et al. (2002) demonstrate that the equilibrium hedonic price function will be separable in the structural characteristics of houses and the effect of public goods. In this case, community-specific fixed effects estimated from a hedonic regression can be used to construct a theoretically-consistent index for the cost of consuming public goods in each community.
\[ I_k^L = \sum_j \sum_l I_{jk} . \] (9)

As in (4) the demand for housing and the supply of labor both depend on the distribution of prices, wages, and local public goods across the urban landscape, and on the distribution of preferences, skills, and income in the population of households.

The parametric specification in (5)-(9) captures the key features of a dual-market locational equilibrium. Households with heterogeneous preferences and skills make a joint job-house choice and their collective behavior determines spatial variation in the supply of labor and the demand for housing. The model also nests Epple and Seig (1999) as a special case. In their model, income is exogenous to location choice, households have identical relative preferences for public goods, and the shape of the joint distribution of income and preferences is assumed to be known. To recover their specification from (5) simply drop the job skill \((\theta_1)\) and time cost \((\theta_2)\) parameters, drop the \(i\) subscripts on \(\gamma_{oi}, \ldots, \gamma_{oiN}\), and assume \(f(\alpha, y)\sim \text{lognormal}\). These restrictions simplify estimation, but they have the potential to influence policy implications.

Kuminoff (2007) discusses the identification of the model in (5)-(9) and develops an estimator which recovers all the parameters of the indirect utility function from information on the sorting behavior of working and retired households. He uses the estimator to decompose the extent to which assumptions about preference heterogeneity and job opportunities influence estimates of the willingness-to-pay for marginal changes in air quality. Estimates of marginal willingness-to-pay are frequently used to develop “first-order” approximations to the benefits from non-marginal changes in public goods. The advantage of this approach is that it is easy to implement. The disadvantage is that it is best suited to small changes. When the results from a marginal analysis are used to predict the effects of a large-scale change in public policy, the predictions can be extremely inaccurate (Heckman et al. [1997]). This is important because public policies which target air quality, school quality, and other public goods are usually intended to achieve large changes over some subset of the target population. Recent applications have begun to consider this issue. Smith et al. (2004) use the Epple-Seig model to simulate the

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7 To close the model we need to define the supply of housing and the demand for labor. Neither is estimated in this paper. The simulations are implemented under assumptions about their elasticities. Walsh (2007) demonstrates how the estimation of a land supply function can be integrated into an empirical model of Tiebout sorting.
general equilibrium adjustment process following large improvements to air quality in the Los Angeles air basin, and Walsh (2007) considers large changes in the public provision of open space in Wake County, North Carolina. Both studies report substantial differences in partial and general equilibrium welfare measures. However, the migration patterns which drive these differences are based on the assumption of zero moving costs. If moving to a new home requires accepting a longer commute or a lower wage, the simulations may exaggerate the magnitude of migration and its impact on capitalization rates. Furthermore, the directions of migration reflect what each household perceives as its opportunities for spatial substitution. This perception stems from the assumed form of preference heterogeneity. The next two subsections illustrate how assumptions about heterogeneity in preferences and job opportunities influence what we learn about preferences and welfare measures from observed sorting behavior.

B. Identifying Preferences for Public Goods from Equilibrium Sorting Behavior

Given a specification for utility and a definition for the choice set, a household’s observed location provides “set identification” of their preferences. In other words, their choice implicitly defines a set of values for the parameters of the utility function that describe how local public goods contribute to sorting behavior. To attach values from this set to the population of households requires additional assumptions about the distribution of each preference parameter.

The indirect utility function can be used together with the data that describe the choice set to partition preference space into regions that define the set of values for the heterogeneous parameters capable of explaining each observed location choice. More precisely, applying the revealed preference conditions in (4.A) to the indirect utility function in (5) generates a system of inequalities which implicitly define the $\Omega_{jk}$ sets in (7). This process provides a graphical analog to Samuelson’s (1948) revealed preference logic by illustrating how a household’s preferences are identified by the choices they make and by the choices they could have made, but did not.

To illustrate the identification logic, consider the population of retired households who choose among the communities in table 1. In this simple example, each community differs in only two public goods, $g_1$ and $g_2$, both of which are observable. Given values for the elasticity of substitution and the housing demand parameters in (5), the revealed preference condition in (4.A) defines 16 inequalities. These can be solved to identify bounds on the sets of values for the
heterogeneous preference parameters, $\alpha, \gamma_1,$ and $\gamma_2$, which are capable of explaining each household’s observed choice. For example, with $\beta = 2$, $\eta = -.963$, $\nu = .75$, $\rho = -.01$, and $y = $50,000, preference space can be partitioned into the four regions shown in figure 2A. A household with preferences anywhere in region $\Omega_\beta$ of the partition will maximize its utility by choosing to live in community A, a household with preferences in $\Omega_\beta$ will choose to live in B, and so on.

The borders which separate individual regions of the partition define the values for $\alpha, \gamma_1,$ and $\gamma_2$, that would make a household exactly indifferent between the corresponding communities. Thus, the borders reflect substitution patterns. Community B, for example, shares borders with each of the other communities. Consider a marginal increase in the price of housing in B. Households that currently reside in B but have preferences on the border between B&D will respond to the price increase by moving to D. Likewise, households on the borders between B&A and B&C will move to communities A and C.

The partition reflects Tiebout’s (1956) observation that households reveal their preferences for public goods by the communities they choose. Consider communities A and D. Households in D must pay more for housing but are rewarded with higher provision of both public goods. Therefore, conditional on income, households who move from A to D must be willing to decrease the size of their home in order to increase their consumption of public goods. By making this choice, a household reveals relatively strong preferences for public goods, which is reflected in a large value for $\alpha$. Now consider B and C, two communities with similar housing prices. Community B provides more of $g_1$ and C provides more of $g_2$. Therefore, a household’s choice to live in B (C) reveals it has relatively strong preferences for $g_1$ ($g_2$), which is reflected in a large value for $\gamma_1$ ($\gamma_2$).

For working households, the partition has two additional dimensions, $\theta_1$ and $\theta_2$. This is difficult to visualize, but the intuition for how job opportunities influence the identification of preferences can be seen by considering a scenario where working households who live in

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9 The definition of substitution used here is defined as “strong gross substitution” in Anderson, DePalma and Thisse (1992), where $k$ is a substitute for $j$ iff $\partial h_i / \partial P_j > 0$.
community D earn a higher wage, $50,500. The extra $500 could reflect a shorter commute to the same job or a new commute to a different job. Figure 2B illustrates how this information changes what we can infer about preferences from sorting behavior. Notice that we lose some precision in our ability to identify the preferences of households who live in D. They may have chosen to live there because it provides access to a higher-paying job, not because of their preferences for the public goods it provides. By the same logic, the choice not to exploit the job opportunities provided by D increases the precision in our ability to identify the preferences of households in B and C. This example demonstrates how information on job opportunities relaxes the strict connection between location choices and preferences that forms the basis for empirical models of Tiebout sorting such as Epple and Seig (1999) and Bayer et al. (2007).

Assumptions about the form of preference heterogeneity determine the dimensionality of the partition. Suppose we restrict households to have identical relative preferences for the two public goods, as in Epple and Sieg (1999). If we fix the weights in the public goods index at \((\gamma_1, \gamma_2) = (0.48, 0.52)\), for example, figure 2A reduces to a horizontal line at \(\gamma_1 = 0.48\). This one-dimensional partition is reproduced in figure 2C. Comparing this with the other two partitions illustrates how our assumptions about the choice set and the extent of preference heterogeneity influence the size and shape of the preference sets which are capable of rationalizing observed behavior. This is important because each \(\Omega_{jk}\) set corresponds to a range of welfare effects for a policy intervention.

C. Measuring the Welfare Implications of a Policy Intervention

An individual household’s willingness-to-pay for a marginal change (MWTP) in \(g_1\) can be derived from the indirect utility function as follows:

\[
\text{MWTP}(g_1) = \frac{\partial V / \partial g_1}{\partial V / \partial Y} = \frac{V_{jk}^{\rho} \gamma_{ji} \alpha_{p} g_{ij}^{\rho-1}}{V_{jk}^{\rho} - \alpha_{p} g_{ij}^{\rho}}.
\]  \hspace{1cm} (10)

Since MWTP is a function of preferences, each point in the partition of preference space corresponds to a specific MWTP. Suppose we want to evaluate the welfare implications of a policy which will marginally improve \(g_1\) in community C. The choice of C reveals only that
households living there have preferences somewhere in region $\Omega_c$ of the partition. Two extreme cases allow us to provide bounds for the MWTP. The first case is where every household has preferences at the point (***) in figure 2A, which corresponds to the lowest MWTP of any point in $\Omega_c$. The opposite extreme is where every household has preferences at (*), which corresponds to the highest MWTP. Thus, $[\text{MWTP}(**), \text{MWTP}(*])$ spans the range of possible measures for individual MWTP. The wider this range the greater the sensitivity of welfare effects to the distributional assumptions made in order to identify the density of preferences within each region of the partition.

Comparing the three partitions in figure 2 illustrates a type of bias/variance tradeoff faced by the analyst. Suppose the “true” model is characterized by working households making a joint job-house choice based, in part, on their heterogeneous preferences for multiple public goods. In this case, estimating an Epple-Seig type model of pure-Tiebout sorting, where income is treated as exogenous and relative preferences are assumed to be identical, will have two effects. It will lead to biased welfare measures and it will decrease the sensitivity of those welfare measures to distributional assumptions. Moving to the dual-market framework eliminates the restrictions that introduce bias, but the added dimensionality of the $\Omega_{jk}$ sets increases the scope for distributional assumptions to influence results. The economic implications of this tradeoff will increase with the size of the change in $g_1$.

The information contained in the partition of preference space can also be used to calculate exact partial equilibrium measures of the Hicksian willingness-to-pay (WTP$^{PE}$) for large scale changes. Equation (11) defines this measure for an individual household, using superscripts to denote the periods before and after a change to the provision of public goods in community $j$.

$$V[g_j(y_1), p_j^0, \alpha, y_{jk} (q_1, w_{zk}, t_{jk}) - WTP^{PE}_j] = V[g_j(y_1), p_j^0, \alpha, y_{jk} (q_1, w_{zk}, t_{jk})].$$

WTP$^{PE}$ measures the amount of money that can be taken away from an individual and leave them exactly as well off as they were before the change, holding prices, wages, and location choices constant.

Of course, a sufficiently large shock to the provision of public goods may induce some
households to move. They may move to a new community, they may choose a new job, or they may change both their home and their job. As households move, prices and wages may need to adjust in order to clear the housing and labor markets, and these adjustments will feed back into welfare measures. Equation (12) defines the “ex post” willingness-to-pay for a change for a household that moves from location \((j,k)\) to location \((l,m)\).

\[
WTP_{GE} = V\left[\bar{g}_i'(y_{ij}), p_i, \alpha_i, y_{ilm} (\theta_i, w_{z,k}, t_{jm}) \right] - V\left[\bar{g}_i'(y_{il}), p_i, \alpha_i, y_{ilm} (\theta_i, w_{z,k}, t_{jm}) \right].
\]  

WTP_{GE} measures the household’s willingness-to-pay for the change in public goods at its new location, after accounting for capitalization of the quality change into housing prices and wage rates. Given information on the distribution of preferences in the population of households, the model in (5)-(9) can be used to simulate the general equilibrium adjustment process, and solve for the prices, wages, and location choices that define a new locational equilibrium.

IV. A Model of Equilibrium Sorting in Northern California

This section summarizes the data and results from using the parametric specification from the previous section to estimate household preferences for air quality and school quality from their sorting behavior across housing and labor markets in Northern California’s two largest population centers—the San Francisco and Sacramento Consolidated Metropolitan Statistical Areas (CMSAs). A full description of the data, estimator, and results is provided in a companion paper (Kuminoff [2007]). Here, the objective is to highlight the key features of the data and results which are used to calibrate the subsequent policy simulation.

A. Data

The Sacramento-San Francisco region contains about 9 million people, roughly 25% of the state’s population and 3% of the U.S. population. This region can be divided into 122 housing communities and 8 work destinations using definitions for a “community” and a “work destination” from the empirical literatures on Tiebout sorting and interregional hedonics. Specifically, housing communities are defined as unified school districts and work destinations...
are defined as Primary Metropolitan Statistical Areas (PMSA). Figure 3A shows how the region is divided into eight PMSAs. The population is mostly concentrated around the San Francisco Bay and the city of Sacramento, as seen by the density of census tracts. The choice set used to estimate the model is defined as the top 268 community-PMSA combinations which, together, account for 99% of the working population. A working household’s job skills are classified according to the occupation of its primary earner, using the 22 categories in the Standard Occupational Classification System (e.g. managers, healthcare support workers, etc.). Retired households comprise an additional category.

The data were generated in three steps. First, for each of the 268 locations, distributions of non-wage income by occupation were generated from publicly available special tabulations of Census data. Then, for each community, data were collected on the price of housing and the provision of two public goods, air quality and school quality. Finally, for all the potential job locations associated with each community, data were collected on the mean wage rate and mean commute time for workers in each occupational category.

The price of housing in each community \( (p_1, \ldots, p_{122}) \) was calculated from data on 540,642 individual housing transactions compiled from county Assessor records. These transactions represent most homes sold in the region between 1995 and 2005. Each record contains the actual sale price and structural characteristics of the home, including the number of bedrooms, number of bathrooms, square feet, lot size, and age. These data were used to calculate an index of housing prices using the hedonic procedure described in Seig et al. (2002). In short, this procedure recovers a set of community-specific fixed effects, while controlling for the relationship between the price and structural characteristics of a home. The fixed effects provide an index for the price of housing as it reflects the cost of consuming public goods.

The fixed effects recovered from the regression indicate that housing in the most expensive community costs 6.51 times as much as in the cheapest community. After normalizing by the lowest price, the index ranges from 1.00 in Sacramento’s Grant Union high

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10 The Census Bureau describes a PMSA as “a large urbanized county or cluster of counties…that demonstrate very strong internal economic and social links, in addition to close ties to other portions of the larger area [CMSA]”.  
11 The criterion used to select locations is that they must account for at least 500 working households (0.02% of the working population). This effectively excluded multiple-hour commutes between distant locations.  
12 60% of married couples in the study region reported both the husband and wife working in 1999. While a dual-earner job search would be an interesting extension, it is not possible given present data limitations.
school district to 6.51 in San Francisco’s second supervisorial district. Overall, the distribution is consistent with the conventional wisdom that the Bay Area is an expensive place to live. The 11 cheapest communities are all located in the Sacramento PMSA, while 24 of the 25 most expensive communities are in the San Francisco and San Jose PMSAs.

Ozone concentrations are used as a proxy for air quality because it is the chief component of urban smog which, for households, is perhaps the most readily observable measure of air quality. The California Air Resources Board records hourly concentrations of ozone at monitoring stations throughout the state. Figure 3B overlays the location of 210 monitoring stations on school districts in the study region. The exact measure used in this analysis is the average of the top 30 1-hour daily maximum readings (in parts per million) recorded at each monitoring station during the course of a year. Households are assumed to be primarily concerned with air quality near their home, not their job. Under this assumption, community-specific measures are constructed by first assigning to each house the ozone measure recorded at the nearest monitoring station, and then taking an average over all the houses in the community. Then, to control for annual fluctuation in ozone levels, the process was repeated for 1999, 2000, and 2001, and the results averaged. The final measure ranges from 0.031 (parts per million) in the highest air quality community to 0.106 in the lowest.

Data on school quality come from the California Department of Education. The measure used in this study is the Academic Performance Index (API), a composite index of standardized test scores, weighted across all subjects and grade levels. For each community, a three-year average API was constructed by weighting the score of each school in the community by its number of students from 1999-2001. The resulting measure ranges from 528 to 941.

For each occupational category and PMSA, mean annual wages were obtained from the California Employment Development Department. Wages can very substantially between PMSAs. Workers with jobs in the construction and excavation category are paid 32% more in San Jose than in Sacramento, for example. Some of this variation may reflect local cost-of-living adjustments in markets where housing is particularly expensive, like San Jose and San Francisco. The variation may also reflect unobserved heterogeneity in the mix of jobs within each category, or location-specific attributes of jobs.

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13 Wages include base pay, production bonuses, tips, and cost-of-living adjustments, but exclude nonproduction bonuses, overtime pay and the value of benefits.
Finally, data on the mean time for every tract-to-tract commute were taken from the Census Transportation Planning Package special tabulation. These figures were used to calculate the average one-way commute time between each home community and PMSA. It ranges from 1 to 114 minutes, with a mean of 36 minutes and a standard deviation of 19 minutes.

B. Estimation Results

The estimator developed in Kuminoff (2007) uses data on the characteristics of households and their location choices to recover the partition of preference space which explains their observed sorting behavior. This process uses the same type of information as the GMM approach proposed by Seig et al (2004) and the maximum likelihood estimator in Bayer et al (2007). Unlike these methods, however, there is no need for a priori assumptions about the shape of the distributions used to characterize heterogeneous preference parameters. This is accomplished by dividing the estimation into two stages, similar to Bajari and Benkard (2005). The process begins by estimating all the homogeneous parameters which enter the utility function: $\beta, \eta, \nu, \rho$, and $\xi$. The housing demand parameters are estimated from the empirical analog to the demand function in (6), and $\rho$ and $\xi_{1}, \ldots, \xi_{122}$ are recovered through an iterative process that selects values for these parameters which match predicted and observed behavior. Given values for the homogeneous parameters, a Gibbs algorithm is used to draw a random sample of points from each cell of the partition of preference space. The algorithm samples uniformly within each cell, effectively tracing its shape. Repeating this process for every cell generates a population of points which, together, approximate the partition of preference space.

Working households are assumed to choose among the 268 (district, PMSA) locations, recognizing that their wages and commutes will be determined by their choice. Recall that this model reduces to Epple and Sieg (1999) when the utility function in (5) is simplified by dropping the job skill and time cost parameters $(\theta_{1}, \theta_{2})$, dropping the $i$ subscripts from $(\gamma_{1}, \ldots, \gamma_{N})$, and assuming $f(\alpha, y)$ is lognormal. Estimating this “single-market” version of the model provides a

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14 Prior to estimation, the demand function in (6) is multiplied by price in order to transform it into an expenditure function which can be estimated from quantiles of the distribution of income and housing expenditures in each community. In this case, the 25th, 50th, and 75th quantiles were used.
link to the existing literature and a baseline for comparison in the subsequent policy simulation.\footnote{The first stage of the estimation is the same as in the dual-market case. The remaining parameters are recovered using the simulated GMM approach from Sieg et al. (2004), which exploits the (a priori) lognormality assumption.}

Table 2 summarizes the resulting parameter estimates, which are used to calibrate the simulation in section VI. Point estimates are reported for the homogeneous parameters and means and standard deviations are reported the marginal distribution of each heterogeneous parameter. Since the differences between the two models do not affect $\beta, \eta, \text{ and } \nu$, the first stage of the estimation was only performed once. The resulting estimates for the price elasticity ($\hat{\eta} = -0.38$) and income elasticity ($\hat{\nu} = 0.66$) are typical for the empirical literature on Tiebout sorting. The negative values for $\rho$ indicates the demand for public goods is downward sloping. While the dual-market estimate is considerably larger in absolute magnitude, both imply similar values for the elasticity of substitution between public and private goods (0.89 and 0.98).\footnote{The elasticity of substitution is defined as: $\sigma = 1/(1 - \rho)$.}

Estimates for $\xi_1, \ldots, \xi_{122}$ are also very similar between the two models. In general, $\xi$ is negatively correlated with distance to San Francisco Bay. Climate, open space, and cultural amenities are three unobserved public goods that seem likely to influence this result. The Bay Area has the mildest weather in the study region, the most opportunities for dining and nightlife, and a large share of land in open space. This pattern is consistent with Walsh (2007) who finds open space to be an important determinant of where households choose to live.

In the single-market case, preference heterogeneity is characterized by the parameters which define $f(\ln \alpha, \ln y)$. To recover preferences in the dual-market case, households were first classified according to 10 income bins reported in the Census data, and each household was assigned a level of income equal to the midpoint of its bin.\footnote{Measured in thousands, the midpoints are: $[5 12.5 22.5 35 45 55 67.5 87.5 112.5 175]$.} Then the Gibbs algorithm was used to draw 1000 points from each cell of the partition, conditional on income. This translates to 60,108,000 points—1000 points drawn from each of the 122 cells at each of the 10 income levels for retired households, plus 1000 points drawn from each of the 268 cells for each of the 220 (occupation, non-wage income) types of working households.\footnote{This followed a burn-in of 100 draws to reduce sensitivity to starting values.}

The dual-market partition generalizes the revealed preference logic from Epple and Sieg’s model of pure Tiebout sorting. This can be seen by comparing the preference sets
assigned to households in three communities—Pittsburg, Milpitas, and Sunol Glen. Of the three, Sunol Glen and Milpitas provide more of every public good than Pittsburg.\footnote{Their normalized values for \{air, school, price\} are: Pittsburg \{0.82, 0.79, 1.42\}; Milpitas \{0.96, 1.05, 2.61\}; Sunol Glen \{0.91, 1.20, 2.62\}. Both models assign higher values of $\xi$ to Milpitas and Sunol Glen than to Pittsburg.} Therefore, regardless of relative preferences, every household will perceive Pittsburg as providing the lowest quality bundle of public goods. Given this unanimous ordering, a household’s choice to live in Pittsburg reveals that they have weaker preferences for public goods (relative to private goods) compared to households with the same income in the other two communities. This logic is reflected by the stratification of households in panels A and B of figure 4. Panel A presents the ordering of households in the single-market case and panel B presents the preference sets for retired households in the dual-market case. In both figures, the preference sets for Sunol Glen and Milpitas lie above the set for Pittsburg in the $\alpha$ dimension. However, notice that retired households in Sunol Glen and Milpitas have overlapping ranges of values for $\alpha$ in the dual-market case. This occurs because the two communities are not strictly ordered by their provision of public goods. Sunol Glen has higher quality schools and Milpitas has cleaner air. Thus, the choice between them helps to identify relative preferences. Specifically, households in Sunol Glen are revealed to have strictly higher values for $\gamma_{school}/\gamma_{air}$. This is illustrated in panel C which projects the preference sets from panel B into $\gamma$ space.

Adding job destinations to the choice set expands the borders of the preference sets. Intuitively, heterogeneity in job skill and the opportunity cost of time provide new ways to explain observed behavior. This can be seen by comparing figure 4C with the corresponding $\gamma$ projection for managers in 4D. Notice the striking difference between the preference sets assigned to working and retired households in Milpitas. Milpitas has approximately average values for air and school quality, which helps to explain why retired households who choose to live there are assigned similar values for the weights in the public good index, i.e. $\gamma_{air}/\gamma_{school} \approx 1$. Meanwhile, this ratio can be much larger for managers who commute to San Jose. The reason is that San Jose is the highest paying job destination and Milpitas offers one of the shortest commutes. This explains why managers with strong preferences for air quality would choose to live in Milpitas instead of a different community with cleaner air.

Finally, the dual-market partition was translated into a distribution of preferences for the
policy simulation by sampling uniformly over each cell of the partition according to the population of households in the corresponding location. For example, the census data report 232 households with a primary earner in the architecture and engineering occupation who live in the Acalanes school district, work in the Oakland PMSA, and have total income of $112,500. Therefore, 232 draws were chosen uniformly from the region of the partition that corresponds to this household “type”. This process was repeated for every type so that the resulting distributions represent all 3.2 million households in the study region. The last five columns of table 2 report the results. The mean value of $\theta_2$ implies the shadow value of time is approximately 40% of the wage rate—similar to the rule-of-thumb (33%) used in the recreation demand literature (Phaneuf and Smith [2005]). The mean of $\theta_1$ suggests a high degree of geographic job specialization and/or a high job search cost. It implies the average worker would earn approximately half of the market wage if they were to change job locations. Estimates for $\alpha$ and $\gamma$ are not directly comparable between the two models in terms of magnitude since they correspond to different estimates for $\rho$ and $\xi$. Nevertheless, there is a striking difference between their relative values: $\gamma_{air}/\gamma_{school}$ is an order of magnitude larger in the dual-market case. This difference will affect how households react to improved air quality in the policy simulation.

V. Policy Scenario: California’s New Standard for Ground Level Ozone

Due to concerns over the negative health effects of ground-level ozone, the Environmental Protection Agency (EPA) recently established stricter standards for ambient ozone concentrations. The Phase 2 Ozone Rule finalized in November, 2005 identifies “nonattainment areas” across the country that fail to meet the national 8-hour limit on ambient ozone concentrations of 0.08 parts per million (ppm). These areas cover 18% of the counties in the United States. The Phase 2 Rule outlines a set of corrective actions that must be taken by the states which contain nonattainment areas. First, they must install abatement equipment that EPA considers to be reasonably available. Second, they must restrict construction of new stationary sources of ozone precursors and restrict modifications to existing sources. Finally, states with the most severe violations may be required to use cleaner-burning reformulated gasoline.

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20 Note that this does not imply a uniform distribution of preferences in the population of households.
The four nonattainment areas with the most severe violations of the new standard are all located in California: the Los Angeles Air Basin, the Sacramento CMSA, Riverside County, and the San Joaquin Valley. These are the only four regions which EPA designates as having a “severe” or a “serious” problem. California state officials addressed this problem in May, 2006 by adopting an even stricter 8-hour standard of 0.07 ppm. This new standard is the focus of the policy simulation, which asks the hypothetical question: what would households in the Sacramento-San Francisco region be willing-to-pay to attain the new 0.07 ppm ozone standard?

There are two issues which must be addressed in order to define the spatial distribution of ozone in the attainment scenario. First, the 8-hour limit which defines the new “attainment” rule must be converted into the same units as the 1-hour measure of ozone concentrations used as a proxy for air quality during the estimation. The second issue is that the implied reduction in emissions of ozone precursors needed to meet the new standards in communities with low air quality would be likely to spill over into communities with high air quality. For example, 8-hr ozone levels in the western part of the San Francisco Bay Area already satisfy the new 0.07 ppm limit. This is largely due to natural wind currents that tend to push ozone toward the East Bay and into Sacramento, contributing to their air quality problems. Assuming ozone reductions are derived from new regulations on emissions that apply throughout the region, a reduction in ozone that would bring Sacramento into attainment would stem partly from reduced emissions of ozone precursors in the San Francisco Bay Area. Since wind currents do not remove ozone from the Bay Area entirely, the decrease in emissions would lower ozone levels there as well.

The spatial distribution of ozone concentrations in the attainment scenario was developed in two steps. First, data on 8-hr ozone were used to identify individual monitoring stations that violated the 0.07 ppm limit during the baseline years of the study period (1999-2001). For each of these monitors, the reduction in 8-hr ozone required to bring it into attainment was translated into the corresponding reduction in the 1-hour ozone measure that was used to define air quality during the estimation. The second step was to estimate the historical relationship between changes in ozone at nonattainment stations and changes in ozone at attainment stations. The resulting estimate was used together with the ozone reductions required at nonattainment stations to predict the corresponding reductions for attainment stations.

Section IV described how the level of air quality in each community was measured using
a three-year average of the annual top 30 1-hr daily maximum ozone readings. In contrast, California’s new ozone standard is based on a 3-year average of the 4th highest annual 8-hr ozone reading. To make the conversion between the two measures, the reduced-form relationship between them was estimated using annual data for each monitoring station in the study region. First, the 8-hr measure was constructed for each monitoring station for 1999-2001. Then, the 1-hr data were regressed on the 8-hr data. The results imply that a 1 ppm reduction in the 8-hr measure corresponds to a 1.09 ppm reduction in the 1-hr measure. The coefficient explained almost all of the variation in ozone concentrations ($R^2 = .97$). Next, for each nonattainment monitor, the reduction in the 8-hr measure needed to bring that monitor into attainment was multiplied by 1.09 to generate an estimate for the corresponding reduction in the 1-hr measure.

During the second step of the process, annual data from 1980 to 2003 were used to estimate the historical relationship between air quality changes at attainment and nonattainment monitors. While ozone concentrations have decreased steadily in the areas with the lowest air quality, they have remained fairly flat in attainment regions. Figure 5 illustrates this trend, using data from representative monitoring stations in Sacramento and Oakland. The relatively flat trend for Oakland reflects the way weather in the San Francisco Bay limits the sensitivity of ozone concentrations to changes in precursor emissions. Regressing the annual change in the log of 8-hr ozone (ppb) at attainment monitors on the annual change in 8-hr ozone at nonattainment monitors indicates we should expect a 1 ppb decrease at the average nonattainment monitor to be accompanied by a 0.06% decrease at the average attainment monitor. Therefore, for the monitoring stations that were in attainment of the new standards during 1999-2001, the percentage ozone reduction in the attainment scenario was estimated by multiplying the average change at nonattainment stations (-11.6 ppb) by the regression coefficient (0.06%). This calculation implies a 0.7% decrease at attainment monitors. In comparison, ozone concentrations are predicted to decrease by 12% at the average nonattainment monitor.

Finally, the 1-hr ozone levels predicted for the individual monitoring stations were used to produce community-specific measures of air quality, using the same aggregation procedure used to prepare the data for estimation. Figure 6 shows the difference between the attainment scenario and baseline ozone concentrations in 1999-2001. Air quality improves significantly for most communities physically located in the Sacramento and Yolo primary metropolitan
statistical areas, as well as for some communities in Oakland and San Jose. In contrast, the ozone reductions are marginal for communities in the San Francisco, Santa Cruz, and Santa Rosa PMSAs. Table 3 reports the average reduction over all the communities in each PMSA, as well as the range of changes across the individual communities. The reductions range from 0.6% in the San Mateo Union High school district (San Francisco PMSA) to 27.9% in the Black Oak Mine Unified school district (Sacramento PMSA).

VI. General Equilibrium Simulation

Given the distribution of preferences recovered during the estimation, the task in this section is to solve for a new set of housing prices, wage rates, and location choices that satisfy the conditions for a locational equilibrium following the air quality improvement defined in the attainment scenario. This can be done by using the distribution of preferences to simulate how households would respond to the shock. However, recall that the distribution of preferences is not sufficient to fully characterize a locational equilibrium. Some additional information must be provided. Part A of this section explains how each component of the simulation was defined in order to close the model. Then parts B and C interpret the simulation results from the single-market and dual-market versions of the model. Finally, part D compares the resulting welfare measures to the existing literature on the willingness-to-pay for air quality.

A. Components of the General Equilibrium Model

In the limit, all the attributes of a location may be endogenous and interrelated in a general equilibrium. For example, in order to achieve EPA’s Phase 2 ozone standard, firms may be required to install new pollution abatement equipment at existing facilities. These regulatory costs may affect the demand for labor if they lead to the closure of older facilities. Likewise, if households respond to an air quality improvement by adjusting their commuting patterns, the corresponding change in vehicle miles traveled could alter the level of automobile emissions, which would feed back into the level of air quality. While these feedback effects are interesting and potentially important, they are excluded from the present analysis in order to focus attention on the implications of preference heterogeneity and the interactions between housing and labor.
Assuming the provision of public goods is exogenous, the general equilibrium model has four sets of components: the supply and demand curves for housing in every community and the supply and demand curves for labor in each PMSA. The housing demand and labor supply curves are implicitly defined by the joint distribution of income and preferences that was estimated for the population of households in each version of the model. Additional information must be provided to define the supply of housing and the demand for labor. In previous work, the housing supply curves have been treated as perfectly inelastic (Smith et al. [2004]), calibrated using a range of elasticities (Sieg et al. [2004]), and estimated independently (Walsh [2007]). Here, the housing supply and labor demand are both treated as perfectly inelastic.

Finally, an assumption is required about who collects the capital gains (or losses) from changes in housing prices and wage rates. All the applications cited above treat households as renters and assume that changes in property values are absorbed by absentee landlords. The same assumption is maintained here and extended to the labor market. In other words, changes in profits that arise from adjustments to wage rates are assumed to be collected by the absentee owners of firms (i.e. “shareholders”). The decision to treat households as renters rather than homeowner/shareholders has potentially important welfare implications. For example, suppose an improvement in the quality of a public good raises housing prices. This would be strictly welfare improving for a retired homeowner. The quality improvement increases their utility and the increase in housing prices can not make them worse off. Likewise, if the retired homeowner decides to move, they collect the capital gains from the increase in the price of their home. In contrast, a retired renter living in the same community will experience a welfare loss if the increase in their housing expenditures exceeds their willingness-to-pay for the quality improvement. According to the 2000 Census of population and housing, 60% of the homes in the San Francisco-Sacramento region are owner-occupied.

B. Simulation Results: Single-Market Model

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21 Ferreyra (2007) and Walsh (2007) use structural parameter estimates from equilibrium sorting models to calibrate simulations with endogenous provision of school quality (Ferreyra) and open space (Walsh). Unlike the present analysis, these studies treat wage income as exogenous and limit the extent of preference heterogeneity.
In the single-market case, the simulation process is straightforward. It begins by using the estimation results summarized in table 2 to characterize the joint distribution of income and preferences in the initial equilibrium. Then the distribution of public goods is shocked by the air quality improvement in the attainment scenario. Following this shock, the challenge is to solve for the new utility-maximizing location choice made by every household, and a vector of housing prices that guarantees these choices equate the supply and demand for housing in every community. The relatively simple form of preference heterogeneity in the single-market model allows this problem to be formulated as a 1-dimensional rootfinding problem, which is easily solved using the algorithm developed by Sieg et al. (2004).22

Table 4 reports the average changes in ozone, prices, and welfare for the attainment and nonattainment communities in each PMSA. All welfare measures are based on households’ initial locations. For example, the $22 MWTP and $41 WTPGE for nonattainment communities in Sacramento correspond to the households who started in those communities, regardless of where they may have moved during the simulation. Not surprisingly, the table reflects the type of sorting behavior that underlies the empirical model and the estimator. On average, households who initially chose to live in nonattainment communities have a lower average MWTP for improved air quality ($27) than households who chose to live in attainment communities ($111). The reverse is true for partial equilibrium welfare measures because nonattainment communities experience much larger ozone reductions. These air quality improvements make the (formerly) nonattainment communities relatively more desirable, inducing households to bid up their rental prices, which partly offsets welfare improvements from the ozone reduction.

Since the simulation framework is a “closed” model and there are no income effects, the 122 housing markets cannot clear simultaneously if housing prices increase everywhere. As more households move into nonattainment communities and the demand for housing decreases in their initial locations, some prices must fall. The communities with relatively small air quality improvements are generally the ones with price decreases, adding to the welfare improvement for current residents. On average, rents in attainment communities decrease by 0.54%, which is

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22 The key observation is that $y f(\ln \alpha, \ln \gamma)$ can be used to define a chain of households across communities according to overall public goods provision. One must solve for the prices implicitly defined by “links” in the chain that equate supply and demand in each community. This problem can be defined recursively; i.e. the first price is modified until the housing market clears in the last community. See the appendix for details.
why $WTP^{GE}$ typically exceeds $WTP^{PE}$ in these communities.

Table 5 highlights some of the diversity in welfare effects within the metro areas by comparing the results for 10 individual communities in the Oakland PMSA. Oakland provides a convenient example because its communities span much of the range in housing prices and air quality in the initial equilibrium. As expected, the relatively large ozone reductions in Acalanes (-10.9%) and Livermore Valley (14.6%) are accompanied by price increases (0.2% and 0.6%). Likewise, the relatively small reductions in the remaining Oakland communities lead to small decreases in the price of housing. For example, although ozone concentrations drop by 0.7% in Alameda City, the much larger reductions in communities like Acalanes and Livermore Valley make them more attractive, inducing some of the households in Alameda City to move there. Consequently, the price of housing in Alameda City has to drop by -0.5% to clear the market.

Table 5 also illustrates how a policy that pursues “environmental justice” can make renters worse off.\(^{23}\) In the initial equilibrium, Black Oak Mine has the second lowest price of housing and the lowest air quality. People who initially chose to live there may have done so because they are indifferent to air quality, or because they have low income. In either case, the estimation results imply these households have the lowest average MWTP for air quality ($14). They would prefer higher ozone levels and inexpensive housing to the higher prices that follow the ozone reduction. Consequently, their welfare goes down when prices increase.

Finally, notice that the model depicts a large share of the population moving between communities. In particular, every household in Antioch, Castro Valley, Livermore Valley, Pittsburg, Sunol Glen, and El Dorado moves to a different community during the simulation. This reflects changes to the position of these communities in the ranking by overall public goods provision. For example, prior to the air quality improvement, Antioch was ranked 23rd by the public goods index. The ozone reduction decreases its rank to 21. While the ranking of communities changes, households are still strictly ordered according to their (one-dimensional) preferences for public goods. The households who previously lived in Antioch move to Travis and Vacaville, the new 22nd and 23rd ranked communities. These restrictive migration patterns help to explain why there is so little variation in the welfare obtained by movers relative to non-

\(^{23}\) According to the US Environmental Protection Agency, “Environmental justice is achieved when everyone, regardless of race, culture, or income, enjoys the same degree of protection from environmental and health hazards and equal access to the decision-making process to have a healthy environment in which to live, learn, and work.”
movers. In addition to having similar preferences, they occupy communities with similar provision of public goods both before and after the air quality improvement.

C. Simulation Results: Dual-Market Model

Introducing labor markets and generalizing the depiction of preference heterogeneity complicates the task of solving for a locational equilibrium. Unlike the single-market case, there is no obvious way to sort households across communities. Nevertheless, households can always be ranked according to the maximum price they would be willing to pay to live in any given community, conditional on their current utility. Likewise, working households can be ranked according to the minimum wage they would be willing to accept to work in any given labor market. These rankings form the basis for an algorithm that iteratively adjusts housing prices and wage rates until all markets clear simultaneously. The mechanics of the algorithm are described in the appendix. Intuitively, it begins by asking: what is the maximum price that would clear each community’s housing market after air quality improves? This price is determined by solving for every household’s reservation price as a function of their current utility, and then using these prices to sort households into the community until the aggregate demand for housing equals the supply. After updating the utility of movers, the process is repeated for every other community and labor market. The prices (wages) from this first iteration provide an upper (lower) bound on the new equilibrium prices (wages). Subsequent rounds of adjustments decrease prices and increase wages until all markets clear. While this algorithm results in a new locational equilibrium, the process is computationally intensive. To reduce the burden, the simulation was performed using a 1% sample of the population.

Table 6 reports the average changes in prices, income, and welfare for each PMSA. The results differ considerably from the single-market case. In particular, average WTP\textsuperscript{GE} increases from $128 to $845 in non-attainment communities and decreases from $278 to $92 in attainment communities. These differences can be explained by four features which distinguish the dual-market simulation: (1) greater dimensionality in the distribution of preferences, (2) “cost-of-living” adjustments which arise from interaction between housing and labor markets, (3) job-

\footnote{With the full set of 3.2 million households, the algorithm takes more than 2 weeks to converge. With a 1% sample, it converges in approximately 24 hours.}
related “moving costs” that limit the geographic mobility of working households, and (4) greater opportunities for spatial substitution implied by the form of preference heterogeneity. Each of these features is explained before comparing the two sets of general equilibrium welfare measures.

Moving to a dual-market framework tends to increase partial equilibrium welfare measures, especially in nonattainment communities. This can be seen by comparing the estimates for MWTP and WTPPE in table 6 with their single-market counterparts in table 4. To help explain these aggregate outcomes, figures 7A through 7B plot average MWTP in each community against baseline ozone concentrations. Both models depict a similar decreasing trend. Intuitively, all else held constant, the choice to live in a community with cleaner air reveals a higher MWTP. Likewise, figures 7C and 7D illustrate how WTPPE tends to increase in ozone concentrations since communities with higher initial concentrations have larger reductions. Moving to the dual-market framework increases the variability in these relationships by offering alternative explanations for why households with strong preferences for air quality would choose to live in communities with high ozone concentrations. For example, the average MWTP in Sacramento City is $26 in the single-market case compared to $73 in the dual-market case. While Sacramento City has relatively high ozone concentrations (86 ppb), working households with strong preferences for air quality may choose to live there because it offers one of the shortest commutes to the Sacramento PMSA.

The second distinguishing feature of the dual-market simulation is that it predicts an increase in housing prices for every community. The average increase is 6.0% in nonattainment communities compared to 0.3% in attainment communities. These increases are typically accompanied by increases in wage rates that effectively serve as “cost-of-living” adjustments. When the price of housing increases in a nonattainment community, working households with strong preferences for private goods (i.e. low $\alpha$) seek to move to less expensive areas. This often requires moving to a new job in a different PMSA. Therefore, in order to clear the labor markets that serve nonattainment communities, wage rates have to increase to offset the higher cost-of-living. This explains why the PMSAs with the largest ozone reductions (Sacramento, 25 It is also true that households with higher incomes tend to live in communities with cleaner air. This contributes to the predicted relationship between air quality and MWTP because, all else constant, MWTP is increasing in income.

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Yolo) also have the largest wage adjustments, whereas wages are virtually unchanged in San Jose and San Francisco which are within commuting distance to relatively few nonattainment communities. Now consider two facts: 19% of workers commute between PMSAs and half of the PMSAs contain both attainment and nonattainment communities. Thus, the cost-of-living adjustments to wages in PMSAs with high ozone concentrations also benefit workers who commute to attainment communities elsewhere in the region. The resulting income effects increase their demand for housing which, in turn, requires prices to increase in order to clear the housing markets in attainment communities.

The third factor which contributes to the difference between single and dual-market estimates for WTPGE is their different implications for household mobility. As discussed earlier, allowing households to differ in their relative preferences for public goods means they perceive more opportunities for spatial substitution. Meanwhile, the distribution of $\theta_i$ recovered during the estimation implies that the average worker would be paid less if they were to move to a different labor market, which effectively limits their geographic mobility. Thus, working households are less likely to move far from their job, but more likely to perceive nearby communities as potential substitutes for their current location. During the simulation, 24% of retired households moved to a different community compared to 13% of working households. Meanwhile, only 0.2% of working households changed jobs. Not surprisingly, the workers who change jobs have relatively high values for $\theta_i$. For movers, the mean value of $\theta_i$ is 0.94 compared to the population mean of 0.46. This reinforces the interpretation of $\theta_i$ as a “job mobility” parameter.

Heterogeneity in job mobility, interactions between rent and wage adjustments, and the increased dimensionality of preferences all interact to increase the diversity in general equilibrium welfare measures. This can be seen by comparing the results for individual communities in table 7 with the single-market results in table 5. In some communities such as Antioch, Livermore Valley, and Pittsburg, cost-of-living adjustments are not sufficient to compensate the average household for higher rents, leading to a net welfare loss. The opposite result applies to the average household in Berkeley, Dublin, and Sunol Glen. Furthermore, WTPGE can differ substantially between households who move and those who do not. For example, consider El Dorado. In the initial equilibrium it has the second lowest ozone
concentrations, the 5th lowest price of housing, and it requires a relatively long commute to job destinations in the Sacramento PMSA. Consequently, the estimation results indicate that households who live there have a relatively low WTPPE for improved air quality. When rents increase in El Dorado following the ozone reduction, the average resident who chooses to stay there experiences a net welfare loss. Meanwhile, the residents who move experience a net welfare gain which exceeds their WTPPE. These households move to six other communities in the Sacramento PMSA, all of which experience smaller price increases. In contrast, the restrictions on preference heterogeneity in the single-market version of the model rule out this type of diversity in migration patterns.

Figures 7E and 7F illustrate how the average WTPGE varies across communities in each version of the model. In the single-market case, communities with the highest initial ozone concentrations also tend to have the lowest average WTPGE. This is due to a combination of three factors. First, the households who live in communities with the lowest air quality were assigned the lowest values for $\alpha \mid \gamma$ during the estimation. These households will have the lowest per/unit WTPPE for the change. Second, communities with higher initial ozone concentrations have larger reductions in the attainment scenario and, therefore, larger price increases. For many households in nonattainment communities, the welfare loss from the price increase outweighs the welfare gain from the ozone reduction. Finally, the strict ordering of households across communities means they have few opportunities to adjust to price increases by moving. On average, a household that moves during the simulation locates in a new community that differs from its initial location by 0.6 places in the price ranking.

In the dual-market case, communities with the highest initial ozone concentrations tend to have the highest average WTPGE, amid considerable variability. While the price increases in nonattainment communities are much larger in the dual-market simulation, so is the welfare gain from the ozone reduction. This is because, during the estimation process, the model recognized that there may be some households in nonattainment communities who have relatively strong preferences for air quality and chose to live there for other reasons. Furthermore, the cost-of-living adjustments to wages do much to compensate working households for the higher prices. Finally, since households are not strictly ordered across communities, they have more flexibility in how they adjust to the change. The average mover chooses a new location that differs from its
initial community by 3.3 places in the price ranking.

D. Interpretation

The simulation results summarized in tables 4 through 7 provide theoretically consistent predictions for the distributional welfare implications of California’s new ozone standard. The richness of detail in these distributions offers the potential to evaluate the standard based on numerous criteria which matter to policymakers. For example, by recovering welfare effects for households that differ by location, income, and occupation, the model permits consideration of the implications for environmental justice. But are its predictions for general equilibrium adjustment reliable? An ideal way to answer this question would be to observe the behavior of individual households both before and after an air quality improvement and then compare their actual migration patterns (and the ensuing price and wage adjustments) with the predictions made by the model. While this quasi-experimental approach to model validation would provide helpful feedback, it is also extremely difficult to implement. It would require tracking the population of households across space and time, and isolating an air quality change which is not confounded by changes in unobserved characteristics of households and communities. Identifying quasi-experiments that meet these criteria and developing alternative ways to evaluate the predictive power of the general equilibrium model are two important topics for further research.26 The remainder of this section provides some initial feedback on the partial equilibrium version of the model by comparing the estimates for MWTP to those from the existing literature on valuing air quality changes.

Measures of the willingness-to-pay for reduced ozone concentrations are not directly comparable with MWTP estimates reported in much of the existing literature where air quality is typically measured by particulate matter or by the number of days during a year that ozone levels exceed state or federal standards. However, assuming that all of these measures are simply different proxies for clean air, they can be compared in terms of a common proportionate change. Converting the range of values from the existing literature into measures that would be equivalent to a marginal (1 part-per-billion) reduction in ambient ozone concentrations implies a

26 There is a growing literature on structural model validation. Keane (forthcoming) provides an overview, and Provenchur and Bishop (2004), and Keane and Wolpin (2007) provide examples of empirical validation exercises.
range from $7 to $154 year 2000 dollars (Seig et al. [2004]). The corresponding estimate from the single-market version of the model was $80, compared to $140 in the dual-market case. The result that average MWTP increases when the choice set is expanded to include job opportunities is consistent with the early interregional hedonic literature which found that housing prices and wage rates both appear to reflect a substantial share of the implicit price of environmental amenities (e.g. Roback [1982], Blomquist et al. [1988]). The fact that the $80 and $140 estimates are both relatively high could stem from methodological differences or simply from differences in the study region.

From a methodological perspective, the closest comparison to the existing literature is to Sieg et al’s (2004) application of the single-market version of the model to Los Angeles in 1990. They report an average MWTP of $66. However, the average level of ozone concentrations across the communities in their application is 150 ppb, compared to a maximum of 109 here. Moreover, median income in the San Francisco CMSA is 35% higher than in the Los Angeles CMSA. If Northern and Southern California were considered as part of the same choice set, the relationship between MWTP, air quality, and income would imply that households in San Francisco and Sacramento would tend to have a higher MWTP than those in Los Angeles. Thus, estimates of the willingness-to-pay for marginal changes from the dual-market model appear to be reasonably consistent with the existing literature.

VII. Policy Implications

Table 8 summarizes the estimation and simulation results by reporting the average per/household changes in rents, wages, and welfare. In the single-market case, accounting for general equilibrium adjustment produced an estimate for the average willingness-to-pay of $230 compared to a partial equilibrium measure of $129. The difference between them is mainly due to a $114 decrease in annualized expenditures on housing. Moving to the dual-market framework increased both the partial ($292) and the general equilibrium ($346) measures. While average rents and income both increased in the dual-market simulation, the cost-of-living adjustments ($502) more than compensate the average working household for the higher rents ($438). To the extent that partial equilibrium measures fail to capture the gains from adjustment, they will underestimate willingness-to-pay. General equilibrium measures will overestimate
these gains to the extent that they fail to fully model limits to mobility. Treating the partial and
general equilibrium estimates from the single-market version of the model as bounds and
multiplying them by the number of households in the San Francisco-Sacramento area would
imply that cumulative annualized benefits from California’s new standard on ground level ozone
lie between $0.41 and $0.73 billion. Recognizing that households face differentiated job
opportunities increases this range to $0.93 to $1.10 billion.

The welfare measures reported here differ from the results that would be obtained by
following the standard practice of multiplying an estimate for average MWTP by the size of the
improvement. The importance of this difference is illustrated in table 8 by presenting the results
from three “back of the envelope” calculations. All three calculations multiply average MWTP
by a measure of the average ozone reduction. They differ in how they aggregate the community-
specific ozone reductions to generate a regional average. The first calculation takes a weighted
average by the size of each community, measured in acres. This is denoted in the table as “acre
weights”. The second measure weights each community by its population, and the third takes an
arithmetic average of the ozone reductions over the 122 communities. All three calculations
grossly overestimate willingness-to-pay. They produce estimates which are between 153% and
300% higher than the general equilibrium measures in the single-market case and between 171% and
336% higher in the dual-market case.

The difference between exact benefit measures and back-of-the-envelope calculations
based on average MWTP highlights the economic importance of Charles Tiebout’s insight for
public policy evaluation. That is, all else constant, households with the weakest preferences for
air quality and the lowest willingness-to-pay for an improvement will choose to live in the
communities with the highest ozone concentrations. Since these communities are the ones which
need the largest ozone reductions to meet the new standards, the aggregate benefits from the
reduction are much smaller than if air quality were improved uniformly across the study region.
The opposite would be true if the largest ozone reductions were to occur in the communities with
the highest air quality. This logic applies generally to the evaluation of new policies which
impose standards on the provision of public goods and environmental amenities.
References


TABLE 1
A HYPOTHETICAL CHOICE SET

<table>
<thead>
<tr>
<th>Community</th>
<th>Public Goods</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$g_1$</td>
<td>$g_2$</td>
</tr>
<tr>
<td>A</td>
<td>1.25</td>
<td>1.25</td>
</tr>
<tr>
<td>B</td>
<td>1.85</td>
<td>1.65</td>
</tr>
<tr>
<td>C</td>
<td>1.66</td>
<td>1.86</td>
</tr>
<tr>
<td>D</td>
<td>2.00</td>
<td>2.00</td>
</tr>
</tbody>
</table>

NOTE.—Higher values for a public good indicate higher quality.

TABLE 2
PARAMETER ESTIMATES: MEAN (STANDARD DEVIATION) USED IN POLICY SIMULATION

<table>
<thead>
<tr>
<th>Model</th>
<th>$\beta$</th>
<th>$\eta$</th>
<th>$\nu$</th>
<th>$\rho$</th>
<th>$\log (\alpha)$</th>
<th>$\gamma_{school}$</th>
<th>$\gamma_{air}$</th>
<th>$\theta_1$</th>
<th>$\theta_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-Market</td>
<td>11.97</td>
<td>-0.38</td>
<td>0.66</td>
<td>-0.22</td>
<td>0.92</td>
<td>1.00</td>
<td>0.13</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(0.75)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dual-Market</td>
<td>11.97</td>
<td>-0.38</td>
<td>0.66</td>
<td>-0.12</td>
<td>-6.98</td>
<td>0.16</td>
<td>0.17</td>
<td>0.46</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(3.88)</td>
<td>(0.20)</td>
<td>(0.18)</td>
<td>(0.28)</td>
<td>(0.32)</td>
</tr>
</tbody>
</table>

NOTE.—The “single-market” version of the model uses the specification from Epple and Sieg (1999). In this case, the weight on school quality is normalized to 1, and the joint lognormal distribution of income and preferences is also characterized by: $\mu_{ln y} = 11.10$, $\sigma_{ln y} = .78$, and $\text{corr}(\alpha, \ln y) = -.49$.

TABLE 3
DESCRIPTION OF THE ATTAINMENT SCENARIO, BY PMSA

<table>
<thead>
<tr>
<th>Primary Metropolitan Statistical Area</th>
<th>Average Ozone Concentrations</th>
<th>Changes in Individual Communities</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baseline (ppb)</td>
<td>Attainment (ppb)</td>
</tr>
<tr>
<td>Oakland</td>
<td>77.0</td>
<td>71.1</td>
</tr>
<tr>
<td>Sacramento</td>
<td>93.9</td>
<td>75.3</td>
</tr>
<tr>
<td>San Francisco</td>
<td>55.6</td>
<td>55.2</td>
</tr>
<tr>
<td>San Jose</td>
<td>74.2</td>
<td>70.8</td>
</tr>
<tr>
<td>Santa Cruz</td>
<td>63.3</td>
<td>62.9</td>
</tr>
<tr>
<td>Santa Rosa</td>
<td>65.1</td>
<td>64.6</td>
</tr>
<tr>
<td>Vallejo-Fairfield-Napa</td>
<td>74.2</td>
<td>70.1</td>
</tr>
<tr>
<td>Yolo</td>
<td>86.4</td>
<td>76.4</td>
</tr>
</tbody>
</table>

NOTE.—Average ozone concentrations in a PMSA were calculated as a weighted average over the communities in the PMSA, using the total acreage of each community as a weight. The measure of ozone in each community is the average of the top 30 1-hour ozone concentrations during the course of a year.
### TABLE 4
SINGLE-MARKET WELFARE MEASURES AND CAPITALIZATION RATES, BY PMSA

<table>
<thead>
<tr>
<th>Primary Metropolitan Statistical Area</th>
<th>Mean Δ Ozone (%)</th>
<th>Non-Attainment Communities</th>
<th>Attainment Communities</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Δ rent (%)</td>
<td>MWTP ($)</td>
</tr>
<tr>
<td>Oakland</td>
<td>-7.7</td>
<td>-0.01</td>
<td>31</td>
</tr>
<tr>
<td>Sacramento</td>
<td>-19.7</td>
<td>2.54</td>
<td>22</td>
</tr>
<tr>
<td>San Francisco</td>
<td>-0.7</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>San Jose</td>
<td>-4.6</td>
<td>-0.13</td>
<td>36</td>
</tr>
<tr>
<td>Santa Cruz</td>
<td>-0.7</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Santa Rosa</td>
<td>-0.7</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Vallejo-Fairfield-Napa</td>
<td>-5.5</td>
<td>-0.12</td>
<td>37</td>
</tr>
<tr>
<td>Yolo</td>
<td>-11.6</td>
<td>0.40</td>
<td>29</td>
</tr>
<tr>
<td>All Communities</td>
<td>-9.7</td>
<td>1.39</td>
<td>27</td>
</tr>
</tbody>
</table>

### TABLE 5
SINGLE-MARKET WELFARE MEASURES AND CAPITALIZATION RATES, SELECTED COMMUNITIES

<table>
<thead>
<tr>
<th>Community</th>
<th>PMSA</th>
<th>Ozone (ppb)</th>
<th>Δ rent (%)</th>
<th>MWTP ($)</th>
<th>WTP&lt;sub&gt;PE&lt;/sub&gt; ($)</th>
<th>WTP&lt;sub&gt;GE&lt;/sub&gt; ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Baseline</td>
<td>Attainment</td>
<td>% Δ</td>
<td>movers (%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>85.8</td>
<td>76.4</td>
<td>-10.9</td>
<td>0.2</td>
<td>5.1</td>
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<tr>
<td>Acalanes</td>
<td>Oakland</td>
<td>31.2</td>
<td>31.0</td>
<td>-0.7</td>
<td>-0.5</td>
<td>7.7</td>
</tr>
<tr>
<td>Alameda City</td>
<td>Oakland</td>
<td>54.2</td>
<td>53.8</td>
<td>-0.8</td>
<td>-0.5</td>
<td>17.5</td>
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<tr>
<td>Albany City</td>
<td>Oakland</td>
<td>78.0</td>
<td>76.4</td>
<td>-2.1</td>
<td>-0.8</td>
<td>100.0</td>
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<tr>
<td>Antioch</td>
<td>Oakland</td>
<td>47.0</td>
<td>46.6</td>
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<td>-0.5</td>
<td>3.2</td>
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<tr>
<td>Berkeley</td>
<td>Oakland</td>
<td>63.2</td>
<td>62.8</td>
<td>-0.7</td>
<td>-0.7</td>
<td>100.0</td>
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<tr>
<td>Castro Valley</td>
<td>Oakland</td>
<td>75.0</td>
<td>71.5</td>
<td>-4.7</td>
<td>-0.3</td>
<td>28.1</td>
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<tr>
<td>Dublin</td>
<td>Oakland</td>
<td>89.5</td>
<td>76.4</td>
<td>-14.6</td>
<td>0.6</td>
<td>100.0</td>
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<tr>
<td>Livermore Valley</td>
<td>Oakland</td>
<td>76.9</td>
<td>76.3</td>
<td>-0.8</td>
<td>-1.0</td>
<td>100.0</td>
</tr>
<tr>
<td>Pittsburg</td>
<td>Oakland</td>
<td>70.0</td>
<td>69.5</td>
<td>-0.7</td>
<td>-0.6</td>
<td>100.0</td>
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<tr>
<td>Sunol Glen</td>
<td>Oakland</td>
<td>100.7</td>
<td>76.4</td>
<td>-24.1</td>
<td>3.4</td>
<td>100.0</td>
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<tr>
<td>Black Oak Mine</td>
<td>Sacramento</td>
<td>105.9</td>
<td>76.4</td>
<td>-27.9</td>
<td>5.1</td>
<td>16.3</td>
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<tr>
<td>El Dorado</td>
<td>Sacramento</td>
<td>86.2</td>
<td>76.4</td>
<td>-11.4</td>
<td>1.5</td>
<td>1.7</td>
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</tbody>
</table>
## Table 6
**DUAL-MARKET WELFARE MEASURES AND CAPITALIZATION RATES, BY PMSA**

<table>
<thead>
<tr>
<th>PMSA</th>
<th>Mean Δ Ozone (%)</th>
<th>Δ rent (%)</th>
<th>Δ inc (%)</th>
<th>MWTP ($</th>
<th>WTPPE ($)</th>
<th>WTPGE ($)</th>
<th>Δ rent (%)</th>
<th>Δ inc (%)</th>
<th>MWTP ($</th>
<th>WTPPE ($)</th>
<th>WTPGE ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oakland</td>
<td>-7.7</td>
<td>1.98</td>
<td>1.17</td>
<td>36</td>
<td>227</td>
<td>-155</td>
<td>0.18</td>
<td>1.05</td>
<td>129</td>
<td>50</td>
<td>189</td>
</tr>
<tr>
<td>Sacramento</td>
<td>-19.7</td>
<td>8.86</td>
<td>6.72</td>
<td>71</td>
<td>1,075</td>
<td>1,517</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>San Francisco</td>
<td>-0.7</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.17</td>
<td>0.17</td>
<td>185</td>
<td>64</td>
<td>39</td>
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<td>San Jose</td>
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<td>1.66</td>
<td>0.02</td>
<td>38</td>
<td>230</td>
<td>-120</td>
<td>0.23</td>
<td>0.05</td>
<td>122</td>
<td>57</td>
<td>-7</td>
</tr>
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<td>Santa Cruz</td>
<td>-0.7</td>
<td>--</td>
<td>--</td>
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<td>--</td>
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<td>0.18</td>
<td>1.44</td>
<td>209</td>
<td>96</td>
<td>27</td>
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<td>Santa Rosa</td>
<td>-0.7</td>
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<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.33</td>
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<td>177</td>
<td>77</td>
<td>242</td>
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<td>Vallejo-Fairfield-Napa</td>
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<td>-141</td>
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<td>247</td>
</tr>
<tr>
<td>Yolo</td>
<td>-11.6</td>
<td>4.93</td>
<td>2.31</td>
<td>136</td>
<td>1,296</td>
<td>1,465</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>All Communities</td>
<td>-9.7</td>
<td>6.01</td>
<td>4.31</td>
<td>63</td>
<td>746</td>
<td>845</td>
<td>0.25</td>
<td>0.66</td>
<td>153</td>
<td>61</td>
<td>92</td>
</tr>
</tbody>
</table>

## Table 7
**DUAL-MARKET WELFARE MEASURES AND CAPITALIZATION RATES, SELECTED COMMUNITIES**

<table>
<thead>
<tr>
<th>Community</th>
<th>PMSA</th>
<th>Ozone (ppb)</th>
<th>Δ Δ rent (%)</th>
<th>Δ Δ inc (%)</th>
<th>movers (%)</th>
<th>MWTP ($)</th>
<th>WTPPE ($)</th>
<th>WTPGE ($)</th>
<th>movers</th>
<th>nonmovers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acalanes</td>
<td>Oakland</td>
<td>85.8</td>
<td>76.4</td>
<td>-10.9</td>
<td>1.0</td>
<td>1.0</td>
<td>6.2</td>
<td>17</td>
<td>172</td>
<td>84</td>
</tr>
<tr>
<td>Alameda City</td>
<td>Oakland</td>
<td>31.2</td>
<td>31.0</td>
<td>-0.7</td>
<td>0.6</td>
<td>1.2</td>
<td>7.5</td>
<td>379</td>
<td>80</td>
<td>-107</td>
</tr>
<tr>
<td>Albany City</td>
<td>Oakland</td>
<td>54.2</td>
<td>53.8</td>
<td>-0.8</td>
<td>0.7</td>
<td>1.3</td>
<td>13.0</td>
<td>272</td>
<td>115</td>
<td>120</td>
</tr>
<tr>
<td>Antioch</td>
<td>Oakland</td>
<td>78.0</td>
<td>76.4</td>
<td>-2.1</td>
<td>2.7</td>
<td>1.3</td>
<td>39.5</td>
<td>49</td>
<td>80</td>
<td>-470</td>
</tr>
<tr>
<td>Berkeley</td>
<td>Oakland</td>
<td>47.0</td>
<td>46.6</td>
<td>-0.7</td>
<td>0.3</td>
<td>0.9</td>
<td>7.1</td>
<td>238</td>
<td>84</td>
<td>216</td>
</tr>
<tr>
<td>Castro Valley</td>
<td>Oakland</td>
<td>63.2</td>
<td>62.8</td>
<td>-0.7</td>
<td>1.1</td>
<td>1.1</td>
<td>21.4</td>
<td>69</td>
<td>30</td>
<td>279</td>
</tr>
<tr>
<td>Dublin</td>
<td>Oakland</td>
<td>75.0</td>
<td>71.5</td>
<td>-4.7</td>
<td>0.5</td>
<td>1.2</td>
<td>37.3</td>
<td>62</td>
<td>224</td>
<td>392</td>
</tr>
<tr>
<td>Livermore Valley</td>
<td>Oakland</td>
<td>89.5</td>
<td>76.4</td>
<td>-14.6</td>
<td>1.8</td>
<td>1.0</td>
<td>32.1</td>
<td>13</td>
<td>193</td>
<td>-114</td>
</tr>
<tr>
<td>Pittsburg</td>
<td>Oakland</td>
<td>76.9</td>
<td>76.3</td>
<td>-0.8</td>
<td>2.7</td>
<td>1.2</td>
<td>21.1</td>
<td>44</td>
<td>26</td>
<td>-136</td>
</tr>
<tr>
<td>Sunol Glen</td>
<td>Oakland</td>
<td>70.0</td>
<td>69.5</td>
<td>-0.7</td>
<td>0.3</td>
<td>1.1</td>
<td>20.8</td>
<td>92</td>
<td>43</td>
<td>534</td>
</tr>
<tr>
<td>Black Oak Mine</td>
<td>Sacramento</td>
<td>105.9</td>
<td>76.4</td>
<td>-27.9</td>
<td>29.2</td>
<td>7.3</td>
<td>74.1</td>
<td>65</td>
<td>2116</td>
<td>-34</td>
</tr>
<tr>
<td>El Dorado</td>
<td>Sacramento</td>
<td>100.7</td>
<td>76.4</td>
<td>-24.1</td>
<td>9.5</td>
<td>6.6</td>
<td>57.7</td>
<td>14</td>
<td>424</td>
<td>1,558</td>
</tr>
<tr>
<td>Sacramento City</td>
<td>Sacramento</td>
<td>86.2</td>
<td>76.4</td>
<td>-11.4</td>
<td>6.1</td>
<td>6.3</td>
<td>31.3</td>
<td>73</td>
<td>725</td>
<td>3,246</td>
</tr>
</tbody>
</table>

## Table 8
**PER HOUSEHOLD WILLINGNESS-TO-PAY TO MEET CALIFORNIA’S NEW OZONE STANDARD**

<table>
<thead>
<tr>
<th>Equilibrium Concept</th>
<th>MWTP</th>
<th>MWTP x Δ ozone</th>
<th>MWTP x Δ ozone</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>acre weights</td>
<td>pop weights</td>
<td>district weights</td>
</tr>
<tr>
<td>Single-Market</td>
<td>80</td>
<td>649</td>
<td>409</td>
</tr>
<tr>
<td>Dual-Market</td>
<td>140</td>
<td>1,130</td>
<td>715</td>
</tr>
</tbody>
</table>

**NOTE.**—In the “acre weights” scenario, Δ ozone is measured as the average ozone reduction per acre. In the “pop weights” scenario, Δ ozone is measured by first assigning each household the ozone reduction in their home community and then averaging over households. In the “community weights” scenario, Δ ozone is measured as an average over communities.
A. Hedonic Property Value Model

- Location = house
- Provision of public goods varies across individual homes
- Wage income is exogenous to location choice

B. Interregional Hedonic Model

- Location = metro area
- Provision of public goods varies across metro areas
- Wage income is endogenous to location choice
- No commuting between metro areas

C. Tiebout Sorting Model

- Location = house
- Provision of public goods varies across communities
- Wage income is exogenous to location choice

D. Dual-Market Equilibrium Sorting Model

- Location = house, work metro area
- Provision of public goods varies across communities
- Wage income is endogenous to location choice
- Some commuting between metro areas

FIG 1.— Depiction of the Urban Landscape in Four Alternative Models of a Locational Equilibrium. Metropolitan areas are indexed by \( k \). Panel B illustrates how metropolitan areas constitute unique locations in the interregional hedonic model. Panel A displays the locations of individual homes within each metro area. In panel C, the metro areas are divided into communities. Finally, in panel D the asterisks represent central business districts and the arrows indicate commuting patterns to work.
A. Partition for retired households with $y=50,000$

B. Partition for working households with $y=50,000$ in communities A,B,C, and $y=50,500$ in community D

C. Partition for retired household with $y=50,000$ and identical relative preferences

\[
\alpha \\
\begin{array}{cccc}
\Omega_A & \Omega_B & \Omega_C & \Omega_D \\
0.00 & 1.09 & 1.28 & 2.29 \\
\end{array}
\]

FIG 2.— A Partition of Preference Space in Three Competing Models. All three partitions correspond to the hypothetical choice set in Table 1. Panels A and B recognize that households may differ in their relative preferences for public goods and reflect the normalization that $\gamma_{iY} + \gamma_{iP} = 1$. In panel C, households are restricted to have identical relative preferences: $(\gamma_{iY}, \gamma_{iP}) = (0.48, 0.52) \forall i$.
A. Primary Metro Areas & Census Tracts     B. School Districts & Air Monitoring Stations

FIG 3.—The San Francisco and Sacramento Consolidated Metropolitan Statistical Areas

A. Single-Market

B. Dual-Market, Retired Households

C. Dual-Market, Retired Households

D. Dual-Market, Managers

FIG 4.—Partition of Preference Space, Three Communities

FIG. 6.—Ozone Concentrations in the San Francisco-Sacramento Region. The left panel displays the average ozone concentrations in individual school districts between 1999 and 2001. The right panel displays the ozone concentrations in the attainment scenario. Ozone is measured in parts per million.
FIG. 7.—Marginal and General Equilibrium Welfare Measures, by Equilibrium Concept. The figures display average WTP in each community, ordered by ozone concentrations in 1999-2001.
APPENDIX: SOLVING FOR A LOCATIONAL EQUILIBRIUM

Single-Market

In the single-market case, the general equilibrium problem requires solving for households’ location choices and a vector of prices that clears the housing market in every community following a shock to public goods. The restrictions on preference heterogeneity in this version of the model allow the problem to be reformulated as a one-dimensional rootfinding problem, which is easily solved.

To begin, order the communities by their price of housing such that \( p_1 < p_2 < \ldots < p_J \). In order for each community to have a positive population, it must be the case that \( \bar{g}_1 < \bar{g}_2 < \ldots < \bar{g}_J \). Equation (A.1) defines all the combinations of income and preferences that would make a household exactly indifferent between \( j \) and \( j+1 \).

\[
\ln(\alpha_j) - \rho \left( \frac{y_j^{1+\nu} - 1}{1 - \nu} \right) = \ln \left( \frac{Q_{j+1} - Q_j}{g_j^\rho - g_{j+1}^\rho} \right) = R_{j,j+1}, \quad \text{where} \quad Q_j = \exp \left[ -\frac{p}{1 + \eta} \left( \bar{p}_j^{q_{j+1}} - 1 \right) \right].
\]

Notice that all the heterogeneity in income and preferences appears to the left of the equality. A household with income and preference such that: \( \ln(\alpha_j) - \rho \left( \frac{y_j^{1+\nu} - 1}{1 - \nu} \right) < R_{j,j+1} \) will prefer community \( j \) to every higher ranked community: \( j+1, j+2, \ldots, J \). Therefore the left side of (A.1) can be used to systematically sort households across communities.

Following a shock to public goods, the new equilibrium price ranking of communities must be identical to the new ranking by \( \bar{g} \). Given a guess for the new price of housing in the cheapest community (\( \bar{p}_1 \)), the left side of (A.1) can be used to sort households into community 1 until the housing market clears. The preferences and income of the final “border” household are then used to solve (A.1) for the price of housing in community 2. The resulting value for \( p_2 \) is used to sort the next group of households into community 2 which generates a value for \( p_3 \), and so on. Equation (A.2) depicts the structure of the problem, using star superscripts to indicate market clearing.

\[
p_2^* = f(\bar{p}_1) \quad \Rightarrow \quad p_3^* = f(p_2^*) \quad \Rightarrow \quad \ldots \Rightarrow \quad p_J^* = f(p_{J-1}^*).
\]

This recursive structure effectively reduces the simulation to a one-dimensional problem where the new equilibrium price of housing in community 1 is adjusted until the market clears in community \( J \). Excess supply in community \( J \) indicates that \( p_1 \) has been set too high and excess demand indicates it has been set too low.
**Dual-Market**

The housing market problem cannot be defined recursively if households differ in their relative preferences for multiple public goods. This is because the market clearing price of housing in each community generally depends on the price of housing in every other community. Equation (A.3) illustrates this $J$-dimensional problem.

$$p_i^* = f(p_2, \ldots, p_J), \quad p_z^* = f(p_1, p_3, \ldots, p_J), \quad \ldots, \quad p^*_J = f(p_1, \ldots, p_{J-1}).$$

(A.3)

While there is no obvious way to sort households across communities, they can still be ranked according to the maximum price they would be willing to pay to live in every community. Equation (A.4) defines this *Hicksian Equivalent Price* (HEP).

$$p_{ij}^{\text{HEP}} : V_{ij}(g_j, p_{ij}^{\text{HEP}}; \alpha_i, \gamma_i, y_i) = V_{ij}(g_j, p_j^{\alpha_i}, \gamma_j, y_j).$$

(A.4)

Suppose household $i$ lives in community $q$. Then $p_{ij}^{\text{HEP}}$ is the price of housing in community $j$ that would allow household $i$ to maintain its current level of utility, were it to move there. In a locational equilibrium, the price of housing in $j$ must be greater or equal to the maximum HEP for any household living outside that community: $p_j^* \geq \max \left\{ p_{ij}^{\text{HEP}} \right\}$. This necessary condition provides the basis for the solution algorithm. Its basic mechanics are discussed before extending the problem to the labor market.

Following a shock to public goods, the algorithm starts by solving (A.4) for every household. The household with the highest HEP is assigned to community 1 and this price is used to solve (6) for the amount of housing they consume. If the supply of housing exceeds the demand, the algorithm moves to the household with the next highest HEP and their price is used to solve for the quantity of housing consumed by both households. This process continues until the housing market clears. The new market-clearing price ($p_i^*$) is then used to update the utility of every household in community 1. Next, the algorithm repeats the process to update housing prices in communities 2 through $J$, and the utility of the households who live there. The $J \times 1$ price vector that results from the first round of adjustments is unlikely to define a new locational equilibrium. For example, some of the households who were initially sorted into community 1 may have been subsequently sorted into other communities, leaving community 1 with an excess supply of housing. In this case $p_i$ must decrease, initiating a second round of adjustments. The algorithm continues to iterate over subsequent rounds until all prices converge, signaling that markets have cleared and that each household occupies its utility maximizing location.
The same logic used to define the Hicksian equivalent price can be used to define a *Hicksian Equivalent Wage* (HEW) that would make a working household exactly indifferent between its current location and another location in a different labor market.

\[
W^\text{HEW}_{s,k} : \begin{align*}
V_{i,k}[g, p; \alpha, y, \gamma_i, \theta, W^\text{HEW}_{s,k}, t_k] &= V_{i,s+1}[g, p; \alpha, y, \gamma_i, \theta, W_{s,k}, t_j].
\end{align*}
\]  

(A.5)

In (A5), \(W^\text{HEW}_{s,k}\) is the wage in labor market \(k\) that would allow a household with occupation \(s\) to change its job location to \(k\) and maintain the same level of utility it gets from its current location in labor market \(r\). Community-specific subscripts are suppressed in the equation because working households are assumed to choose the utility-maximizing community, conditional on their job location. A necessary condition for locational equilibrium is: \(W^\text{HEW}_{s,k} \leq \min \{ W^\text{HEW}_{s,i,k} \}\). That is, there cannot be any households in alternative job locations who would be willing to work for less than the current market wage.

Simultaneously solving for a new set of housing prices and wage rates simply requires adding another loop to the HEP sorting algorithm that solves for the HEW for each occupation in each labor market. Equation (A.6) summarizes the steps in the algorithm. It iterates over updates to housing prices given wages and updates to wages given housing prices:

(i) \(p^i_1 = \max \{ p^\text{HEW}_{1,i} \} = f(p^0_2, \ldots, p^0_J | w^0)\).

(ii) \(p^i_2 = \max \{ p^\text{HEW}_{2,i} \} = f(p^i_1, p^0_2, \ldots, p^0_J | w^0)\).

.  

(J) \(p^i_J = \max \{ p^\text{HEW}_{J,i} \} = f(p^i_1, \ldots, p^i_{J-1} | w^0)\).

(J+i) \(W^\text{HEW}_{1,i} = \min \{ W^\text{HEW}_{1,i} \} = f(w^0_2, \ldots, w^0_J | p^1)\).

.  

(J+SK) \(W^\text{HEW}_{s,k} = \min \{ W^\text{HEW}_{s,k} \} = f(w^0_2, \ldots, w^0_{s,k-1} | p^s)\).

(J+SK+i) \(p^i_1 = \max \{ p^\text{HEW}_{1,i} \} = f(p^i_2, \ldots, p^i_J | w^1)\).

.  

(2J+2SK) \(W^\text{HEW}_{s,k} = \min \{ W^\text{HEW}_{s,k} \} = f(w^i_2, \ldots, w^i_{s,k-1} | p^i)\).

.  

until all prices and wages converge.