Augmented Cost-of-Living Indices for Public Goods:

US Air Quality, 1971-2003*

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Key Words: air quality, cost-of-living index, green accounting, price index.

JEL Classification Numbers: E31, H40, I00, Q25, R10.

* I thank Robert Hill, Kerry Smith, Roger von Haefen, and participants at the International Conference on Index Number Theory and the Measurement of Prices and Productivity for valuable comments and suggestions on this and a companion paper.

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Introduction

> If a poll were taken of professional economists and statisticians, in all probability they would designate (and by a wide margin) the failure of the price indices to take full account of quality changes as the most important defect of these indices. And by almost as large a majority, they would believe that this failure introduces a systematic upward bias in the price indices—that quality changes have on average been quality improvements.
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> —The 1961 Price Statistics Review Committee (Stigler et al. p. 35)

Apparently, not much has changed since the Stigler Commission wrote these words almost forty-five years ago, in its external review of the US Consumer Price Index (CPI). More recently, the 1996 Boskin Commission continued to highlight the problems of quality change and new goods, attributing to them over half their estimated bias of 1.1 percent in the CPI (Boskin et al. 1996, see also Lebow and Rudd 2003). These findings have motivated much new important research,[1] but perhaps one of the most important sources of such quality change remains unaddressed: the changing quality of public goods over time.

The intuition for adjusting for the quality of public goods lies directly in the interpretation of price indices. For at least these forty-five years, economists have advocated that price indices—at least when used to adjust wages and pensions for inflation—should be interpreted as

[1] See for example Bresnahan and Gordon (1997), Cutler et al. (1998), Erickson (2000), Hausman (1999), Nevo (2003), and Triplett (1999). Nordhaus (1999) issues a similar call for adjustment for public goods, but only nets out their costs.

Konüs-type cost-of-living indices and brought as close to that theoretical ideal as possible. The "over-arching recommendation" of the Boskin Commission as well as the Stigler Commission, such a cost-of-living concept lies at the heart of the rationale for adjusting for quality change for market goods.[2] The US Bureau of Labor Statistics has now official adopted this perspective for the US CPI, and has done so unofficially for some time (Triplett 2001).

The Konüs cost-of-living index is the adjustment required to maintain a constant standard of living. Since the standard of living is as much a function of the quality of automobiles, computers and so forth as their prices, it follows from this definition that such indices should account for quality change. But the standard of living is as much a function of public goods as market goods. By the same reasoning, it follows that public goods also belong in a cost-of-living index.

While one might prefer to think in terms of a "conditional cost-of-living index" which holds public goods constant (Pollak 1989), such an index is not appropriate theoretically unless public and private goods are separable in preferences, and, in any case, would still fail to hold over-all welfare constant. Moreover, it would not be truly neutral with respect to public goods: price increases in final goods following government regulations would increase the index, but the increase would not be offset by the public goods that the regulations provide. If the regulations

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[2] The more recent Schultze-Mackie Commission (2002) was less sanguine about the Konüs cost-of-living interpretation and quality adjustment. See Banzhaf (2004) for a history of these ideas and their connection to debates about quality change.

are socially desirable in a benefit-cost sense, the conditional cost-of-living index would give the wrong welfare signal.

This paper reviews specific suggestions for ways in which public goods might be incorporated into a cost-of-living index and provides a specific example for US air quality, as measured by concentrations of airborne particulates, from 1971 to 2003. While only one of many public goods that might enter a cost-of-living index, air quality is particularly salient because of its importance in private and social decisions, its wide measurement, and its steady improvement. Over the 32 year period considered here, measures of airborne particulate pollution fell by one half (an average of 2.1% each year). If such steady improvements do not affect the index, other public goods are less likely to. In fact, the estimated adjustments are substantial—on the order of 0.1 percentage points annually, consistent with the order of magnitude estimated by Boskin et al. (1996) and Lebow and Rudd (2003).

Although the focus of this paper is cost-of-living indices, note that price indexes that account for public goods would also be appropriate as deflators for green income accounts.[3] Blomquist, Berger, and Hoehn (1988) and Cragg and Kahn (1999), for example, estimate related quantity indices of public goods. The indices estimated here can be thought of as roughly the dual to such quantity indices.

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[3] In particular for accounts that include public and other non-market services (see e.g. Nordhaus and Tobin 1973 for an early example). A related issue is extensions to Net GDP which account for depreciation of natural assets (e.g. Repetto et al. 1989 and Weitzman 2003). See Nordhaus and Kokkelenberg (1999) and Hecht (2005) for overviews of green accounting issues.

Theory of Green Cost-of-Living Indices

Following the classic definition of Konüs (1939), a cost-of-living index is defined as the ratio of expenditures required, in two time periods or other scenarios, to hold a representative household's utility constant. Beginning with the standard case where periods differ only by the prices of market goods, let utility in period t be given as $u^t = u(\boldsymbol{x}^t)$, where $\boldsymbol{x}^t$ is a vector of consumption goods and let $m(\boldsymbol{p}_x, u)$ denote the minimal cost of achieving a given utility level at a given vector of prices. Finally, let the reference (i.e. baseline) period be denoted with superscript 0 and the comparison period by superscript 1. Then the cost-of-living index at reference-period utility is

$$\mathrm{I}^{01}\left(\boldsymbol{p}^1, \boldsymbol{p}^0, u^0\right) = \frac{m(\boldsymbol{p}_x^1, u^0)}{m(\boldsymbol{p}_x^0, u^0)}. \tag{1}$$

It measures the proportionate change in expenditures required to maintain the utility level of the reference period at comparison period prices.

Of course, the cost-of-living index cannot be computed in practice because of its reliance on unobserved information about preferences. However, Konüs (1939) showed that the following empirically tractable compromises each bound a true cost-of-living index:

$$L^{01} \equiv \frac{\sum_k p_k^1 x_k^0}{\sum_k p_k^0 x_k^0} = \sum_k \frac{p_k^1}{p_k^0} w_k^0 \geq I^{01}(\boldsymbol{p}^1, \boldsymbol{p}^0, u^0) \tag{2}$$

$$P^{01} \equiv \frac{\sum_k p_k^1 x_k^1}{\sum_k p_k^0 x_k^1} = \sum_k \frac{p_k^1}{p_k^0} w_k^1 \leq I^{01}(\boldsymbol{p}^1, \boldsymbol{p}^0, u^1), \tag{3}$$

where w_k^t is the expenditure share for good k computed at period t quantities and reference prices. These are the well-known Laspeyres and Paasche indices, the arithmetic average of the relative prices of each commodity, respectively weighted by their share of total expenditures in the reference or the comparison scenario. The Laspeyres index is an upper bound on the true cost-of-living index at reference utility; the Paasche index is a lower bound on the true cost-of-living index at comparison utility. Because its use of historical expenditure data facilitates prompt releases of the index, and because a historical perspective for normative comparison seems more natural, the Laspeyres index is used in most national price statistics.

Banzhaf (2005) proposes two ways to incorporate public goods into a cost-of-living index. The first approach, the "augmented cost-of-living index," is simply to add additional commodities to the Laspeyres or Paasche indices. Not traded in markets, the commodities are evaluated at their *implicit* or *virtual* prices (Neary and Roberts 1980). Virtual prices are those prices at which consumers hypothetically would choose to consume that quantity of goods that they actually are forced to consume, when income is also adjusted to cover these expenditures. Virtual prices are applicable to cases of rationing or to public goods, or to any case where goods that enter preferences are determined by other agents, political processes, and nature.

Denote the quantity (or quality) of public goods by the vector $\bar{\boldsymbol{q}}$, where the over-bar emphasizes the fact that the quantity of these goods is determined exogenously from an individual consumer's perspective. The Marshallian virtual price vector $\bar{\boldsymbol{p}}_q$ associated with a level of these public goods $\bar{\boldsymbol{q}}$ is defined implicitly as

$$\bar{\boldsymbol{q}} = \arg\max u(\boldsymbol{x},\boldsymbol{q}) \;\; s.t. \;\; \boldsymbol{p}_x \cdot \boldsymbol{x} + \bar{\boldsymbol{p}}_q \cdot \boldsymbol{q} \le y + \bar{\boldsymbol{p}}_q \cdot \bar{\boldsymbol{q}} \tag{4}$$

where y is money income. Virtual prices are a function of the prices of other goods, the rationing level, and the budget constraint. They are the price at which households would (just) demand the rationed quantities, if they were actually free to choose their levels. Like market prices, the virtual price can be interpreted as the marginal willingness to pay for the good.

By focusing on prices, albeit virtual ones, this approach is readily consistent with standard price index formulae, such as the Laspeyres index. Specifically, by analogy to the usual Laspeyres argument, the following bound holds:

$$\frac{\left(\boldsymbol{p}_x^{1} \cdot \boldsymbol{x}^{0} + \overline{\boldsymbol{p}}_q^{1} \cdot \overline{\boldsymbol{q}}^{0}\right)}{\left(\boldsymbol{p}_x^{0} \cdot \boldsymbol{x}^{0} + \overline{\boldsymbol{p}}_q^{0} \cdot \overline{\boldsymbol{q}}^{0}\right)} \geq \frac{m\left(\boldsymbol{p}_x^{1}, \overline{\boldsymbol{p}}_q^{1}, u^{0}\right)}{m\left(\boldsymbol{p}_x^{1}, \overline{\boldsymbol{p}}_q^{1}, u^{0}\right)}. \tag{5}$$

This is the usual Laspeyres upper bound, with additional terms for the virtual prices. Multiplying both sides by $(\boldsymbol{p}_x^{0} \cdot \boldsymbol{x}^{0} + \overline{\boldsymbol{p}}_q^{0} \cdot \overline{\boldsymbol{q}}^{0}) / \boldsymbol{p}_x^{0} \cdot \boldsymbol{x}^{0}$, subtracting $\overline{\boldsymbol{p}}_q^{1} \cdot \overline{\boldsymbol{q}}^{1} / \boldsymbol{p}_x^{0} \cdot \boldsymbol{x}^{0}$ from both sides, and recognizing that $\boldsymbol{p}_x^{0} \cdot \boldsymbol{x}^{0} + \overline{\boldsymbol{p}}_q^{0} \cdot \overline{\boldsymbol{q}}^{0} = m(\overline{\boldsymbol{p}}_q^{0}, \boldsymbol{p}_x^{0}, u^{0})$, the expression can be re-written in the form

$$\frac{\left(\boldsymbol{p}_x^{1} \cdot \boldsymbol{x}^{0} + \overline{\boldsymbol{p}}_q^{1} \cdot \overline{\boldsymbol{q}}^{0}\right) - \overline{\boldsymbol{p}}_q^{1} \cdot \overline{\boldsymbol{q}}^{1}}{\left(\boldsymbol{p}_x^{0} \cdot \boldsymbol{x}^{0} + \overline{\boldsymbol{p}}_q^{0} \cdot \overline{\boldsymbol{q}}^{0}\right) - \overline{\boldsymbol{p}}_q^{0} \cdot \overline{\boldsymbol{q}}^{0}} \geq \frac{m\left(\boldsymbol{p}_x^{1}, \overline{\boldsymbol{p}}_q^{1}, u^{0}\right) - \overline{\boldsymbol{p}}_q^{1} \cdot \overline{\boldsymbol{q}}^{1}}{m\left(\boldsymbol{p}_x^{0}, \overline{\boldsymbol{p}}_q^{0}, u^{0}\right) - \overline{\boldsymbol{p}}_q^{0} \cdot \overline{\boldsymbol{q}}^{0}}, \tag{6}$$

which shows the Laspeyres bound with an explicit adjustment for the difference between "virtual income" and actual income.

Finally, denote by $\tilde{m}(\boldsymbol{p}_x^{t}, \overline{\boldsymbol{q}}^{t}, u^{a})$, the *conditional* expenditure function, in which the levels of the public goods are held constant at their exogenous levels in the expenditure minimization problem. Using the fact that $\tilde{m}(\boldsymbol{p}_x^{t}, \overline{\boldsymbol{q}}^{t}, u^{0}) = m(\boldsymbol{p}_x^{t}, \overline{\boldsymbol{p}}_q^{t}, u^{0}) - \overline{\boldsymbol{p}}_q^{t} \cdot \overline{\boldsymbol{q}}^{t}$ (that is, the fact that they would be the same but for the need to "cover" expenditures in the hypothetical case where public goods are purchased at their virtual prices), Expression (6) can be rewritten further as

$$\frac{(\boldsymbol{p}_x^{1} \cdot \boldsymbol{x}^{0}) - \overline{\boldsymbol{p}}_q^{1} \cdot \Delta\boldsymbol{q}}{(\boldsymbol{p}_x^{0} \cdot \boldsymbol{x}^{0})} \geq \frac{\tilde{m}(\boldsymbol{p}_x^{1}, \overline{\boldsymbol{q}}^{1}, u^{0})}{\tilde{m}(\boldsymbol{p}_x^{0}, \overline{\boldsymbol{q}}^{0}, u^{0})}. \tag{7}$$

This is a Laspeyres index for market goods, with an adjustment in the numerator for the changing level of public goods, evaluated at comparison-period virtual prices. Although it is a derivation of Expression (5), which is an ordinary Laspeyres index with the addition of virtual prices, it is more directly interpreted as a Laspeyres index modified by an index of quantity changes weighted by prices.

Such an augmented index is probably the most straight-forward way to introduce public goods into the cost-of-living index, as it converts the welfare information of quantity changes into price changes and proceeds with the usual definition of the price index. Banzhaf (2005) also proposes an alternative "adjusted cost-of-living index," based on Willig (1978), which we describe briefly. In cases where public goods are weak complements to market goods, they may enter an adjusted cost-of-living index through adjustments of the prices of the linked market goods—much as quality-adjusted goods now increasingly are hedonically adjusted for quality change.[4] In particular, spatially delineated public goods, such as air quality, crime, and education, can be viewed as hedonic attributes of spatially differentiated housing.

Denote p_h as the price of housing and $\boldsymbol{q}_h$ as a vector of characteristics measuring the quality of housing and weakly complementary public goods. Define p^* and p^{**} implicitly as

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[4] Weak complementarity describes a situation where one good is only enjoyed if it's associated weak complement is consumed in positive quantities. Fisher and Shell's (1972) example is that the coldness of a freezer is not enjoyed unless the freezer is first obtained. Similarly, the air quality in a neighborhood is not enjoyed unless housing in that neighborhood is obtained (i.e. unless one resides in the neighborhood). See Bockstael and McConnell (1993), Smith and Banzhaf (2004), and Palmquist (2005) for more on this preference restriction.

$$v(p_h^{*}, \boldsymbol{q}_h^0, \boldsymbol{p}_x^1, m(p_h^1, \boldsymbol{q}_h^1, \boldsymbol{p}_x^1; u^0)) = v(p_h^0, \boldsymbol{q}_h^0, \boldsymbol{p}_x^0, y^0) \tag{8}$$

and

$$v(p_h^{**}, \boldsymbol{q}_h^1, \boldsymbol{p}_x^0, m(p_h^0, \boldsymbol{q}_h^0, \boldsymbol{p}_x^0; u^1)) = v(p_h^1, \boldsymbol{q}_h^1, \boldsymbol{p}_x^1, y^1), \tag{9}$$

where $v(\,)$ is the indirect utility function. These are the price adjustments, in lieu of the more familiar income adjustments, that compensate for quality changes. Note that the price adjustments are defined at a point where income *already* is adjusted to maintain utility.

Using p^* and p^{**}, Willig (1978) shows that the following bounds for the Laspeyres and Paasche indices still hold:

$$L^{*01} \equiv \frac{p_h^{*} h^0 + \boldsymbol{p}_x^1 \cdot \boldsymbol{x}^0}{p_h^0 h^0 + \boldsymbol{p}_x^0 \cdot \boldsymbol{x}^0} \geq I^{01}(\boldsymbol{p}^1, \boldsymbol{p}^0, \boldsymbol{q}^1, \boldsymbol{q}^0, u^0) \tag{10}$$

$$P^{**01} \equiv \frac{p_h^1 h^1 + \boldsymbol{p}_x^1 \cdot \boldsymbol{x}^1}{p_h^{**} h^1 + \boldsymbol{p}_x^0 \cdot \boldsymbol{x}^1} \leq I^{01}(\boldsymbol{p}^1, \boldsymbol{p}^0, \boldsymbol{q}^1, \boldsymbol{q}^0, u^1) \tag{11}$$

L^* is the Laspeyres index with p^* replacing p^b, while P^{**} is the Paasche index with p^{**} replacing p^a. They are the usual Laspeyres and Paasche concepts with a subindex defined in cost-of-living terms replacing the usual price relative for the good with quality change.

In this paper, I illustrate the augmented cost-of-living index for changes in national air quality over a thirty year period.[5] Before turning to this illustration however, we first consider some practical issues in implementing these indices.

[5] Banzhaf (2005) illustrates both the augmented and adjusted indices for a more limited application to local public goods in Los Angeles over a five-year period.

Issues of Practical Implication

To fully implement such "green" cost-of-living indices in national accounts, additional thought would have to be given to several issues. First, how would the set of public goods that enter a cost-of-living index be selected? Several criteria present themselves. As with market goods, the more important public goods should be a priority, with importance judged by total virtual income ($p*q$). Likewise, public goods that are viewed as changing the most over time, whether the changes be secular or cyclical, should be a priority, as they are most likely to affect the level of the index. More pragmatically, public goods for which quantities can be physically measured more easily are also better candidates. In many cases, this criterion will not so much determine which goods enter the index, as the form in which they enter. For example, "air quality" has many chemical dimensions to it, creating many possible physical measures, but the criterion of accessibility to current monitoring networks (as well as the criterion of importance) would lead to the choice of particulates and ozone levels.

Similarly, public goods whose virtual prices are easier to measure should be prioritized over those where such measures are unreliable. Virtual prices for weakly complementary goods, for which preferences are revealed in linked markets, can be estimated using established revealed preference techniques such as hedonics and discrete choice models, currently used for quality-adjustment of market goods. More pure public goods, such as national defense or existence values for exotic locales and species, can only be valued using survey-based stated-preference measures. Even among these goods, a hierarchy may be established based on the ease of communicating the commodity and the public's acceptance of a hypothetical market for the goods. In choosing the cut-off point, comprehensiveness of the index must be traded off against its precision (or defensibility)—a trade-off now made very conservatively by omitting all public goods.

A second question of implementation is how are virtual prices, or, in the case of the adjusted cost-of-living index, marginal rates of substitution between prices and qualities are to be estimated. As already suggested, established non-market valuation procedures, similar to procedures used for correction for quality change in market goods, may be used. Hedonic price regressions, discrete choice-based models, averting behavior methods, and state preference surveys are all candidates. They must be chosen based on assessments of their credibility, their suitability for a given good, and their expense. While in the short term in may be possible to "transfer" previously estimated virtual prices, taken as it were off the shelf, for use in cost-of-living indices, a serious effort would require new data collection and new estimates on a scale equal to that now mustered for market goods.

Third, and closely related to the second, what sampling techniques are to be used for such virtual prices? Under the ideal conditions of a neoclassical economist, a good obeys the law of one price within a single market. The averages of the prices of the good across markets are the basis of the index. However far the reality is from these ideal conditions, for quality-differentiated goods even the ideal conditions are different: for such goods, the analogy to a single price is a single hedonic price *function* over differentiated goods, suggesting a continuum of virtual prices within a market. For important transportable goods such as computers and automobiles, arbitrage may be strong enough to create a national price function. In contrast, such transportation is not possible for spatially delineated public goods, and separate markets exist in each metro area. In such contexts, national hedonic estimates (or national choice models) would not be appropriate. Instead, a set of urban areas must first be sampled, virtual price functions estimated in each, and average virtual prices estimated within and across urban areas. Finally, for pure public goods, there is no market whatsoever and so no arbitrage to create any such equilibrium conditions as the law of one price; great variability in virtual prices across households can be expected.

Note in passing here that the emphasis on differences in virtual prices across households, even within a single market, raises an important distinction in the interpretation of traditional national price statistics. National price indices, based on average price ratios and average expenditure shares, are often compared to "plutocratic indices," expenditure-weighted averages of consumer-level price indices. The comparison is exact when all consumers face the same prices, but collapses when prices differ. Accordingly, as more goods with heterogeneous prices enter the index, the plutocratic index concept becomes less useful.

A final implementation issue is how to address the fact that average virtual prices are sure to be estimated much more noisily than average market prices. If Expression (7) is to be used, changes in the quantities of public goods will be the main driver of changes in the index over time, though weighted by virtual prices. At some level of intuition, the usual roles in the price indices played by quantities and prices in the case of market goods are exchanged in the case of public goods. Accordingly, just as expenditure-share weights are held constant over a number of years in current practice, virtual price weights for changes in public goods might be held constant over a number of years. As an alternative, *real* virtual prices (i.e., relative to the price of the basket of market goods) might be held constant. Such practice would smooth fluctuations in the index caused by year-to-year changes in estimated virtual prices caused only by noise. Still another alternative might be to hold constant virtual price relations, as a function of quantities.

No doubt other such implementation questions would arise. Many are now being asked for national indicators of environmental health and for green income accounts. And many similar questions were asked during the formative years of national price indices (see, e.g., the discussion in Mitchell 1921). Indeed, the questions and obstacles must appear small in contrast to those faced by index number pioneers such as Wesley Clair Mitchell and Irving Fisher, who had weaker models to build upon.

Empirical Example: The Case of US Air Quality, 1971-2003

This paper illustrates the concept of augmented or green cost-of-living indices with an application to air quality improvements on a national scale over a 32 year period (1971-2003). Air quality, in turn, is represented by concentrations of particulate matter (dust in the air of unspecified chemical properties), which has been linked to the most serious health effects and routinely accounts for the lion's share of all damages in benefit assessments (e.g. Desvousges et al. 1998, US EPA 1999).

In light of the discussion in the previous section, air quality provides a good case study for several reasons. First, although it is not at the very top of the list of important public goods—public school quality and public safety would likely take precedent—it is near the top. The environment overall is certainly at the of people's awareness, and air quality is probably the most important single factor. Evidence of this is the information sought in newspapers and weather reports about daily smog alerts and the fact that environmental regulations account for the largest share of regulatory costs borne by industry in the United States. Second, air quality has generally improved over the long term over this period, providing ideal conditions for it to actually affect the level of the cost-of-living index over time. Other public goods which are more cyclical over the period are less likely to do so. Thus, it is reasonable to start with this application: if we do not find any affect here, we are unlikely to do so for most public goods.

Third, because of its regulatory performance, extensive research has been devoted to the best ways to measure air pollution, in terms of both reliability of the measure and importance for human welfare. Moreover, extensive measurements have been made, with 500 to 1300 monitors active in the United States measuring particulates in any year during this period. Finally, perhaps for the same reasons, there has been a similar research effort into measuring virtual prices (marginal willingness to pay), generally for benefit-cost applications.

Implementing the augmented cost-of-living index on the left-hand side of Expression (7) involves four basic steps. First, note that, as shown in the expression, the virtual expenditures associated with changes in public goods enter into the numerator of a ratio of total expenditures. These total expenditures are calibrated to the average US household expenditure in 1984 as estimated from the US Consumer Expenditure Survey. This figure represents the denominator in the left-hand side of Expression (7) for that year. The US CPI is then used to fill in the remaining data in all other years.[6]

The second step is to obtain the Δq in Expression (7), in this case the changes in concentrations for each year. These data were obtained for all US monitors from 1971 to 2003 with a special request to the US Environmental Protection Agency. As noted above, there are

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[6] This procedure is essentially consistent with US Bureau of Labor Statistics practices, without allowance for the splicing in of additional expenditure data for the other base years (1967 and 1993-95).

about 500 to 1300 particulate monitors active in the US during any year of this period, and they cover 84 to 1200 counties.

Three issues arise in computing the Δq experienced by the "average" or typical household in the United States. First, averages across space must be weighted by the number of households living in each location. Accordingly, I compute county-level averages of all monitors within a single US county, weighted by the number of days active in monitoring,[7] and then take the population-weighted average of those county-level pollution measures.

Second, over the period, as the science began to suggest that smaller particles were more damaging to human health (because they lodge deeper in the lung), monitors for total suspended particulates (TSP) began to give way to monitors for particulate matter smaller than 10 microns in diameter (PM_{10}), with the total number of PM_{10} monitors surpassing the number of TSP monitors in 1990.[8] In such cases, a linking procedure can be used to replace TSP with PM_{10}, much like that used for rotating other goods in and out of the sample of prices. One linking method, which I call SPLICE, simply takes changes in TSP over time to 1990, and changes in PM_{10} thereafter. TSP and PM_{10} are linked together at 1990 by assuming that 55% of total particulates qualify as PM_{10}, the average ratio in these data and a common rule of thumb. A second linking method is to utilize PM_{10} whenever available in each county, and to otherwise use TSP. The measures can be similarly linked together, but on a year-by-year and county-by-

[7] Monitors with fewer than 45 days are dropped from the analysis altogether.

[8] More recently, the focus has shifted to even finer particles measured by $PM_{2.5}$.

county basis. Because it uses data whenever a TSP or a PM_{10} monitor is present, I call this measure INTERSECT.

The third issue is whether to take the average change in particulate concentrations from year to year, or the changes in averages. (These measures would be the same were data available for the same set of counties in all years; they differ only in their treatment of counties as they rotate in and out of the sample.) For each respective linking method, I refer to the first approach as SPLICE1 and INTERSECT1, and to the second as SPLICE2 and INTERSECT2. Not surprisingly, the measures track one another closely, with the six pair-wise measures of correlation among them ranging from 0.95 to 0.99. Figure 1 shows the changes in two of these measures, SPLICE1 and INTERSECT1 over time, in units of PM_{10}. As shown in the figure, particulate concentrations fell dramatically and steadily over the period, with 2003 levels at almost exactly half of 1971 levels. Because it makes use of more monitoring data, and because it uses counties only where back-to-back annual measures are available (like individual consumption goods in the CPI used only when consecutive prices are available), INTERSECT1 is used in this analysis.

The third step is to estimate virtual prices for these changes in particulates. As noted previously, there is a long history of estimating virtual prices, or marginal willingness to pay, for air quality. Two general approaches stand out. The first approach, used the most frequently in official government benefit-cost analyses, is the damage cost approach (e.g. Desvousges et al. 1998, US EPA 1999). The damage cost approach employs physically estimated functional relationships between air pollution levels and physical injuries (health effects, visibility levels, etc.), multiplied by estimates of marginal values for those injuries. The second approach uses revealed preference techniques, generally by linking air quality as a weak complement to housing in a specific location. Hedonic regressions on housing prices, or discrete choice models of residential locations, are then employed to estimate marginal values (see e.g. Smith and Huang 1995 for a review and bibliography of numerous hedonic studies for housing).

In this paper, I use both approaches to estimate virtual prices, to assess the sensitivity of results to this choice. To implement the damage-cost approach, I estimate predicted mortality effects from particulate concentrations based on a meta-analysis of 11 time-series studies in Desvousges et al. (1998, ch. 4). Following the functional relationship of the underlying studies, which consistently find a linear relative risk, the meta analysis predicts a 0.0950 percent increase in mortality for each 1 unit ($\mu g/m^3$) increase in PM_{10}. The predicted change in mortality for each year resulting from the change in particulates is then computed based on the death rate for each year as reported in the *Statistical Abstract of the United States*. In relative risk functions, these baseline deathrates implicitly play the role of controlling for the background health and demographic composition of the population. Finally, this computed change in the expected number of lives lost to pollution is multiplied by a $2.2m per statistical life (in 1998 dollars), based on a meta analysis of value-of-statistical life (VSL) wage hedonics reported in Mrozek and Taylor (2002). These VSL estimates are inflated using the CPI to maintain a constant relative virtual price. Real changes in virtual prices, then, fluctuate over time only from changes in the death rate.[9]

These estimates involve several important judgments, to which the final cost-of-living adjustments are sure to be sensitive. In particular, I have used relatively low, or conservative, estimates from the literature. The damage-cost literature would highlight multiple injuries from particulate concentrations, including effects on rates of chronic respiratory disease and daily respiratory symptoms, as well as injuries to materials—although mortality injuries generally make up the lion's share of damages. In addition, the mortality estimate itself is based on time series epidemiological studies, while cross-sectional studies such as Pope et al. (1995) have found larger estimates. Finally, the valuation of mortality effects is based on a recent, conservative estimate by Mrozek and Taylor (2003), which is barely half the estimate used by the US EPA.[10]

To use hedonic values, I employ the meta analysis of Smith and Huang (1995), which analyzed 86 estimates from 37 hedonic studies of housing prices and particulate concentrations. They report a median annual value of $22.40 (1982-84 dollars) for a one unit change in TSP

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[9] As discussed above, an alternative would be to employ year-by-year estimates of virtual prices. Although they would fluctuate more widely, they might also better reflect current conditions. (Much as one might one to update more frequently the expenditure weights determining the basket of market goods.) Costa and Kahn (2004), for example, estimate VSLs for each decade from 1940 to 1980.

concentrations. These values were converted to units of PM_{10} by again dividing by 0.55. As with the VSL estimates, the real virtual price for these changes in particulates is held constant over time using the US CPI.[11]

The fourth and final step is to multiply the average changes in particulate levels by the average virtual price. Note that this is not the same as the average of the products. In other words, unlike benefit-cost analysis, no effort is made here to match spatially regional- or household-specific virtual prices to experienced changes in pollution. While such a procedure might be broadly consistent with a plutocratic index, it would not be consistent with the interpretation of the price index as a "typical" household's experience.

The estimated adjustments to the US CPI from these improvements in public goods are small, as one might expect, but noticeable. Using geometric means, the average annual change in the US cost of living from 1971 to 2003 was 4.84% using the CPI, 4.71% using the damage cost adjustment, and 4.67% using the hedonic adjustment. The difference is 0.13 to 0.18 percentage points per year for each adjustment, respectively. The similarity of the adjustments

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[10] On the other hand, based on wage studies of workplace fatalities, such studies may overstate values for the mortality effects of air pollution, which many believe are only short reductions in the lifespans of people at the end of their lives.

[11] Again, in principle an alternative would be to use year-by year estimates based on panels of hedonic data. See e.g. Beron et al. (2001).

based on damage-cost and hedonic methodologies is consistent with the finding of Brucato et al. (1990).

Figure 2 illustrates the annual cost of living adjustments for the US CPI and the Augmented Index based on the damage cost approach. With the two data series almost indistinguishable, the figure highlights the small adjustments involved. Only a few years with large improvements in air quality (e.g. 1972 and 1982—see Figure 1) stand out. Figure 3, however, illustrates the cumulative cost-of-living index for both these indices as well as the Augmented Index based on the hedonic virtual prices. At the end of the period, the cost of maintaining a given standard of living was 4.54 times the baseline cost, according to the CPI. According to the Augmented Indices based on the damage cost and hedonic methods respectively, the cost was 4.37 or 4.30 times greater.

Summary and Conclusions

The results of this research suggest that recent estimates of the bias in the Consumer Price Index may well be understated relative to an augmented cost-of-living index that includes public goods, at least when such goods are improving over time. In the case of US air quality, the bias appears to be an additional 0.13 to 0.18 percentage points per year. Of course, not all public goods are improving over time: crime over this period worsened before improving, and educational attainment has arguably been diminishing, at least for the median household. Nevertheless, the potential importance of these goods, whatever the direction of the effect, is evident.

While more work and considerable judgment would have to go into any official price indices incorporating public goods, this research demonstrates that it would be feasible to estimate augmented indices that are released along side the CPI (see Nordhaus et al. 1999). At a minimum, such an index would be useful in deflating incomes for quality of life comparisons across regions of the country. In the future, such an index also arguably would be a better way to determine cost-of-living adjustments for government expenditures: since these adjustments are designed to offset costs of achieving a standard of living, they should reflect the supply of public goods which are substitutes to private goods in the achievement of that standard of living.

The estimates in this paper suggest incorporating public goods would make a significant difference to such cost-of-living adjustments. The bias due to omitting improving air quality, 0.13 to 0.18, is of the same order of magnitude as that found by the Boskin Commission for market goods, adding one-sixth to the total bias for quality change. Using even the low end of this range would reduce government outlays to Social Security and other programs by over one billion dollars in the first year alone (CBO 1997).

Given the importance of public goods to households' welfare, the important changes in public goods over time, and the sums at stake in compensations meant to hold welfare constant, further research into such augmented accounts at least is warranted.

References

Banzhaf, H.S. 2004. "The Form and Function of Price Indexes: An Historical Accounting," *History of Political Economy* 36: 589-616.

Banzhaf, H.S. 2005. "Green Price Indices." *Journal of Environmental Economics and Management*, forthcoming.

Beron, K., J. Murdoch, and M. Thayer. 2001. "The Benefits of Visibility Improvement: New Evidence from the Los Angeles Metropolitan Area." *Journal of Real Estate Finance and Economics* 22: 319-37.

Blomquist, G., M.C. Berger, and J.P. Hoehn. 1988. "New Estimates of the Quality if Life in Urban Areas." *American Economic Review* 78: 89-107.

Bockstael, N.E., and K.E. McConnell. 2003. "Public Goods as Characteristics of Non-Market Commodities." *Economic Journal* 103: 1244–57.

Boskin, M.J., E.R. Dulberger, R.J. Gordon, Z. Griliches, and D. Jorgenson, *Toward a More Accurate Measure of the Cost of Living*, Final Report to the U.S. Senate Finance Committee, December 4, 1996.

Bresnahan, Timothy F., and Robert J. Gordon, ed. 1997. *The Economics of New Goods*. Chicago: The University of Chicago Press.

Brucato, P.F., Jr., J.C. Murdoch, and M.A. Thayer. 1990. "Urban Air Quality Improvements: A Comparison of Aggregate Health and Welfare Benefits to Hedonic Price Differentials." *Journal of Environmental Management* 30: 265–79.

Congressional Budget Office (CBO). 1997. *The Economic and Budget Outlook, Fiscal Years 1998-2007*. Chapter 2. Washington DC.

Costa, D.L., and M.E. Kahn. 2004. "Changes in the Value of Life, 1940-1980." *Journal of Risk and Uncertainty* 29: 159-80.

Cragg, M.I., and M.E. Kahn. 1999. "Climate Consumption and Climate Pricing from 1940 to 1990." *Regional Science and Urban Economics* 29: 519-539.

Cutler, David M., Mark McClellan, Joseph P. Newhouse, Dahlia Remler. 1998. "Are Medical Prices Declining?" *Quarterly Journal of Economics* 11: 991-1024.

Desvousges, William H., F., Reed Johnson, and H. Spencer Banzhaf. 1998. *Environmental Policy Analysis with Limited Information: Principles and Applications of the Transfer Method*. Cheltenham, UK: Edward Elgar.

Erickson, Timothy. 2000. "The Ambiguous Effect of New and Improved Goods on the Cost of Living." *Economics Letters* 68: 143-147.

Fisher, F.M., and K. Shell. 1972. "Taste and Quality Change in the Pure Theory of the True Cost-of-Living Index." In *The Economic Theory of Price Indexes: Two Essays on the Effects of Taste, Quality, and Technical Change*. New York: Academic Press, pp. 1-48.

Hausman, Jerry A. 1999. "Cellular Telephone, New Products and the CPI." *Journal of Business and Economic Statistics* 17: 188-194.

Hecht, J.E. 2005. *National Environmental Accounting: Bridging the Gap between Ecology and the Economy*. Washington, DC: Resources for the Future.

Konüs, A.A. 1939. "The Problem of the True Index of the Cost of Living." Translated by Jacques Bronfenbrenner. *Econometrica* 7 10–29.

Lebow, D.E., and J.B. Rudd. 2003. "Measurement Error in the Consumer Price Index: Where Do We Stand?" *Journal of Economic Literature* 41: 159-201.

Mitchell, W.C. 1921. "The Making and Using of Index Numbers." Bulletin 284, Part I, pp. 7-114. Washington, DC: US Bureau of Labor Statistics.

Mrozek, J.R., and L.O. Taylor. 2002. "What Determines the Value of Life? A Meta-Analysis." *Journal of Policy Analysis and Management* 22, 253-70.

Neary, J.P., and K.W.S. Roberts 1980. "The Theory of Household Behaviour under Rationing." *European Economic Review* 13 25–42.

Nevo, A. 2003. "New Products, Quality Changes, and Welfare Measures Computed from Estimated Demand Systems." *Review of Economics and Statistics* 85: 266-275.

Nordhaus, W.D., and J. Tobin. 1973. "Is Growth Obsolete?" In *The Measurement of Economic and Social Performance,* edited by Milton Moss. New York: National Bureau of Economic Research.

Nordhaus, W.D. 1999. "Beyond the CPI: An Augmented Cost-of-Living Index." *Journal of Business and Economic Statistics* 17: 182–87.

Nordhaus, W.D., and E.C. Kokkelenberg, eds. 1999. *Nature's Numbers: Expanding the National Economic Accounts to Include the Environment*. Washington, DC: National Academy Press.

Palmquist, R.B. 2005. "Weak Complementarity, Path Independence, and the Intuition of the Willig Condition." *Journal of Environmental Economics and Management* 49: 103-15.

Pollak, R.A. 1989. *The Theory of the Cost-of-Living Index*. New York: Oxford University Press.

Pope, C. A. III, M. J. Thun, M. M. Namboodiri, D. W. Dockery, J. S. Evans, F. E. Speizer, and C. W. Heath, Jr., 1995. "Particulate Air Pollution as a Predictor of Mortality in a

Prospective Study of U.S. Adults." *American Journal of Respiratory and Critical Care Medicine* 151, 669-674.

Repetto, R., W. Magrath, M. Wells, C. Beer, and F. Rossini. 1989. *Wasting Assets: Natural Resources in the National Income Accounts*. New York: World Resources Institute.

Schultze, C., and C. Mackie, Eds. 2002. *At What Price? Conceptualizing and Measuring Cost-of-Living and Price Indexes*. Washington, DC: National Academy Press.

Smith, V.K., and H.S. Banzhaf. 2004. "A Diagrammatic Exposition of Weak Complementarity and the Willig Condition." *American Journal of Agricultural Economics* 86: 455-466.

Smith, V.K., and J.-C. Huang, 1995. Can Markets Value Air Quality? A Meta-Analysis of Hedonic Property Value Models. *Journal of Political Economy* 103, 209-227.

Stigler, G., D.S. Brady, E. Denison, I.B. Kravis, P.J. McCarthy, A. Rees, R. Ruggles, and B.C. Swerling. 1961. *The Price Statistics of the Federal Government*. National Bureau of Economic Research.

Triplett, J.E, ed. 1999. *Measuring the Prices of Medical Treatments*. Washington, DC: Brookings Institution Press.

Triplett, J.E. 2001. "Should the Cost-of-Living Index Provide the Conceptual Framework for a Consumer Price Index?" *Economic Journal* 111: 311-34.

U.S. EPA (Environmental Protection Agency). 1999. *The Benefits and Costs of the Clean Air Act, 1990 to 2010*. Washington, DC: Office of Air and Radiation/Office of Policy.

Weitzman, M. 2003. *Income, Wealth, and the Maximum Principle*. Cambridge, MA: Harvard University Press.

Willig, R.D. 1978. "Incremental Consumer's Surplus and Hedonic Price Adjustment." *Journal of Economic Theory* 17: 227–53.

Figure 1. Plot of Average US Particulate Concentrations, 1971-2003

Figure 2. Annual Cost-of-Living Index with and without Adjustment, 1971-2003

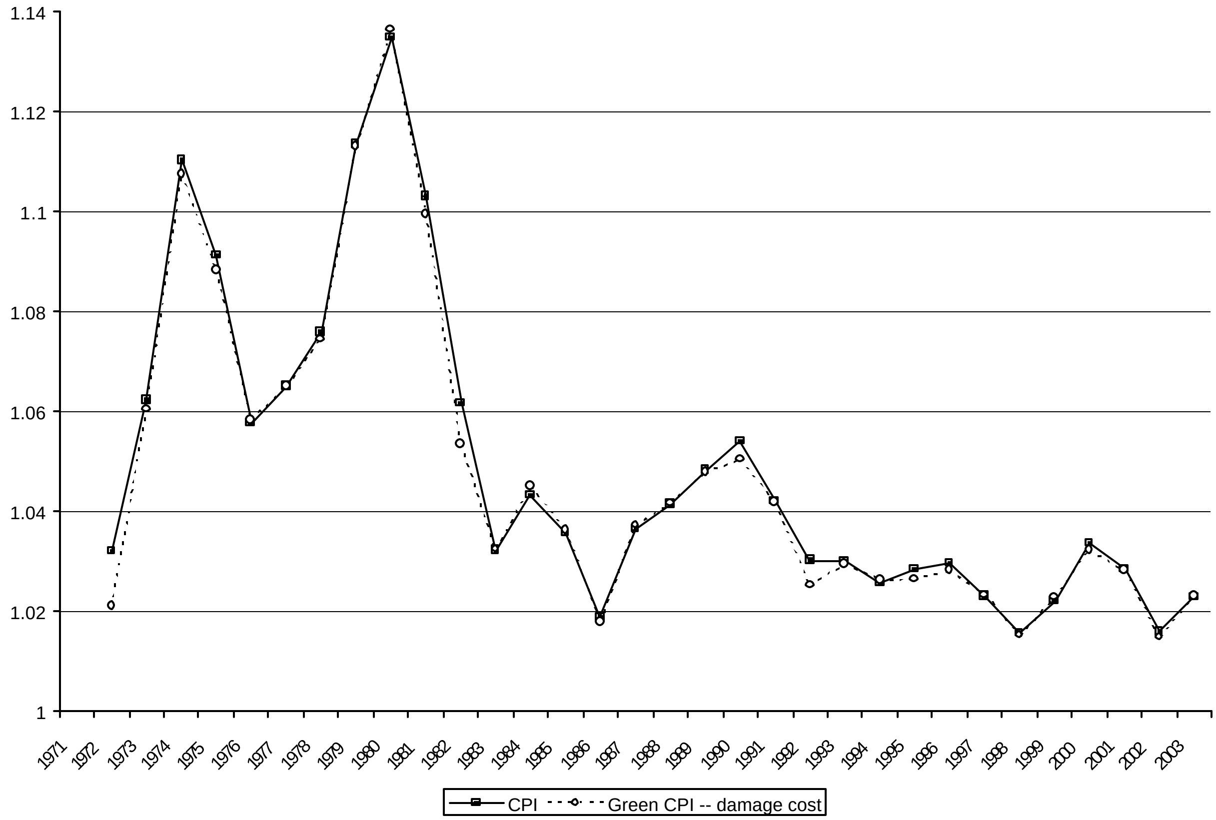

Figure 3. Cumulative Cost-of-Living Index with and without Adjustment, 1971-2003 (1971=100)