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Estimating the Economy-Wide Effects of Mortality Risk Reductions: A General Equilibrium Approach

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Economy-wide feedbacks can affect the efficiency and incidence of policy interventions, and have long been of interest to stake-holders and researchers. When concerns are raised about the general equilibrium (GE) effects of environmental regulations it is most often with respect to the costs of compliance. However, both regulators and researchers have recently shown interest in the potential economy-wide effects of health improvements, including mortality risk reductions. In a study of the cumulative effects of the Clean Air Act, the U.S. Environmental Protection Agency found the benefits of air quality improvements were more than an order of magnitude smaller when estimated with a GE approach compared with a traditional partial equilibrium (PE) approach. It has been suggested that these results are evidence that the PE benefits of environmental regulations are implausibly large. However, previous GE analyses of environmental policies have characterized the expected health improvements using highly simplified approximations whose validity have yet to be closely examined. We present the first explicit characterization of mortality risk changes in a GE model applied to environmental regulations. We find that reductions in mortality risks can have significant GE feedbacks and that these effects are important for estimating the benefits, economic impacts, and potentially the costs of environmental policies. However, our results also suggest that critical methodological limitations led to biased results in previous studies and that the PE estimates of mortality risk reductions are not necessarily implausibly large.

Keywords: mortality risk reduction benefits, general equilibrium, air quality

JEL Codes: Q50, Q53

Economy-Wide Effects of Mortality Risk Reductions from Environmental Policies*

Alex L. Marten† and Stephen C. Newbold‡

1 Introduction

The general equilibrium (GE) effects of environmental policies have long been a concern of stakeholders and researchers due to the potential for economy-wide feedbacks that could affect the efficiency and incidence of those policy interventions. Moreover, for policy makers the effect of environmental regulation on economic output is a key concern. The seminal work of Hazilla and Kopp (1990) and Jorgenson and Wilcoxen (1990) provided a quantitative foundation for such concerns by highlighting the potential for GE cost estimates to deviate significantly from engineering assessments of compliance costs and the possibility for environmental policies to have large impacts on economic output. Concerns about the potential economy-wide effects of environmental regulations are most often focused on the costs of compliance. The beneficial outcomes of these policies are typically excluded from GE analyses and debates about changes in economic output, even though they theoretically may have important feedbacks that affect the economic and social welfare outcomes (Williams, 2002). Recently, both regulators (EPA, 2011a) and researchers (Mayeres and Van Regemorter (2008); Matus et al. (2008); Carbone and Smith (2013)) have begun to show an interest in understanding whether the non-market impacts of environmental policies also have important GE effects in practice. The initial focus has been predominantly on the economy-wide feedbacks associated with improving human health, most notably the mortality risk reductions induced by decreases in emissions of criteria air pollutants. This growing body of literature has provided evidence that improvements in human health from environmental policies could: significantly affect economic growth (Matus et al., 2008); invalidate the conditions that would allow benefits and costs to be evaluated separately (Carbone and Smith, 2013); and have large GE effects that lead PE approaches to substantially overestimate benefits EPA (2011a). These findings all have important implications for the design and evaluation of environmental regulations. However, previous GE analyses of environmental policies have characterized the expected health improvements using highly simplified approximations whose validity have yet to be closely examined. We present the first explicit characterization of mortality risk changes in a GE model applied to environmental regulations, and find that

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some of these previous conclusions do not hold under greater scrutiny, but that human health improvements can still have positive effects on economic output that rivals the expected contraction associated with the costs of providing those improvements.

Policies expected to reduce mortality risks have traditionally been evaluated using a partial equilibrium (PE) approach: a monetized estimate of the benefits is calculated by multiplying the expected reductions in the number of deaths per year by an estimate of the value of a statistical life (VSL) (Levy et al. (2009); Fann et al. (2012); and Tagaris et al. (2009)). A crucial assumption underlying the traditional PE approach is that we should not expect mortality risk changes to cause significant behavioral adjustments that could lead to feedback effects on the estimates of benefits or costs. However, many of the techniques for estimating the benefits of health improvements exploit this change in behavior as an identification strategy. In particular, hedonic wage studies examine how variation in on-the-job risks influence labor market choices (e.g., Aldy and Viscusi (2007); Hersch and Viscusi (2010); and Scotton and Taylor (2011)), and hedonic property studies examine housing market behaviors in response to variation in neighborhood attributes to estimate households' WTP for improvements in air quality and other locational amenities (e.g., Gayer et al. (2002)). Theory suggests that such changes in behavior can interact with pre-existing market distortions (e.g., factor taxes) that have been found to be of first-order importance in other contexts (Williams, 2002).

Furthermore, The effect of environmental regulations on the overall mortality rate in the United States is estimated to be on the order of hundreds of thousands of deaths per year (EPA, 2011a). The size of the expected health impacts from environmental policies suggests that if there were behavioral responses by households to changes in their mortality risks, there is the strong potential for general equilibrium effects. This potential has motivated a growing interest in the economy-wide impact of human health improvements due to environmental policies. A number of recent studies have incorporated changes in mortality risks into computable general equilibrium (CGE) models to examine either the macroeconomic impacts or economy-wide GE welfare effects (e.g., Li (2002); Mayeres and Van Regemorter (2008); Matus et al. (2008); Carbone and Smith (2013)). The approach taken in these studies to incorporate human health improvements, principally mortality risk reductions, into CGE models has been based on increasing the time endowment of the representative agent(s) in the model in proportion to the expected reduction in mortality. For example, a 30 year old facing an increase in their probability of surviving from 59 to 60 by 1% is modeled as having an additional 3.65 days of available time when they are 60 years old, all else equal.

In 2011 the U.S. EPA used this time-endowment approach to analyze the expected cumulative impacts of regulations promulgated under the Clean Air Act and its Amendments (CAAA) (EPA, 2011a). A unique feature of this analysis was that it developed both PE and GE estimates of the benefits associated with improved air quality. The traditional PE approach produced a central WTP estimate of 1,300 billion [2015 $] for mortality risk reductions due to exposure reductions in 2010 (EPA (2011a); Table 7-1). In comparison the GE approach implied the CAAA had benefits of only $73 billion [2015 $] in 2010 (EPA (2011a); Tables 8-7 and 8-8). There is more than an order-of-magnitude difference between these benefit estimates.

We can think of at least three possible explanations for this large discrepancy: GE feedback effects, decreasing returns on a non-marginal change, and the adequacy of the time-endowment approach for representing the mortality risk reductions. To examine these possible explanations, we develop a new CGE model based on an overlapping generations framework that allows us to explicitly incorporate individual-level age-specific mortality risks. The model incorporates the same basic production, trade, and government structures found in the class of CGE models commonly used to assess the economy-wide benefits of environmental regulations, but adds detail on the life-cycle behavior of households necessary to characterize the role of mortality risk in labor supply and consumption-savings decisions. We use this new framework to examine the differences between PE and GE estimates of mortality risk reduction benefits, and to enhance our understanding of the economy-wide impacts of the health improvements produced by environmental policies.

We reconsider the GE benefits assessment of the CAAA and find that the commonly used time-endowment approach is an inadequate approximation for characterizing mortality risk reductions from environmental policies in a GE framework. The time endowment approximation is evaluating a change that is fundamentally different than a reduction in mortality risk, and we find this difference is the primary reason that previous PE and GE estimates of benefits have been over an order of magnitude apart. When mortality risk reductions from environmental policies are explicitly evaluated in a structurally constrained GE framework, the forecast welfare change is not more than an order of magnitude different from PE estimates, and is closer to the PE estimates than welfare estimates based on the time-endowment approach. However, we do find significant GE effects from the mortality risk reductions produced by environmental policies and that these may be important in the evaluation of future regulations. In particular, decreasing marginal WTPs for risk reductions are relevant for evaluating the aggregate welfare improvements of large policies and so is capturing the point during their life that households learn about changes in their life expectancy.

Our results corroborate previous findings that non-market changes, through their effects on behavior and relative prices, can have an important role in defining the economy-wide outcome of environmental policies. However, our results also have important implications for interpreting the quantitative, and in some cases qualitative, results of previous research based on the time-endowment approximation. The time endowment approach is making the strong assumption that households will respond to an increase in their future time endowment in the same way as they would respond to reductions in their future mortality risks. The majority of mortality risk reductions from many large environmental policies are predominantly realized at older ages when individuals are more vulnerable to environmental stressors. When a household sees a reduction in their future mortality risks leading to an increase in life expectancy, they may increase contemporary savings (through increased labor supply or reduced current consumption) to fund future consumption given the increased probability of living long enough to enjoy it. If instead the household's time endowment during retirement were increased, they may attempt to borrow against the increase in future assets to smooth consumption, thereby increasing contemporary consumption and reducing contemporary savings and labor. Therefore, the time endowment approach leads to predicted behavioral responses that move in the opposite direction of those expected in response to mortality risk reductions. We find that these differences lead the time-endowment approximation to project very different responses in aggregate economic outcomes, such as GDP, investment, and relative prices. For a number of economic variables, changes projected by the time-endowment approximation turn out to be in the opposite direction of what is expected when mortality risk changes are modeled explicitly.

We proceed by first reviewing previous approaches to incorporating mortality risk reductions in CGE models in Section 2, followed by a description of our approach to directly modeling mortality risk changes in Section 3. In Section 4 we present the results of our re-analysis of the benefits of the CAAA, and in Section 5 we discuss the implications of our findings for policy analysis.

2 Background

There has been growing interest among researchers and policy makers in the economy-wide effects of health improvements produced by environmental regulations. In particular, the large projected mortality risk reductions from improvements in air quality (Krewski et al. (2009); Lepeule et al. (2012)) may lead households to change their behavior to a degree that there are notable economic feedbacks that affect the household's WTP for the changes. This relatively new body of literature has found evidence that health improvements may have significant GE effects, however, none of the previous studies that have explicitly modeled the role of mortality risks in the household decision problem. In each case researchers have applied highly simplified approximations under the unverified assumption that they would adequately capture the response by households to changes in mortality risks. We begin by reviewing these previous approximation approaches to properly frame the context for the current study.

Vennemo (1997) was one of the first studies to incorporate environmental externalities into an applied CGE model. The model provided an integrated framework linking production to emissions to human health and well being in an endogenous manner. However, the impacts of changes in mortality risk associated with air pollution were modeled as an additively separable increment to household utility. This strong separability assumption precludes any household behavioral adjustments to changes in their mortality risks, which also precludes potentially important interactions with the economy.

Recognizing the potential for changes in health to affect household decisions, Mayeres and Van Regemorter (2008) extended the GEM-E3 CGE model of the European economy to include non-separable health impacts of air pollution (in the standard version of the model all non-market impacts of air pollution were treated as separable in the utility function). Mayeres and Van Regemorter (2008) incorporated the effects of exposure-related morbidity and the medical costs of pollution-induced mortality by considering the effect of air pollution on private and public spending for medical services and morbidity's effect on the time endowment. To model the effect of air pollution on households' demands for medical services the top nest of the Stone-Geary utility function, which previously included only composite consumption and leisure, was extended to include an endogenous measure of health. Health was defined as the outcome of a household production function, such that its level was determined by the level of air pollution and expenditures on medical services. Morbidity was also modeled as having an impact on the time endowment of households and the productivity of workers to firms due to paid sick leave.

Mayeres and Van Regemorter (2008) compared the results from the extended GEM-E3 model to the case where all air pollution damages were assumed to be separable. They found the macroeconomic effects (e.g., GDP, labor) of air pollution reductions to be very similar between the two cases, with the extended model estimating a slightly larger increase in consumption.[1] The only non-separable effect of mortality risk reductions included were changes in medical expenditures faced by an aggregate representative agent. Given the relatively small size of changes in medical expenditures compared to the WTP for marginal mortality risk reductions, the approach may have missed a large component of why households value changes in mortality risk and how those changes might affect household behavior and the economy.

Other studies examining the direct health impacts of air pollution using a CGE model have taken a

[1] Mayeres and Van Regemorter (2008) modeled the case of a country-specific carbon dioxide (CO_2) tax commensurate with commitments under the Kyoto Protocol. The health impacts considered were due to reductions in emissions of criteria air pollutants as a result of the CO_2 tax.

different approach to including the impacts of mortality risk changes. Most of these studies have used an extended version of MIT's Emission Prediction and Policy Analysis (EPPA) model, which includes some health impacts of air pollution and is referred to as the EPPA Health Effects (EPPA-HE) model (Matus et al., 2008). To date, the EPPA-HE model has been used to study the impacts of historical air pollution (ozone and PM_{10}) in the U.S. (Matus et al., 2008), Europe (Nam et al., 2010), and China (Matus et al., 2012), and future ozone pollution globally (Selin et al., 2009). While there are some slight differences in terms of the data employed and calibration of the model, the general methodology used to incorporate health impacts associated with air pollution and the interaction with the economy in the model was the same across these applications.

The EPPA-HE model incorporated the impacts associated with acute and chronic premature mortality, and pollution-induced morbidity. To capture these health impacts the EPPA-HE model modified the original model structure in two ways. First, leisure was introduced into the model by including an additional top-level nest in the household utility function along with a constraint on the time endowment, which was split between labor and leisure. Second, a household healthcare production sector was added to account for the time and medical service expenditures required to respond to pollution-induced morbidity. The household healthcare sectors were health endpoint and pollutant specific, and Leontief in labor and medical services. The cost shares were calibrated based on external studies that estimate the composite costs of health endpoints.

Studies using the EPPA-HE model have focused on a unidirectional coupling, where atmospheric concentrations of pollutants are taken as exogenous and fixed (in contrast to the bi-directional coupling of Mayeres and Van Regemorter (2008), where household utility was affected by emissions and emissions were influenced by household behaviors). The model used a series of exposure-response functions from the epidemiological literature to map the atmospheric concentrations into health endpoints. For morbidity related endpoints, which were all assumed to be from acute exposures, this stage provided an estimate of the number of adverse health cases or events expected to occur in each model year. The exposure-response functions provided an estimate of the proportional increase in mortality rates in the model year, which must be applied to baseline mortality rates to estimate the expected level of mortality. To account for the influence of chronic exposures on mortality rates, a cohort population model was used to track the number of individuals in a given age group in each model year. For each cohort the annual average exposure was computed and entered into the appropriate exposure-response function to estimate the change in the mortality rate. The results of this mapping were then used to adjust the time endowment of the model's representative agent to approximate the effect of premature mortality.[2] Morbidity-related health endpoints were applied effectively as Hicks neutral shocks to the household healthcare sector to represent an increased need for time and medical services to maintain a given level of health.

In a given simulation year, the modeled welfare loss associated with pollution damages was based on the value of the lost time endowment in that period, the distortion imposed by the additional demand for medical services, and the cumulative economic impacts associated with reduced investment in previous years due to pollution. The lost time endowment in a given year was valued at the wage rate on the margin. Since the model only accounts for working age individuals, to account for the loss of time endowment from cohorts that are not of working age (children and the elderly), the value of time was adjusted to be 1/3 and 2/3 of

[2]For premature mortality of working age individuals (assumed to include only individuals younger than 65) it was effective units of labor that were removed from the time endowment. Effective labor includes time that was adjusted for labor productivity growth, which was included as an exogenous increase in the time endowment over the model's time horizon.

the wage rate, respectively.

Studies that have used the EPPA-HE model to estimate the GE effects of health improvements have found a notable effect on economic growth, in the sense that the welfare impacts in a given year have a non-trivial share that is the result of investment changes in previous years (Selin et al. (2009); Matus et al. (2012)). However, since the EPPA model is a recursive dynamic framework, these effects are driven by changes in labor supply in previous periods due to the increased time endowment in those periods (i.e., the households do not substitute across time periods). It is unclear how well this behavioral response approximates the aggregate response of individuals at different stages of life facing new mortality risk profiles. The suitability of this approximation for evaluating welfare effects or economic impacts has not been previously examined.

In 2011 the EPA conducted a study of the cumulative effects of human health benefits from air quality regulations on the economy (EPA, 2011a). Similar to Matus et al. (2008), they examined the expected impacts of all regulations promulgated under the CAAA through 2005. The majority of the analysis was based on PE measures of costs and benefits, while a GE analysis using the forward-looking EMPAX CGE model was conducted to provide supplemental information. As previously noted, the nature of the GE analysis and the stark contrast between the PE and GE results, provided a large part of our motivation for the current study.

The EPA modeled two scenarios in a CGE framework to examine the economy-wide impacts of the CAAA: a "cost-only" scenario, which introduced only the compliance costs of the regulations into the model, and a "labor force-adjusted" scenario, which introduced both the compliance costs and human health impacts into the model. To incorporate the human health impacts of the CAAA, the EPA followed an approach similar to that of the EPPA-HE model. The labor force-adjusted scenario incorporated the mortality risk and morbidity reductions expected to accrue to members of the labor force as an increase in their available time endowment. For premature mortality, the time endowment was increased proportional to the number of avoided premature deaths divided by the size of the counterfactual population. The expected reductions in the demand for medical services as a result of reduced morbidity were also included. If one takes the difference between the Hicksian equivalent variation for the "costs only" and "labor force-adjusted" cases as a measure of the benefits of the CAAA, as suggested by (Smith, 2012), this leads to an estimate of $73 billion [2015 $] in 2010 (EPA (2011a), Tables 8-7 and 8-8). In the same study, EPA reported a traditional PE benefits estimate of $1,300 billion [2015 $] for avoided premature mortality due to exposure reductions in 2010 (EPA (2011a), Table 7-1). This figure is over an order of magnitude larger than the GE estimate of benefits.

According to (Smith, 2012), the substantial difference between the PE and GE measures of the benefits of the CAAA indicates that a PE approach will overestimate the value of large reductions in mortality risks. On the other hand, the large difference could indicate that the time-endowment adjustment provides a poor approximation of the mortality risk reductions in CGE models. Given the assumption of homothetic preferences in the model and the relatively small size of the shock (0.34% of the time endowment in 2010), the value of the change in a given year will be approximately equal to the product of the wage rate and the increase in the time endowment. Therefore, the estimate from the CGE analysis is akin to the human capital approach of valuing changes in mortality risk based on the expected present value of lost lifetime income. This is in contrast to the damage function approach underlying the PE assessment, which is based on an estimate of the marginal willingness-to-pay (WTP) for mortality risk reductions. Under the assumption of risk aversion one would not expect these two metrics to be equivalent, with the WTP measure being higher than the measure based on the human capital approach. The important distinctions between these approaches was first emphasized by Schelling (1968), who noted the potentially large difference between the expected lost income and the WTP for a given change in mortality risks.

This distinction between what is being measured in the two analyses—time endowment increase versus mortality risk reduction—can explain the sign of the difference and also the magnitude. The present value of future earnings for a middle-aged worker in the United States paid an average wage is around 0.8 million 2015$.[3] This figure can be compared to empirical estimates of the VSL based on hedonic wage and stated preference studies. Central estimates of the VSL from recent meta-analyses of both revealed and stated preference studies are between 2.1 and 11 million 2015$ (Cropper et al., 2011), and EPA's central estimate of the average VSL is 8.3 million 2015$ (EPA, 2010). Therefore, contemporary central estimates of the WTP for marginal mortality risk reductions are up to an order of magnitude larger than the average remaining lifetime earnings for a middle-aged U.S. worker. Therefore, the difference between the two estimates of benefits in EPA's study of the CAA may not arise from the difference in the scope of the assessments—PE versus GE—but rather from the fact that they are measuring the value of two distinct commodities—time endowment increase versus mortality risk reduction.

This choice to represent changes in mortality risks by changes in the time endowment is not unique to the EPA study; it has been the standard practice in the recent literature analyzing the economy-wide impacts of changes in human health (Matus et al. (2008); Selin et al. (2009); Nam et al. (2010); Carbone and Smith (2013)).The stated goal of these analyses is not always to derive a monetized estimate of welfare change, instead focusing on changes in other macroeconomic variables. For example, EPA's study of the CAAA demonstrated the importance of accounting for the beneficial effects of environmental policies when evaluating their economic impacts. Specifically, when both the human health impacts and the costs of the policy were included in the model, the net effect on GDP was less than half of what it was when only the compliance costs were considered. However, if the representative agent's WTP for a mortality risk reduction is in fact an order of magnitude larger than the expected value of the change in the agent's time endowment, then we might also suspect that the agent's behavior would be substantially different if health impacts are modeled explicitly as a change in mortality risk rather than implicitly as a change in the time endowment. Therefore, the adequacy of the time-endowment approach has important implications for the use of CGE models to estimate the welfare effects of environmental regulations and the ability to accurately represent the impacts of those regulations on GDP and other macroeconomic outcomes.

3 Methods

To examine the benefits of mortality risk reductions in a general equilibrium setting, we use an overlapping generations (OLG) framework similar to the applied models of Auerbach and Kotlikoff (1987) and Rasmussen and Rutherford (2004). We focus on the case of a single production sector economy to keep the model and

[3] This figure was computed based on an individual who is 40 years of age and earns 43,556 2015$ per year, which was the annual mean labor compensation in the U.S. in 2010 (U.S. Bureau of Economic Analysis Table 2.2B and U.S. Bureau of Labor Statistics Series LNS11000000). The individual's real wage is assumed to remain constant for the remainder of her working career (i.e., her nominal wage grows at the rate of inflation), she will retire at age 65, and she discounts future consumption at a rate of 3% per year. We also assumed that the individual is subject to a life cycle mortality risk profile that matches average mortality risks among the U.S. population as presented in Section A.3.

presentation tractable. But we keep many of the same basic features, including factor taxes, government, and international trade, found in the more complex CGE models that have been used to analyze the impacts of environmental policy, such as the EMPAX CGE model used by EPA in their analysis of the CAAA (EPA, 2008). The main distinguishing feature of our model is that we incorporate more detail on households' life-cycles and preferences. Specifically, we replace the standard infinitely-lived representative household with with a set of overlapping generations comprised of individuals who have uncertain life expectancies. Overlapping generations models have been previously used to study the cost and incidence of environmental policies (e.g., (Williams et al., 2015)), but to our knowledge our study is the first to examine the health benefits of environmental policy by explicitly incorporating mortality risks using a life-cycle framework. Other studies analyzing mortality risk changes from environmental policies in a CGE framework have used population cohort models exogenously to determine the effect of emissions/concentration changes on premature mortality and population levels Matus et al. (2008). But those changes are introduced into the CGE models as an increase in the time endowment of the infinitely-lived representative agent in the model, such that changes in household decisions on consumption, leisure, and savings are made by the representative agent responding to the increased time endowment. In contrast, by using an OLG framework we can introduce mortality risk reductions directly into the households' life-cycle decision-making problem and allow each generation to respond this change in their life expectancy, instead of attempting to approximate the effect by a change in their time endowment.

3.1 Model Structure

Our model is based on the Rasmussen and Rutherford (2004) extension to the overlapping generations model of Auerbach and Kotlikoff (1987). We extend this framework further to include household preferences and mortality risks in a manner consistent with Aldy and Smyth (2014) and the broader structural literature on incorporating mortality risks into life-cycle models of households (e.g., Yaari (1965); Cropper (1977); Shepard and Zeckhauser (1984)). Since mortality risk reductions due to environmental policies are not expected to be uniform across the age distribution, it is important to capture the shape of life-cycle consumption and income patterns. Therefore, we follow Hansen and İmrohoroğlu (2008) in extending the overlapping generations framework to include imperfect private annuity markets and mandatory public annuity programs (i.e., old age survivors insurance), as the availability of annuities has been shown to affect the expected WTP for mortality risk reductions (Shepard and Zeckhauser, 1984).

3.1.1 Production

To maintain transparency and tractability we consider a single aggregate commodity. However, outside of this simplifying assumption we maintain a structure that is generally consistent with the CGE models typically used to analyze environmental policies, in particular the EMPAX model used by EPA in their analysis of the CAA. Production is based on a constant elasticity of substitution (CES) technology, markets are assumed to be perfectly competitive, the world good price is determined based on the small economy assumption, and the international trade structure is based on the assumption of imperfect substitutes (Armington (1969) trade). We maintain consistency with the class of more complex CGE models not just on the basis of these assumptions, but also in terms of the functional forms used to implement them and the basic strategy for calibrating the model parameters.

Given the CES technology assumption, output, Y_t, given inputs of labor, L_t, and capital services, K_t, is defined in its calibrated share form as

$$Y_t = Y_0 \left[\theta_Y \left(\frac{L_t}{L_0} \right)^{\frac{\epsilon_Y - 1}{\epsilon_Y}} + (1 - \theta_Y) \left(\frac{K_t}{K_0} \right)^{\frac{\epsilon_Y - 1}{\epsilon_Y}} \right]^{\frac{\epsilon_Y}{\epsilon_Y - 1}}, \tag{1}$$

where benchmark levels are denoted by a time subscript of zero, θ_Y is the input value share of labor in the benchmark, and ϵ_Y is the elasticity of substitution between labor and capital. Firms maximize profits with respect to the production technology in (1) and the cost of production

$$(1 + \tau^r) r_t K_t + \left(1 + \tau^l + \tau_t^{oasi}\right) p_t^l L_t, \tag{2}$$

where r_t and p_t^l are the rental rate on capital and the wage rate, respectively, and τ^r, τ^l, and τ_t^{oasi} are ad valorem taxes on capital and labor. The evolution of the capital stock is linked to investment by investment, I_t, such that

$$K_{t+1} = (1 - \delta) K_t + I_t, \tag{3}$$

where δ is the depreciation rate.

Output is split between domestic consumption, Y_t^D, and exports, X_t, through a constant elasticity of transformation function, such that

$$Y_0 \left[\theta_X \left(\frac{X_t}{X_0} \right)^{\frac{\epsilon_X - 1}{\epsilon_X}} + (1 - \theta_X) \left(\frac{Y_t^D}{Y_0^D} \right)^{\frac{\epsilon_X - 1}{\epsilon_X}} \right]^{\frac{\epsilon_X}{\epsilon_X - 1}} = Y_t, \tag{4}$$

where θ_X is the value share of exports in the benchmark and ϵ_X is the elasticity of transformation. The import of foreign goods and services is specified using the Armington representation of imperfect substitutes to combine imports, M_t, and domestic production into an aggregate good, A_t, such that

$$A_t = A_0 \left[\theta_A \left(\frac{Y_t^D}{Y_0^D} \right)^{\frac{\epsilon_A - 1}{\epsilon_A}} + (1 - \theta_A) \left(\frac{M_t}{M_0} \right)^{\frac{\epsilon_A - 1}{\epsilon_A}} \right]^{\frac{\epsilon_A}{\epsilon_A - 1}}, \tag{5}$$

where θ_A is the value share of domestic production in the benchmark value of the aggregate good and ϵ_A is the Armington elasticity of substitution between domestic goods and imports. The aggregate good may be used for final household consumption, C_t, government consumption, G_t, or investment, I_t. Therefore, market clearance of the goods market requires

$$A_t = C_t + I_t + G_t. \tag{6}$$

3.1.2 Households

In each period a new generation (or cohort), indexed by g, comprised of $N_{g,g}$ individuals of age 20 enters the model (i.e., individuals are "born" at age 20). $N_{g,t}$ denotes the size of generation g in period t, and the periods are 5 years long. Individual lifespans are uncertain and subject to survival probabilities $\mu_{g,t}$, where $\mu_{g,t}$ represents the probability that an individual of cohort g who is still alive in period $t-1$ will survive from period $t-1$ to period t. Any individual member of the generation does not know with certainty whether they will survive to the subsequent period, but we assume that the generations are large and therefore

$$N_{g,t+1} = \mu_{g,t+1} N_{g,t} \ \forall t \geq g. \tag{7}$$

For generations that enter the model on or after the initial period it will be the case that $\mu_{g,g} = 1 \ g \geq 0$, while for individuals that were born before the initial period but are still alive at the initial period it will be the case that $\mu_{g,0} = 1 \ g < 0$.

We adopt the utility function used by Aldy and Smyth (2014), who developed a stochastic dynamic life-cycle consumption model to examine heterogeneity in the VSL. Leisure, $l_{g,t}$, and consumption of goods and services, $c_{g,t}$, determine utility, u_t, according to

$$u_{g,t} = \kappa + \frac{\left(c_{g,t} l_{g,t}^{\xi}\right)^{1-\phi}}{1-\phi}. \tag{8}$$

The agents seek to maximize the expected present value of inter-temporal utility

$$w_{g,t} = \sum_{s=t}^{g+\bar{a}} \left(\frac{1}{1+\rho}\right)^{s-t} \left(\prod_{h=t}^{s} \mu_{g,h}\right) u_{g,s}, \tag{9}$$

where $\bar{a}$ is the maximum age an individual can reach and ρ is the pure rate of time preference. Generations that are born on or after the initial period will maximize $W_{g,g}$, whereas generations born before the initial model period will seek to maximize $W_{g,0}$.

Each agent's utility maximization problem is subject to both a time endowment and budget constraint. Each member of the generation is endowed with ω in each period, which they endogenously choose to split between labor and leisure. The value of supplying labor to the market is determined by both the wage rate, p_t^l, and a life-cycle productivity curve, $\pi_{g,t}$, so the wages paid to an individual equals the product of their labor supply, their productivity level, and the wage rate.

Following Blanchard (1985), many studies containing uncertain lifetimes in an overlapping generations framework have made the simplifying assumption of perfect and complete private annuity markets that agents may use to insure themselves against old age. The assumption is convenient in that the budget constraint reduces to ensuring that expected lifetime expenditures does not exceed expected lifetime income. However, in the case where the interest rate exceeds the pure rate of time preference, as is the case in most calibrated applications, consumption monotonically increases over the life-cycle, which is inconsistent with the hump-shaped profile commonly observed in micro-level data (Fernández-Villaverde and Krueger, 2007). In the absence of perfect private annuity markets, the effective discount rate for the agent, taking into account the increasing mortality risk over the life-cycle, will eventually exceed the pure rate of time preference therefore causing a hump-shaped consumption profile (Hansen and İmrohoroğlu, 2008). The assumption of imperfect annuity markets is also consistent with the thin nature of actuarially fair private old age insurance markets that do exist. Therefore, we allow the parameter $\alpha \in [0, 1]$ to represent the availability of private annuity markets, with a value of unity denoting perfect private annuity markets and a value of zero denoting the lack of any private annuity markets. In the case of $\alpha < 1$ there will be unintended bequests, which we assume are returned as homogeneous lump sum payments to all agents still alive at the end of the current period.

The budget constraint then takes the form

$$\sum_{t=s}^{g+\bar{a}} \left[\prod_{h=s}^{t} 1 - \alpha \left(1 - \mu_{g,h}\right) \right] \left[p_t^l \pi_{g,t} \left(\omega - l_{g,t}\right) + p_t^f \left(\psi_{g,t} + \beta_{g,t}\right) + b_t - \left(1 + \tau_c\right) p_t^a c_{g,t} \right] \geq 0, \tag{10}$$

where p_t^a is the price of consumption, τ_c is an ad valorem consumption tax, $p_t^f = p_0^f \left(1 + \bar{r}\right)^{-t}$ is the price of foreign exchange, $\psi_{g,t}$ are lump-sum government transfers to the agent, $\beta_{g,t}$ are payments from a mandatory public old age survivors insurance (OASI) program, and b_t are unintended bequests. The savings of an agent in generation g going into period $t+1$ are

$$z_{g,t+1} = \frac{z_{g,t} + p_t^l \pi_{g,t} \left(\omega - l_{g,t}\right) + p_t^f \left(\psi_{g,t} + \beta_{g,t}\right) + b_t - \left(1 + \tau_c\right) p_t^a c_{g,t}}{1 - \alpha \left(1 - \mu_{t+1}\right)}, \tag{11}$$

where savings at the beginning of an agents life will be equal to zero for generations born on or after the initial period, $z_{g,g} = 0$. Therefore, the unintended bequests in period t will be

$$b_t = \frac{\sum_g \left(1 - \alpha\right) \left(1 - \mu_t\right) z_{g,t} n_{g,t-1}}{\sum_g n_{g,t}}. \tag{12}$$

Our implementation of the U.S. Social Security OASI program is similar to that of Hansen and İmrohoroğlu (2008). OASI payments to an agent, $\beta_{g,t}$, are a fraction, ν, of their average annual earnings between ages a_{lo} and a_{hi}, such that

$$\beta_{g,t} = \begin{cases} 0 & \text{if } t < g + a_{oasi} \\ \frac{\nu}{a_{hi} - a_{lo}} \sum_{s=g+a_{lo}}^{g+a_{hi}} \frac{p_t^l}{p_s^f} \pi_{g,t} \left(\omega - l_{g,t}\right) & \text{otherwise} \end{cases}, \tag{13}$$

where a_{oasi} is the age at which the OASI payment begin, and annual earnings are normalized based on purchasing power on the world market. We allow the agents to consider the role of labor decisions on future OASI payments, but we assume that the age at which benefits begin is exogenous.

3.1.3 Government

The government collects revenue through ad valorem taxes on capital rents, τ^k, labor income, τ^l, and consumption, τ_t^c. Government expenditures include purchases of goods and services, G_t, and lump-sum transfers to households, $T_t = \sum_g \psi_{g,t} N_{g,t}$. Therefore, the government's per period budget constraint is

$$p_t^a G_t + p_t^f T_t = \tau^k r_t K_t + \tau^l p_t^l L_t + \tau_t^c p_t^a C_t + p_t^f D_t, \tag{14}$$

where r_t is the capital rental rate, $L_t = \sum_g N_{g,t} \pi_{g,t} \left(\omega - l_{g,t}\right)$ is aggregate labor supply, $C_t = \sum_g N_{g,t} c_{g,t}$ is aggregate consumption, and D_t is the deficit in period t.

3.1.4 Closures

We maintain general consistency with the closure rules of Rasmussen and Rutherford (2004), augmenting them where necessary to accommodate the inclusion of mortality risks for individuals, the decreasing returns to scale utility function, and the public OASI program. The assumption that the model returns to steady-state by the terminal period forms the basis for the terminal conditions. To determine the choices for individuals who survive beyond the terminal period, we need to track the post-terminal consumption and leisure so that an agent's full life-cycle may be considered when solving for her behavior during the model horizon. This is accomplished under the steady-state assumption by assuming that relative prices decline from the terminal period value at the steady-state interest rate.

The level of the terminal capital stock is endogenously determined by requiring steady-state growth in investment in the terminal period

$$\frac{I_H}{I_{H-1}} = \frac{\sum_g N_{g,H-1}}{\sum_g N_{g,H-1}}. \tag{15}$$

The terminal condition for investment in (15) is based on the assumption that any mortality risk change has allowed the population growth rate to reach a steady-state by the terminal period, which we impose in all of the simulations.

For simplicity, we assume that per period government consumption, transfers, and deficit per capita are all exogenous and constant in real terms at their benchmark level. Given these assumptions, the per period government budget constraint is maintained by allowing the ad valorem consumption tax to float (i.e., the tax is increased to cover any shortfall or decreased to eliminate any surplus in the government's net revenues). In the baseline the consumption tax is assumed to be zero with all government revenue being raised through capital and labor income taxes, along with deficit financing.

The public OASI program is supported by an ad valorem payroll tax, τ_t^{oasi}, but is assumed to be unfunded such that the tax floats to cover the program's period-by-period budget constraint[4]

$$\tau_t^{oasi} p_t^l L_t = \sum_g n_{g,t} \beta_{g,t}. \tag{16}$$

As discussed further in Section 3.2, benchmark year bond holdings are calibrated to ensure the sustainability of running the current trade and government deficit indefinitely in the baseline. In general the model follows Rasmussen and Rutherford (2004) and requires that all values denominated in the price of foreign exchange balance over the model horizon. In other words, we force the trade budget to balance inter-temporally conditional on any change in holdings of foreign bonds. Also following Rasmussen and Rutherford (2004), the terminal asset values are selected to maintain a constant equivalent variation across generations with persons alive beyond the terminal period.

3.2 Model Calibration and Solution

Calibrating the model requires characterizing the benchmark economy that represents the initial year of the model, growth rates that define flows in the baseline economy, along with parameters defining production

[4] Appendix C examines the sensitivity of our results to assuming that the OASI program is balanced through endogenous taxes versus endogenous benefits. We find that our results are not sensitive to this assumption.

technologies and household preferences. We briefly discuss each of these in turn. Appendix A provides complete details of the calibration procedure along with values of the resulting calibrated model parameters.

To provide a more consistent comparison to the EPA's analysis of the CAAA, which helps motivate our core research questions, we calibrate our benchmark to the 2005 U.S. economy, as was the case in the EPA analysis. The benchmark data is from the U.S. Bureau of Economic Analysis'(BEA) National Income and Product Account (NIPA) tables and the Penn World Tables Version 9 (Feenstra et al., 2015).

Labor tax rates are based on state and federal income tax rates and payroll taxes. The state and federal income tax rates are drawn from the 2005 values from the National Bureau of Economic Research (NBER) Average Marginal U.S. Income Tax Rate database (Feenberg and Coutts, 1993). We use BEA estimates of personal income by state, from their Regional Income table SA1, to calculate a national weighted average of the state level combined state and federal average marginal income tax rates to which non-OASI payroll taxes are added. The capital tax rate is calculated as the rate that would balance the government budget constraint in (14) for the benchmark year conditional on the labor tax rate. As noted in Section 3.1.4, we assume a consumption tax rate of zero in the baseline.

We calibrate the OASI program such that the average per beneficiary payment in the benchmark matches the average per beneficiary payment for the U.S. OASI program in 2005. The baseline OASI tax rate is calibrated to balance the program's budget according to (16). To approximate the U.S. OASI program we compute average earnings between the age of $a_{lo} = 20$ and $a_{hi} = 55$ and assume that benefits are earned starting at age $a_{oasi} = 65$. Conditional on the other parameters in the model, the fraction of average annual earnings paid as OASI benefits is calibrated to match the benefits payment per person.

In our production function we assume $\epsilon_Y = 1$, noting that the CES specification in (1) converges to Cobb-Douglas as the substitution elasticity approaches unity, following the recommendations of Balistreri et al. (2003). This assumption is also consistent with the previous work using aggregated models of this nature, including Auerbach and Kotlikoff (1987) and Rasmussen and Rutherford (2004). In calibrating the elasticity of transformation of output between domestic production and exports, ϵ_X, we use a value of 2 following the assumption used by Caron and Rausch (2013) in the USREP CGE model. To calibrate the Armington elasticity, which defines the substitutability of imports and domestic production, we use an import weighted average of sector specific empirical estimates from Hertel et al. (2007).

For simplicity, we assume that the economy is on a steady-state path with growth rate γ and steady-state interest rate $\bar{r}$. Adjustments to benchmark investment required to implement the balanced growth assumption with respect to the capital stock are offset by changes to benchmark consumption to ensure the aggregate income balance is maintained. The depreciation rate is set to the average U.S. capital depreciation rate from 1950 to 2014 as reported in the Penn World Table (Feenstra et al., 2015).

We calibrate γ to the average U.S. population growth rate from 1950 to 2014. We assume that individuals enter the model at age 20 and therefore the total modeled population in the benchmark year is equal to the U.S. population minus the estimated number of individuals under the age of 20 as reported in the U.S. Census Bureau's Current Population Survey for 2005. The survival curve in the model is based on the U.S. Department of Health and Human Services life tables for 2005 (cdc). We assume that this survival curve is representative of all generations in the model and that no individual survives past age 100, such that $\zeta_{g,g+\bar{a}} = 0$, where $\bar{a} = 100 - 20 = 80$.[5] The calibrated survival curve is presented in Figure 1a. For

[5] In the most recent census, 0.017% of the U.S. population was over the age of 100.

simplicity, we assume that the number of births each year is independent of any policy induced changes to mortality risk, such that the size of successive generations is growing at rate γ.

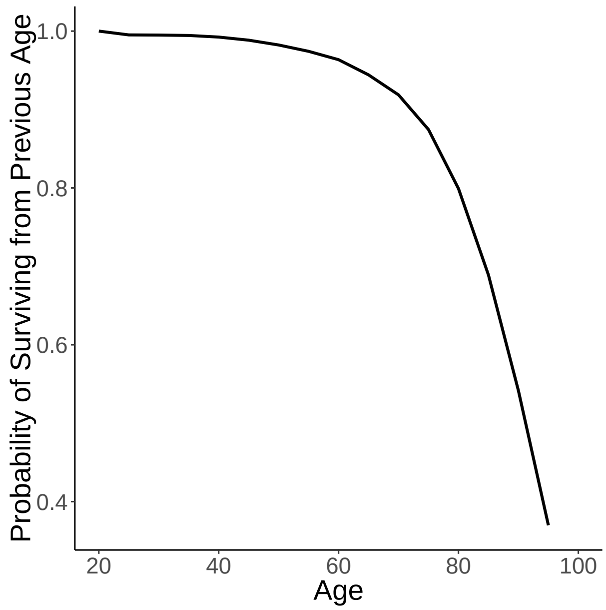
The benchmark data constrains the values of the parameters representing the agents' endowments and preferences through adding-up conditions that require the life-cycle variables aggregated across the population to equal the national level accounts. Specific adding-up conditions include aggregate consumption, aggregate labor supply, and aggregate assets holdings. The adding-up condition for household assets incorporates the deficit and trade imbalance following Rasmussen and Rutherford (2004), as discussed in Appendix 3.2. We calibrate the time endowment, ω, and pure rate of time preference, ρ, to maintain the adding-up conditions for aggregate consumption and assets in the benchmark year.

The life-cycle labor productivity index, $\pi_{g,t}$, is calibrated to match benchmark model behavior to observed labor force participation rates by age from the U.S. Bureau of Labor Statistics (Toossi, 2015). The calibrated productivity curve is presented in Figure 1b. The productivity profile has the typical shape, increasing rapidly through an agent's 20s and 30s, peaking around 50, and declining thereafter.

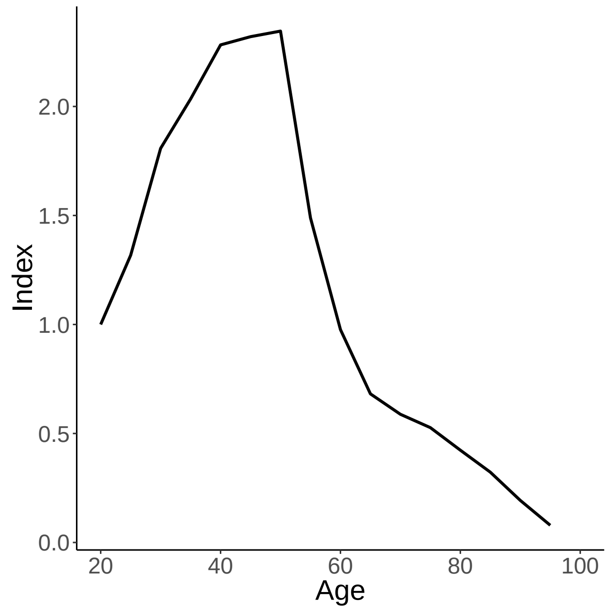
The model is calibrated to match the VSL used by the EPA in their second prospective analysis of the CAA. The EPA's estimate of the VSL is the mean of a Weilbull distribution that was fitted to 26 published estimates of the VSL, of which 21 are studies of wage differentials in labor markets. Since the studies based on compensating wage differentials will necessarily only consider the preferences of labor market participants in their samples, and this class of studies makes up the majority of those included in the estimate, we calibrate the population weighted average VSL across the working age population in our model to match the EPA's VSL estimate. This is accomplished by calibrating the constant in the agents' utility function, κ. The additive nature of κ in the utility function means that it will not have an effect on agents' consumption or labor supply decisions, but it will influence the amount of income the agent would be willing to forgo to increase the probability of living through the period.

Given this calibration of the model, the life-cycle profile of the VSL for agents in the model is presented in Figure 1d, which also presents approximations of other life-cycle VSL curves estimated empirically through hedonic wage studies (Kniesner et al. (2006) and Aldy and Viscusi (2008)) and through structural life-cycle modeling (Murphy and Topel (2006) and Aldy and Smyth (2014)).[6] The life-cycle VSL curve that emerges from our model has the inverted-U shape characteristic of previous estimates. Our decline in the second half of the life-cycle matches well with the simulated results of Aldy and Smyth (2014), but declines slightly slower than the results of the hedonic wage studies. This may be due to the lower mortality rates included in the structural models relative to those implicitly included in the empirical studies using data from the 1990's. Our calibrated curve exhibits a higher initial level relative to the peak compared to the hedonic wage results and the structural model of Aldy and Smyth (2014). This may be due to the potential for borrowing or lack of lifetime wage uncertainty in our framework, which differs from Aldy and Smyth (2014) and may not match liquidity constraints and income uncertainty implicit in the empirical estimates. In both cases these difference could cause higher consumption in our initial years of the life-cycle, thereby increasing the life-cycle VSL in those years. Since the focus of our study is on mortality risk changes induced by air pollution reductions, this difference is not likely to effect our results as air pollution tends to primary affect

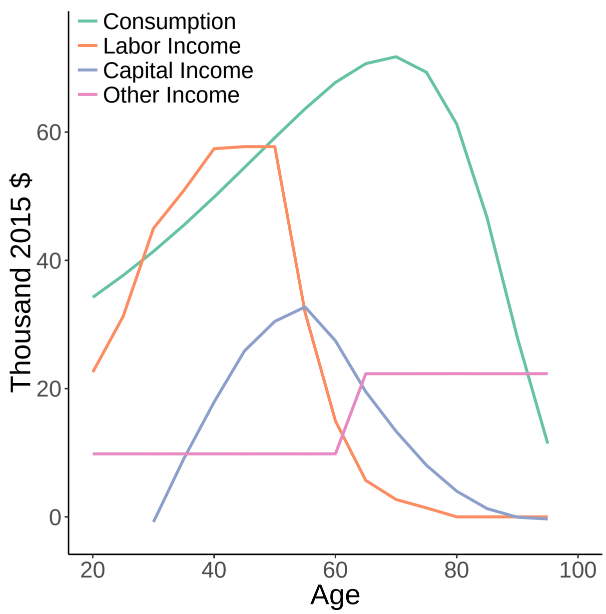
[6]Life-cycle VSL curves shown in the figure for previous studies are polynomial approximations fit to the studies' summary results and shifted vertically so that the peak VSL is equal to the peak VSL in our calibrated VSL curve. The shift is to focus the comparison on the shape of the curve over the life-cycle and not the level, which is determined by our choice to calibrate the average working age VSL to the estimate used by the EPA.



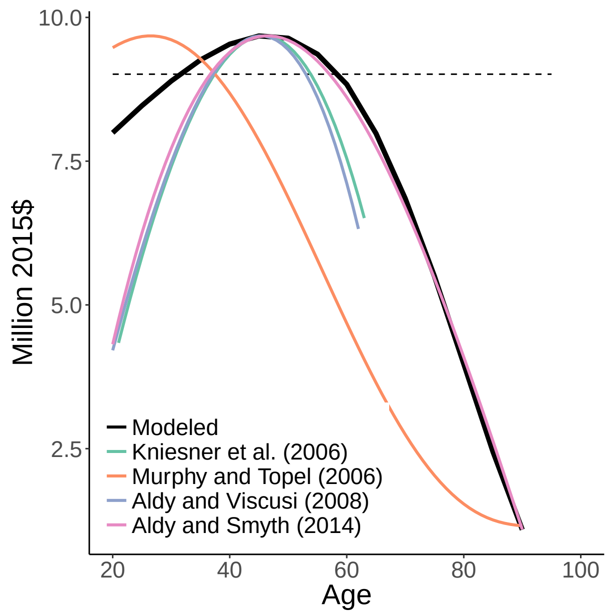
(a) Survival Probability - μ_a



(b) Labor Productivity Index



(c) Consumption and Income



(d) Value of a Statistical Life

the older populations included in the model.

Other household preference parameters are calibrated to match observed labor supply elasticities and life-cycle consumption patterns. Figure 1c presents the baseline life-cycle profile of consumption and income for agents in the model. Consumption exhibits the hump-shaped profile observed in practice, though the peak occurs later in life than usually observed. Through sensitivity analysis we have found our results to be robust across significantly different life-cycle consumption profiles (see Appendix B).

We solve the model as a mixed complimentarity problem (MCP) following the approach of Rasmussen and Rutherford (2004). The MCP approach represents the zero-profit conditions, market clearance conditions, budget constraints, household first-order conditions, and closure rules. The problem is formulated in the General Algebraic Modeling System (GAMS).[7] The MCP is solved using the PATH solver (Ferris and Munson, 2000).[8]

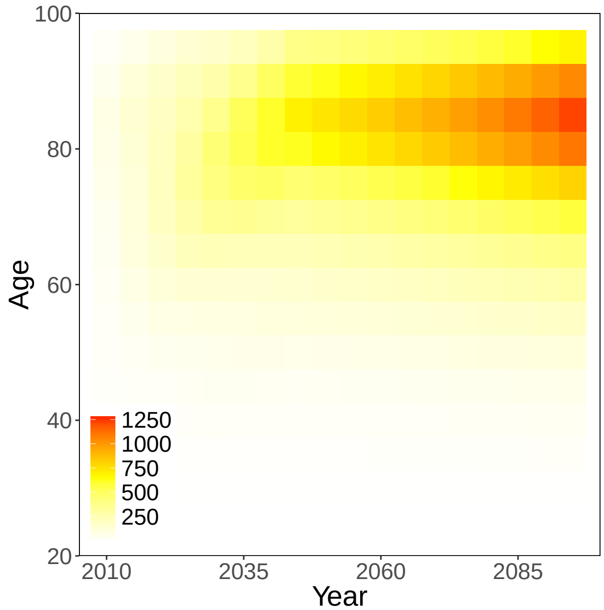
3.3 Mortality Risk Reductions under the Clean Air Act

In this paper we focus on the case of the Clean Air Act and its Amendments (CAAA), to provide a consistent platform to examine the aforementioned discrepancies between EPA's partial equilibrium based benefits assessment and their general equilibrium analysis in the second prospective analysis under Section 812 of the Act (EPA, 2011a). To isolate the economy-wide impacts of mortality risk reductions associated with the CAAA we focus exclusively on these effects, similar to previous studies of the impact of air pollution on the economy (e.g., Matus et al. (2008); Nam et al. (2010)). We study the expected reduction in mortality risk over time due to the ongoing emission reductions associated with regulations promulgated under the CAAA through 2005. We are not modeling the costs of compliance with the CAAA or endogenously determining emission reductions in equilibrium. Incorporating compliance and emissions endogenously in a GE framework that also captures their impact on human health and household behavior, may be critically important for determining the net welfare impact of environmental policies, a point we return to in Section 5. However, to transparently study the potential economic impacts of mortality risk reductions from air quality improvements and the validity of the time endowment approach, versus the mortality risk approach, we focus on the human health impacts of the CAAA.

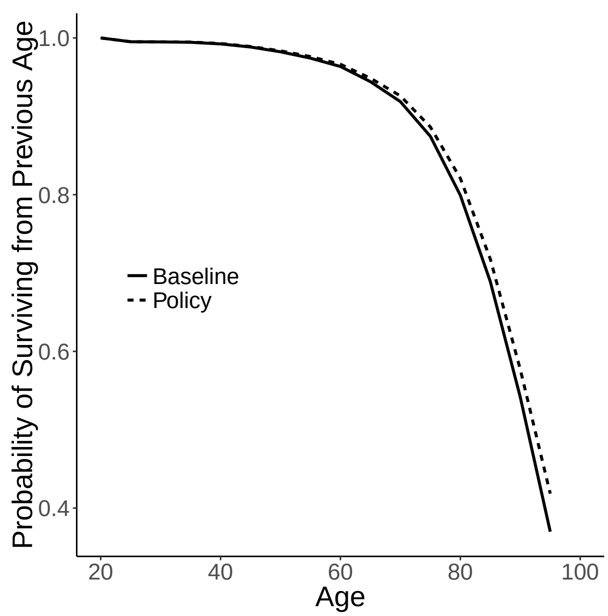
EPA conducted two complementary ex ante analyses of the predicted mortality incidence avoided as a result of the EPA's policies promulgated under the CAAA through 2005. The first approach, which was a PE analysis and produced their primary estimates of premature mortality reductions, used the BenMAP model to link detailed air quality modeling results to population and baseline mortality risk information at a relatively high spatial resolution. While the additional spatial detail allows for a more accurate assessment of the health impacts, it comes at a cost as BenMAP calculates benefits for a static population in a given year and does not accommodate a dynamic assessment of mortality incidence. Therefore, EPA supplemented its static benefit estimates using a dynamic population simulation model, though at the more spatially aggregated national level. Since a dynamic CGE model requires a forecast of population change over time, EPA relied on the latter health impact analysis as the basis for the time endowment shock in it's CGE modeling of the CAAA. Similarly, we also use the results from EPA's dynamic population simulation to

[7]GAMS Development Corporation. General Algebraic Modeling System (GAMS) Release 24.2.3. Washington, DC, USA, 2014.

[8]The source code for building the benchmark data, calibrating the model, and solving the model is available at http:// <link to be added at time study is finalized>.



(a) Change in Population [Thousands]



(b) Change in Steady-State Survival Curve [$\geq$ 2045]

Figure 2: Estimated Impact of the Clean Air Act

represent the impact of the CAAA. It is worth noting that the two approaches to estimating the reduction in premature mortality due to emission reductions under the CAAA (static and dynamic) provide relatively similar estimates for a given year at the national level.

We use the predicted changes in population sizes over time for each cohort from the EPA's dynamic population simulation model as the basis of our expected mortality risk reductions from the CAAA (EPA (2011b) - Exhibit 7-3). These estimates only account for the mortality incidence avoided due to reductions in $PM_{2.5}$ concentrations, and while the CAAA is expected to have additional health impacts, avoided premature mortality due to changes in $PM_{2.5}$ exposure is estimated to account for 97% of the monetized health benefits. Similar to EPA's CGE analysis, we use 2005 as the initial year in our model, so for consistency we only consider the effect of emissions reductions on mortality risk after this date. The dynamic health impact results from EPA include phased-in compliance with the CAAA starting in 1990 and therefore the estimates of population changes include impacts from emission reductions prior to 2005, which would theoretically already be represented in our benchmark population. Therefore, we remove these effects to isolate the impacts of emission reductions after 2005. The EPA analysis of the health impacts ends in the year 2045, so we must make an assumption regarding the survival curve relative to the baseline beyond this date. In this paper, we assume that the life-cycle schedule of mortality risks in 2045 represent a new steady-state for the survival curve for the foreseeable future.

Figure 2a presents a heat map of the expected increase in the population size at each age over time as a result of the change in mortality risks due to air pollution reductions. Individuals are expected to live longer under the CAAA, represented by the increase in the number individuals alive at older ages. The mortality risk reductions expected for individuals under the age of 60 are relatively small, due to their lower baseline vulnerability to environmental factors relative to older individuals. In fact, over the time period studied 55%-74% of the individuals expected to realize delayed mortality due to the CAAA are aged 75 and older. Figure 2b presents the steady-state survival curve under the baseline and policy scenarios starting in 2045. Even though the effect of the policy on mortality risks is assumed to remain constant past 2045, the magnitude of the population change continues to increase over time due to the positive population growth rate.

To calculate the willingness to pay for the mortality risk reductions associated with the CAAA, we aggregate measures of compensating variation (CV) across generations. CV is calculated as the present value of the payment a cohort could make and still achieve the baseline level of welfare conditional upon the new equilibrium prices, unintended bequests, and survival curves under the CAAA.[9] For our primary GE estimate of total WTP, we directly adjust the generation-specific survival curves, $\mu_{g,t}$, to reflect the updated mortality risks as presented in Figure 2a. For comparison, under the time endowment approach we leave the survival curves at their baseline level but increase the time endowment for each generation and year. Specifically, under the time endowment approach we multiply the baseline time endowment, ω, by the increase in the population presented in Figure 2a, denoted as $\Delta_{g,t}$, such that the updated time endowment in each period is $\omega'_{g,t} = (1 + \Delta_{g,t}/N_{g,t})\,\omega$.

4 Results

Our main results from explicitly modeling the mortality risk reductions from the CAAA in a GE framework are shown in Table 1. We present our results as the annualized present value of benefits over the time horizon in which the agents represented in the model are expected to be alive. For comparison, we also include the results from EPA's PE and GE analyses off the CAAA. These estimates highlight one of the main motivations for this study, in that the PE benefits estimates based on directly applying the VSL are over an order of magnitude larger than the GE estimates based on the time-endowment approximation. Two factors present challenges in interpreting this comparison. First, the GE estimates produced by the EPA include estimated impacts from reductions in morbidity associated with $PM_{2.5}$ and ozone exposure. These were implemented as increases in the time endowment, like the mortality impacts, and were estimated to have an impact on the time endowment nearly equivalent to the mortality reductions.[10] Furthermore, EPA's GE estimates include a reduction in household medical expenditures due to reduced morbidity of 13.4 and 22 billion 2015$ in 2010 and 2020, respectively (EPA (2011a) - Exhibit 8-6). In both cases the inclusion of morbidity effects reduces the difference between EPA's GE and PE estimates, as the PE estimates presented in Table 1 do not include any morbidity effects. The second confounding factor in the comparison is that EPA only adjusted the time endowment based on mortality risk changes associated with working age individuals. As noted earlier, it is expected that a significant share of the mortality incidence of the CAAA will fall on older individuals, likely to be out of the work force. This will cause the difference between EPA's GE and PE estimates to over-state the difference between the two measures if they were both comprehensively applied to all affected ages.

In contrast, our set of benefits estimates in the second half of Table 1 provide a consistent comparison across the PE and GE benefits measures. Our PE and GE estimates represent the same expected mortality

[9]For generations alive at the start of the model, this hypothetical payment would occur in the initial year. For subsequent generations the payment would occur at the period they enter the model.

[10]In the EPA's CGE model, the share of the time endowment increase related to morbidity reductions was 47.1% and 47.4% in 2010 and 2020, respectively (EPA (2011a) - Exhibit 8-5).

Table 1: $PM_{2.5}$ Mortality Benefit Estimates for the Clean Air Act [Billion 2015$]

Method	**Year**	**Value**
EPA (2011a) VSL	2010	1,350
EPA (2011a) VSL	2020	1,910
EPA (2011a) GE[a]	2010	72.9
EPA (2011a) GE[a]	2020	117
Average VSL	Annualized[b]	2,000
Life Cycle VSL	Annualized[b]	1,290
General Equilibrium - Mortality Risk Shock	Annualized[b]	1,340
General Equilibrium - Endowment Shock	Annualized[b]	10.7

[a] Estimated as the difference between the year-specific equivalent variation measures in the "cost only" and "labor force adjusted" simulations.
[b] Annualization of the estimates is over 225 years, which includes the model's time horizon and any effects realized by generations alive past the terminal period.

risk reduction from lower $PM_{2.5}$ exposure applied to the same underlying population of all individuals over the age of 20. Our average VSL estimate, using the same average VSL estimate applied by the EPA, is within the range of EPA's PE benefits estimates, though slightly higher due to the longer time horizon considered. We also present a PE estimate of the benefits based on the life-cycle VSL curve in Figure 1d that was estimated from the calibrated version of our CGE model. Our PE estimate of the benefits based on the life-cycle VSL schedule is significantly lower than the case where the average working age VSL was applied to all individuals independent of their age. This difference reflects the inverted-u shape of the life-cycle VSL curve and the large share of impacts realized by older individuals.[11] The life-cycle VSL curve better reflects the household preferences represented in the CGE model, so the PE estimate based on the life-cycle VSL schedule provides a more consistent comparison with our GE benefit estimates.

The time endowment approach produces an estimate of the benefits that is two orders of magnitude lower than the life-cycle VSL based PE estimate, 10.7 compared to 1,290 billion 2015$. This difference is similar to that found by EPA (2011a). However, when we directly perturb the survival curves in the model to reflect the reduction in mortality risks, our GE estimate of WTP is only 3.8% different than our PE estimate of WTP based on the life-cycle VSL schedule. These results strongly suggest that the substantial difference between previous PE and GE benefits estimates is primarily due to inadequacy of the time endowment approach as a proxy for the WTP approach.

While these results suggest that the large discrepancies between previous PE and GE estimates of mortality risk reduction benefits is mainly due to the inadequacy of the time endowment approximation, the similarity between our life cycle VSL and GE mortality risk shock estimates should not be taken to suggest that the GE effects will always be small and that life-cycle VSL based PE approach will always provide a close approximation. In fact, we find the potential for notable GE effects, but that these involve competing influences that can push the aggregate WTP estimate up or down. It turns out that in the case of the CAAA policies considered in this study, these opposing effects are nearly offsetting. There is little reason to expect

[11] This difference is not unique to our model as the inverted-u shape of the life-cycle VSL curve implicit in our CGE model is consistent with shape of age dependent estimates of the WTP for marginal mortality risk reductions observed in the empirical revealed preference literature (e.g., Viscusi and Aldy (2007); Aldy and Viscusi (2008)).

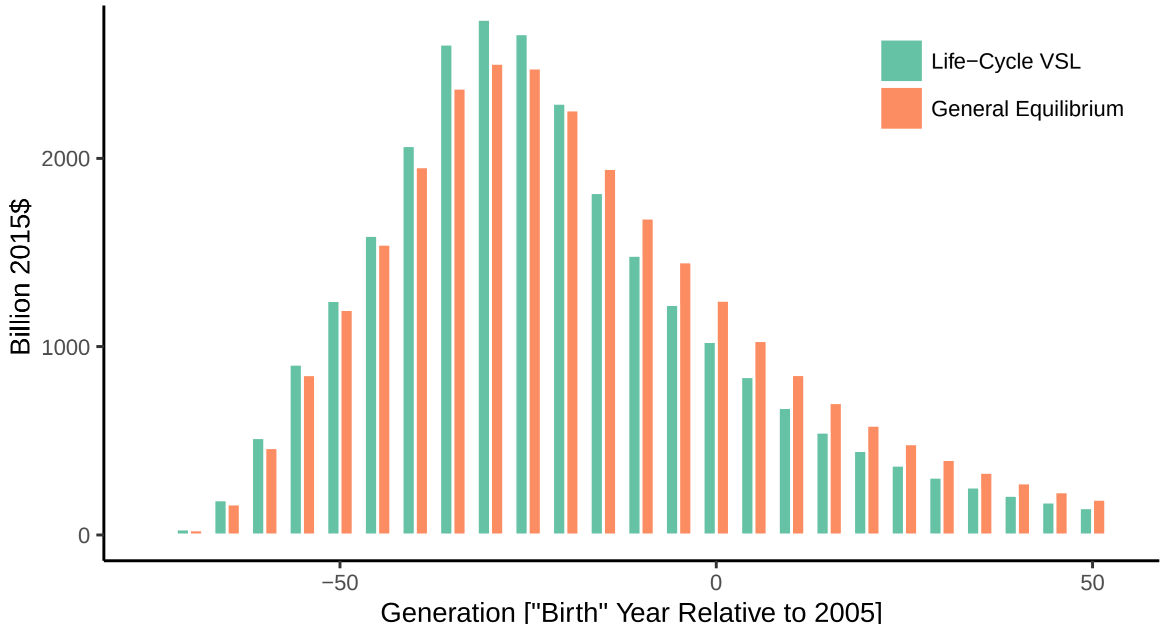


Figure 3: Incidence of Benefits by Generation

that this would occur for future policies or updated analyses of the CAAA including recently promulgated regulations. To examine these effects we begin with a break down of the WTP by generation in Figure 3. The x-axis represents the generations, denoted as g, measured by the year the cohort turned 20 in relation to the initial year in the model, 2005. There is a notable difference in the distribution of benefits across generations, though the decline for generations greater than zero largely represents discounting as the levels of the bars represent the present value of the benefits in 2005.

The variation in the differences between the PE and GE WTP estimates across generations can help us understand the primary GE effects being captured. The difference between the GE and PE estimates ranges from -15% to 31.2% across the generations plotted in Figure 3. The change in the life-cycle schedule of mortality risk is nearly the same for each generation. Therefore, the size of the PE estimate represents the magnitude of the change experienced by the generation. In some cases generations are experiencing changes of a similar magnitude as measured by the PE estimate, but have notably different GE estimates. For example, generations -50 and -5 have relatively similar PE estimates, but for generation -50 there is very little difference between the PE and GE estimates, whereas for generation -5 the GE estimate is notably larger than the PE estimate. This is arises due to the point in their life-cycle that those generations learn about the policy and the resulting change in their survival curves. For individuals that are older, particularly those that have already exited the labor force, when the policy is enacted there is less scope to re-optimize their remaining life-cycle behavior in response to the policy as compared to individuals that are at the beginning of their life-cycle when the policy is adopted. The naive PE measure of benefits based on the VSL will not differentiate between these two situations, but the GE measure will account for this re-optimization/consumption-smoothing effect. The result is a lower GE WTP estimate for generations "surprised" by the shock later in their life-cycles compared to agents with advance knowledge who can incorporate it into their life-cycle optimization (Cave, 1988).

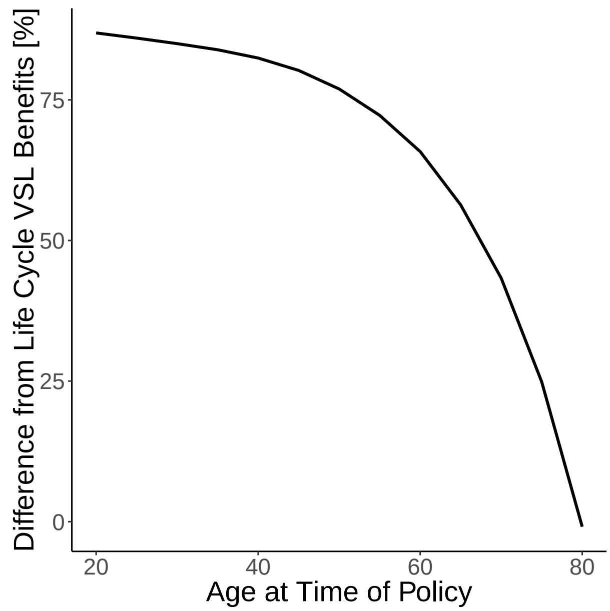


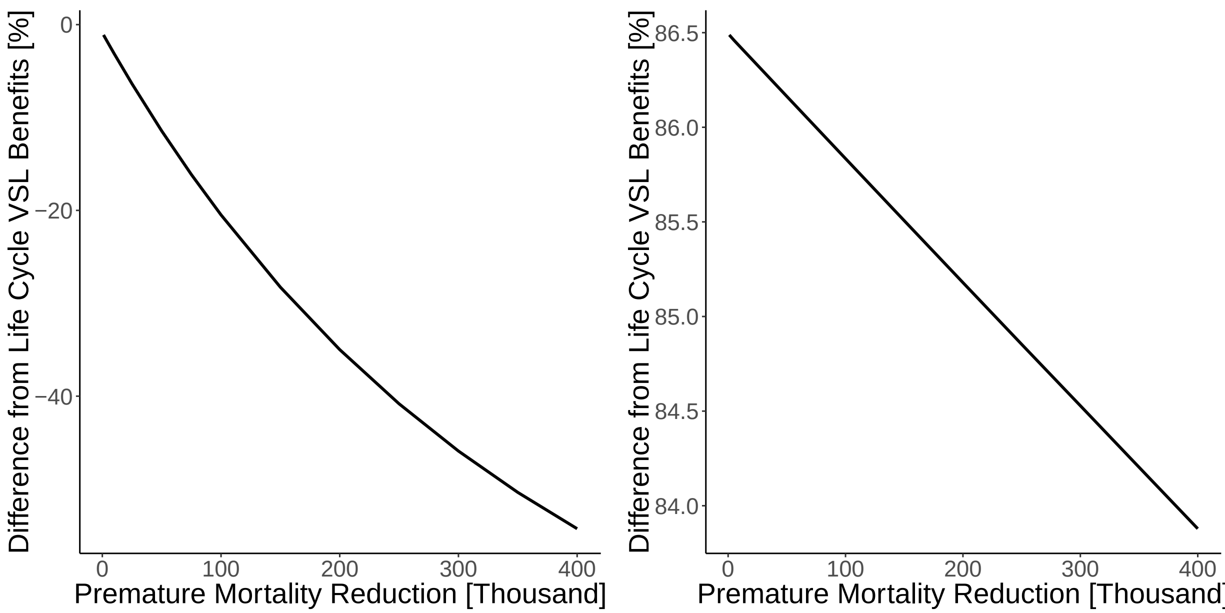
Figure 4: GE vs. PE Benefits for Mortality Risk Reduction at Age 85 Conditional on Timing

By definition of the VSL in (29), the life-cycle VSL is measuring the WTP for a change in the probability of surviving to the subsequent period. Therefore, in the case of a policy that results in a *marginal* change in one generation's probability of surviving from age a to $a+1$, introduced when they are at age a, the GE WTP estimate should coincide with the life-cycle VSL estimate. Alternatively, holding the policy impact and timing fixed, but allowing individuals to learn about the forthcoming change earlier in their life-cycle should change their WTP for two reasons: first because there is uncertainty as to whether they will live long enough to benefit from the policy, and second because they are able to plan for the change to better take advantage of the policy's benefits. To study the effect of a policy's timing, we compare the GE WTP for mortality risk reductions at a given age based on when agents learn that the policy will be implemented. In the case of the CAAA, more premature deaths are expected to be avoided for individuals of age 85 then for any other age group. Therefore, we conduct an experiment in which a representative individual expects a small mortality risk reduction associated with surviving from age 80 to 85.[12] By conducting the experiment for multiple generations, $g \in [-60, 0]$, we can assess the effect of policy timing on the agents' WTP.[13]

Figure 4 shows the percentage difference between the GE WTP estimate and the PE WTP estimated based on the life-cycle VSL curve for a policy that marginally increases the probability of surviving from age 80 to 85 depending on the age at which the agents first anticipate the change. As expected, when they are able to anticipate this marginal change only one period ahead, the GE and VSL based estimates coincide. However, if agents anticipate the change in their mortality risk earlier in life they are willing to pay substantially more for the policy, even though there is greater uncertainty about whether they will survive

[12] To represent a marginal mortality risk reduction we use a shock equivalent to an additional 100 individuals surviving from age 80 to 85. This shock is small enough to remain marginal but large enough to avoid issues associated with the tolerance of the numerical solution.

[13] Because there is no productivity growth in the model and the baseline is assumed to be along a balanced growth path, using the fact that generations cannot change behavior before the initial period is equivalent to surprising a single generation at different periods during their life-cycle, in the case of a marginal change.



(a) Age 80 at Time of Policy

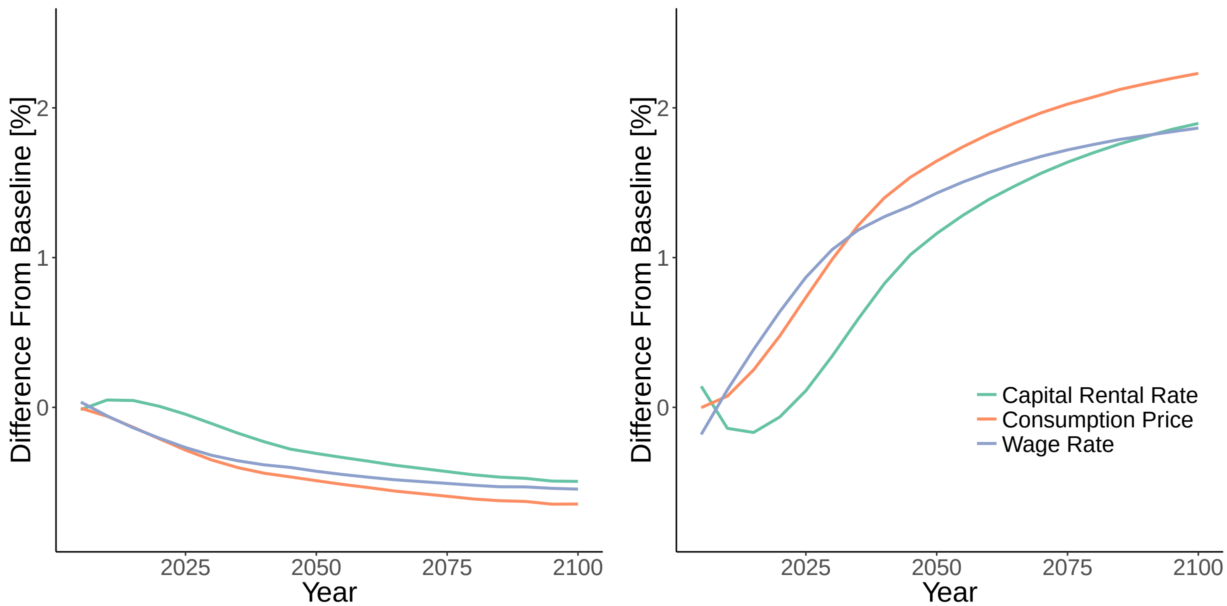
(b) Age 20 at Time of Policy

Figure 5: GE vs. PE Benefits for Mortality Risk Reduction at Age 85 Conditional on Policy Size

long enough to see the benefits. This suggests that capturing the life-cycle behavior of forward-looking agents is important for capturing differences in the WTP for mortality risk reductions based on the point in the life-cycle at which individuals are able to anticipate the changes in their later-life survival prospects.

However, for none of the generations, even those born after the policy was implemented, are the GE benefit estimates presented in Figure 3 ∼85% larger than the PE estimates, as would be suggested by Figure 4. Furthermore, if you refocus on generation -50 and then look at the generations that are just slightly younger at the time of the policy (e.g., generation -35 to -25), the GE benefit estimate is actually getting smaller relative to the PE estimate. This suggests that there is at least one other effect of similar magnitude working in the opposite direction. In this case it is a decreasing marginal WTP with respect to the size of the change in mortality risks. Generations just to the right of generation -50 are receiving substantially larger changes in their mortality risks as represented by the substantially larger PE benefit estimates. The GE estimates take into account any decline in the marginal WTP for mortality risk reductions as the shock increases due to the concavity of the agents' utility functions.

To examine the rate of decline in the marginal WTP for mortality risk reductions, we again increase the probability that an individual survives from age 80 to 85. However, in this case we fix the time at which the individual learns about the change and we vary the size of the change. Figure 5a illustrates the effect of the magnitude of the mortality risk reduction on the GE WTP relative to the PE WTP for an individual of age 80 at the time the policy is implemented. By definition, a marginal shock in this case will be valued similarly in both the PE and GE setting, since it will be a surprise to the agents affected. As the size of the mortality risk reduction increases, the marginal WTP decreases quickly and therefore the PE estimate based on the life-cycle VSL schedule begins to overestimate the cumulative WTP for the change. This characteristic is a direct result of the concavity of the utility function. WTP is the income the individual would have to



(a) Time Endowment Approximation

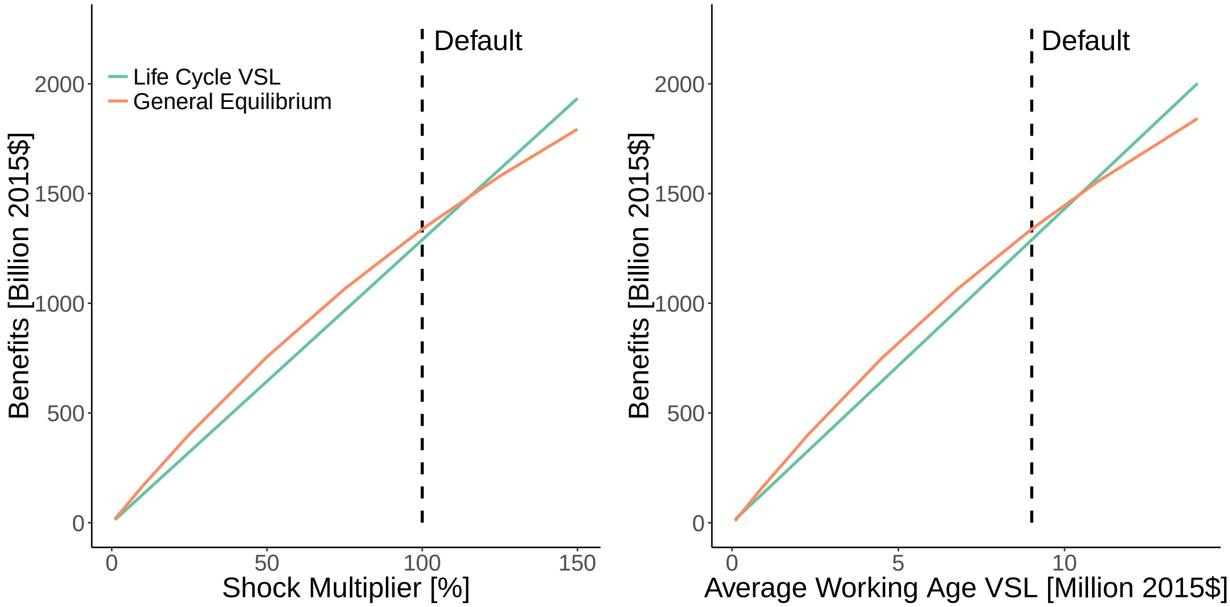
(b) Mortality Risk Change

Figure 6: Change in Relative Prices

forgo in the policy case to return to her level of utility before shock was implemented. The concavity of the utility function requires that the individual forgo a decreasing amount of income for each additional unit of mortality risk reduction. For older generations at the time of the policy with less flexibility, this decreasing marginal WTP over a non-marginal shock appears to be the dominant effect, leading to GE benefit estimates that are lower than the PE benefit estimates.

For generations that are relatively young at the time the policy is realized, the WTP is notably less sensitive to the size of the shock. As previously demonstrated, the VSL can underestimate an individual's WTP for an expected mortality risk reduction if they learn about it in advance, as the VSL does not account for the value of having additional time to adjust to the change. For similar reasons the GE benefit estimates are less sensitive to the size of the mortality risk reduction when agents learn about the change early in their life-cycle. Figure 5b replicates the previous experiment but for agents that are of age 20 at the time of the policy. For the smallest shock considered, the markup of the GE benefit estimate above the PE estimate is equivalent to that of Figure 4 for an agent learning about the policy at age 20. From there we increase the size of the policy. The difference between the GE and PE estimates declines due to the decreasing marginal WTP with respect to the size of the change. However, in this case the rate of decline is far slower than in Figure 5a. Since the hypothetical payment (compensating variation) for the mortality risk reduction can be spread over a larger set of years, the concavity of the utility function does not cause the WTP to decrease with the size of the change as quickly as when the agents are surprised by the change later in their life cycle.

The value of learning about changes in life expectancy earlier in life helps explain why the GE benefit estimate is larger than the PE estimate for relatively younger generations. However, the decreasing marginal WTP for mortality risk reductions may not be enough to explain why the GE benefit estimates for relatively younger generations are only around 30% greater than the PE benefit estimates, given that the results of



(a) Benefits Estimate Conditional on Policy Size

(b) Benefits Estimates Conditional on VSL Estimate

Figure 7: Role of VSL Estimate in Definition of a Marginal Policy

Figure 4 suggest the value of learning about the changes early in life could make the GE benefits up to 85% greater. The primary reason that the difference between the approaches does not reach this level is the downward pressure that changes in relative prices place on the GE WTP for relatively younger generations. The increase in life expectancy leads to an increase in savings, and to a lesser degree labor supply. These shifts in supply of the primary factors leads to a reduction in their relative prices. At the same time the increase in the population leads to an increased demand for consumption which increases its relative price. These dynamics are presented in Figure 6b, and mean that relatively younger generations are expected to experience a notable decrease in the real return they receive for their savings at the same time they would like to increase their savings to fund the increase in their expected life span.[14] These changes in equilibrium prices appear to have a significant impact on the WTP of some generations.

Given the potential for significant GE effects that could cause the GE estimate of benefits to differ notably from the PE estimate, the similarity between the GE and life-cycle based PE estimates in Table 1 is more unexpected than it may seem to be at first glance. There is nothing in the GE approach we employ that would guarantee this result. To demonstrate this we consider sensitivity analysis over the size of the policy shock assumed for the CAAA. Specifically, we scale the expected reduction in premature mortality from the CAAA uniformly across time and generations and model the changes in mortality risk implied by those alternative outcomes. Figure 7a presents the benefits from policies that reduce premature mortality between 1% and 150% of the CAAA, keeping the distribution of effects across time and generations the same. One may also interpret the x-axis as depicting the individual regulations promulgated under the CAAA before the analysis of EPA (2011a) and those promulgated after that analysis (including those yet

[14]Figure 6 presents the price of consumption including the ad valorem consumption tax, which increases slightly in the policy case to fund increases in real government spending as a result of the increased population size.

to be promulgated).[15] Under that interpretation, Figure 7a would suggest as regulations were promulgated under the CAAA the PE benefit estimates were underestimates, though eventually the GE effects including the decreasing marginal WTP for mortality risk reductions began to dominate, such that the PE approach may over estimate society's WTP for future CAAA regulations.

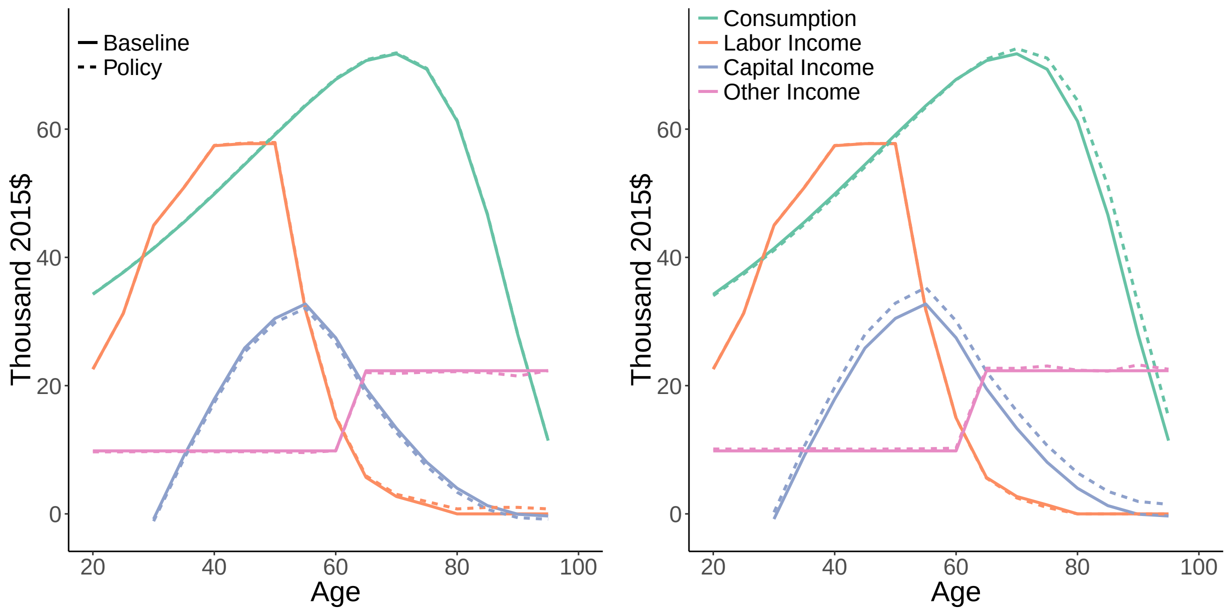
The similarity between our aggregate PE and GE estimates for the CAAA regulations analyzed is in part driven by the calibration of household preferences to the same average VSL used by EPA (2011a). A major reason for the concavity of the GE benefits in Figure 7a is the decreasing marginal WTP. The question of whether the mortality risk reductions associated with the CAAA are marginal or not depends, in part, on the magnitude of the VSL. A higher VSL would suggest that an individual would have to forgo more consumption and leisure for each unit of mortality risk reduction to return to the original welfare level, relative to a lower estimate of the VSL. Figure 7b presents estimates of benefits of the mortality risk reductions under the CAAA when the model is calibrated to different assumptions about the VSL of the average working age individual. If the average VSL were notably lower than the estimate used by EPA (2011a) than the GE effects of the CAAA may be relatively small, such that the life-cycle VSL based PE measure of the benefits provides a reasonable approximation of the benefits. However, if the average VSL is nearly as large or greater than the estimate of EPA (2011a), then conducting an assessment of the CAAA benefits under the assumption that they are marginal will result in an overestimate of the social benefits.

4.1 Economic Impacts of Mortality Risk Reductions

Incorporating the non-market impacts of pollution reduction into GE analyses has also been motivated by a demand from stakeholders to understand the net economic impacts of environmental policies and the potential for feedbacks between benefits and costs that could be important for evaluating the efficiency of policies (Matus et al. (2008); Carbone and Smith (2013)). It is therefore, useful to understand how the time endowment approach to approximating mortality risk reductions that is currently used in GE analyses captures the expected economic impacts of environmental policies. In our assessment of the mortality risk reductions from the CAAA, the time endowment approximation estimates a change in real GDP of -0.0292% to 0.49%, depending on the simulation year, while the explicit shock to mortality risk estimates a change of 0.155% to 0.823%. This suggests that the time endowment approach is not fully capturing the expected changes in household behavior as a result of the mortality risk reductions and the subsequent economic impacts.

The time endowment approximation yields substantially different results for the expected economic impacts because of the difference between how households value and respond to a change in their time endowment versus their mortality risk. In both cases households are forward looking and expect the changes induced by the policy, but the impact on their life-cycle behavior differs notably. The role of generations "surprised" by the policy are important for understanding the nuances of the transition dynamics, but a comparison between steady-states provides intuition as to the general difference between the modeling approaches. Figures 8a and 8b present the change between the baseline steady-state life-cycle profile for the time endowment and mortality risk approaches, respectively. In both cases the effect is primarily realized in the last decades of the life-cycle, as previously discussed. In the case of the time endowment approximation,

[15]This is a loose interpretation as the generational and temporal incidence of mortality risk reductions across CAAA regulations are not homogeneous.



(a) Time Endowment Approximation

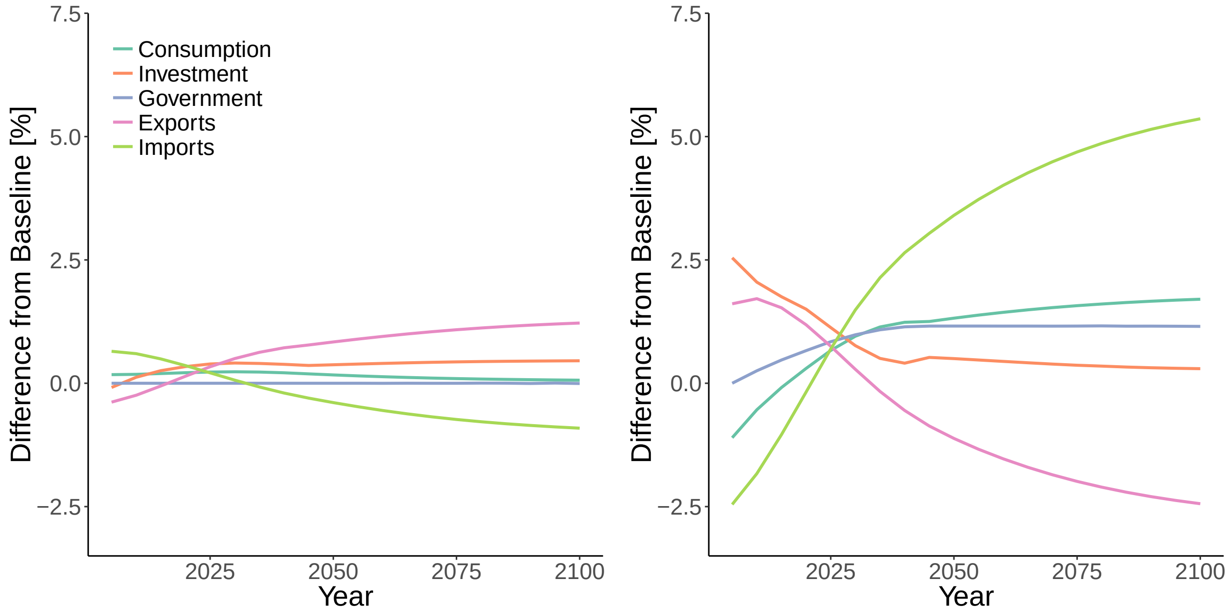
(b) Mortality Risk Change

Figure 8: Change in Real Steady-State Life-Cycle Profiles

the primary effect is a small increase in labor income at the time of the change due to an increase in labor supplied by the household. There is a small reduction in overall household savings in anticipation of the extra labor income later in the life-cycle leading to a slight reduction in capital income. There is also a very small increase in consumption, but that is not discernible in the plot of the individual agents' life-cycle and remains small even when aggregated over the entire population.

There are two reasons that the time endowment change does not more heavily influence behavior earlier in the life-cycle. First, there are limited opportunities for agents to monetize the increased time endowment as it occurs late in the life-cycle after most agents have retired and the expected wage is relatively low. Therefore, the majority of the additional time endowment is enjoyed as leisure. Second, the opportunities to substitute the increase in labor income late in life for labor income earlier in the life-cycle is limited due to the probability that an individual may not survive long enough to fully realize the increased time endowment. When the policy is explicitly modeled as a reduction in mortality risk we expect a very different response by agents across their life-cycle, as shown in Figure 8b. To accommodate the increased life expectancy, individuals increase their savings and do so primarily by reducing consumption early in their life-cycle, the opposite effect of what occurs under the time endowment approach. Furthermore, because the impact is an increase in life expectancy and not an increase in the time endowment we do not observe an increase in labor income later in the life-cycle, and in fact observe a very slight decrease later in the life-cycle and a small increase early in the life-cycle. However, the latter effect is very small and does not show up in Figure 8b and remains relatively small when aggregated over all individuals.

The difference in changes in life-cycle behavior between the two modeling approaches leads to notable differences in the way the health impacts of the CAAA are expected to affect macroeconomic aggregates. This is apparent when examining changes to the components of GDP from the expenditure side. Figure 9a and



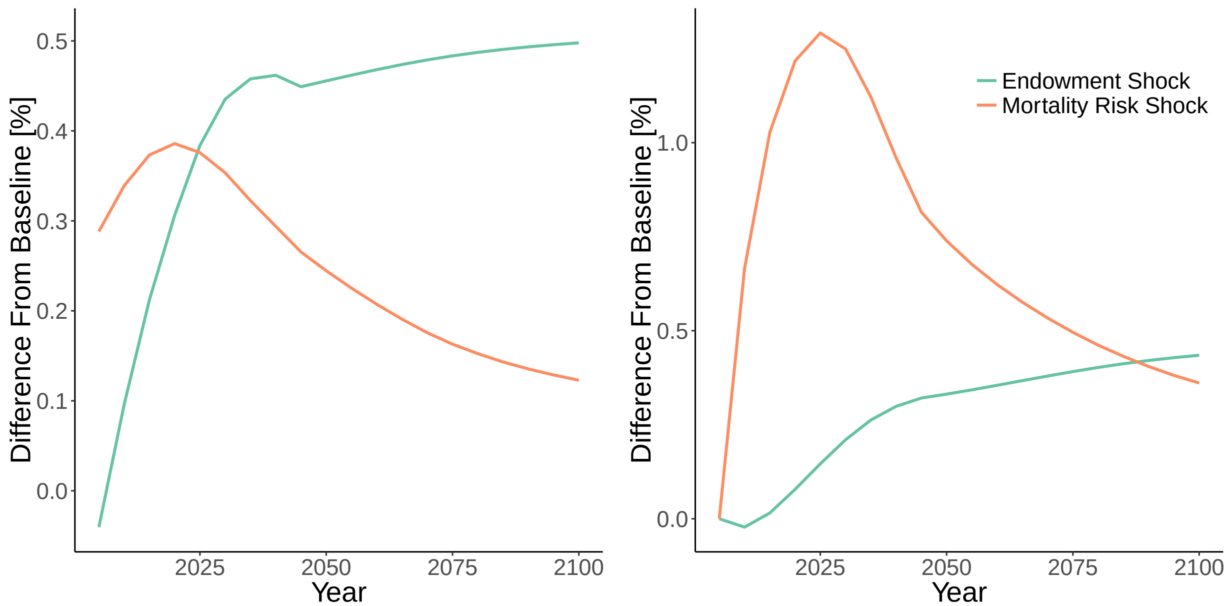
(a) Time Endowment Approximation

(b) Mortality Risk Change

Figure 9: Change in Real National Accounts

9b present changes in national accounts for the time endowment and mortality risk approaches, respectively. Under the time endowment approach there is a significantly more muted economic response compared to the case where the mortality risk reductions are explicitly modeled. This difference follows directly from the more muted changes in life-cycle behavior observed in Figure 8. The increase in the time endowment represents an increase in the agent's expected wealth and therefore leads to an increase in aggregate consumption right from the beginning mirroring the effect on the individual agents' life-cycles. We also see a slight increase in investment the in domestic capital stock. Given the reduction in life-cycle savings observed in Figure 8a, this investment is mainly driven by substitution of assets from foreign bonds to domestic capital as a result of the increased competitiveness of the domestic economy given the expansion of labor supply. This is also observed through the decrease in the trade deficit.

In comparison, when the mortality risk reductions are explicitly modeled aggregate consumption initially falls as agents increase their savings to help fund the expected increase in their life span. The initial spike in investment is, in part, driven by agents who were surprised by the change in their life expectancy and are trying to "catch up" to their optimal level of savings given their new survival curve. Over time, the increase in investment falls from the initial peak and levels off as the affected generations all anticipate the change from the beginning of their life-cycles. Individuals fund the initial spike in savings mainly by reducing their consumption, such that aggregate consumption initially moves in the opposite direction of the time endowment approach. In the long-run, aggregate consumption is expected to increase along with the increase in population. This increase in consumption, along with the increase in the relative price of domestic production (observed in Figure 6b) leads to an increase in the trade deficit as opposed to the reduction seen under the time endowment approach. The time endowment approach, therefore, not only underestimates the absolute magnitude of economic impacts, but in some cases also forecasts the wrong sign.



(a) Labor Supply

(b) Capital Stock

Figure 10: Changes in Factors of Production

As would be expected from the previous results, the time endowment approach also projects significantly different effects in factor markets relative to the explicitly modeled mortality risk reductions. Figure 10a presents the percentage change in aggregate labor supply (in effective units) across the two approaches and Figure 10b presents the change in capital stock. The difference between the time endowment and mortality risk approaches again mirror the differences in how agents respond in their life-cycle behavior. Under the mortality risk approach, individuals immediately increase their supply of labor to help fund the increase in their savings intended to accommodate the unexpected increase in their life expectancy. Eventually some of that increase dissipates as generations begin to fully anticipate the new survival curve. However, under the time endowment approach households gradually begin to increase their labor supply as the increased endowment is realized by older generations, eventually leveling off at a higher level. Similar dynamics are observed in the capital stock with the time endowment approach missing the initial increase in capital stock associated with the spike in savings previously discussed.

5 Conclusions

The GE effects of environmental regulations have long been a concern of stakeholders and researchers, who have argued that understanding potential economy-wide feedbacks is critical to efficient policy design and evaluation. Most often these concerns are expressed with regards to the costs of environmental policies, going back to the seminal work of Hazilla and Kopp (1990) and Jorgenson and Wilcoxen (1990) who found that the GE social costs may be significantly higher than the PE estimates. Given that PE estimates of benefits for major environmental regulations can be far larger than PE estimates of the costs, there has been growing interest in understanding whether the non-market impacts of these policies also have important GE effects that should be considered in the decision making process (e.g., Matus et al. (2008); EPA (2011a); and Carbone and Smith (2013)). Much of the initial focus has been on the economy-wide feedbacks associated with improving human health, most notably the mortality risk reductions induced by decreases in emissions of criteria air pollutants. This growing body of literature has provided evidence that improvements in human health could: significantly affect economic growth (Matus et al., 2008); prevent benefits and costs from being evaluated separately (Carbone and Smith, 2013); and have large GE effects that lead PE approaches to substantially overestimate benefits EPA (2011a). These findings all have important implications for the evaluation and design of environmental policies. However, these studies are all based on the strong assumption that households will respond to a time endowment increase in the same way as they would to a reduction in future mortality risks. Using a GE framework capable of explicitly modeling reductions in mortality risk induced by air pollution regulations, we test the validity of this assumption and find no support for the commonly used time endowment approximation, though we do find the potential for important GE feedbacks.

The time endowment approach is representing a change that is fundamentally different than a reduction in mortality risk, and as such the modeled response in household behavior is significantly different. When we model the mortality risk reductions explicitly, households are responding to an increase in their life expectancy, which motivates increased savings and reduced consumption earlier in the life-cycle. In contrast, an increase in the available time endowment is treated like an income effect so households increase consumption throughout their life-cycle. In the case of air pollution reductions, the majority of the health impacts are expected to be realized when individuals are aged 75, so they may have difficulty monetizing an increase in their time endowment through the labor market. As a result the overall economic impacts forecast under the time endowment approach are much more muted than the case where the mortality risk reductions are explicitly modeled. For some economic impacts, including aggregate consumption after the shock, the time endowment approximation even projects changes in the wrong direction relative to the case where mortality risk reductions are explicitly modeled.

The inability of the time endowment approach to adequately approximate the effect of mortality risk reductions extends beyond economic impacts to welfare analysis. We find that the results of previous studies showing GE and PE benefits estimates differing by more than an order of magnitude are due to inconsistencies in what was being valued, making the estimates incomparable. When we examine comparable GE and PE estimates that are both explicitly valuing mortality risk reductions we find that the PE measures are not implausibly large relative to a structurally constrained GE measure. In the specific case of CAAA regulations through 2005, we find that the two measures are reasonably close. However, this result does not suggest that PE estimates of mortality risk reduction benefits will always provide an acceptable approximation to the GE measure.

In examining the mortality risk reductions expected from the CAAA we find evidence that the human health benefits of environmental policies may have important GE effects that influence both estimates of the social benefits and the economic impacts. These effects are varied and have opposing signs making the overall difference between GE and PE estimates of a policy's benefits ambiguous in general and dependent upon the specific timing and distribution of a policy's changes in mortality risks. Policies that lower rates of premature mortality through pollution reductions, for example direct or indirect reductions in tropospheric concentrations of ozone and fine particulate matter, typically impact households later in their life-cycle when they are more vulnerable. When households learn about these changes to their future mortality risks is highly relevant. In general, households are expected to be willing to pay more for mortality risk reductions that will occur later in their life when they learn about those effects early enough to plan for the change in life expectancy. We find that this effect has an important role in determining the aggregate value and distribution of benefits. This effect also has meaningful implications for the economic impacts of a policy, as households that have many years to plan for the increase in life expectancy will respond in a different fashion compared to those households surprised by the change late in life.

Concavity of households' utility functions leads to a decreasing marginal WTP for mortality risk reductions. We find that the marginal WTP decreases faster when households are surprised by those changes and that cumulatively air pollution regulations in the U.S. are non-marginal in this regard. Current practice when conducting PE assessments of mortality risk reduction benefits is to assume that individual regulations are sufficiently small that the concavity of utility functions can be set aside. However, the relevant reference point for assessing whether the policy currently being evaluated is non-marginal is not baseline mortality risk without the policy but the baseline mortality risk at the time that the VSL was estimated (noting the VSL the estimate currently used in federal environmental policy analysis is based on studies from 1974 to 1991). We find evidence that the cumulative expected mortality risk reductions from air pollution regulations promulgated through 2005 are non-marginal, such that, all else equal, PE estimates of the benefits of future regulations will likely overestimate the WTP. Given that it is unlikely that a full GE analysis would be conducted for all regulations, particularly those with relatively small impacts, this finding is important for the interpretation of future PE benefits estimates. As an alternative, the VSL estimates used in the PE analyses could be regularly updated using the most recent data to ensure that they are representative of the same baseline off of which the regulations are being evaluated.

We also find that changes in household behavior due to mortality risk reductions can have a large enough effect on relative prices that the new equilibrium can alter households' willingness to pay for a policy's benefits, if the reduction is sufficiently large. In the long run, we expect an increase in aggregate consumption due to the increased size of the population and an increase in aggregate investment due to higher household savings intended to support the increase in life expectancy. This results in a reduction in the real rate of return on capital which drives down households' willingness to pay for the mortality risk reductions. A reduction in the long run real wage rate adds to this effect.

While we find that the time endowment approach provides an inadequate approximation to modeling reductions in morality risks, our results nevertheless reinforce findings of previous studies that have suggested it is important to include the human health impacts of policies in GE analysis. In general we find that non-marginal reductions in mortality risks can have significant economy-wide effects by themselves and are therefore important to include in GE analyses. Given that the time endowment approach is likely to underestimate the magnitude of the economic impacts, our results strengthen previous findings regarding the economy-wide effects. For the same reason, our results strengthen previous findings that abatement costs and non-market benefits may interact in equilibrium in ways that make it difficult to estimate the two separately for large policies. For example, we find that the relative rental rate on capital is likely to face downward pressure as a result of households increasing their savings in response to increases in life expectancy. This would have important implications for estimating social costs if the policy achieves those mortality risk reductions through incentivizing firms to make capital investments in abatement technologies.

Further research into the ways that compliance costs and non-market benefits interact through changes in household behavior may provide further insight into the relative effectiveness of different policy instruments in second best settings. However, this future work should take care to ensure that non-market impacts are modeled in a way that adequately captures their affect on household behavior.

References

Joseph E Aldy and Seamus Smyth. Heterogeneity in the value of life. *NBER Working Paper*, (w20206), 2014.

Joseph E Aldy and W Kip Viscusi. Age differences in the value of statistical life: revealed preference evidence. *Review of Environmental Economics and Policy*, 1(2):241–260, 2007.

Joseph E Aldy and W Kip Viscusi. Adjusting the value of a statistical life for age and cohort effects. *The Review of Economics and Statistics*, 90(3):573–581, 2008.

Paul S Armington. A theory of demand for products distinguished by place of production. *Staff Papers*, 16 (1):159–178, 1969.

Alan J Auerbach and Laurence J Kotlikoff. *Dynamic fiscal policy*. Cambridge University Press Cambridge, 1987.

Edward J Balistreri, Christine A McDaniel, and Eina Vivian Wong. An estimation of us industry-level capital–labor substitution elasticities: support for cobb–douglas. *The North American Journal of Economics and Finance*, 14(3):343–356, 2003.

Olivier J Blanchard. Debt, deficits, and finite horizons. *Journal of Political Economy*, 93(2):223–247, 1985.

Jared C Carbone and V Kerry Smith. Valuing nature in a general equilibrium. *Journal of Environmental Economics and Management*, 66(1):72–89, 2013.

Justin Caron and Sebastian Rausch. A global general equilibrium model with us state-level detail for trade and environmental policy analysis–technical notes, 2013.

Jonathan AK Cave. *Age, time, and the measurement of mortality benefits*. Rand Corporation, 1988.

Maureen Cropper, James Hammitt, and Lisa Robinson. Valuing mortality risk reductions: Progress and challenges. *Annual Review of Resource Economics*, 3(1):313–336, 2011.

Maureen L Cropper. Health, investment in health, and occupational choice. *Journal of Political Economy*, 85(6):1273–1294, 1977.

U.S. EPA. EMPAX-CGE model documentation. `http://www.epa.gov/ttnecas1/models/empax_model_documentation.pdf`, 2008.

US EPA. Valuing mortality risk reductions for environmental policy: A white paper. Technical report, U.S. Environmental Protection Agency, 2010. URL \url{http://yosemite.epa.gov/ee/epa/eerm.nsf/vwAN/EE-0563-1.pdf/$file/EE-0563-1.pdf}.

US EPA. The benefits and costs of the clean air act from 1990 to 2020. Technical report, U.S. Environmental Protection Agency, April 2011a. URL \url{https://www.epa.gov/sites/production/files/2015-07/documents/fullreport_rev_a.pdf}.

US EPA. Uncertainty analyses to support the second section 812 benefit-cost analysis of the clean air act. Technical report, U.S. Environmental Protection Agency, March 2011b. URL \url{https://www.epa.gov/sites/production/files/2016-01/documents/uncertaintyfullreport.pdf}.

Neal Fann, Amy D Lamson, Susan C Anenberg, Karen Wesson, David Risley, and Bryan J Hubbell. Estimating the national public health burden associated with exposure to ambient pm2. 5 and ozone. *Risk analysis*, 32(1):81–95, 2012.

Daniel Feenberg and Elisabeth Coutts. An introduction to the taxsim model. *Journal of Policy Analysis and management*, 12(1):189–194, 1993.

Robert C Feenstra, Robert Inklaar, and Marcel P Timmer. The next generation of the penn world table. *The American Economic Review*, 105(10):3150–3182, 2015.

Jesús Fernández-Villaverde and Dirk Krueger. Consumption over the life cycle: Facts from consumer expenditure survey data. *The Review of Economics and Statistics*, 89(3):552–565, 2007.

Michael C Ferris and Todd S Munson. Complementarity problems in gams and the path solver. *Journal of Economic Dynamics and Control*, 24(2):165–188, 2000.

Ted Gayer, James T Hamilton, and W Kip Viscusi. The market value of reducing cancer risk: Hedonic housing prices with changing information. *Southern economic journal*, pages 266–289, 2002.

Gary D Hansen and Selahattin İmrohoroğlu. Consumption over the life cycle: The role of annuities. *Review of economic Dynamics*, 11(3):566–583, 2008.

Michael Hazilla and Raymond J Kopp. Social cost of environmental quality regulations: A general equilibrium analysis. *Journal of Political Economy*, 98(4):853–873, 1990.

Joni Hersch and W Kip Viscusi. Immigrant status and the value of statistical life. *Journal of Human Resources*, 45(3):749–771, 2010.

Thomas Hertel, David Hummels, Maros Ivanic, and Roman Keeney. How confident can we be of cge-based assessments of free trade agreements? *Economic Modelling*, 24(4):611–635, 2007.

Dale W Jorgenson and Peter J Wilcoxen. Environmental regulation and us economic growth. *The Rand Journal of Economics*, pages 314–340, 1990.

Thomas J Kniesner, W Kip Viscusi, and James P Ziliak. Life-cycle consumption and the age-adjusted value of life. *The BE Journal of Economic Analysis & Policy*, 5(1), 2006.

Daniel Krewski, Michael Jerrett, Richard T Burnett, Renjun Ma, Edward Hughes, Yuanli Shi, Michelle C Turner, C Arden Pope III, George Thurston, Eugenia E Calle, et al. Extended follow-up and spatial analysis of the american cancer society study linking particulate air pollution and mortality. *Res Rep Health Eff Inst*, 140(5):5–114, 2009.

Johanna Lepeule, Francine Laden, Douglas Dockery, and Joel Schwartz. Chronic exposure to fine particles and mortality: an extended follow-up of the harvard six cities study from 1974 to 2009. *Environmental health perspectives*, 120(7):965, 2012.

Jonathan I Levy, Lisa K Baxter, and Joel Schwartz. Uncertainty and variability in health-related damages from coal-fired power plants in the united states. *Risk Analysis*, 29(7):1000–1014, 2009.

Jennifer Chung-I Li. Including the feedback of local health improvement in assessing costs and benefits of ghg reduction. *Review of Urban & Regional Development Studies*, 14(3):282–304, 2002.

Kira Matus, Trent Yang, Sergey Paltsev, John Reilly, and Kyung-Min Nam. Toward integrated assessment of environmental change: air pollution health effects in the usa. *Climatic Change*, 88(1):59–92, 2008.

Kira Matus, Kyung-Min Nam, Noelle E Selin, Lok N Lamsal, John M Reilly, and Sergey Paltsev. Health damages from air pollution in china. *Global environmental change*, 22(1):55–66, 2012.

Inge Mayeres and Denise Van Regemorter. Modelling the health related benefits of environmental policies and their feedback effects: a cge analysis for the eu countries with gem-e3. *The Energy Journal*, pages 135–150, 2008.

Robert McClelland and Shannon Mok. A review of recent research on labor supply elasticities: Working paper 2012-12. Technical report, Congressional Budget Office, 2012.

Kevin M Murphy and Robert H Topel. The value of health and longevity. *Journal of political Economy*, 114 (5):871–904, 2006.

Kyung-Min Nam, Noelle E Selin, John M Reilly, and Sergey Paltsev. Measuring welfare loss caused by air pollution in europe: A cge analysis. *Energy Policy*, 38(9):5059–5071, 2010.

Badri Narayanan, Angel Aguiar, and Robert McDougall. Global trade, assistance, and production: The gtap 9 data base. *Center for Global Trade Analysis, Purdue University*, 2015.

Tobias N Rasmussen and Thomas F Rutherford. Modeling overlapping generations in a complementarity format. *Journal of Economic Dynamics and Control*, 28(7):1383–1409, 2004.

Thomas C Schelling. The life you save may be your own. In S. Chase, editor, *Problems in Public Expenditure Analysis*. The Brookings Institution, Washingtion, DC, 1968.

Carol R Scotton and Laura O Taylor. Valuing risk reductions: Incorporating risk heterogeneity into a revealed preference framework. *Resource and Energy Economics*, 33(2):381–397, 2011.

Noelle E Selin, Shiliang Wu, Kyung-Min Nam, John M Reilly, Sergey Paltsev, Ronald G Prinn, and Mort D Webster. Global health and economic impacts of future ozone pollution. *Environmental Research Letters*, 4(4):044014, 2009.

Donald S Shepard and Richard Zeckhauser. Survival versus consumption. *Management Science*, 30(4): 423–439, 1984.

V Kerry Smith. In search of crosswalks between macroeconomics and environmental economics. *Review of Environmental Economics and Policy*, 6(2):298–317, 2012.

Efthimios Tagaris, Kuo-Jen Liao, Anthony J DeLucia, Leland Deck, Praveen Amar, and Armistead G Russell. Potential impact of climate change on air pollution-related human health effects. *Environmental science & technology*, 43(13):4979–4988, 2009.

Mitra Toossi. Labor force projections to 2024: the labor force is growing, but slowly. *Monthly Labor Review*, 138, 2015.

Haakon Vennemo. A dynamic applied general equilibrium model with environmental feedbacks. *Economic Modelling*, 14(1):99–154, 1997.

W Kip Viscusi and Joseph E Aldy. Labor market estimates of the senior discount for the value of statistical life. *Journal of Environmental Economics and Management*, 53(3):377–392, 2007.

Roberton C Williams. Environmental tax interactions when pollution affects health or productivity. *Journal of Environmental Economics and Management*, 44(2):261–270, 2002.

Roberton C Williams, Hal Gordon, Dallas Burtraw, Jared C Carbone, and Richard D Morgenstern. The initial incidence of a carbon tax across income groups. *National Tax Journal*, 68(1):195, 2015.

Menahem E Yaari. Uncertain lifetime, life insurance, and the theory of the consumer. *The Review of Economic Studies*, 32(2):137–150, 1965.

A Model Calibration

Calibration of the model requires characterizing the benchmark economy that represents the initial year of the model and the parameters that form the basis for the path of the economy in the baseline scenario. We also must calibrate the parameters of the production function, the household utility function, and endowments. We discuss the calibration of these sets of parameters in turn.

A.1 National Accounts Data

To provide a more consistent comparison to EPA's analysis of the CAAA we calibrate our benchmark to the 2005 U.S. economy. The EMPAX CGE model used by EPA was also calibrated to 2005 (EPA, 2008). Most of the benchmark data is from the U.S. Bureau of Economic Analysis'(BEA) National Income and Product Account (NIPA) tables. Table 2 presents the benchmark data along with a list of the sources for each variable.

Gross labor income, L_0, is calculated from Y_0 and the estimate of labor compensation as a share of GDP from the Penn World Table Version 9, which is reported as $\theta_Y = 0.611$ (Feenstra et al., 2015). Consistent

Table 2: Benchmark Data

Parameter	Description	Value	Units	Source
Y_0	Output	15,100	Billion 2015$	BEA NIPA Table 1.1.5
G_0	Government consumption	2,870	Billion 2015$	BEA NIPA Table 1.1.5
X_0	Exports	1,510	Billion 2015$	BEA NIPA Table 1.1.5
M_0	Imports	2,340	Billion 2015$	BEA NIPA Table 1.1.5
B_0	Trade deficit	831	Billion 2015$	BEA NIPA Table 1.1.5
C_0	Aggregate consumption	10,600	Billion 2015$	Equation (23)
I_0	Aggregate investment	2,430	Billion 2015$	Equation (20)
D_0	Government deficit	641	Billion 2015$	BEA NIPA Table 3.1
T_0	Lump-Sum transfers	1,230	Billion 2015$	BEA NIPA Table 3.1
L_0	Net labor income	6,720	Billion 2015$	Penn World Table v9
R_0	Net capital income	4,350	Billion 2015$	Equation (17)
τ^r	Capital tax rate	0.35		NBER TAXSIM
τ^l	Labor tax rate	0.29		Equation (14)
τ^{oasi}	OASI payroll tax rate	0.081		Equation (18)
N_0	Modeled population	205	Million People	Census CPS

with the perfect competition assumption and the production technology in (1), gross capital income is defined as the residual after labor's compensation, such that

$$(1 + \tau^r) R_0 = (1 - \theta_Y) Y_0. \tag{17}$$

Note that Table 2 presents labor and capital income net of taxes.

Labor tax rates are based on state and federal income tax rates and payroll taxes. The state and federal income tax rates are drawn from the 2005 values from the National Bureau of Economic Research (NBER) Average Marginal U.S. Income Tax Rate database (Feenberg and Coutts, 1993). We use BEA estimates of personal income by state, from their Regional Income table SA1, to calculate a national weighted average of the state level combined state and federal average marginal income tax rates, which is 26.2%. We add payroll taxes of 2.9% to account for Federal Insurance Contributions Act taxes excluding OASI taxes, for a total labor tax rate of 29.1%. The capital tax rate is calculated as the rate that would balance the government budget constraint in (14) for the benchmark year conditional on the labor tax rate, and is equal to 34.7%. As noted in Section 3.1.4, we assume a consumption tax rate of zero in the baseline.

We calibrate the OASI program such that the average per beneficiary payment in the benchmark matches the average per beneficiary payment for the U.S. OASI program in 2005, which was 12,501 2015$.[16] The baseline OASI tax rate is calibrated to balance the program's budget according to (16), such that

$$\tau_t^{oasi} L_0 = 1.25e - 05 \sum_{-g \geq a_{oasi}} N_{g,0}. \tag{18}$$

To approximate the U.S. OASI program we compute average earnings between the age of a_{lo} =20 and a_{hi} =55 and assume that benefits are earned starting at age a_{oasi} =65. Conditional on the other parameters in the

[16] Based on Social Security Administration reported aggregate benefits payments at: https://www.ssa.gov/oact/STATS/table4a1.html and total beneficiaries available at: https://www.ssa.gov/oact/STATS/OASDIbenies.html.

model, the fraction of average annual earnings paid as OASI benefits is calibrated to match the benefits payment per person, such that

$$\frac{\sum_{-g\geq a_{oasi}}\beta_{g,0}N_{g,0}}{\sum_{-g\geq a_{oasi}}N_{g,0}}=1.25e-05. \tag{19}$$

For simplicity, we assume that the economy is on a steady-state path with growth rate γ and steady-state interest rate $\bar{r}$. The after-tax return on capital in equilibrium will then cover steady-state interest plus depreciation, $R_0=(\bar{r}+\delta)\,K_0$, where δ is the depreciation rate. The steady-state assumption requires that investment cover depreciation and growth, such that

$$I_0=(\delta+\gamma)\,K_0=\frac{\delta+\gamma}{\bar{r}+\delta}R_0. \tag{20}$$

However, adjusting investment to match the steady-state assumption requires a further adjustment to ensure that the aggregate income balance

$$R_0+L_0+T_0=C_0+S_0, \tag{21}$$

and the savings-investment balance

$$S_0=I_0+D_0-B_0, \tag{22}$$

where S_0 is benchmark savings, continue to hold across the benchmark data. Therefore, we adjust the level of consumption listed in the U.S. national accounts, $\tilde{C}_0$, to account for any change in investment, $\tilde{I}_0$, necessary to match the steady state assumption, such that

$$C_0=\tilde{C}_0+\tilde{I}_0-I_0. \tag{23}$$

This represents a 4.7% change in the value of aggregate consumption from the BEA national accounts to match the steady-state assumption.

A.2 Production Parameters

Parameterizing the production side of the model requires estimates of the capital depreciation rate, δ, and the substitution elasticities for the series of CES functions in the model, ϵ_Y, ϵ_X, and ϵ_A. A list of these parameters and their calibrated values is presented in Table 3.

The depreciation rate is set to 0.0482, which is the average U.S. capital depreciation rate from 1950 to 2014 as reported in the Penn World Table (Feenstra et al., 2015).

There are notable differences between point estimates of the capital-labor substitution elasticity, particularly for disaggregated sectors. However, in an analysis of U.S. production data, Balistreri et al. (2003) was unable to reject the Cobb-Douglas assumption for aggregate manufacturing and suggested that their "findings lend support to the Cobb-Douglas specification as a transparent starting point in simulation analysis." We follow this recommendation with the assumption that $\epsilon_Y=1$, noting that the CES specification in (1) converges to Cobb-Douglas as the substitution elasticity approaches unity. This assumption is also consistent with the previous work using aggregated models of this nature, including Auerbach and Kotlikoff (1987) and Rasmussen and Rutherford (2004). In calibrating the elasticity of transformation of output between domestic production and exports, ϵ_X, we use a value of 2 following the assumption used by Caron and

Table 3: Calibrated Parameters

Parameter	Description	Value	Source
γ	Generation growth rate	0.011	Penn World Table v9
$\bar{r}$	Steady-state interest rate	0.05	
δ	Capital depreciation rate	0.048	Penn World Table v9
ϵ_Y	Capital-Labor substitution elasticity	1	Balistreri et al. (2003)
ϵ_X	Domestic-Export transformation elasticity	2	Caron and Rausch (2013)
ϵ_A	Armington elasticity	3.17	Hertel et al. (2007)
ρ	Pure rate of time preference	0.029	Calibrated
ω	Time endowment	0.029	Calibrated
ϕ	Elasticity of marginal utility	1	Aldy and Smyth (2014)
ξ	Leisure-Consumption Marginal Rate of Substitution	0.2	Calibrated
κ	Utility function constant	1,050	Calibrated
ν	OASI payment fraction of average earnings	0.25	Equation (19)

Rausch (2013) in the USREP CGE model.

To calibrate the Armington elasticity, which defines the substitutability of imports and domestic production, we use an import weighted average of sector specific empirical estimates. Hertel et al. (2007) estimated the Armington elasticity for 40 individual sectors in the Global Trade Analysis Project (GTAP) database. We use a weighted average of the sector specific estimates, with weights based on the U.S. value of imports for each of the sectors as reported in the GTAP database version 9 (Narayanan et al., 2015). This leads to a value of $\epsilon_A = 3.17$.

A.3 Household Parameters

Calibrating the the household side of the model requires assumptions about the agents' utility function parameters, κ, ξ, and ϕ, time endowment, ω, and their inter-temporal parameters, such as the pure rate of time preference, ρ, survival curve, $\mu_{g,t}$, and productivity index, $\pi_{g,t}$.

We assume that individuals enter the model at age 20 and therefore the total modeled population in the benchmark year is equal to the U.S. population minus the estimated number of individuals under the age of 20 as reported in the U.S. Census Bureau's Current Population Survey for 2005. The survival curve in the model is based on the U.S. Department of Health and Human Services life tables for 2005 (cdc). We assume that this survival curve is representative of all generations in the model and that no individual survives past age 100, such that $\zeta_{g,g+\bar{a}} = 0$, where $\bar{a} = 100 - 20 = 80$. (In the most recent census, 0.017% of the U.S. population was over the age of 100.)

For simplicity, we assume that the number of births each year is independent of the survival curve and that the size of successive generations is growing at rate γ. We calibrate γ to the average U.S. population growth rate from 1950 to 2014 (Feenstra et al., 2015). Given the generation growth rate γ and the survival curve $\mu_{g,t}$, we can calibrate the benchmark age distribution in the model as

$$N_{g,0} = N_0 \frac{\zeta_{g,0} \left(1+\gamma\right)^g}{\sum_{s=-75}^{0} \zeta_{s,0} \left(1+\gamma\right)^s}, \tag{24}$$

where g represents the year the generation turned 20 relative to 2005 (e.g., the generation turning 20 in 2000 is denoted as $g = -5$) and $\zeta_{g,t}$ is the cumulative survival probability, such that

$$\zeta_{g,t} = \prod_{s=g}^{t} \mu_{g,s}. \tag{25}$$

The benchmark data constrains the values of the parameters representing the agents' endowments and preferences through adding-up conditions that require the life-cycle variables aggregated across the population to equal the national level accounts. Specific adding-up conditions include aggregate consumption

$$C_0 = \sum_{g=-75}^{0} N_{g,0} c_{g,0}, \tag{26}$$

aggregate labor supply

$$L_0 = \sum_{g=-75}^{0} N_{g,0} \pi_{g,0} \left(\omega - l_{g,0}\right), \tag{27}$$

and aggregate assets holdings. The adding-up condition for household assets requires that the aggregate savings for agents currently alive equals the value of the capital stock, and the deficit and trade imbalance pathways.

Given the steady-state assumption and the presence of a trade imbalance in the benchmark, we assume that individuals hold enough foreign bonds in the benchmark to allow the imbalance to continue into perpetuity, $B_0 \left(1 + \bar{r}\right) / \left(\bar{r} - \gamma\right)$.[17] A similar requirement for the government deficit is that individuals hold debt equal to the present value of deficit flow, $D_0 \left(1 + \bar{r}\right) / \left(\bar{r} - \gamma\right)$. The adding-up condition for life-cycle assets is then

$$\left(1 + \bar{r}\right) K_0 + \left(B_0 - D_0\right) \frac{\left(1 + \bar{r}\right)}{\left(\bar{r} - \gamma\right)} = \sum_{g} \left(z_{g,0} + b_0\right) n_{g,0}, \tag{28}$$

where capital is multiplied by $(1 + \bar{r})$ to account for the price difference associated with the one period lag in investment.

The adding-up condition in (28) also provides consistency with national level capital income in the benchmark through the relationship $R_0 = \left(\bar{r} + \delta\right) K_0$. Given that the income balance condition in (21), savings-investment balance in (22), and the government budget constraint in (14) all hold for the benchmark data, we only need to ensure that either (26) or (27) hold and the other will also hold by definition. Therefore, we calibrate the time endowment, ω, and pure rate of time preference, ρ, by solving the life-cycle optimization problem in (9) subject to the budget constraint in (10) and the time endowment constraint, while maintaining the adding-up conditions in (26) and (28). Conditional on the other parameters in the model the calibrated values of ρ and ω are presented in Table 3.

The life-cycle labor productivity index, $\pi_{g,t}$, is calibrated to ensure that labor supply for each generation in the benchmark year relative to the youngest generation that just entered the model matches observed labor participation rates by age. Specifically, we use estimates from the U.S. Bureau of Labor Statistics on labor force participation rates by age for 2004 (Toossi, 2015). The calibrated productivity curve is presented in Figure 1b. The productivity profile has the typical shape, increasing rapidly through an agent's 20s and

[17] See Appendix B of Rasmussen and Rutherford (2004) for a derivation of this relationship.

30s, peaking around 50, and declining thereafter.

The value of the constant in the agents' utility function, κ, is important for determining the agents' WTP for marginal mortality risk reductions. The additive nature of κ in the utility function means that it will not have an effect on agent's consumption or labor supply decisions, but it will influence the amount of income the agent would be willing to forgo to increase the probability of living through the period.[18] Within this framework the partial equilibrium WTP for a marginal reduction in one period ahead mortality risk (i.e., the VSL) is

$$VSL_{g,t} = \frac{\partial w_{g,t}/\partial \zeta_{g,t+1}}{\partial w_{g,t}/\partial c_{g,t}} = \frac{\sum_{s=t+1}^{g+\bar{a}} \left(\frac{1}{1+\rho}\right)^{s-t} \frac{\zeta_{g,s}}{\zeta_{g,t}} u_{g,s}}{c_{g,t}^{-\phi} l_{g,t}^{\xi(1-\phi)}}. \tag{29}$$

In their second prospective analysis of the CAA EPA used a value of 9.01 million 2015\$ for the VSL in 2005.[19] EPA's estimate of the VSL is the mean of a Weibull distribution that was fitted to 26 published estimates of the VSL, of which 21 are studies of wage differentials in labor markets. Since the studies based on compensating wage differentials will necessarily only consider the preferences of labor market participants in their samples, and this class of studies makes up the majority of those included in the estimate, we calibrate the average VSL across working age populations in our model to match the EPA's VSL estimate. Specifically, κ is calibrated such that in 2005 the population weighted average partial equilibrium WTP for a one period ahead marginal reduction in mortality risk across individuals aged 20 to 64 equals the VSL estimate of 9.01 million 2015\$. Or in other words, κ is determined according to

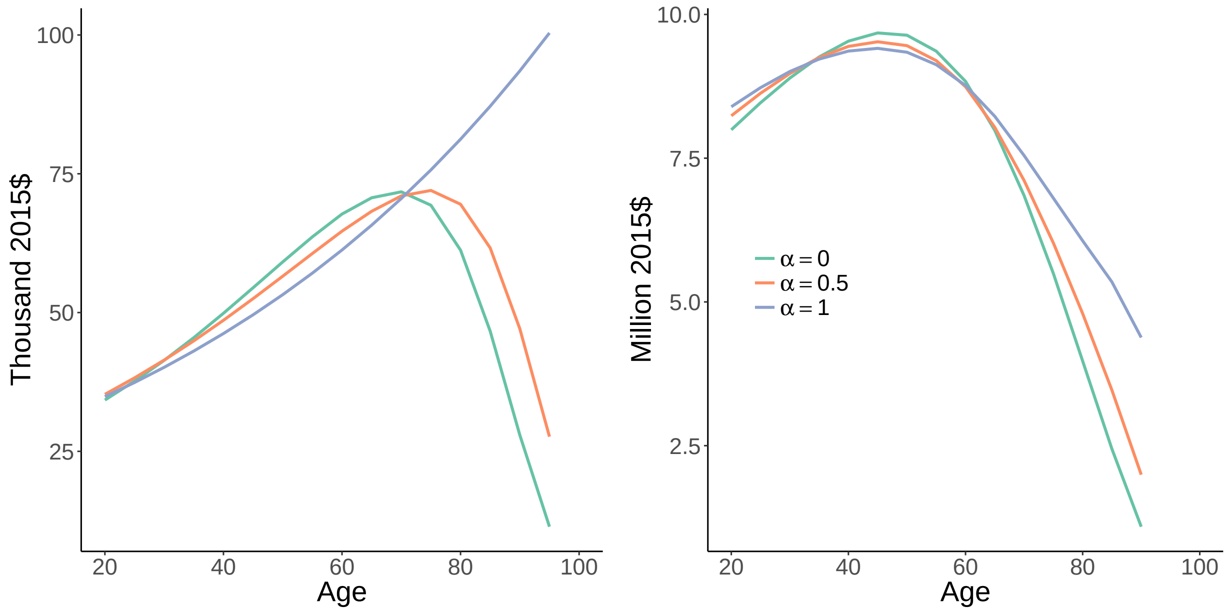
$$\frac{\sum_g N_{g,0} VSL_{g,0}}{N_0} = 9.01. \tag{30}$$

The exponent on leisure, ξ, in (8) defines the marginal rate of substitution between leisure and consumption in the utility function. As such, it plays a strong role in determining the labor supply elasticity of households in the model. Therefore, we calibrated ξ so that the labor supply elasticity of cohorts in the middle of the career (i.e., at age 40) match microeconomic estimates. McClelland and Mok (2012) conducted a recent literature review of current estimates and found substitution elasticities in the range of 0.1 to 0.3 and income elasticities in the range of -0.1 to zero. We select a value of 0.204 for ξ as it leads to a elasticities that are close to the midpoints of these ranges for cohorts at age 40. Specifically, they have a substitution elasticity of 0.201 and an income elasticity of -0.05, conditional on the other parameters in the model.

For the elasticity of marginal utility, ϕ, we select a value of 1.001, which leads to a nearly log utility function following Hansen and İmrohoroğlu (2008). A log specification provides a better fit between the baseline life-cycle consumption profile of the calibrated model and empirical observations. Consumption exhibits the hump-shaped profile observed in practice, though the peak in our model is later in life than usually observed. Higher values for ϕ that introduce a greater degree of concavity into the utility function with respect to full consumption shift this peak an even older age in the calibrated model.

[18] This can be seen in a simple two-period model as follows. Let $U = \kappa + u(c_1) + s\beta[\kappa + u(c_2)]$, where s is the probability of survival from period 1 to period 2 and β is the utility discount factor. The marginal WTP for an increase in survival is $\frac{\partial U/\partial s}{\partial U/\partial c_1} = \frac{\beta[\kappa+u(c_2)]}{u'(c_1)}$.

[19] In their analysis EPA (2011a) used a value for the VSL in 1990 of 8.3 million 2015\$ and updated it for future years based on forecast income growth and an assumed income elasticity of 0.4. Using this approach they report a 2020 value for the VSL of 9.87 million 2015\$. Assuming a constant income growth rate across this interval would lead to a 2005 value for the VSL of 9.01 million 2015\$.



(a) Life-Cycle Consumption

(b) Life-Cycle VSL

Figure 11: Sensitivity of Life-Cycle Calibration to α

B Sensitivity to Private Annuity Markets

In the default version of the model we assume a lack of private annuity markets, $\alpha = 0$, to better match observations of consumption over the life-cycle. In the calibration of our model the pure rate of time preference, ρ, is below the steady-state interest rate $\bar{r}$. As a result, in the case of perfect private annuity markets consumption will be monotonically increasing over the life-cycle, which does not match the hump-shaped consumption profile typically observed. With imperfect private annuity markets the effective discount rate including both the pure rate of time preference and the mortality rate will eventually exceed the interest rate as the household gets older and the mortality risk increases, causing consumption to decline later in the life-cycle.[20] In Figure 11a we demonstrate this effect on the baseline consumption profile across a range of values for α.

The increase in expected consumption leads to an increase in the life-cycle VSL later in the life-cycle as demonstrated in Figure 11b. In terms of the model calibration, the value of κ is increasing with α. While the change in the life-cycle VSL curve suggests that agents would be willing to pay more for marginal risk reductions later in the life-cycle relative to the case of imperfect annuity markets, this does not mean that the assumption of perfect private annuity markets would lead to a higher aggregate benefits estimate. For aggregate consumption across the population alive in the benchmark year to match the observed aggregate consumption in national accounts, the higher value of α also requires a higher value of the calibrated rate of pure time preference, ρ. At the calibrated value of ρ for the default case consumption later in the life-cycle would be even higher with higher values of α than is presented in Figure 11a thereby causing aggregate

[20] Hansen and İmrohoroğlu (2008) provide a detailed explanation of how the availability of actuarially fair private annuity markets affects the profile of consumption in life-cycle models.

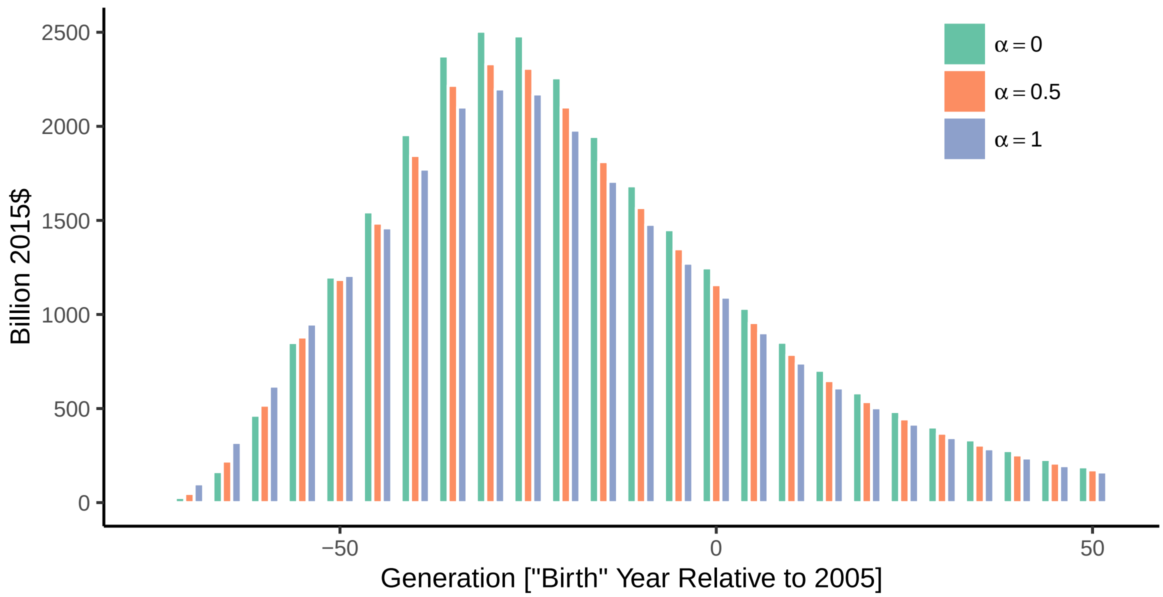
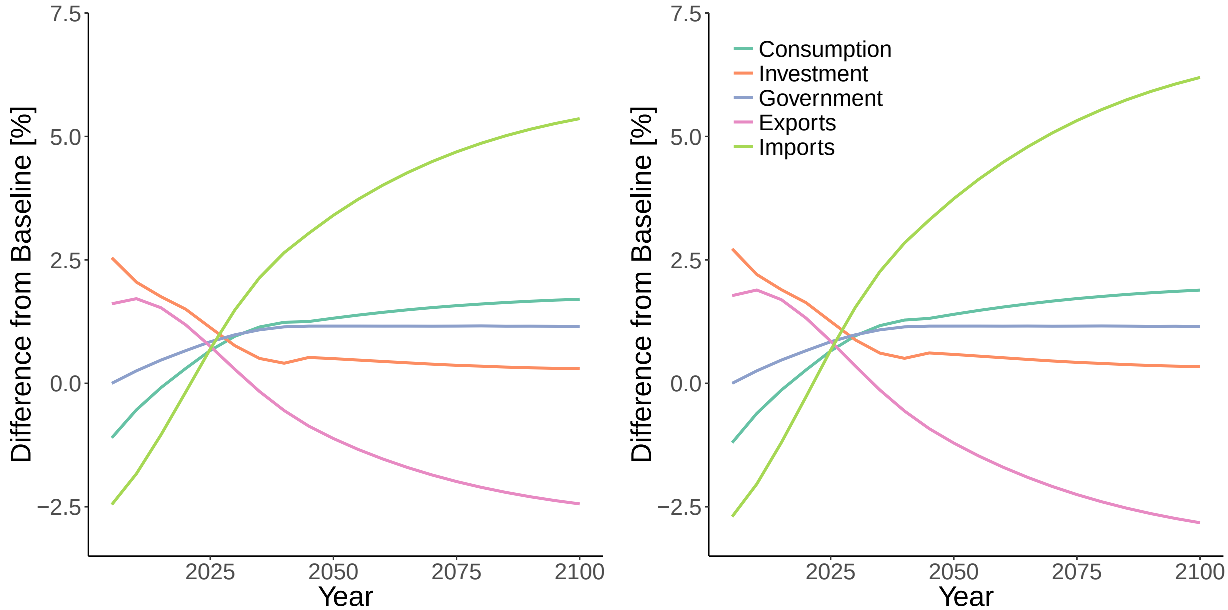


Figure 12: Sensitivity of Incidence of Benefits by Generation to α

consumption across the households to be greater than is observed in the benchmark year. The higher calibrated value of ρ, with the higher value of α, reduces the household's present value of their WTP for mortality risk reductions occurring in the future. Figure 12 presents the generational incidence of benefits across the range of α values. For relatively younger generations who will experience the risk reductions farther out into the future, the larger pure rate of time preference dominates and their WTP decreases as actuarially fair private annuity markets are assumed to be more widely available. However, for relatively older generations who would be experiencing the risk reductions immediately or within a short time, the higher value of κ dominates and their WTP increases as actuarially fair private annuity markets are assumed to be more widely available. The overall effect is a decline in the aggregate WTP for the policy as actuarially fair private annuity markets are assumed to be more widely available.

C Sensitivity to OASI Closure

In the default version of the model we assume that the payroll tax funding the mandatory public annuity program floats to maintain the budget constraint associated with the program. In contrast one could assume that benefits provided by the program will adjust in order to maintain the program's solvency on a per-period basis. To test the implications of this specification we consider both closure rules for the OASI program. The magnitude of the program's benefits are determined by the fraction of average annual earnings households receive after age a_{oasi}, denoted as ν. The expected economic impacts under the default specification, that allows τ_{oasi} to be endogenously determined, is presented in Figure 13a and the impacts under the alternative closure rule, that allows ν to be endogenously determined, are presented in Figure 13b. The reduction in mortality risks under the CAAA are expected to increase the number of individuals receiving payments from the public annuity program. Whether the budget constraint is maintained through an increase in the payroll



(a) Endogenous Tax

(b) Endogenous Benefits

Figure 13: Sensitivity of National Accounts to OASI Closure

tax or through a reduction in benefits does not notably affect the quantitative estimates of the economic impacts. Aggregate consumption farther out in the time horizon is slightly higher under that case where benefit payments are endogenous, potentially because the expectation of lower benefit payments increases household savings which increases the level of capital stock in what is a distorted market due to the tax on payments to capital.

The estimate of generations' WTP for the policy under the two closure rules does not differ notably. Older generations at the time of policy, particularly those that are retired or close to being retired would prefer that the increase in the population receiving benefits be funded by higher taxes on those currently working. Whereas the younger generations at the time of the policy, who have more time to adjust savings, would prefer the reduction in benefits. The difference across the generations is intuitive, but the quantitative impact on the aggregate benefit estimates is negligible.

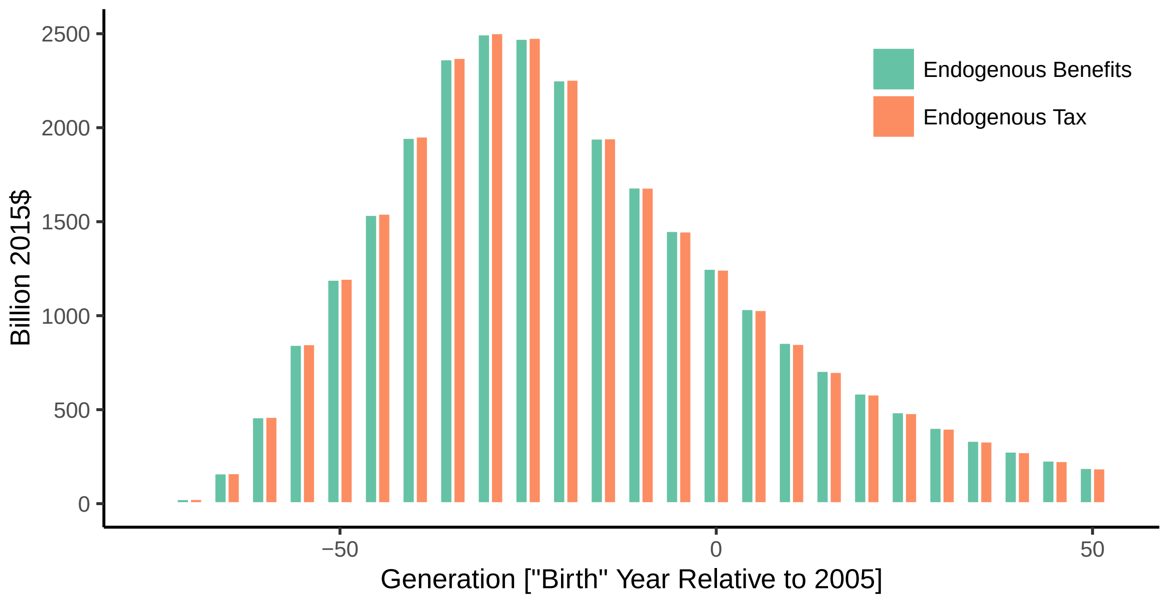


Figure 14: Sensitivity of Incidence of Benefits by Generation to OASI Closure