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AGGREGATE MORTALITY RISK AND THE INSURANCE VALUE OF ANNUITIES***

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ABSTRACT: Future improvements in mortality are difficult to forecast. In this paper, we incorporate uncertainty about future mortality, or aggregate mortality risk, into an otherwise standard life cycle model with an intertemporal consumption-savings decision. The aggregate mortality process is calibrated based on European mortality series. We use the model to quantify the welfare cost of aggregate mortality risk and the extent to which individuals can insure themselves against it using life annuities with a constant payout stream.

Keywords: annuities, aggregate mortality risk

JEL Classification: G22, D14

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TIIVISTELMÄ: Kuolevuuden alenemisvauhdin ennustaminen on epävarmaa. Tarkastelemme säästämis-kulutuspäätöksen sisältävää elinkaarimallia tilanteessa, jossa kuluttaja tuntee kuolevuuden ennustejakauman. Kalibroimme ennustejakauman eurooppalaisen aineiston perusteella. Arvioimme mallin avulla, miten kuolevuuteen liittyvä epävarmuus vaikuttaa kuluttajan hyvinvointiin ja missä määrin kuluttajat pystyvät suojautumaan sitä vastaan eläkevakuutusten avulla.

Avainsanat: eläkevakuutus, kuolevuusriski

1 Introduction

There is a large literature on the insurance value of annuitization for consumers (e.g., Brown and Poterba 2000, Brown 2001 and 2003, and Davidoff et al. 2005). It measures the welfare gain from access to annuity markets for a representative life cycle consumer. The value of annuities has been found to be quite sensitive to the level of pre-existing annuitized wealth, the strength of a bequest motive, and whether or not the consumer can pool savings within a household, among other things.

This literature has focused on idiosyncratic lifetime uncertainty. Lifetime uncertainty is usually calibrated directly from life tables giving age-specific mortality rates at a given point in time or by adjusting them so as to reflect expected decline in future mortality. However, mortality forecasts have proved to be highly inaccurate (e.g., Bongaarts and Bulatao 2000). This uncertainty is often referred to as *aggregate mortality risk*.

Aggregate mortality risk is a major concern for insurance companies providing annuities (e.g., Blake and Burrows, 2001, Friedberg and Webb, 2005). It may be a concern for consumers as well. To see this, consider a young consumer who plans to annuitize her savings when she retires. Because of aggregate mortality risk, the future price of annuities is uncertain. Moreover, her own life expectancy at retirement age is likely to be positively correlated with the annuity prices. Consumers should somehow take these issues into account when making their savings decisions.

In this paper, we seek to evaluate the quantitative importance of aggregate mortality risk for consumers. There are two main reasons why we believe that such an analysis is needed. First, when measuring the insurance value of annuities, the previous literature has abstracted from aggregate mortality risk. This clearly underestimates the overall degree of lifetime uncertainty that consumers face. It is of interest to see how much aggregate mortality risk matters for the consumers relative to the idiosyncratic lifetime uncertainty. Second, annuity products vary in whether or not they pass the aggregate mortality risk to annuitants. In order to compare these products from consumers' point of view, we need to quantify how much consumers are willing to pay for not being exposed to the aggregate mortality risk.

Following the previous literature that measures the insurance value of annuities, we formulate a simple life cycle model with a standard preference structure and a consumption-savings decision. The novel aspect in the model is that it incorporates a stochastic process for aggregate mortality. The consumers in the model have rational expectations about future mortality and they understand how mortality is in turn related to annuity prices. We calibrate the mortality process using European data and use the model to measure the welfare cost of aggregate mortality risk and the extent to which consumers can insure themselves against it by buying life annuities with a constant payout stream.

The paper is structured as follows. In section 2, we describe the stochastic process for aggregate mortality that will be incorporated into the consumer's problem. In section 3, we outline the consumer's problem. In section 4, we explain the different types of annuities that we consider. In section 5, we describe the different consumer's problems that we consider. In section 6, we present our results. We conclude in section 7.

2 Demographics

In this section, we present the stochastic process for aggregate mortality. The challenge here is to specify a process which is simple enough so that it we can solve the life cycle savings problem of a fully rational consumer, yet can be calibrated so that it is empirically relevant.

We assume that time is discrete and index the periods as $t = 1, 2, ..., T$ and ages as $j = 1, 2, ..., J$. Death occurs at the end of the period only.

Let $m_t(j) \geq 0$ be age-specific mortality rate among consumers in age j during period $t = 1, 2, ...$ The true future mortality rates are taken to be random. Following loosely the bilinear model of Lee and Carter (1992), we specify the probability law of future mortality as follows. Let $m(j)$ be the current mortality rate in age j and assume that it is known. Its expected rate of decline is $b(j)$, and the median mortality is $\widehat{m}_t(j) = m(j)\exp(-tb(j))$. For a highly simplified representation of the uncertainty of the forecast, we define a Bernoulli process X_t such that $P(X_t = 1) = P(X_t = 0) = 1/2$ and then a discrete random walk $Y_t = Y_{t-1} + X_t$, where $Y_0 = 0$. This is a first order Markov process with mean $t/2$. Let us further define function $Z_t(y) = (y - t/2)\phi$, where ϕ is a volatility parameter. Then, the true age-specific mortality is assumed to be of the form

$$m_t(j) = m(j)\exp(-(t + Z_t(Y_t))b(j)). \tag{1}$$

Denote the probability that a consumer who is alive in age j at time t will be alive in the beginning of the next period by $s_t(j)$. For calibration purposes we assume that each period corresponds to five calendar years. Assuming that mortality is constant within a period, we have

$$s_t(j) = \exp(-5m_t(j)). \tag{2}$$

In the analysis below, we will consider only the problem of consumers who are of age 1 in period 1. That is, we specialize to the case $t = j$. We will take the first period to correspond to age 20-24 and the last period to age 105-109. After that everyone is assumed to die. Therefore, the latest time period we will have to consider is $T = 18$. On the other hand, it will be important to keep in mind that the probabilities (2) are random, since they are functions of Y_t via (1). To make this transparent, when $t = j$ we will write $s_t(j) = S_t(Y_t)$ for (2).

We assume that period t mortality rates are observed at the end of period t. Due to the Markovianity of process Y_t, the expected length of the remaining lifetime in the beginning of period t depends on Y_{t-1} alone, and is denoted by $\widehat{L}_t(Y_{t-1})$. It gives the expected number of periods, including period t, that a consumer who is alive in period t will still live.

A technical issue that arises here is that under our model, randomness is incorporated in a nonlinear manner, so setting aggregate variance to zero does not exactly yield unconditional expected values. Instead, the relevant quantities must be determined numerically. We need to use simulation methods to determine the expected remaining lifetimes $\widehat{L}_t(Y_{t-1})$.

The mortality process is parameterized by the values $m(j)$, $b(j)$ and ϕ. We use combined male and female mortality data from Finland in 2002 for the $m(j)$'s (these correspond to a life expectancy at birth of about 78 years), and average rates of decline in mortality from eleven European countries during 1970-2000 (Alho and Spencer 2005, p. 235). Empirical data were available up to age 99. These estimates were extended to age-group 100-104 by assuming mortality to increase at the same rate as it increased from age 90-94 to age 95-99. The rate of decline over time was assumed to be the same as in age 95-99. For simplicity, we further specify $m(j) = 0$, for $j < 10$. To specify the volatility of the process, we use data from nine European countries with long mortality series of good quality. The data suggest that a random walk can provide an approximate representation for the forecast error of the log of the age-specific mortality, when the standard deviation of the process increment is taken to be 0.06 (Alho and Spencer 2005, p. 256). By taking into account that an average value for the $b(j)$'s is about 0.08, we arrive at a value $\phi = 3.3541$. Table 1 displays $m(j)$ and $b(j)$. In addition, it displays mean probabilities of surviving from one period to the next.

As an illustration of the degree of uncertainty related to future mortality, we present in Figure 1 the distribution of average lifetimes over 10 000 realizations of the mortality process.

Real age	Model age	m	b	mean survival prob.
$20-64$	$1-9$	0	0	1
$65-69$	10	0.026	0.105	0.955
$70-74$	11	0.044	0.102	0.932
$75-79$	12	0.072	0.091	0.903
$80-84$	13	0.119	0.078	0.822
$85-89$	14	0.190	0.062	0.702
$90-94$	15	0.283	0.044	0.532
$95-99$	16	0.404	0.029	0.330
$100-104$	17	0.577	0.029	0.221
$105-109$	18	∞	0	0

Table 1: Parameter values for the mortality process and the mean survival probabilities

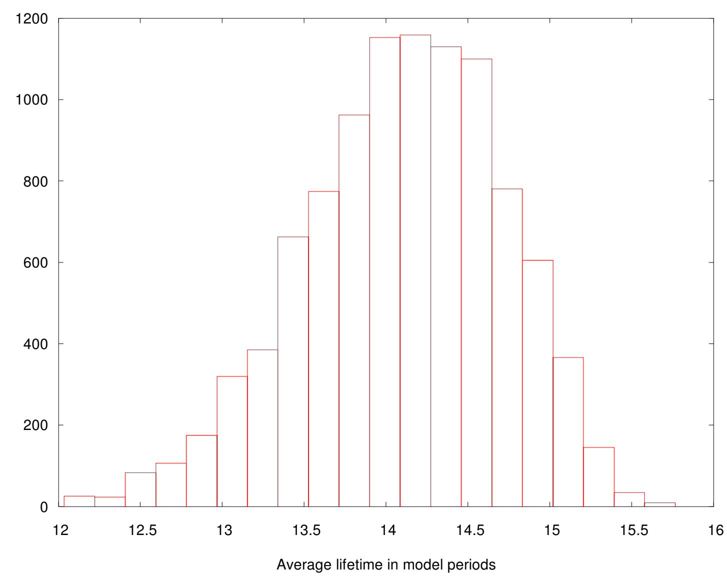

Figure 1: Histogram of average lifetimes in 10 000 simulations.

3 The consumer

Annuities are often analyzed by considering a consumer's problem starting at the time of retirement. The issue is then how to optimally dissave wealth that has been accumulated during working life. However, in the presence of aggregate mortality risk, it is interesting to consider also the accumulation phase because aggregate mortality risk should be reflected in consumer's optimal savings decisions already when she is young. Therefore, we consider the whole life cycle of a consumer who receives wage income during the first periods and is retired for the last periods of her life. During retirement, the consumer needs to finance her consumption with own savings. Her problem is to choose consumption and savings in each period so as to maximize her expected lifetime utility.

The retirement age is set at 10 which corresponds to real age 65. Until retirement, the consumer earns a wage income of 1 every period, i.e. $w_t = 1$ for $t < 10$ and $w_t = 0$ for $t \geq 10$. Preferences are time-separable and the periodic utility function is of the standard constant-relative-risk-aversion form:

$$u(c) = \frac{c^{1-\sigma}}{1-\sigma} \text{ for } \sigma \geq 0, \ \sigma \neq 1 \quad (3)$$

$$u(c) = \log(c), \text{ for } \sigma = 1, \quad (4)$$

where $c > 0$ stands for consumption and σ measures the constant relative risk aversion.

Wages are paid and consumption occurs at the beginning of the period. For simplicity, we assume that both the interest rate and the subjective discount rate are equal to zero.

4 Annuities

We consider two different types of annuities which we refer to as "period annuities" and "life annuities". Both types of annuities are purchased in the beginning of the period. The price of a period annuity in period t is one and it pays $1/S_t(Y_t)$ in the beginning of the following period to the annuitant if she is still alive. Abstracting from costs, an insurance company selling period annuities to a large number of consumers makes always zero profits (recall that the interest rate is zero). In other words, period annuities are actuarially fair.

Our life annuities provide a constant payment stream until death. A life annuity bought in period t pays one unit in the beginning of period starting from the beginning of period t, until death. Because of aggregate mortality risk, the overall amount that an insurance company pays out for life annuities is stochastic even when it has a large pool of annuitants. We assume that the price of a life annuity corresponds to its expected value. For a consumer of age t in period t, the price of a life annuity giving a constant income stream of one unit is then $\widehat{L}_t(Y_{t-1})$.

Of course, our assumption concerning the pricing of life annuities is somewhat extreme. From the insurance company's point of view, life annuities are risky because of aggregate mortality risk. Presumably, even with perfect competition it would require a compensation for bearing the aggregate mortality risk unless it can perfectly and costlessly hedge the aggregate mortality risk.[1] Nevertheless, this pricing assumption allows us to quantify how much consumers value annuities that provide insurance against both the idiosyncratic lifetime uncertainty over and above annuities that provide insurance against the idiosyncratic lifetime uncertainty alone.

In the absence of the aggregate mortality risk, the consumer would be indifferent between period annuities and life annuities. Given that the subjective discount rate equals the interest rate, she desires a perfectly flat consumption profile and she achieves it with either of the two annuity types without ever leaving accidental bequests. In our set-up, the relevant difference between the two types of annuities is that while period annuities allow consumers to perfectly insure themselves against the idiosyncratic lifetime uncertainty, they provide no insurance against aggregate mortality risk. This is because their price varies on a period basis together with aggregate mortality. In contrast, by providing a constant payout stream, life annuities provide insurance against the aggregate mortality risk as well.

[1] Results in Friedberg and Webb (2005) suggest that insurance companies may be able to transfer the aggregate mortality risk to financial markets at a low cost through newly-available mortality-contingent bonds.

5 The consumer's problems

Our results are based on comparing the expected lifetime utilities in a set of consumer's problems that differ according to the type of annuities available and whether or not the consumer faces uncertainty about future mortality rates. It is important to stress, however, that the underlying mortality process is the same in all problems. This allows for a meaningful comparison of expected welfare between different problems. In this section, we describe the different problems, discuss the solution method, and explain our welfare measure.

5.1 Problem 1 - no annuities.

Our benchmark case is the one where there are no annuities whatsoever. The only asset available to the consumer is a one period bond with a fixed return (equal to zero). Let us denote the amount of bonds bought in period $t-1$ by k_t. We assume that $k_1 = 0$. We also impose a short-selling constraint, i.e. $k_{t+1} \geq 0$.

It is the easiest to write the consumer's problem recursively. Given the simple structure of the mortality process, a single integer, namely $Y_t = 0, 1, ..., t$, is sufficient to determine the current mortality rates and make the best possible forecasts about future mortality. Hence, Y_t is the only state variable needed to capture all relevant information about aggregate mortality in period t. Denoting the period t value function by V_t, the problem can be written recursively as follows:

$$V_t(k_t, Y_{t-1}) = \max_{k_{t+1} \geq 0} \{u(c_t) + E_{Y_t|Y_{t-1}} S_t(Y_t) V_{t+1}(k_{t+1}, Y_t)\} \tag{5}$$

subject to

$$c_t + k_{t+1} = w_t + k_t \tag{6}$$

The equality (6) is the flow budget constraint: consumption plus purchases of bonds equals current wage income and bond holdings.

The solution to this problem includes a "policy function" $k_{t+1}(k_t, Y_{t-1})$. In other words, every period the consumer takes the most recent information about mortality into account.

5.2 Problem 2 - period annuities

We now assume that the consumer has access to period annuities. So let k_t now denote the amount of period annuities bought in period $t-1$. This problem can be written as Problem 1 but replacing k_t in the right-hand side of the consumer budget constraint of Problem 1 by $\frac{1}{S_{t-1}(Y_{t-1})}k_t$, for $t > 1$.

5.3 Problem 3 - life annuities

In this case, we assume that the consumer has access to life annuities at the retirement age. Before the retirement age, the consumer saves with bonds (since $S_t(Y_t) = 1$ for $t < 10$, this is equivalent to saving with period annuities). Let k_{10} denote her savings in the beginning of the retirement period. Since the consumer doesn't receive income anymore, the best she can do is to annuitize all her wealth with a life annuity so as to guarantee herself a constant consumption stream equal to $k_{10}/\widehat{L}_{10}(Y_9)$ from period 10 until death. Let $V_{10}(k_{10}, Y_9)$ denote the associated expected remaining lifetime utility. For $t = 1, ..., 9$, the consumer's problem then reads as Problem 1.

5.4 Problem 4 - perfect foresight and period annuities

In this case, we assume that the consumer has access to a "cristall ball" that reveals the future mortality hazard without error, but does not tell her own actual life time. This problem reads as Problem 1 with the exception that the true mortality rate is known. This is effectively a deterministic problem and the consumer's consumption profile over the life cycle is always perfectly flat.

5.5 Solving the consumer's problem

The consumer's problem will be solved backwards, starting from period T, as a finite-horizon dynamic programming problem.[2] Since, Y_t may take values $0, 1, ..., t$, the relevant state space (over which we need to solve the consumer's problem) is increasing with the time period. However, it increases only linearly. Therefore, the state space is still relatively small in the last period. We discretize the continuous state variable, k_t, and interpolate for the values between gridpoints. The fact that Y_t is a discrete variable is helpful in that we need not consider two-dimensional interpolation. As a result, the problem can be solved relatively fast with high accuracy.

5.6 The welfare measure

Our welfare measure is the consumption equivalent variation. It gives the percentage increase in consumption in all periods and for all possible mortality rates that is needed in a benchmark case to make the expected lifetime welfare as high as in a comparison case. For instance, in order to compute the insurance value of period annuities, we first solve Problems 1 and 2. Next, we generate a large number N of randomly drawn aggregate mortality paths. Let $c^1_{i,j}$ denote the optimal consumption level at age j given aggregate mortality path $1 \leq i \leq N$ in Problem 1. Similarly, let $c^2_{i,j}$ denote the optimal consumption at age j given the same mortality path in Problem 2. Finally, let Y^i_j denote the value of Y in period j and in mortality path i. The consumption equivalent variation measuring the insurance value of period annuities is a scalar x such that

$$\sum_{i=1}^{N}\left\{u(c^2_{i,1})+\sum_{j=2}^{J}\prod_{l=1}^{j-1}S_l(Y^i_l)\beta^{j-1}u(c^2_{i,j})\right\}=\sum_{i=1}^{N}\left\{u((1+x)c^1_{i,1})+\sum_{j=2}^{J}\prod_{l=1}^{j-1}S_l(Y^i_l)\beta^{j-1}u((1+x)c^1_{i,j})\right\}. \tag{7}$$

[2] This discussion only relates to Problems $1-3$. Problem 4 is very easy to solve.

In a similar way we can compare expected lifetime utilities between any of our four consumer's problems[3].

6 Results

Our main results are shown in table 2. We first consider the value of annuities as insurance against the idiosyncratic lifetime uncertainty. Specifically, the figures in the first row show how much consumption needs to be increased (at all ages and for all possible mortalities) in Problem 1 (no annuities) so as to make the expected lifetime utilities the same in Problems 1 and 2 (period annuities). The results are shown for different values of the risk aversion parameter σ. The second row of table 2 in turn shows how much welfare increases when the consumer is given access to life annuities at retirement age. That is, the figures show how much consumption needs to be increased in Problem 1 so as to make the expected lifetime utilities the same in Problems 1 and 3 (life annuities). Finally, the third row displays the increase in consumption in Problem 1 needed to make the expected lifetime utilities the same in Problems 1 and 4. In other words, the third row shows the welfare gain from giving the consumer access to period annuities together with the removal of the aggregate mortality risk.

Compared to a situation with no annuities whatsoever, period annuities improve welfare dramatically: the welfare gain ranges from 10.57% with $\sigma = 1$ to 19.18% with $\sigma = 5$.

[3] Except for Problem 4, the consumption equivalent variation can be computed more efficiently using the value functions alone. For instance, let V^1 denote the value function associated with the Problem 1 and V^2 the value function associated with the comparison case. For $\sigma \neq 1$, the insurance value of annuities can be computed as :

$$x = \left(\frac{V_1^1(0,0)}{V_1^2(0,0)} \right)^{1/(1-\sigma)} - 1.$$

Problem 4 is different because in that case the value function is conditional on the mortality path.

	$\sigma = 1$	$\sigma = 3$	$\sigma = 5$
Period annuities	10.57%	17.03%	19.18%
Life annuities at retirement	10.70%	17.42%	19.75%
Perfect foresight and period annuities	10.74%	17.57%	20.02%

Table 2: Welfare effects

This is in line with the previous literature. In the absence of a bequest motive and informal risk-sharing arrangements, annuities that insure against the idiosyncratic lifetime uncertainty are very valuable.

Life annuities must improve welfare even more than period annuities. However, the interesting question is how much do they improve welfare over and above period annuities. Comparing figures in the first and the second row of table 2 reveals that this additional welfare gain ranges from 0.13% with $\sigma = 1$ to 0.57% with $\sigma = 5$. While this effect is certainly non-negligible, it is only a small fraction of the welfare gain resulting from insurance against the idiosyncratic lifetime uncertainty.

Life annuities do not insure the consumer completely against the aggregate mortality risk because before retirement she faces uncertainty about future annuity prices. Comparing the figures in the second and the third row of table 2 shows that the consumer can insure herself against about two thirds of the overall aggregate mortality risk with life annuities at retirement. Comparing the figures in the first and the third row in turn gives us a measure of the welfare cost of uninsured aggregate mortality risk. It ranges from 0.17% with $\sigma = 1$ to 0.84% with $\sigma = 5$.

It is also interesting to consider the distribution of lifetime utilities accross different mortality paths and with different types of annuities. Figure 2 shows the distribution of consumption equivalent variations between Problems 3 and 2 over 1000 different mortality paths. Here we set $\sigma = 3$. On the $x-$axis we have the welfare gain (or loss) resulting from having life annuities compared to having only period annuities. Clearly, there are substantial changes in realized lifetime utility between a consumer that has access to only period annuities and a one that has access to life annuities at retirement. In this sense, aggregate mortality risk matters for the consumers. It is just that the *average* welfare gain of life annuities over period annuities is only slightly larger than zero.

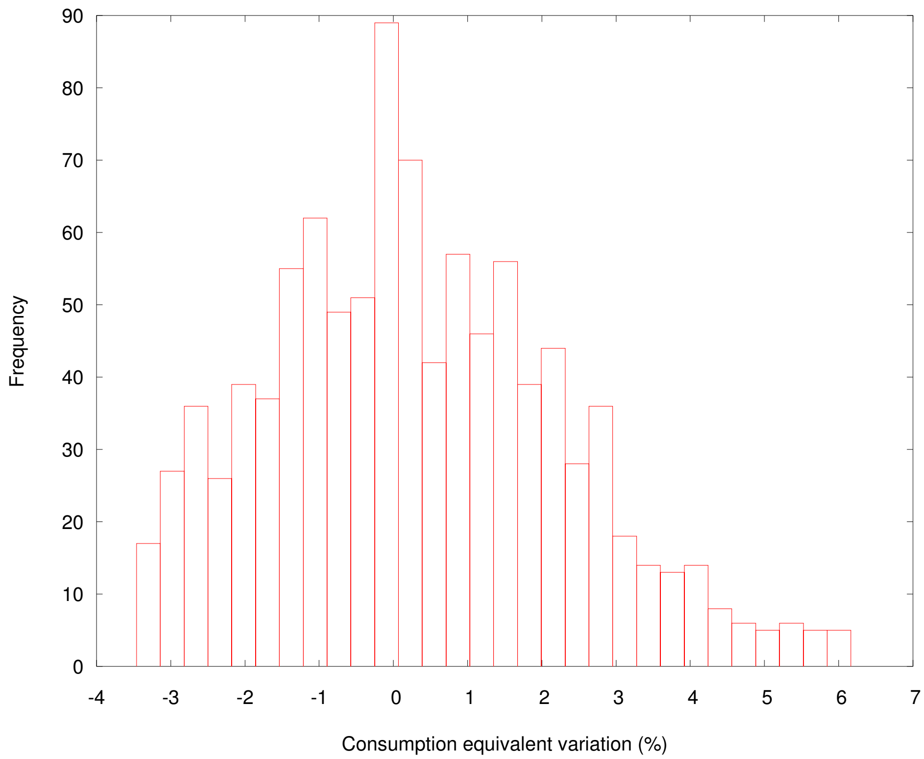

Figure 2: The distribution of welfare gains: life annuities over period annuities.

7 Discussion

We have analyzed a life cycle model with a consumption-savings decision that incorporates aggregate mortality risk. Our results suggest that the welfare loss of uninsured aggregate mortality risk is relatively small, especially in comparison to the welfare loss of uninsured idiosyncratic lifetime uncertainty. Intuitively, this is because the component of variance in an individual's lifetime that derives from aggregate uncertainty is quite a bit smaller than the component of variance that derives from her idiosyncratic survival experience. In addition, consumer's information about the mortality of her cohort improves over time.

It should also be noted that even life annuities that provide a constant payout stream, independently of changes in aggregate mortality, insure consumers only partially against the aggregate mortality risk. This is because young consumers always face uncertainty about future annuity prices or the rate at which they can annuitize their future savings. Consequently, consumers should not be willing to pay substantially higher charges for annuity contracts where the insurance company bears the aggregate mortality risk compared to contracts where consumers bear that risk themselves.

Perhaps the most important caveat of our results concerns the way that the consumers form their expectations. We have assumed that the consumer has rational expectations about future mortality. This means, among other things, that she is fully aware of the degree of uncertainty related to future mortality and that she keeps revising her expectations with news about current mortality rates. Of course, this is a strong assumption. The welfare cost of uninsured aggregate mortality risk may be much larger if the consumer fails to take the uncertainty into account or if she makes her savings decisions based on outdated information about mortality.

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