Aging on a Short Clock: Demographic Compression, Fiscal Adjustment, and Growth*

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Abstract

This paper studies the speed, fiscal scale, and growth implications of population aging across 103 economies using Penn World Table 11.0 and the 2024 United Nations World Population Prospects. Its central object is demographic compression: the calendar time available for an economy to move between economically meaningful old-age dependency ratio (OADR) thresholds. Economies that became old early generally had decades to adjust their institutions; many economies that remain comparatively young must traverse the same range in a fraction of the time.

The paper's central result is that the fiscal urgency created by aging and its effect on growth are distinct margins that need not coincide. Speed through the critical OADR 25–50 percent range—a decline from four working-age adults per elderly person to two—strongly predicts the scale of the required retirement-boundary adjustment ($\rho = -0.69$) but is nearly unrelated to the Solow demographic growth effect ($\rho = 0.14$). Korea and China are severe on both margins, yet across the full sample this coincidence breaks down. Conventional growth drag is therefore not a sufficient statistic for fiscal urgency: many late-aging economies must distribute large adjustments across cohorts despite having little calendar time in which to do so.

I establish this using three transparent accounting measures built on a common demographic input. Threshold-crossing times measure the speed of aging. A demographically equivalent retirement boundary measures the age cutoff in 2100 that would reproduce each country's 2024 OADR; it is an accounting equivalent, not a policy recommendation. A calibrated Solow model, with a Shapley decomposition, separates the effect of projected working-age shares on growth from the effect of normalizing country-specific TFP growth toward a long-run benchmark.

Keywords: Population aging, dependency ratios, retirement age, growth drag.
JEL Codes: E62, H55, J11, J26

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1 Introduction

Population aging has a level, a speed, and a growth effect. These dimensions are related, but they are not interchangeable. Two economies can reach the same old-age dependency ratio (OADR) after very different adjustment windows, and two economies aging at similar speeds can experience different effects on output growth. The distinction matters because pension reform occurs in calendar time. A country that must spread a large adjustment across many cohorts faces a different political and fiscal problem from one that must compress the same adjustment into one or two decades.

This paper measures those dimensions on a common basis for 103 economies. The central comparison is not simply Japan versus China or Korea in 2100. It is the long window over which Japan and much of Western Europe adapted their institutions versus the much shorter window now facing economies that enter old age later, often at lower income levels. I call this difference *demographic compression*.

Recent fertility outcomes make this comparison especially consequential. Japan recorded 686,061 births in 2024, China's total fertility rate fell to roughly 1.0 in 2023, and Korea's fell to 0.68 in 2024. Because these outcomes have tracked the low-fertility projections more closely than the fertility rebound embedded in the medium variant, the main text uses the WPP 2024 low-fertility variant as an adverse demographic benchmark. The medium variant is reported as a more optimistic sensitivity. The low variant should therefore be read as a disciplined stress scenario—particularly relevant for ultra-low-fertility East Asia—rather than as a claim that it is the most likely forecast for every country through 2100.

The sample contains 34 "early-aging" and 69 "late-aging" economies, classified by whether their 2024 OADR is above or below 30 percent. These labels describe when an economy enters the high-OADR region, not how slowly or rapidly it subsequently ages. The continuous measures of threshold-crossing speed carry the main analytical weight; results are also robust to nearby classification cutoffs. The paper deliberately does not estimate behavioral elasticities or solve a country-specific pension equilibrium for each economy. Instead, it constructs transparent cross-country accounting benchmarks that any richer structural analysis of pension reform must confront.

The first contribution is to measure demographic compression directly. I record the time required to cross OADR thresholds of 12.5, 25, 50, and 100 percent. The 25–50 percent interval corresponds to a decline from four working-age adults per elderly person to two. Germany and Sweden take 60 and 80 years, respectively, to traverse this range; Korea is projected to take 14 years and China 18. Endpoint OADRs alone conceal this difference in the time available for institutional adaptation.

The second contribution is a demographically equivalent retirement boundary. For each country, I calculate the age cutoff in 2100 that would reproduce its 2024 OADR. This is an age-structure accounting equivalent, not a feasible retirement-age recommendation: it treats all persons below the boundary as potential supporters and abstracts from health, productivity, participation, and behavioral responses. Extreme implied ages are therefore evidence that retirement-age policy alone cannot stabilize the support ratio. They summarize the scale of adjustment that must instead be divided among later retirement, lower benefits, higher contributions, broader taxation, greater participation, and immigration.

The third contribution is to place the same demographic projections inside a simple

Solow growth model. The model uses working-age population as the labor input, following the idea that standard GDP-per-capita comparisons can misstate performance in aging economies. The growth exercise uses a Shapley decomposition to separate two channels. The first is a demographic growth effect: the contribution of changes in the working-age share, relative to a counterfactual that keeps the 2024 working-age share fixed while allowing total population to follow the WPP path. The second is a TFP-normalization effect: the contribution of convergence in country-specific TFP growth paths. For countries with recent TFP growth above the U.S. frontier rate, TFP growth converges down to the frontier by 2045; for countries with negative historical TFP growth, TFP growth converges up to zero by 2045. This second effect is a disciplined growth scenario, not a consequence of population aging and not an estimated forecast. Its purpose is to identify economies in which demographic compression may coincide with the normalization of catch-up growth. Throughout the paper, drag is reported as baseline growth minus the relevant counterfactual, so a negative number denotes a growth headwind and a positive number denotes a tailwind. The Shapley decomposition is useful because the demographic and TFP channels interact through capital accumulation, and the Shapley allocation makes the demographic and TFP components add exactly to total drag.

The paper's main result is that these fiscal and growth measures capture distinct margins. Speed through the critical OADR 25–50 percent range strongly predicts the scale of the retirement-boundary adjustment ($\rho = -0.69$), but is nearly orthogonal to the Solow demographic growth effect ($\rho = 0.14$). The former is an endpoint age-structure statistic; the latter depends on the path of working-age population shares after 2024. China and Korea are severe cases on both margins, but that coincidence does not hold mechanically across the sample. Projected growth drag is therefore not a sufficient statistic for the fiscal urgency created by demographic compression.

The appendix provides two fiscal stock measures that complement the retirement-age sufficient statistic. First, it converts projected demographic change into a common balanced-2023 demographic gap for old-age and survivors' insurance systems in the economies for which comparable expenditure data are available. Under low fertility, these gaps average about 140 percent of 2023 GDP among early-aging economies and close to 200 percent among late-aging economies; the corresponding medium-fertility figures are about 125 and 185 percent. The larger late-aging gap reflects the fact that early-aging economies have already absorbed much of their demographic transition, whereas late-aging economies face most of the deterioration in old-age dependency ratios over 2024–2100. Second, the appendix uses Japan and the United States to illustrate the fiscal value of early automatic adjustment: Japan's 2004 macroeconomic slide reduces projected unfunded pension obligations by roughly 50 percentage points of GDP relative to a no-slide counterfactual, and a stylized version of the same mechanism applied to U.S. Social Security would cut projected unfunded obligations from 84 percent to 41 percent of GDP. The broader policy lesson is that automatic mechanisms are most valuable when adopted before late adjustment forces sharper changes in benefits, contributions, or retirement ages.

The paper proceeds as follows. Section 2 reviews related literature. Section 3 documents OADR trajectories, aging speed, and required retirement-age adjustments. Section 4 develops the Solow model, reports the Shapley decomposition of demographic and TFP-path components, and compares fiscal and growth pressure. Section 5 concludes.

2 Related Literature

This paper connects four strands of research on demographic aging, public pensions, and long-run growth, but differs from much of the existing literature by using a deliberately simple cross-country accounting framework rather than a country-specific structural pension model.

The first strand studies pension reform and fiscal sustainability in overlapping-generations models. Auerbach and Kotlikoff (1987) develop the benchmark multi-cohort framework linking demographic change, capital accumulation, and government budgets in general equilibrium. Huang, İmrohoroğlu, and Sargent (1997), Kotlikoff (1997), Kotlikoff, Smetters, and Walliser (1999), and De Nardi, İmrohoroğlu, and Sargent (1999) use large-scale OLG models to evaluate Social Security reforms and the transition costs of moving from pay-as-you-go to more funded systems. These studies show that demographic change creates large implicit liabilities and that reforms with similar long-run effects can have very different transitional welfare consequences across cohorts. Unlike that literature, this paper abstracts from behavioral responses and distributional consequences within countries in order to provide a unified set of cross-country benchmarks. Instead of building a structural pension model for each country, I use a simple cross-country statistic—the demographically equivalent retirement boundary that reproduces the 2024 OADR—to compare the magnitude of demographic pressure across many economies.

A second strand studies automatic stabilizers and institutional design in pension systems. Nonfinancial defined contribution systems, sustainability factors, and demographic indexation rules adjust benefits or contributions in response to longevity, wage growth, or contributor-beneficiary ratios; Holzmann, Palmer, and Robalino (2017) provides a broad discussion. Sweden's NDC system, Germany's sustainability factor, and Japan's macroeconomic slide are examples of mechanisms designed to reduce the need for repeated discretionary reforms. In the Japanese context, İmrohoroğlu and Sudo (2011), Braun and Joines (2015), Kitao (2015), İmrohoroğlu, Kitao, and Yamada (2016), Hansen and İmrohoroğlu (2016), and Hansen and İmrohoroğlu (2023) quantify macroeconomic and welfare consequences of alternative pension reforms. The appendix calculations in this paper are much simpler than these structural analyses, but they highlight the same principle: early automatic adjustment can create large fiscal space because small annual changes compound over decades.

A closely related applied literature produces cross-country projections of the fiscal cost of population aging.[1] The OECD's *Pensions at a Glance* reports document pension rules, recent pension reforms, and cross-country differences in retirement ages, benefit formulas, and old-age support ratios. The European Commission's *Ageing Report* provides long-run projections of age-related public expenditure on pensions, health care, long-term care, and education for EU countries, while IMF work emphasizes the implications of aging for fiscal sustainability, pension reform, and the composition of public spending. A complementary approach is developed in the National Transfer Accounts literature, which uses age profiles of labor income, consumption, taxes, transfers, and saving to measure how chang-

[1] See OECD (2023), European Commission, Directorate-General for Economic and Financial Affairs (2024), International Monetary Fund (2025), and Lee and Mason (2011).

ing population age structure affects intergenerational resource flows and fiscal support ratios. Relative to these institutional and fiscal-projection exercises, the contribution of this paper is to use a common demographic input and a deliberately simple accounting framework to compare the timing of aging, the retirement-boundary equivalent implied by unchanged old-age dependency ratios, and the associated Solow growth drag across a broad set of economies.

A third strand studies the relationship between population age structure and growth. The neoclassical point of departure is Cutler, Poterba, Sheiner, and Summers (1990), who analyze how a rising dependency burden affects saving, capital intensity, and the appropriate policy response in a Solow framework. A large subsequent literature relates growth to the age composition of the population; Bloom, Canning, Fink, and Finlay (2007), for instance, study the growth dividend from a rising working-age share. A recurring theme is nonlinearity—the aging–growth relationship is hump-shaped, turning negative only once an economy is well past its demographic transition An and Jeon (2006). That nonlinearity is the empirical counterpart of the early-aging/late-aging distinction that organizes this paper.

The recent cross-country evidence is mixed in sign, which is part of what motivates a transparent accounting approach. Acemoglu and Restrepo (2017) find no negative cross-country relationship between aging and growth—if anything a positive one—and attribute the offset to faster automation in aging economies. Maestas, Mullen, and Powell (2023), exploiting variation across U.S. states, instead estimate a sizable negative effect: a ten-percentage-point increase in the population share aged 60 and over lowers GDP per capita by about five percent, roughly two-thirds of it through slower productivity growth. Aksoy, Basso, Smith, and Grasl (2019) find that age structure shapes investment and innovation as well as growth. In the same panel-based vein, Kotschy and Bloom (2023) document that the demographic dividend becomes a demographic drag as countries advance through the later stages of the transition, estimating the growth effect of changing working-age shares in a standard empirical growth model across roughly seventy countries. The present paper reaches a similar conclusion by a different route: rather than estimating the effect from historical panel variation, I impose a calibrated Solow structure, project it forward under common demographic assumptions for 103 countries, and use a Shapley decomposition to separate the demographic channel from a distinct TFP-path channel—a separation the reduced-form estimates do not provide.

The paper's methodological point of departure is Fernández-Villaverde, Ventura, and Yao (2025), who argue that conventional GDP per capita can misrepresent performance in fast-aging economies and introduce working-age population as the relevant labor input in the production function. I adopt this insight in the Solow exercise, using working-age population rather than total employment as the labor input, and extend their framework to 103 countries while separating the demographic component from a distinct TFP-path component that they do not isolate. While Fernández-Villaverde, Ventura, and Yao (2025) use PWT employment in their TFP calibration, this paper uses WPP working-age population throughout for internal consistency with the demographic projection; Appendix D documents the implications.

A fourth strand concerns productivity convergence. Fernández-Villaverde, Ohanian, and Yao (2026) develop the growth-accounting perspective used here to discipline country-specific TFP paths and emphasize the slowdown that follows when fast-growing economies approach the technological frontier. I extend this

logic beyond China by computing a TFP-path component for countries with recent TFP growth above the U.S. frontier rate and for countries with negative historical TFP growth. This is an accounting exercise rather than a structural forecast, but it is useful because it separates a demographic headwind from a productivity-convergence headwind.

A closely related paper is Hayashi (2026), who argues that Japan's rapid population aging is the root cause of its post-1990 reversal of fortune. His mechanism runs through TFP: measuring aging by the old-to-young ratio—the population aged 50–79 relative to that aged 20–49—he documents a negative relationship between the *level* of that ratio and per-worker GDP growth among economies that have completed the demographic transition. Quasi-differencing the canonical growth equation across the 1960–1990 and 1990–2020 periods absorbs the unobserved steady-state level and the convergence (Baumol) term into lagged growth, leaving an "aging speed"—the change in the old-to-young ratio—as the sole regressor for quasi-differenced TFP growth. An OLS regression on 25 early transitioners yields a slope of -3.31 at a two-percent convergence speed, implying that, absent its rapid aging, Japan's per-worker growth over 1990–2020 would have been about 2.1 percentage points higher. The resulting out-of-sample projection has the United States outgrowing continental Europe, the Asian Tigers, and Japan through 2050; the China–U.S. ratio of aggregate PPP GDP, near 1.15 in 2020, is projected to fall toward and possibly below one by 2050, depending on the assumed speed of convergence. The projection is a reduced-form best-linear-predictor exercise—an overlapping-generations model of technology adoption motivates the functional form but is not structurally estimated.

The present paper is complementary in method and aim. Rather than estimating an aging–TFP relationship, I keep the demographic and TFP-path channels distinct inside a calibrated Solow accounting framework applied to 103 countries. The direct demographic channel is the effect of changes in the working-age share; the TFP-normalization component captures the effect of bringing country-specific TFP growth rates toward a long-run benchmark. A Shapley decomposition then assigns growth drag between these two channels. The distinction matters because the central object here is not growth alone but the joint comparison of growth drag and fiscal compression. Two implications follow. First, if aging also depresses TFP growth through Hayashi's channel, the direct demographic effect measured here is a conservative accounting component rather than the full macroeconomic effect of aging. Second, under that same mechanism part of the TFP-normalization component is itself demographic in origin, so the decomposition should be read as an accounting split rather than a causal attribution.

Fernández-Villaverde, Ventura, and Yao (2025) is the closest antecedent to the growth-accounting part of this paper, but the aim here is different. The objective is not to develop a new growth model; it is to use a common demographic input to compare two distinct margins of the aging transition across countries: the fiscal compression implied by rapidly rising old-age dependency ratios, and the demographic growth effect implied by changes in working-age population shares. The Solow exercise is thus a transparent accounting device to be placed alongside the demographically equivalent retirement boundary. Treating the fiscal and growth margins within one framework is what lets the central empirical point emerge: fiscal urgency and growth effects are distinct dimensions of aging that need not coincide across countries—a country can face a large retirement-boundary adjustment without a correspondingly large Solow demographic drag.

The choice of fertility baseline is consequential. Jones (2019) reviews policy responses to ultra-low fertility in East Asia, while Kearney and Levine (2022) documents broad-based fertility decline in the United States. Fernández-Villaverde (2025) argues that recent vital-registry data have often come in below WPP medium projections. These findings motivate using the WPP low-fertility variant as the baseline and treating the medium variant as an optimistic sensitivity, since for the economies with the most severe projected aging — Korea, China, and Japan — the medium variant embeds a fertility rebound that has not yet materialized.

The paper's contribution is to bring these strands together in a single, deliberately transparent framework applied to a common set of 103 economies. It documents how quickly countries cross key old-age dependency thresholds, translates the projected age structure into a demographically equivalent retirement boundary, and then uses a calibrated Solow model with a Shapley decomposition to separate the demographic growth effect from a distinct TFP-normalization scenario. The result is a unified set of benchmarks for the speed, fiscal scale, and growth consequences of demographic aging.

3 Demographic Aging and Fiscal Adjustment

Throughout this section, I measure population aging using the old-age dependency ratio (OADR). Let $N^i_{a,t}$ denote the population of country i at age a in year t. The baseline old-age dependency ratio is defined as

$$\text{OADR}^i_{65,t} \equiv \frac{\sum_{a=65}^{\omega} N^i_{a,t}}{\sum_{a=20}^{64} N^i_{a,t}},$$

where ω denotes the maximum age reported in the population data. Thus, $\text{OADR}^i_{65,t} = 0.50$ means that there is one person aged 65 or older for every two working-age persons aged 20–64. When useful, I also report an alternative measure based on a retirement boundary of age 70,

$$\text{OADR}^i_{70,t} \equiv \frac{\sum_{a=70}^{\omega} N^i_{a,t}}{\sum_{a=20}^{69} N^i_{a,t}}.$$

To ground the cross-country comparisons that follow, I begin with Japan—the country that has experienced population aging most intensively among all economies and has reached the highest current dependency ratio. Several European economies crossed earlier OADR thresholds before Japan, but Japan moved fastest through high dependency levels and remains the benchmark for extreme aging. Then I examine the extent of aging the U.S. economy using population projections from four different sources. Finally, I use the WPP data to characterize projected aging in the full 103-country sample.

3.1 Aging in Japan

Figure 1 illustrates why Japan is the natural benchmark for the rest of the paper. The six projection waves from the Institute of Social Security and Population (IPSS) do not merely show a high level of old-age dependency; they show mostly repeated downward

revisions in the underlying demographic outlook until the 2017 wave. Each new projection before then shifted the expected dependency path upward, implying that a pension system calibrated to earlier demographic assumptions would become increasingly underfunded even without any change in benefit rules.

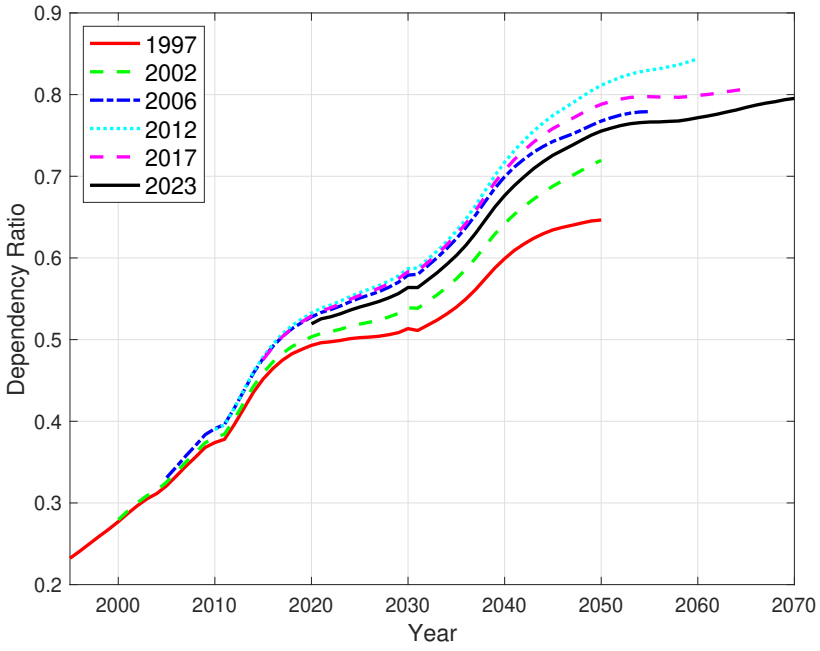


Figure 1: Dependency Ratios Implied by Six IPSS Projection Waves

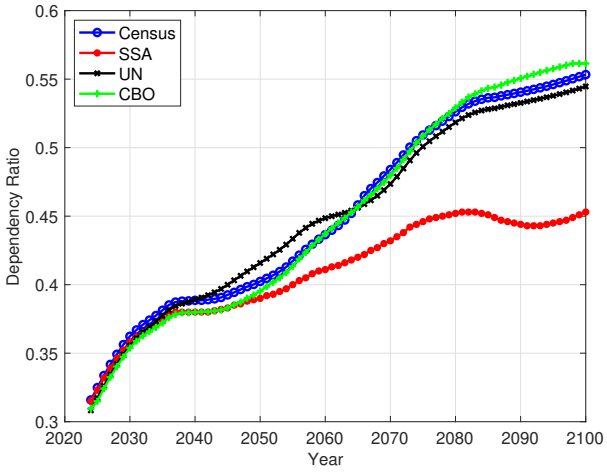
Notes: Each line represents a successive IPSS projection wave (1997–2023). The 2002 wave prompted Japan's 2004 pension reform. Each revision proved more pessimistic than the last; 2024 births fell below the most pessimistic 2023 forecast.

The timing is also informative. The 2002 projection wave arrived before the dependency ratio had reached its subsequent extreme levels, and it helped motivate the 2004 macroeconomic slide. Japan therefore provides both a warning and a policy precedent: when fertility and longevity surprises arrive persistently in the same direction, early automatic adjustment can spread the fiscal burden across cohorts before the old-age dependency ratio becomes very high.

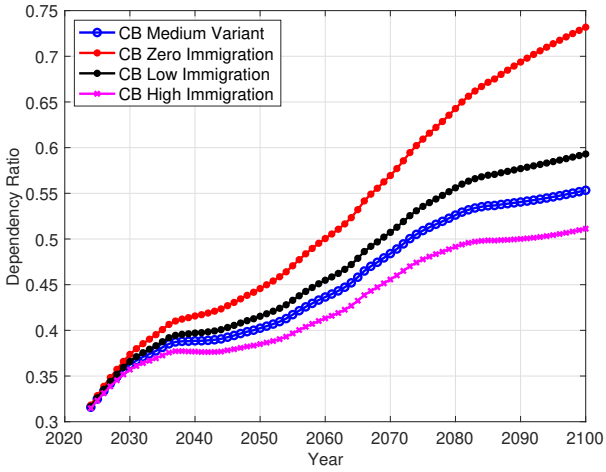
3.2 Aging in the United States

Four institutions publish U.S. population projections: the Congressional Budget Office (CBO), Social Security Administration (SSA), the Census Bureau (CB), and UN WPP. Figure 2 compares their medium-variant OADRs alongside CB immigration scenarios. The OADR from the CB, CBO, and WPP converge to roughly 55% by 2100 from 32% in 2024; SSA is more optimistic at 45%, with implications for Trust Fund solvency detailed in Appendix G. Immigration uncertainty is substantial: CB's high- versus zero-immigration scenarios differ by 25 percentage points by 2100.[2]

[2]Panel (a) plots medium-variant OADRs from the Census Bureau, CBO, and UN World Population Prospects 2024 against the SSA intermediate (best-estimate) projection. The four series are nearly



(a) Alternative projection sources



(b) Census Bureau immigration scenarios

Figure 2: U.S. Old-Age Dependency Ratio Projections

Notes: Panel (a): medium-variant OADRs from CB, CBO, UN, and SSA. Panel (b): CB projections under four immigration assumptions; the high–zero gap reaches 25 pp by 2100.

The U.S. comparison is useful for two reasons. First, the United States is old enough to face meaningful pension pressure but remains younger than Japan and most of Western Europe. The main projection sources therefore agree on the direction of aging but differ in the terminal level of the OADR, with SSA's assumptions producing a less severe path than the Census Bureau, CBO, and UN series. Second, the Census Bureau immigration scenarios show that migration can materially affect the dependency ratio, but it does not eliminate aging. Even under more favorable immigration assumptions, the U.S. OADR rises substantially over the century. The United States is therefore an intermediate case: demographic pressure is milder than in Japan, Korea, or China, but the fiscal consequences remain large because the initial pension system is large and the adjustment horizon is finite.

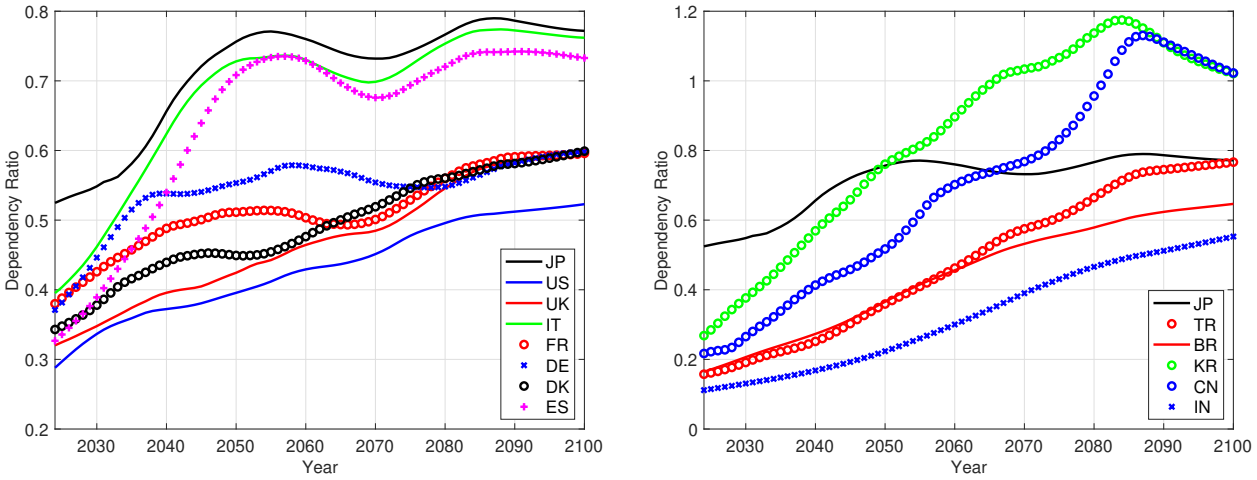
3.3 Early- and Late-Aging Economies

Figure 3 plots OADRs for a few additional economies. Panel (a) shows the OADRs from Japan, the United States, and six European economies—Denmark, France, Germany, Italy, Spain, and the United Kingdom. These countries are already old in 2024, and their

indistinguishable through about 2055 and diverge only thereafter, with the SSA path flattening near 0.45 by 2100 while the others continue rising to 0.54–0.56. The divergence reflects differences in assumed fertility: the Social Security Administration, Office of the Chief Actuary (2024) intermediate assumptions have the U.S. total fertility rate recovering to an ultimate 1.9 children per woman, whereas Congressional Budget Office (2025) converges to about 1.58, the Census Bureau to about 1.52, and the WPP 2024 medium variant to about 1.65 by 2100; because additional births enter the working-age denominator only with a roughly twenty-year lag, the higher SSA fertility assumption lowers its dependency ratio only in the second half of the horizon. The series also rest on slightly different population universes—the Census Bureau and the UN use the resident population of the 50 states and the District of Columbia, while CBO and SSA use the broader Social Security area population that adds the territories and citizens abroad—but because this shifts the numerator and denominator in partly offsetting ways, it affects the dependency *ratio* only modestly and does not account for the late-horizon gap. Differences in immigration and mortality assumptions are likewise minor.

projected paths are comparatively smooth. Japan remains the most aged economy in the panel, while the United States remains the youngest. The European economies converge toward a relatively narrow range by 2100, reflecting the fact that much of their demographic transition has already taken place.

Panel (b) contrasts this early-aging pattern with five late-aging economies: Brazil, China, India, Korea, and Türkiye, along with Japan as the benchmark early-aging economy. The ordering of the late-aging economies in the discussion is alphabetical to emphasize that the point is not a country ranking in 2024 but the shape of the trajectories. China and Korea begin the projection period with much lower OADRs than Japan, but their paths steepen rapidly and overtake Japan around mid-century. Brazil, India, and Türkiye do not reach the same extreme levels as China and Korea under the medium variant, but their increases are large relative to their 2024 starting points. The figure therefore previews the central distinction of the paper: early-aging economies are already old, while late-aging economies face a larger remaining transition compressed into fewer decades. Note that Figure 3 uses the medium variant to show that the late-aging pattern is already visible under the more optimistic projection; the main tables use low fertility.



(a) Advanced Economies (b) Middle-Income Countries

Figure 3: Old-Age Dependency Ratios: Early- vs. Late-Aging Economies

Notes: UN WPP 2024 medium fertility. Panel (a): Japan, United States, Denmark, France, Germany, Italy, Spain, and United Kingdom. Panel (b): Brazil, China, India, Japan, Korea, and Türkiye. Korea and China overtake Japan around mid-century; both exceed an OADR of 100% later in the century.

For China and Korea, the WPP medium variant already projects OADRs close to or above 100% by 2100. Under the low-fertility variant, the projected OADR reaches 121.3% for Japan and approximately 200% for Korea and China.

Fertility scenarios and baseline choice. The choice between fertility scenarios carries substantial implications for projected old-age dependency ratios and required pension adjustments. For the main results of this paper, I use the UN WPP low-fertility variant as the main baseline and treat the medium variant as an optimistic robustness case. This choice reflects the fact that the WPP medium variant embeds a sustained fertility rebound

that has not materialized in many ultra-low-fertility economies. Recent outcomes in China, Korea, Japan, Singapore, Chile, and Thailand are closer to the WPP low variant—and in some cases below it—than to the rebound path embedded in the medium variant. Independent projections from the Institute for Health Metrics and Evaluation (IHME) point in the same direction for several selected countries.[3] The main tables below therefore emphasize low fertility, while medium-fertility counterparts and the fuller WPP–IHME comparison are collected in the appendices.

3.4 Old-Age Dependency Ratios in the Larger Sample

Table 1 presents old-age dependency ratios for 34 early-aging countries spanning current conditions in 2024 and projections through 2100 under alternative fertility assumptions. Table 2 shows the corresponding results for 69 late-aging countries. The cross-country variation in both levels and trajectories reveals the fundamental distinction between early-aging and late-aging economies that motivates this study. The 30% OADR threshold produces the 34/69 grouping used throughout; results are robust to alternative cutoffs of 28% and 32%. A 28% cutoff moves three borderline economies from late- to early-aging (South Korea, Belarus, and Russia), while a 32% cutoff moves up to six economies from early- to late-aging (Norway, United States, Ukraine, Slovakia, Australia, and New Zealand). In neither case does this alter any main finding, since all borderline economies exhibit the same qualitative pattern as the larger group to which they are assigned. The early/late grouping is therefore a level-based taxonomy rather than a direct measure of transition speed. For this reason, the paper separately reports threshold-crossing speeds in Section 3.6 and uses those speeds directly in the fiscal-growth correlation analysis of Section 4.7.

[3]IHME's Global Burden of Disease fertility projections use a methodology independent of the UN WPP projections. In Appendix B, I compare the WPP medium and low variants with IHME reference and lower-bound projections. For selected countries such as the United States, Japan, China, Korea, Spain, Brazil, Türkiye, and India, the IHME reference path is generally closer to WPP low than to the stronger fertility rebound embedded in WPP medium, although the exact ranking differs by country and horizon. The sources are the UN WPP 2024 revision United Nations, Department of Economic and Social Affairs, Population Division (2024) and the Global Burden of Disease fertility forecasting study GBD 2021 Fertility and Forecasting Collaborators (2024).

Table 1: Old-Age Dependency Ratios: Early-Aging Economies

	OADR (%)				OADR (%)		
Country	**2024**	**Med**	**Low**	**Country**	**2024**	**Med**	**Low**
Japan	54.9	79.9	121.3	Belgium	35.7	64.9	90.8
Finland	42.8	68.5	97.5	Hungary	35.4	57.7	81.2
Portugal	42.5	62.0	85.4	Spain	34.9	75.9	113.2
Italy	42.0	79.1	120.1	Netherlands	34.8	64.8	91.0
Greece	41.6	74.1	111.1	Austria	34.1	67.7	95.5
Croatia	40.3	74.5	117.9	Romania	34.1	65.9	106.3
France	40.2	61.8	85.9	United Kingdom	34.0	62.1	86.3
Germany	39.8	62.0	85.8	Poland	33.7	83.8	141.4
Serbia	39.1	72.1	116.4	Lithuania	33.5	84.2	154.2
Latvia	37.9	74.4	125.0	Switzerland	33.3	64.5	87.3
Bulgaria	37.7	64.8	103.1	Canada	33.2	58.8	75.5
Slovenia	37.3	65.0	92.7	Norway	31.9	66.9	94.5
Estonia	37.1	72.9	113.5	USA	30.8	54.5	72.2
Sweden	36.8	64.3	88.2	Ukraine	30.7	90.2	176.7
Denmark	36.3	62.4	86.9	Slovakia	30.6	71.5	111.2
Hong Kong	36.0	193.1	537.1	Australia	30.2	55.5	71.1
Czechia	35.7	60.9	87.3	New Zealand	30.2	55.5	71.1
Mean	36.4	71.7	114.6				

Notes: OADR = population aged 65+ / population aged 20–64 (%). The full sample of 103 countries is sorted by 2024 OADR (descending), with 34 early-aging economies (OADR $\geq$ 30% in 2024) and 69 late-aging economies (OADR $<$ 30%). Med and Low = UN WPP 2024 medium and low fertility projections for 2100.

Among early-aging economies, Japan exhibits the highest current dependency ratio at 54.9%, reflecting its position as the world's most aged society. Other advanced economies display substantial but lower ratios, with Finland, Portugal, Italy, Croatia, France, and Greece all above 40% in 2024. The median early-aging economy has a 2024 dependency ratio of roughly 35%, indicating that there is already about one person aged 65 and above for every three working-age adults. Under the low-fertility variant, the mean OADR for this group rises from 36.4% in 2024 to 114.6% in 2100. Several early-aging countries therefore move from already-high dependency ratios to levels at or above one elderly person per working-age adult. Japan reaches 121.3%, Italy 120.1%, Bulgaria 103.1%, Poland 141.4%, Ukraine 176.7%, and several other Eastern European economies exceed 120%. Hong Kong is a further outlier at 537.1%[4] These numbers underscore that early-aging countries are not finished aging; rather, they start from a high base and continue to deteriorate under persistent low fertility.

[4]Hong Kong is a small, highly urbanized special administrative region of China with one of the world's lowest fertility rates; its long-horizon WPP projections are correspondingly more sensitive to migration and boundary assumptions than those of larger economies, so this figure is best read as indicative of severe aging pressure rather than a precise level.

Table 2: Old-Age Dependency Ratios: Late-Aging Economies

	OADR (%)				OADR (%)		
Country	**2024**	**Med**	**Low**	**Country**	**2024**	**Med**	**Low**
South Korea	29.3	105.9	196.2	Bangladesh	11.7	65.0	103.2
Belarus	29.1	72.6	124.6	Paraguay	11.6	47.9	70.4
Russia	28.6	49.5	68.4	South Africa	11.3	32.8	44.0
Uruguay	27.3	79.0	132.2	Cambodia	11.3	43.2	63.4
Ireland	27.1	67.6	99.7	Uzbekistan	10.6	34.7	46.1
Iceland	26.1	74.4	110.4	Bolivia	10.2	37.8	53.2
Israel	24.1	45.4	58.6	Philippines	9.7	47.9	72.9
Thailand	24.0	72.5	111.7	Egypt	9.5	39.8	54.6
China	23.1	106.4	206.8	Mongolia	9.4	43.4	60.5
Chile	22.5	94.8	161.3	Guatemala	9.1	48.4	71.9
Argentina	21.3	69.7	109.7	Pakistan	8.8	28.8	38.4
Sri Lanka	20.9	66.3	103.5	Rwanda	8.3	31.9	41.9
Singapore	19.8	88.9	135.9	Jordan	8.2	47.8	64.9
Costa Rica	19.8	89.5	148.8	Zimbabwe	8.2	26.5	35.9
Brazil	17.7	67.7	106.5	Honduras	8.0	46.9	67.3
Türkiye	16.8	80.3	133.5	Senegal	7.7	31.6	41.4
Panama	16.2	62.6	90.9	Ghana	7.4	29.4	39.1
Tunisia	16.1	68.2	108.1	Tanzania	7.0	23.3	29.3
Kazakhstan	16.0	41.0	55.3	Ethiopia	6.9	30.6	39.7
Peru	15.8	64.2	96.4	Iraq	6.9	34.3	46.0
Colombia	15.7	73.7	117.4	Nigeria	6.8	20.3	25.9
Viet Nam	15.0	62.0	95.9	Angola	6.8	19.9	25.0
Ecuador	14.3	66.5	102.6	Sudan	6.6	21.2	27.6
Morocco	14.1	59.5	92.7	Niger	6.6	21.8	27.4
Mexico	14.0	63.5	100.9	Mozambique	6.6	21.3	27.9
El Salvador	14.0	65.8	112.8	Mali	6.5	18.4	22.8
Dominican Rep.	13.8	53.2	81.0	Cameroon	6.2	24.0	30.8
Azerbaijan	13.7	52.7	75.7	Kenya	6.1	28.0	38.2
Iran	13.2	72.9	114.9	Burkina Faso	6.0	24.1	31.7
Malaysia	12.4	58.4	82.1	Malawi	5.8	28.7	38.5
Indonesia	12.2	47.8	69.4	Côte d'Ivoire	5.7	17.5	21.6
Myanmar	12.1	42.4	63.4	Uganda	5.1	36.1	50.3
India	12.0	58.1	87.4	Saudi Arabia	4.5	27.6	32.7
Algeria	11.9	56.1	80.2	Zambia	4.3	24.9	32.6
Nepal	11.8	55.0	88.6				
Mean	13.1	50.1	76.0				

Notes: OADR = population aged 65+ / population aged 20–64 (%). $N = 69$ late-aging (OADR $< 30\%$). Sorted by 2024 OADR (descending). Medium (Med) and Low fertility from UN World Population Prospects 2024 Revision.

Late-aging economies occupy a markedly different position in 2024. Korea is still below the early-aging cutoff at 29.3%, China is at 23.1%, Brazil at 17.7%, Türkiye at 16.8%, and India at only 12.0%. The table therefore contains many countries that appear young today but age dramatically over the rest of the century. Even under the medium-fertility variant, China and Korea reach OADRs above 100% by 2100, implying more than one elderly person for each working-age adult. Several late-aging economies approach levels that would today be considered extreme under medium fertility: Chile 94.8%, Singapore 88.9%, Costa Rica 89.5%, Türkiye 80.3%, and Thailand 72.5%.

The low-fertility variant produces much more severe outcomes. Korea reaches 196.2% and China 206.8%, roughly two elderly persons per working-age adult. Chile, Thailand, Singapore, Sri Lanka, Brazil, Argentina, Costa Rica, Colombia, Ecuador, Iran, and Türkiye all reach or exceed an OADR of 100% under low fertility. Thus, the low-fertility scenario is not merely a uniform upward shift in projected aging; it changes the qualitative nature of

the problem for many late-aging economies by moving them into dependency ratios with no historical precedent among large economies.

The United States occupies an intermediate position. Its OADR rises from 30.8% in 2024 to 54.5% under medium fertility and 72.2% under low fertility. This path is less severe than those of Japan, Korea, or China, partly because of higher fertility and sustained immigration, at least until recently, but it is still large enough to create meaningful pressure on Social Security and the federal budget. Australia, Canada, United Kingdom, and New Zealand show broadly similar patterns: aging is substantial, but less compressed than in the fastest late-aging economies.

3.5 Heterogeneity in Aging Speed Across Countries

The demographic transition toward aged societies exhibits substantial heterogeneity both in timing and pace across developed and developing economies. To systematically characterize these patterns, we examine the time required for countries to traverse key thresholds of the old-age dependency ratio (OADR), defined as the population aged 65 and above relative to the working-age population (20–64).

Measuring aging speed. Using the notation introduced at the beginning of Section 3, let T_τ^i denote the first year in which country i's old-age dependency ratio reaches threshold τ:

$$T_\tau^i \equiv \min\left\{t : \text{OADR}_{65,t}^i \geq \tau\right\}.$$

I focus on four thresholds, $\tau \in \{0.125, 0.25, 0.50, 1.00\}$, corresponding respectively to eight, four, two, and one working-age persons per person aged 65 and above. The speed of aging between successive thresholds is defined as

$$S_{0.25}^i \equiv T_{0.25}^i - T_{0.125}^i, \qquad S_{0.50}^i \equiv T_{0.50}^i - T_{0.25}^i, \qquad S_{1.00}^i \equiv T_{1.00}^i - T_{0.50}^i.$$

Thus, $S_{0.25}^i$ is the number of years it takes country i to move from an OADR of 0.125 to 0.25, $S_{0.50}^i$ is the number of years required to move from 0.25 to 0.50, and $S_{1.00}^i$ is the number of years required to move from 0.50 to 1.00. Smaller values of S_τ^i therefore indicate faster demographic compression. Crossing years are computed using UN WPP historical estimates for 1950–2023 and WPP 2024 low-fertility projections for 2024–2100.

Table 3 summarizes these transitions for selected benchmark countries under the low-fertility variant. The table reports the year each country crosses the OADR thresholds 0.125, 0.25, 0.50, and 1.00, together with the number of years required to move between adjacent thresholds. It therefore combines information about levels—how old each economy is in 2024 and how old it is projected to become by 2100—with information about speed—how quickly the transition takes place. The countries are sorted by their 2024 OADR so that the earliest-aging economies appear first.

Table 3: Selected Aging-Speed Benchmarks Under Low Fertility

Country	OADR 2024	2100 Low	Year $T_{0.125}$	$S_{0.25}$	Year $T_{0.25}$	$S_{0.50}$	Year $T_{0.50}$	$S_{1.00}$	Year $T_{1.00}$
Japan	54.9	121.3	1974	23	1997	19	2016	61	2077
Finland	42.8	97.4	1954	47	2001	44	2046	–	–
Portugal	42.5	85.3	1950	44	1994	37	2032	–	–
Italy	42.0	120.0	1950	41	1991	39	2030	48	2078
Greece	41.6	111.0	1950	43	1993	41	2034	49	2083
France	40.2	85.9	1950	27	1977	61	2038	–	–
Germany	39.8	85.8	1950	22	1972	60	2031	–	–
Sweden	36.8	88.2	1950	23	1973	80	2053	–	–
Spain	34.9	113.2	1950	45	1995	41	2036	45	2081
United States	30.8	72.2	1950	67	2017	47	2064	–	–
Ukraine	30.7	176.6	1950	67	2017	32	2049	25	2074
Korea	29.3	196.1	2003	18	2021	14	2035	23	2058
China	23.1	206.8	2004	24	2027	18	2046	25	2071
Chile	22.5	161.2	1994	34	2027	24	2052	21	2072
Brazil	17.7	106.5	2014	20	2034	24	2058	32	2090
Türkiye	16.8	133.5	2013	25	2037	20	2058	24	2082
India	12.0	87.4	2025	25	2051	21	2071	–	–

Notes: OADR is population aged 65+ divided by population aged 20–64. T_x is the first year in which the old-age dependency ratio reaches threshold x. $S_{0.25} = T_{0.25} - T_{0.125}$, $S_{0.50} = T_{0.50} - T_{0.25}$, and $S_{1.00} = T_{1.00} - T_{0.50}$. Smaller values of S_x indicate faster demographic compression. Crossing years are computed by linear interpolation between annual observations using UN WPP historical estimates for 1950–2023 and WPP 2024 low-fertility projections for 2024–2100; T_x and S_x are rounded to the nearest year for presentation. The 2100 column reports the projected OADR level under the WPP low-fertility variant. Countries are sorted by 2024 OADR. A '–' symbol means that the 1.0 threshold for the OADR is not reached by 2100.

The table highlights the contrast between countries that aged early and those whose most consequential demographic adjustment still lies ahead. The data allow precise cross-country comparisons along three speed dimensions.

$S_{0.25}$ **(12.5% to 25% OADR).** Japan took 23 years to move from OADR = 12.5% (1974) to OADR = 25% (1997). Germany accomplished the same doubling in 22 years (1950–1972) and Sweden in 23 years (1950–1973)—strikingly similar paces, confirming that the early industrializers of Europe and Japan traversed the initial threshold band at comparable speeds, despite very different institutional contexts. France moved slightly slower at 27 years (1950–1977). Southern European latecomers were considerably slower: Spain 45 years, Portugal 44 years, and Italy 41 years, reflecting that they crossed the 12.5% threshold later and from a lower base. Korea, by contrast, accomplished the same interval in only 18 years (2003–2021)—meaningfully faster than Japan. China is projected to complete it in 24 years (2004–2027), essentially the same speed as Japan but compressed into the recent past.

$S_{0.50}$ **(25% to 50% OADR).** Japan took 19 years for this doubling (1997–2016). Korea is projected to traverse it in only 14 years (2021–2035)—one-quarter faster than Japan—driven by the uniquely steep fertility cliff created by Korea's extraordinarily rapid demographic

modernization. China is projected at 18 years (2027–2046), close to Japan on this metric. The contrast with gradual-aging Europe is stark: Germany requires 60 years (1972–2031) and Sweden 80 years (1973–2053) for the same band, allowing multiple generations of institutional adaptation that Korea and China simply will not have.

$S_{1.00}$ (50% to 100% OADR). Reaching OADR = 1.00 means one elderly person for every working-age adult—a level without historical precedent among large economies. Under low fertility, it becomes part of the baseline path for Japan, Korea, China, and others. Japan is projected to cross this threshold around 2077, 61 years after reaching 0.50 in 2016. Korea faces the same crossing in only 23 years (2035–2058) and China in 25 years (2046–2071)—less than half of Japan's window. Ukraine also faces a rapid $S_{1.00} = 25$ years (2049–2074), driven by its post-Soviet fertility collapse. The implication is direct: Korea and China face not only larger total increases in dependency ratios but a substantially shorter institutional window in which to reform pension systems, health-care financing, and labour markets compared with Japan or Western Europe.

3.6 The Demographically Equivalent Retirement Boundary

So far, policy responses to rising OADRs and the fiscal burden on public pension plans have been quite different across economies. In some cases, early eligibility has been postponed, the number of years worked to earn full retirement benefits has been changed, the FRA has been phased up, replacement rates reduced, payroll tax rates have been raised, penalties for early claiming have increased, etc. Given the large number of responses in different countries, it is useful to have one simple metric that can be relatively easily applied to all countries to measure the timing and extent of aging and the pressures on public pension programs.

The retirement-boundary statistic also has a simple fiscal interpretation in a stylized pay-as-you-go pension system. Let R_t denote the retired population, L_t the working-age population, w_t the wage, b_t the replacement rate measured as a fraction of the wage, and τ_t the payroll tax rate required for period-by-period balance. The PAYG budget constraint is

$$\tau_t w_t L_t = b_t w_t R_t,$$

so that

$$\tau_t = b_t \frac{R_t}{L_t} = b_t \, OADR_t.$$

Thus, conditional on an unchanged replacement rate and payroll-tax base, holding the old-age dependency ratio at its 2024 level is equivalent to holding the required payroll tax rate at its 2024 level. The demographically equivalent retirement boundary therefore summarizes the age-structure adjustment needed to keep the PAYG tax burden unchanged absent benefit cuts, contribution-base expansions, immigration, higher participation, or other financing changes.

Following De Nardi, İmrohoroğlu, and Sargent (1999), I translate the projected age structure into a common retirement-boundary equivalent. Using age 65 as the initial boundary and ages 20–64 as the initial working-age population, I calculate the boundary X in 2100

that reproduces each country's 2024 OADR. Specifically, I solve:

$$\frac{\sum_{a=X}^{\omega} N_{a,2100}^{i}}{\sum_{a=20}^{X-1} N_{a,2100}^{i}} = \frac{\sum_{a=65}^{\omega} N_{a,2024}^{i}}{\sum_{a=20}^{64} N_{a,2024}^{i}}, \tag{1}$$

for X, where ω is the oldest age reported in the WPP data.

I report two transformations of X: $\Delta\text{FRA} = X - 65$, the change from a common age-65 boundary, and $\Delta\text{FRA}_{\text{stat}} = X - \text{FRA}_{\text{stat}}$, the gap relative to the country's current statutory FRA. The first provides cross-country comparability; the second shows how far current institutions lie from the demographic equivalent. Neither is a recommended or behaviorally feasible retirement age. The calculation mechanically counts everyone below X as working age and everyone above it as old age; it does not incorporate age-specific employment, health, hours, or productivity. At high values, X should therefore be interpreted as evidence that retirement-age policy alone cannot offset the projected age structure.

Tables 4 and 5 present, for each country, the 2024 old-age dependency ratio together with both required-increase measures—from the uniform age-65 baseline (ΔFRA) and from the country's current statutory retirement age ($\Delta\text{FRA}_{\text{stat}}$)—under the low-fertility baseline. Medium-fertility counterparts are reported in Tables 21 and 22 in Appendix E, and required increases measured from an age-70 retirement boundary are reported in Tables 23 and 24. The statutory retirement ages themselves are listed in Tables 27 and 28. The dual presentation of required adjustments reveals how differences in current statutory retirement ages amplify or moderate the policy challenge facing different countries.

Under low fertility, the equivalent boundary rises by 14 years for Japan, 13 years for the United States, 21 years for Brazil and India, 24 years for China and South Korea, and 25 years for Singapore. Values of this magnitude are not plausible single-instrument reforms. They show that the projected adjustment must be shared across retirement ages, benefits, contributions, tax finance, participation, immigration, and other margins.

Table 4: Required Full Retirement Age Postponements: Early-Aging Economies

		FRA Increase (years)				FRA Increase (years)	
Country	OADR 2024	From age 65	From stat. FRA	**Country**	OADR 2024	From age 65	From stat. FRA
Japan	54.9	14	14	Belgium	35.7	15	15
Finland	42.8	14	14	Hungary	35.4	13	13
Portugal	42.5	12	11	Spain	34.9	18	18
Italy	42.0	17	15	Netherlands	34.8	14	12
Greece	41.6	16	14	Austria	34.1	16	16
Croatia	40.3	15	15	Romania	34.1	15	15
France	40.2	13	14	United Kingdom	34.0	15	14
Germany	39.8	13	11	Poland	33.7	19	19
Serbia	39.1	15	15	Lithuania	33.5	19	19
Latvia	37.9	17	17	Switzerland	33.3	15	15
Bulgaria	37.7	14	14	Canada	33.2	13	13
Slovenia	37.3	15	15	Norway	31.9	16	14
Estonia	37.1	17	17	USA	30.8	13	11
Sweden	36.8	14	14	Ukraine	30.7	21	21
Denmark	36.3	14	12	Slovakia	30.6	17	17
Hong Kong	36.0	26	26	Australia	30.2	14	12
Czechia	35.7	14	14	New Zealand	30.2	14	14

Notes: Required increases in the full retirement age to maintain each country's 2024 OADR through 2100 under the UN WPP 2024 **low**-fertility variant, solving equation (1) for X. "From age 65" = $\Delta\text{FRA} = X - 65$; "From stat. FRA" = $\Delta\text{FRA}_{\text{stat}} = X - \text{FRA}_{\text{stat}}$, where statutory retirement ages are from OECD *Pensions at a Glance* 2024 and national legislation (listed in Table 27). OADR = pop(65+)/pop(20–64) (%). Medium-fertility counterparts are in Appendix E; age-70-boundary counterparts are in Tables 23 and 24. $N = 34$; sorted by 2024 OADR (descending).

Table 5: Required Full Retirement Age Postponements: Late-Aging Economies

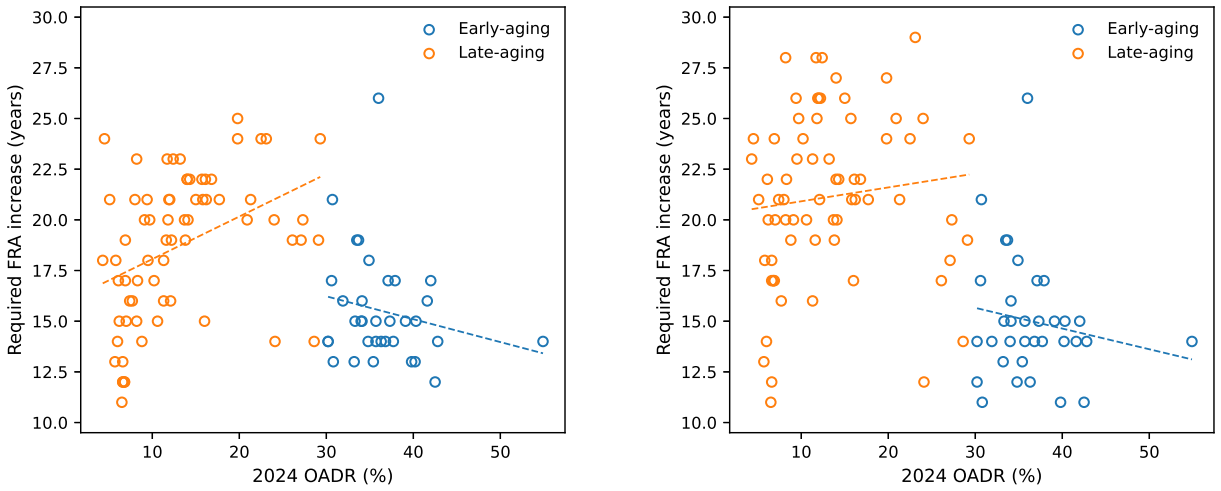
Country	OADR 2024	FRA Increase (years) From age 65	FRA Increase (years) From stat. FRA	Country	OADR 2024	FRA Increase (years) From age 65	FRA Increase (years) From stat. FRA
South Korea	29.3	24	24	Bangladesh	11.7	23	28
Belarus	29.1	19	19	Paraguay	11.6	19	19
Russia	28.6	14	14	South Africa	11.3	16	16
Uruguay	27.3	20	20	Cambodia	11.3	18	23
Ireland	27.1	19	18	Uzbekistan	10.6	15	20
Iceland	26.1	19	17	Bolivia	10.2	17	24
Israel	24.1	14	12	Philippines	9.7	20	25
Thailand	24.0	20	25	Egypt	9.5	18	23
China	23.1	24	29	Mongolia	9.4	21	26
Chile	22.5	24	24	Guatemala	9.1	20	20
Argentina	21.3	21	21	Pakistan	8.8	14	19
Sri Lanka	20.9	20	25	Rwanda	8.3	17	22
Singapore	19.8	25	27	Jordan	8.2	23	28
Costa Rica	19.8	24	24	Zimbabwe	8.2	15	20
Brazil	17.7	21	21	Honduras	8.0	21	21
Türkiye	16.8	22	22	Senegal	7.7	16	16
Panama	16.2	21	21	Ghana	7.4	16	21
Tunisia	16.1	22	22	Tanzania	7.0	15	20
Kazakhstan	16.0	15	17	Ethiopia	6.9	17	17
Peru	15.8	21	21	Iraq	6.9	19	24
Colombia	15.7	22	25	Nigeria	6.8	12	17
Viet Nam	15.0	21	26	Angola	6.8	12	17
Ecuador	14.3	22	22	Sudan	6.6	12	17
Morocco	14.1	20	20	Niger	6.6	12	12
Mexico	14.0	22	22	Mozambique	6.6	13	18
El Salvador	14.0	22	27	Mali	6.5	11	11
Dominican Rep.	13.8	19	19	Cameroon	6.2	15	20
Azerbaijan	13.7	20	20	Kenya	6.1	17	22
Iran	13.2	23	23	Burkina Faso	6.0	14	14
Malaysia	12.4	23	28	Malawi	5.8	18	18
Indonesia	12.2	19	26	Côte d'Ivoire	5.7	13	13
Myanmar	12.1	16	21	Uganda	5.1	21	21
India	12.0	21	26	Saudi Arabia	4.5	24	24
Algeria	11.9	21	26	Zambia	4.3	18	23
Nepal	11.8	20	25				

Notes: Required increases in the full retirement age to maintain each country's 2024 OADR through 2100 under the UN WPP 2024 **low**-fertility variant, solving equation (1) for X. "From age 65" = $\Delta\text{FRA} = X - 65$; "From stat. FRA" = $\Delta\text{FRA}_{\text{stat}} = X - \text{FRA}_{\text{stat}}$, where statutory retirement ages are from OECD *Pensions at a Glance* 2024 and national legislation (listed in Table 28). OADR = pop(65+)/pop(20–64) (%). Medium-fertility counterparts are in Appendix E; age-70-boundary counterparts are in Tables 23 and 24. $N = 69$; sorted by 2024 OADR (descending).

The cross-country correlation between 2024 OADR and required FRA increase is $\rho = -0.24$ from age 65 under low fertility, strengthening to -0.51 from statutory baselines. The pooled correlations mask very different within-group patterns, visible in the separate OLS fits of Figure 4: among late-aging economies the correlation is *positive* (+0.40 from age 65)—countries further into the OADR ascent require larger adjustments—whereas among early-aging economies it is mildly negative (-0.20), because the highest-OADR early-agers, led by Japan, have already absorbed much of their demographic transition. The pooled correlation is negative only because the early-aging group combines high 2024 OADRs with smaller remaining adjustments. The stronger statutory correlation reflects the amplifying role of low statutory retirement ages: countries with statutory ages below 65 (such as China at 60) face larger required adjustments under this measure, adding dispersion that sharpens the negative relationship with OADR. The correlation between compression speed (OADR

25–50%) and required FRA increase is $\rho = -0.69$, confirming that faster aging translates directly into larger required adjustments. Moving from medium to low fertility raises Korea's requirement from 21 to 24 years and Japan's from 7 to 14, illustrating the fertility sensitivity of Section 3.3. The statutory-baseline measure $\Delta\text{FRA}_{\text{stat}} = X - \text{FRA}_{\text{stat}}$ reported in Tables 4 and 5 is the one used in the right panel of Figure 4.

Figure 4 visualizes the relationship for all 103 countries. The left panel measures required increases from a uniform age-65 baseline, while the right panel measures increases from each country's current statutory retirement age. In the left panel, Japan is the striking outlier at the top left: it has the highest 2024 OADR in the sample (54.9%) but among the smallest required increases (14 years), because much of its aging has already occurred. Hong Kong (OADR = 36.0%, 26 years) is the largest required increase among early-aging economies, while China and South Korea (both 24 years) and Singapore (25 years) cluster at the upper boundary among late-aging economies. The statutory-baseline measure tightens the negative relationship because it captures not only future demographic pressure but also how far current pension institutions remain from the age-65 benchmark. Countries with statutory ages well below 65—such as China (60), India (60), and Thailand (60)—face substantially larger required adjustments under this measure.



(a) FRA increase from age 65

(b) FRA increase from statutory FRA

Figure 4: Old-Age Dependency Ratios and Required Retirement Age Increases

Notes: Each panel shows 2024 OADR (65 + /20–64) and required full retirement age (FRA) increases for 103 countries. Panel (a) measures FRA increases from a uniform age-65 baseline (pooled $\rho = -0.24$; within groups, -0.20 early-aging and $+0.40$ late-aging). Panel (b) measures increases from each country's current statutory FRA (pooled $\rho = -0.51$; -0.16 early, $+0.11$ late). Blue circles: early-aging economies ($N = 34$); orange circles: late-aging economies ($N = 69$). Dashed lines show OLS fits. Data: UN World Population Prospects 2024, OECD *Pensions at a Glance* 2024, and national legislation.

4 Aging in the Solow Growth Model

We project output, capital, and living standards for 103 countries from 2024 to 2100 using a Solow growth model in which the working-age population follows country-specific demographic paths from the United Nations World Population Prospects 2024 revision (United Nations, Department of Economic and Social Affairs, Population Division (2024)). The framework is intentionally simple. Because the goal is to isolate the quantitative contribution of demographic change and TFP-path assumptions to long-run growth, I abstract from endogenous saving, human capital accumulation, and general equilibrium interactions, and hold most non-demographic parameters fixed at their historically calibrated values.

The main specification uses the low-fertility population path; medium fertility is reported as an optimistic sensitivity in the appendix. The section has two main results. First, population aging lowers aggregate GDP growth through the decline in the working-age share. Second, for many late-aging middle-income countries, this demographic channel is compounded by a separate TFP-path channel. Countries that grew rapidly while catching up to the frontier, with the United States treated as the frontier economy, cannot maintain above-frontier TFP growth indefinitely. At the same time, countries with negative historical TFP growth are not assumed to experience permanent exponential decline; their TFP growth rates converge to zero. I use a Shapley decomposition to allocate the nonlinear interaction between demographics and TFP paths. The growth-accounting framework follows Fernández-Villaverde, Ohanian, and Yao (2026); the production function follows Fernández-Villaverde, Ventura, and Yao (2025) in using working-age population rather than total employment as the labor input.

4.1 Production Technology

Each economy produces output according to a Cobb-Douglas aggregate production function,

$$Y_t \;=\; A_t \, K_t^{\theta} \, L_t^{1-\theta}, \tag{2}$$

where Y_t is real GDP, K_t is the aggregate capital stock, L_t is the working-age population (ages 20–64), A_t is total factor productivity, and $\theta \in (0, 1)$ is the capital share.

The capital stock evolves according to

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

where δ is the depreciation rate of the capital stock and s is the investment rate (gross capital formation as a share of GDP). Both parameters are treated as fixed at their country-specific historical averages, as described in Section 4.5.

4.2 Data

Real GDP at constant 2021 national prices (`rgdpna`), capital stock (`rnna`), labor share of income (`labsh`), depreciation rate (`delta`), and investment share (`csh_i`) are from Penn World Table 11.0 Feenstra, Inklaar, and Timmer (2015),

which covers the period 1950–2023.[5] Working-age (ages 20–64) and total population series are from the United Nations World Population Prospects 2024 United Nations, Department of Economic and Social Affairs, Population Division (2024), spanning 1950–2023 for historical estimates and 2024–2100 for projections under both the medium and low fertility scenarios. The 103 countries in our sample are listed in Tables 6 and 7; they span a wide range of demographic trajectories, and include both early-aging economies in which working-age populations are already contracting and late-aging economies in which they are still growing or have recently peaked but face steep declines after 2030–2050.

4.3 Counterfactuals and Shapley Decomposition

Demographic changes and TFP-path changes interact through capital accumulation, so their separate contributions cannot be measured cleanly by changing one assumption at a time in an arbitrary order. A declining working-age share lowers output directly, but it also lowers investment and therefore future capital accumulation and output. Similarly, a slower TFP path lowers output and investment, which changes the capital stock on which the demographic effect is measured. A sequential decomposition would assign this interaction mechanically to whichever channel is removed second.[6] The Shapley decomposition (Shorrocks (2013)), which adapts the Shapley value of cooperative game theory (Shapley (1953)) to the attribution of an aggregate outcome among its determinants, avoids this order dependence by assigning each channel its average marginal contribution across the two possible orderings.[7]

The growth decomposition compares the baseline projection with counterfactual paths that remove either the change in age structure, the TFP-path transition, or both. The

[5] PWT 11.0, released in 2025, reports China on its official national accounts rather than the Maddison/Wu adjusted series used through version 10.01. China's annualized per-capita growth over 1990–2020 is 8.14% on the current series against 5.61% on the earlier one, and its Solow residual over 1991–2019 rises correspondingly. We use the current vintage throughout and report the sensitivity of China's drag decomposition to this choice in Section 4.9. No other country in the sample is affected by a comparable methodological revision.

[6] In this application the interaction is economically negligible. Computing the two sequential decompositions—removing aging first, then removing the TFP transition first—and the Shapley average for representative countries shows that even for China, where it is largest, the orderings differ by only 0.07 pp per year (a demographic component ranging from -0.78 to -0.85, with Shapley at the midpoint -0.81); for Korea and Poland the orderings differ by 0.01–0.02 pp, and for Japan, whose calibrated TFP growth is 0.33% and below the frontier rate so that the baseline embeds no TFP-path transition, the two orderings coincide exactly. The Shapley decomposition is the principled, order-independent choice, but the demographic/TFP split does not hinge on it.

[7] The framework is that of Shorrocks (2013); it has recently been used to attribute structural-model counterfactuals to interacting components (Kwon, Lee, and Pouliot (2024)). Two alternatives are standard. The first is the classical growth-accounting practice of reporting each channel's sequential effect alongside an explicit, unallocated interaction term; the Shapley rule instead splits that interaction symmetrically rather than assigning it by an arbitrary order. The second is a continuous-time (Divisia) decomposition that integrates instantaneous contributions along the transition path and is additive by construction; the two-factor Shapley average used here is its natural discrete-time counterpart. All three are order-independent, but the Shapley rule delivers an exact, residual-free split of the simulated paths without imposing a continuous-time approximation.

demographic counterfactual is designed to isolate the effect of a changing working-age share rather than the effect of total population size alone. Let $N_{i,t}$ denote total population and $L_{i,t}$ the working-age population for country i at time t. I define the 2024 working-age share as

$$\omega_{i,2024} = \frac{L_{i,2024}}{N_{i,2024}},$$

and construct a demographic counterfactual labor input

$$L_{i,t}^{\text{cf}} = \omega_{i,2024} N_{i,t}.$$

Thus, the counterfactual keeps the 2024 working-age share fixed while allowing total population to follow the WPP projection. This differs from freezing the absolute level of working-age population: it removes the aging-induced change in the age structure while preserving aggregate population growth or decline.

The TFP counterfactual removes the TFP-path transition. Let $\widehat{g}_{A,i}$ be country i's calibrated historical TFP growth rate and let g^* denote the U.S. frontier TFP growth rate, approximately 1.11% per year over 1991–2019. In the baseline, I assume that countries with $\widehat{g}_{A,i} > g^*$ converge linearly to g^* by 2045. Countries with $0 \leq \widehat{g}_{A,i} \leq g^*$ remain on their historical TFP-growth path. Countries with $\widehat{g}_{A,i} < 0$ are assumed to converge linearly to zero by 2045. The last case is a zero-growth floor that prevents the model from extrapolating negative TFP growth indefinitely. The corresponding no-transition counterfactual keeps each country at its own historical TFP growth rate throughout the projection.

Because the two channels interact through capital accumulation, a one-factor-at-a-time decomposition would depend on the order in which the channels are removed. I therefore define four average annual growth rates for each outcome $z \in \{Y, Y/N\}$: the baseline path, a path with demographic aging removed, a path with the TFP-path transition removed, and a path with both channels removed. Total drag is

$$D_{z,i}^{\text{total}} = g_{z,i}^{\text{base}} - g_{z,i}^{\text{no both}}.$$

The Shapley demographic component is

$$D_{z,i}^{\text{dem}} = \frac{1}{2}\left[\left(g_{z,i}^{\text{base}} - g_{z,i}^{\text{no aging}}\right) + \left(g_{z,i}^{\text{no TFP}} - g_{z,i}^{\text{no both}}\right)\right],$$

and the Shapley TFP-path component is

$$D_{z,i}^{\text{TFP}} = \frac{1}{2}\left[\left(g_{z,i}^{\text{base}} - g_{z,i}^{\text{no TFP}}\right) + \left(g_{z,i}^{\text{no aging}} - g_{z,i}^{\text{no both}}\right)\right].$$

By construction,

$$D_{z,i}^{\text{dem}} + D_{z,i}^{\text{TFP}} = D_{z,i}^{\text{total}}.$$

The averaging in these formulas is the two-factor Shapley value, and it has a simple interpretation. Each bracketed term is the *marginal contribution* of one channel, evaluated under a different assumption about the other channel. In $D_{z,i}^{\text{dem}}$, the first term, $g_{z,i}^{\text{base}} - g_{z,i}^{\text{no aging}}$, is the growth effect of demographic change measured while the TFP transition is switched *on*; the second term, $g_{z,i}^{\text{no TFP}} - g_{z,i}^{\text{no both}}$, is the same demographic effect measured while the TFP

transition is switched *off*. These two marginal contributions are generally not equal, because output finances investment: the growth cost of a shrinking working-age share depends on how fast TFP—and hence output, saving, and capital accumulation—is growing along the path. A sequential decomposition would have to remove one channel first and the other second, and would assign the entire interaction between the channels to whichever channel is removed second; reversing the order would change both reported components. The Shapley decomposition removes each channel first in one ordering and second in the other, averages the two answers, and thereby splits the interaction term evenly. The result is exact, since the components sum to total drag, and independent of the order in which the channels are considered.

A stylized example makes the averaging concrete. Suppose, in percent per year, $g^{\text{base}} = 1.0$, $g^{\text{no aging}} = 1.5$, $g^{\text{no TFP}} = 3.0$, and $g^{\text{no both}} = 3.8$, so total drag is $1.0 - 3.8 = -2.8$ pp. Removing aging first attributes $1.0 - 1.5 = -0.5$ pp to demographics and the remaining $1.5 - 3.8 = -2.3$ pp to the TFP transition; removing the TFP transition first attributes $1.0 - 3.0 = -2.0$ pp to the TFP transition and the remaining $3.0 - 3.8 = -0.8$ pp to demographics. Both orderings sum to -2.8 pp but disagree on the split because of the 0.3 pp interaction. The Shapley components average the two orderings:

$$D^{\text{dem}} = \frac{1}{2}(-0.5 - 0.8) = -0.65 \quad \text{and} \quad D^{\text{TFP}} = \frac{1}{2}(-2.0 - 2.3) = -2.15,$$

which again sum to -2.8 pp. The Shapley decomposition columns in Tables 6–11 are constructed in this way; for example, China's demographic component of -0.813 pp and TFP-path component of -3.415 pp in Table 11 sum exactly to its total per-capita drag of -4.228 pp.

Negative values indicate that the channel lowers growth relative to the relevant counterfactual; positive values indicate a tailwind. The projection period is 2024–2100, but growth rates are computed from 2025 to 2100 because all paths are initialized to be identical in 2024.

4.4 Analytical Benchmarks for the Simulated Drag

The Solow simulations include transitional capital accumulation, but the main demographic channel has a simple closed-form benchmark. With

$$Y_{i,t} = A_{i,t} K_{i,t}^{\theta_i} L_{i,t}^{1-\theta_i},$$

let $m_{i,t} = K_{i,t}/Y_{i,t}$ denote the capital-output ratio and $\omega_{i,t} = L_{i,t}/N_{i,t}$ the working-age share. Rearranging the production function gives

$$\frac{Y_{i,t}}{N_{i,t}} = A_{i,t}^{1/(1-\theta_i)} m_{i,t}^{\theta_i/(1-\theta_i)} \omega_{i,t}.$$

Average annual growth in output per capita over any horizon therefore satisfies

$$g_{Y/N,i} = \frac{1}{1-\theta_i} g_{A,i} + \frac{\theta_i}{1-\theta_i} g_{m,i} + g_{\omega,i},$$

where $g_{\omega,i}$ is the average growth rate of the working-age share and $g_{m,i}$ is the average growth rate of the capital-output ratio. Since the demographic counterfactual holds $\omega_{i,t}$ fixed at its 2024 value while leaving total population on the same WPP path, the closed-form demographic-drag benchmark is

$$\widetilde{D}_i^{dem} = g_{\omega,i} = \frac{1}{T}\left[\log(\omega_{i,2100}) - \log(\omega_{i,2024})\right],$$

where T is the length of the projection horizon. If the capital-output ratio were stable and identical across the baseline and no-aging paths, this expression would be the entire demographic growth effect. More generally, the simulated demographic component can be written approximately as

$$D_{Y/N,i}^{dem} \approx g_{\omega,i} + \frac{\theta_i}{1-\theta_i}\left(g_{m,i}^{base} - g_{m,i}^{no\,aging}\right).$$

Thus, the gap between the simulated demographic component and the closed-form working-age-share benchmark measures the transitional capital-accumulation term. The same logic also explains why the demographic component for aggregate GDP and GDP per capita are nearly identical: the no-aging counterfactual changes the working-age share but not the total population path, so aggregate population growth cancels in the comparison.

A parallel benchmark applies to the TFP-normalization component. Let $\widehat{g}_{A,i}$ be country i's historical TFP growth rate and $\bar{g}_{A,i}^{base}$ the average TFP growth rate along the baseline transition path. Holding the capital-output ratio fixed, the TFP-normalization effect is approximately

$$\widetilde{D}_i^{TFP} = \frac{\bar{g}_{A,i}^{base} - \widehat{g}_{A,i}}{1-\theta_i}.$$

For countries with $\widehat{g}_{A,i} > g^*$, baseline TFP growth converges linearly from $\widehat{g}_{A,i}$ to the frontier rate g^* by 2045 and remains at g^* thereafter. If T is the full projection horizon and T_c is the convergence period, this implies

$$\widetilde{D}_i^{TFP} = \frac{T - T_c/2}{T}\frac{g^* - \widehat{g}_{A,i}}{1-\theta_i}.$$

For countries with $\widehat{g}_{A,i} < 0$, the same expression applies with $g^* = 0$, so the TFP-normalization component is positive: the zero-growth floor creates a tailwind relative to a counterfactual that extrapolates negative historical TFP growth through 2100. Comparing these analytical benchmarks with the simulated Shapley components provides a diagnostic for the role of transitional capital accumulation.

4.5 Calibration

All structural parameters are calibrated using the 1991–2019 period from Penn World Table 11.0 Feenstra, Inklaar, and Timmer (2015). For each country i, we compute

$$\widehat{\delta}_i = \overline{\text{delta}}_{i,\,1991-2019}, \tag{4}$$

$$\widehat{\theta}_i = 1 - \overline{\text{labsh}}_{i,\,1991-2019}, \tag{5}$$

$$\widehat{s}_i = \overline{\text{csh_i}}_{i,\,1991-2019}, \tag{6}$$

where overbars denote sample means and `delta`, `labsh`, and `csh_i` are PWT 11.0 variables for the average depreciation rate, the labor compensation share of GDP at current national prices, and the share of gross capital formation in GDP, respectively.[8] To guard against outliers in the labor share—which can arise from measurement error in countries with large self-employment sectors—we winsorize $\widehat{\theta}_i$ to the interval [0.25, 0.65].

The 2023 capital stock $K_{i,2023}$ is taken directly from the PWT variable `rnna` (capital stock at constant 2021 national prices). The initial TFP level is recovered as

$$A_{i,2023} \;=\; \frac{Y_{i,2023}}{K_{i,2023}^{\widehat{\theta}_i}\, L_{i,2023}^{1-\widehat{\theta}_i}}, \tag{7}$$

where $Y_{i,2023}$ is PWT `rgdpna` and $L_{i,2023}$ is the working-age population in 2023 from the WPP estimates. The historical TFP growth rate $\widehat{g}_{A,i}$ is computed as the average annual growth rate of $A_{i,t}$ over 1991–2019.

Table 18 in the Appendix reports the calibrated parameters for all 103 economies.

4.6 Numerical Results

Before turning to results, it is useful to spell out the mechanics of the numerical exercise. Each country's projection is initialized at a common 2024 starting point: the 2024 capital stock follows from the perpetual-inventory equation (3) applied to the 2023 PWT capital stock and output, $K_{2024} = (1-\widehat{\delta})K_{2023} + \widehat{s}\,Y_{2023}$; the 2024 TFP level follows from the recovered A_{2023} of equation (7) grown along the country's TFP path; and L_{2024} is the WPP working-age population. Output in 2024, $Y_{2024} = A_{2024}K_{2024}^{\widehat{\theta}}L_{2024}^{1-\widehat{\theta}}$, is therefore identical across the baseline and all counterfactuals. From there the model iterates forward one year at a time. Investment out of 2024 output determines the next year's capital stock, $K_{2025} = (1-\widehat{\delta})K_{2024} + \widehat{s}\,Y_{2024}$; combined with the 2025 working-age population from the relevant WPP variant and with A_{2025} grown along the convergence schedule of Section 4.3—linearly toward g^* by 2045 for above-frontier economies, at the historical rate $\widehat{g}_A$ for economies with $\widehat{g}_A \in [0, g^*]$, and linearly toward zero by 2045 for economies with negative historical TFP growth—it delivers $Y_{2025} = A_{2025}K_{2025}^{\widehat{\theta}}L_{2025}^{1-\widehat{\theta}}$, and so on through 2100. The four scenarios of Section 4.3 differ only in the labor input L_t (baseline WPP path versus the fixed-share counterfactual $L_t^{\mathrm{cf}} = \omega_{2024}N_t$) and in the growth path of A_t (convergence schedule versus the no-transition path); the parameters $\widehat{\theta}$, $\widehat{\delta}$, $\widehat{s}$ and the 2024 initial conditions are common to all four. The growth rates entering the drag formulas are the averages of the 76 annual log growth rates for 2025–2100, equivalently $g_{z,i} = \frac{100}{76}\ln\!\big(z_{i,2100}/z_{i,2024}\big)$ for $z \in \{Y,\, Y/N\}$; because all scenarios share identical 2024 values, each drag—the difference between two such growth rates, in percentage points per year—depends only on the divergence of the paths from 2025 onward.

[8] The baseline calibration takes the time-series average of the current-price share of gross capital formation and applies it to constant-price real GDP. In a stylized one-sector Solow model, this is a standard macroeconomic approximation used to capture an economy's aggregate saving effort. By adopting this one-good abstraction, the framework intentionally abstracts from historical changes in the relative prices of investment goods versus consumption goods.

The results can be organized into three broad groups. For most frontier and near-frontier economies, historical TFP growth is below the U.S. frontier rate and nonnegative, so the TFP-path component is zero and total drag is dominated by the demographic channel. For fast-converging middle-income economies with recent TFP growth above the frontier rate, the convergence of TFP growth to the frontier creates an additional TFP-path headwind that can be as large as, or larger than, the demographic component. Finally, for economies with negative historical TFP growth, the zero-growth floor creates a TFP-path tailwind because the baseline improves relative to a counterfactual that extrapolates negative TFP growth through 2100. These three cases provide a useful roadmap for interpreting the country-level tables below.

Demographic drag is negative for most of the 103 countries, confirming that population aging exerts a growth headwind across the sample. Exceptions arise among high-fertility Sub-Saharan African and South Asian economies—Ethiopia, Ghana, Uganda, Pakistan, and Cambodia—where working-age populations continue growing fast enough to generate a demographic tailwind under the corrected capital-share calibration. Among economies with negative drag, it ranges from −0.06 percentage points (Myanmar, medium fertility) to −0.815 percentage points (South Korea, low fertility), with the full-sample median of −0.17 percentage points under medium fertility and −0.24 percentage points under low fertility.

Table 6: Demographic Drag Decomposition, 2024–2100: Early-Aging Economies

Country	g_Y	g_N	Dem. drag	**Country**	g_Y	g_N	Dem. drag
Japan	−0.43	−1.10	−0.292	Belgium	0.35	−0.52	−0.238
Finland	0.89	−0.71	−0.216	Hungary	0.73	−0.82	−0.217
Portugal	−0.11	−0.67	−0.225	Spain	−0.33	−0.96	−0.397
Italy	−1.16	−1.17	−0.341	Netherlands	1.05	−0.51	−0.267
Greece	−0.63	−1.10	−0.275	Austria	0.23	−0.73	−0.316
Croatia	0.08	−1.32	−0.355	Romania	0.24	−1.34	−0.308
France	0.67	−0.40	−0.174	United Kingdom	0.93	−0.34	−0.202
Germany	0.59	−0.68	−0.240	Poland	0.42	−1.47	−0.498
Serbia	−0.30	−1.36	−0.331	Lithuania	0.08	−1.77	−0.463
Latvia	0.31	−1.51	−0.314	Switzerland	0.18	−0.38	−0.295
Bulgaria	−1.99	−1.44	−0.250	Canada	1.05	0.03	−0.207
Slovenia	0.69	−0.80	−0.274	Norway	0.47	−0.49	−0.257
Estonia	0.51	−1.17	−0.326	USA	1.73	−0.15	−0.161
Sweden	1.35	−0.33	−0.201	Ukraine	−2.37	−1.86	−0.456
Denmark	0.73	−0.48	−0.225	Slovakia	0.80	−1.15	−0.367
Hong Kong	−0.91	−2.24	−1.270	Australia	2.00	0.20	−0.162
Czechia	1.05	−0.83	−0.224	New Zealand	2.17	0.20	−0.157
Mean +0.33	−0.86	−0.309					

Notes: UN WPP 2024 **low** fertility. g_Y = baseline average annual aggregate GDP growth rate, 2025–2100; g_N = baseline average annual total population growth rate; baseline per-capita growth is recoverable as $g_{Y/N} \approx g_Y - g_N$. Dem. drag = Shapley demographic component $D^{\text{dem}}_{Y/N,i}$ of Section 4.3, in percentage points per year. Because the demographic counterfactual holds the 2024 working-age share fixed while total population follows the same WPP path, the demographic component is identical for aggregate and per-capita growth ($D^{\text{dem}}_{Y,i} = D^{\text{dem}}_{Y/N,i}$), so a single drag column suffices. Negative = headwind; positive = tailwind. $N = 34$; sorted by 2024 OADR (descending).

The broader 103-country sample reveals interesting geographic patterns. Several post-Soviet economies (Russia, Ukraine, Latvia, Bulgaria) show relatively small negative per-capita drag (−0.146 pp for Russia, −0.456 pp for Ukraine) despite large negative baseline aggregate GDP growth, because shrinking total populations lower the denominator, partially offsetting the working-age decline. Romania (−0.308 pp) and Poland (−0.498 pp) face substantial per-capita headwinds. The severe fertility collapses of the 1990s are most visible in low baseline aggregate GDP growth: Ukraine ($g_Y = -2.37\%$/yr) and Poland ($g_Y = +0.42\%$/yr) with $g_N = -1.47\%$/yr face large economy-wide output headwinds.

Table 7: Demographic Drag Decomposition, 2024–2100: Late-Aging Economies

Country	g_Y	g_N	Dem. drag	**Country**	g_Y	g_N	Dem. drag
South Korea	0.03	−1.72	−0.815	Bangladesh	0.53	−0.33	−0.125
Belarus	−0.10	−1.58	−0.390	Paraguay	1.10	−0.20	−0.060
Russia	0.59	−0.66	−0.146	South Africa	0.66	0.01	−0.012
Uruguay	0.96	−1.11	−0.364	Cambodia	0.45	−0.24	0.013
Ireland	2.23	−0.47	−0.283	Uzbekistan	−0.74	0.48	0.023
Iceland	0.90	−0.58	−0.368	Bolivia	1.23	−0.07	0.039
Israel	2.64	0.59	0.028	Philippines	0.83	−0.63	−0.051
Thailand	0.45	−1.13	−0.426	Egypt	1.88	0.23	0.068
China	0.34	−1.65	−0.813	Mongolia	3.05	0.12	0.012
Chile	0.79	−1.05	−0.514	Guatemala	0.61	−0.11	0.019
Argentina	0.24	−0.78	−0.228	Pakistan	3.06	0.43	0.250
Sri Lanka	0.83	−0.66	−0.244	Rwanda	2.52	0.64	0.254
Singapore	1.58	−0.95	−0.610	Jordan	1.93	0.36	−0.020
Costa Rica	−0.26	−0.93	−0.537	Zimbabwe	1.63	0.53	0.353
Brazil	−0.95	−0.91	−0.348	Honduras	0.00	0.07	−0.034
Türkiye	−0.47	−0.95	−0.364	Senegal	0.89	0.77	0.226
Panama	−0.15	−0.13	−0.162	Ghana	4.26	0.39	0.196
Tunisia	1.14	−0.74	−0.310	Tanzania	3.40	1.35	0.349
Kazakhstan	2.58	0.19	0.011	Ethiopia	3.79	0.90	0.271
Peru	1.12	−0.37	−0.213	Iraq	4.80	0.54	0.193
Colombia	0.73	−0.70	−0.365	Nigeria	2.60	0.48	0.358
Viet Nam	−0.20	−0.68	−0.201	Angola	4.10	1.39	0.398
Ecuador	1.13	−0.47	−0.248	Sudan	2.37	0.41	0.411
Morocco	0.86	−0.58	−0.196	Niger	3.73	1.18	0.525
Mexico	−0.02	−0.58	−0.161	Mozambique	2.95	0.96	0.470
El Salvador	−1.28	−0.95	−0.240	Mali	5.12	1.26	0.509
Dominican Rep.	1.48	−0.55	−0.133	Cameroon	1.89	1.02	0.352
Azerbaijan	−2.45	−0.56	−0.136	Kenya	0.73	0.26	0.255
Iran	−0.57	−0.71	−0.305	Burkina Faso	2.80	0.48	0.404
Malaysia	1.07	−0.19	−0.205	Malawi	6.22	0.82	0.352
Indonesia	0.47	−0.49	−0.128	Côte d'Ivoire	2.72	1.13	0.318
Myanmar	−1.73	−0.74	−0.072	Uganda	1.81	0.65	0.335
India	1.60	−0.50	−0.224	Saudi Arabia	0.18	0.59	−0.020
Algeria	0.92	−0.05	−0.059	Zambia	3.79	0.98	0.326
Nepal	0.61	−0.54	−0.035				
Mean +1.36	−0.10	−0.041					

Notes: UN WPP 2024 **low** fertility. See Table 6 for column definitions. $N = 69$; sorted by 2024 OADR (descending).

Sub-Saharan Africa presents a qualitatively different picture. Many African economies exhibit positive demographic drag—a tailwind—because their working-age populations continue growing robustly. Ethiopia (+0.24 pp medium, +0.27 pp low), Ghana (+0.16, +0.20), Uganda (+0.31, +0.34), and Pakistan (+0.21, +0.25) all show net demographic benefits under the corrected capital-share calibration. However, this dividend is

temporary: these countries' challenge is not imminent working-age decline but the long-run trajectory of aging that begins in earnest after 2060. Nigeria, with a demographic tailwind of +0.31 pp (medium) and +0.36 pp (low), illustrates the eventual transition. Crucially, these countries will be navigating their demographic transitions with far weaker fiscal institutions, lower per-capita incomes, and less-developed pension systems than any previous wave of aging economies—a distinct "third wave" fiscal challenge.

Middle Eastern economies cluster around −0.20 to −0.30 pp under medium fertility, with Iran (−0.28 pp) and Egypt (−0.22 pp) facing pressures comparable to major advanced economies. These countries completed rapid fertility transitions in the 1990s–2010s and are now experiencing the downstream consequence: rapidly rising old-age dependency ratios from very low bases. Iran's fertility decline from 5.5 in 1985 to approximately 1.6 today rivals any historical transition in its speed, and the working-age cohort effects will compound after 2040.

Early-aging economies exhibit generally larger drag magnitudes (median: −0.18 pp under medium fertility, −0.27 pp under low) compared to late-aging economies (median: −0.15 pp under medium, −0.22 pp under low). This pattern reflects the fact that early-agers are already deep into their demographic transition: their working-age shares are declining throughout the 2024–2100 projection window, generating persistent headwinds. Late-aging economies, by contrast, still have growing or recently-peaked working-age populations in 2024, with many Sub-Saharan African and South Asian economies contributing positive demographic tailwinds that pull the late-aging median toward zero.

China illustrates this dynamic most dramatically. Despite a moderate 2024 OADR, China faces a per-capita drag of −0.813 pp under low fertility—among the highest globally. The OADR rises from 23.1% in 2024 to 206.8% by 2100 under low fertility, the legacy of the one-child policy creating an unprecedented demographic cliff. South Korea faces −0.815 pp under low fertility. Moving from medium to low fertility raises China's per-capita drag by approximately 33 basis points and South Korea's by approximately 29 basis points—moderate increments that reflect the anchoring of both scenarios to the same 2024 OADR baseline.

Tables 8 and 9 report, for each economy whose calibrated TFP growth $\widehat{g}_{A,i}$ exceeds the frontier rate $g^* = 1.11\%$, the annual Shapley TFP-path component under the low- and medium-fertility baselines, together with the calibrated TFP growth rate. Because the component applies identically to aggregate and per-capita growth and is nearly invariant to the fertility variant, two columns of drag values suffice.

The no-transition TFP path should not be read as a literal forecast. It is a benchmark that measures the contribution of imposing long-run convergence on economies whose recent TFP growth exceeded the frontier rate. For fast-growing economies such as China ($\widehat{g}_A = 3.84\%$) or Iraq ($\widehat{g}_A = 4.24\%$), the counterfactual path is deliberately demanding—sustaining recent above-frontier productivity growth through 2100. The resulting TFP-path component is therefore best interpreted as the growth contribution of ruling out indefinite above-frontier catch-up growth, not as a forecast of actual TFP slowdown. At the opposite end of the distribution, fourteen economies have *negative* historical TFP growth and converge upward to zero by 2045; Appendix Table 17 lists them with their calibrated rates and the resulting convergence tailwinds.

Table 8 covers the 14 above-frontier early-aging economies. Japan is *absent*: its

$\widehat{g}_A = 0.33\%$ is well below g^*, so it faces no negative TFP-path component and its total drag equals only its demographic component (-0.292 pp/yr). Poland carries the largest TFP-path component in the early-aging group at -1.264 pp/yr ($\widehat{g}_A = 2.167\%$), nearly double the frontier rate. Slovakia (-1.126 pp/yr), Czechia (-0.930 pp/yr), Estonia (-0.744 pp/yr), and Slovenia (-0.722 pp/yr) follow. The Netherlands, barely above the frontier ($\widehat{g}_A = 1.1066\%$ vs $g^* = 1.1061\%$), carries only -0.001 pp/yr.

Table 9 covers 22 above-frontier late-aging economies. Iraq records the largest single TFP-path component in the entire 103-country sample at -5.798 pp/yr ($\widehat{g}_A = 4.237\%$). China faces -3.415 pp/yr ($\widehat{g}_A = 3.838\%$), the largest among late-agers. Nigeria (-2.238 pp/yr), Mongolia (-2.193 pp/yr), and Kazakhstan (-1.562 pp/yr) also carry large TFP headwinds. Korea faces -0.394 pp/yr ($\widehat{g}_A = 1.421\%$)—roughly half its demographic drag (-0.815 pp/yr), making it an economy where both channels impose large but unequal burdens. Relative to Japan (no negative TFP-path component), Korea's combined exposure illustrates how faster historical catch-up amplifies the convergence penalty.

Table 8: Shapley TFP-Path Component of Growth Drag, 2024–2100: Early-Aging Economies

Country	Low	Med	$\hat{g}_A$ (%)	**Country**	Low	Med	$\hat{g}_A$ (%)
Finland	−0.026	−0.027	1.1284	Hungary	−0.489	−0.496	1.5269
Croatia	−0.363	−0.368	1.4282	Netherlands	−0.001	−0.001	1.1066
Latvia	−0.617	−0.630	1.6459	Romania	−0.274	−0.278	1.2982
Slovenia	−0.722	−0.730	1.7567	Poland	−1.264	−1.281	2.1674
Estonia	−0.744	−0.755	1.7374	Lithuania	−0.330	−0.338	1.3793
Sweden	−0.265	−0.268	1.3310	Slovakia	−1.126	−1.143	1.9629
Czechia	−0.930	−0.943	1.8200	Australia	−0.028	−0.028	1.1293

Notes: Shapley TFP-path component $D^{\text{TFP}}_{Y/N,i}$ of Section 4.3, pp/yr, under the WPP 2024 low (Low) and medium (Med) fertility baselines. $N = 14$ above-frontier early-agers ($\hat{g}_{A,i} > g^* = 1.11\%$).

Table 9: Shapley TFP-Path Component of Growth Drag, 2024–2100: Late-Aging Economies

Country	Low	Med	$\hat{g}_A$ (%)	**Country**	Low	Med	$\hat{g}_A$ (%)
South Korea	−0.394	−0.401	1.4209	India	−1.175	−1.189	2.0272
Belarus	−0.154	−0.157	1.2368	Mongolia	−2.193	−2.220	2.4540
Uruguay	−0.490	−0.499	1.4979	Rwanda	−1.117	−1.122	2.1510
Ireland	−1.148	−1.162	1.9294	Ghana	−1.150	−1.161	1.7419
Iceland	−0.298	−0.302	1.3735	Iraq	−5.798	−5.849	4.2366
China	−3.415	−3.464	3.8377	Nigeria	−2.238	−2.269	2.5189
Singapore	−0.031	−0.032	1.1276	Sudan	−0.286	−0.288	1.3657
Tunisia	−0.386	−0.392	1.3992	Niger	−0.703	−0.709	1.6026
Kazakhstan	−1.562	−1.578	2.1843	Mali	−2.809	−2.826	2.5799
Ecuador	−0.035	−0.035	1.1332	Malawi	−1.877	−1.893	2.1080
Dominican Rep.	−0.901	−0.915	1.8001	Zambia	−1.033	−1.044	1.7721

Notes: Shapley TFP-path component $D^{\text{TFP}}_{Y/N,i}$ of Section 4.3, pp/yr, under the WPP 2024 low (Low) and medium (Med) fertility baselines. $N = 22$ above-frontier late-agers ($\hat{g}_{A,i} > g^* = 1.11\%$).

Tables 10 and 11 combine both channels into a single summary under the low-fertility

scenario, reporting for each economy the Shapley demographic drag, the TFP-path component, and total drag, all on $g_{Y/N}$. Under the fixed-working-age-share demographic counterfactual, total population is identical in baseline and counterfactual, so the Shapley aggregate-GDP drag equals the per-capita drag; aggregate baseline growth g_Y is separately available in Tables 6 and 7. Table 10 covers the 34 early-aging economies. For the majority of early-agers—Japan (−0.292 pp), Germany (−0.240 pp), France (−0.174 pp), and most of Western Europe—TFP growth lies in the interval $[0, g^*]$, so the no-transition TFP path is identical to the baseline and the TFP-path component is zero: total per-capita drag equals demographic drag and ranges roughly −0.157 to −0.397 pp. A separate pattern arises for economies with historically *negative* TFP growth: Bulgaria, Italy, and Ukraine carry positive TFP-path components (tailwinds) because the baseline's convergence to zero improves on the no-transition counterfactual's permanently negative productivity path. These tailwinds partially offset the demographic headwind in total per-capita drag. A distinct sub-group of post-Soviet early-agers that began the sample period well below the frontier face both channels simultaneously and carry the largest total burdens: Poland (−1.762 pp/yr total per-capita: demographic −0.498, TFP −1.264 pp), Slovakia (−1.493 pp/yr), Czechia (−1.153 pp/yr), Slovenia (−0.996 pp/yr), and Estonia (−1.070 pp/yr). Latvia and Lithuania, despite smaller demographic drags (−0.314 and −0.463 pp respectively), face large total per-capita burdens (−0.931 and −0.793 pp) because their TFP convergence costs are substantial. Hong Kong's total per-capita drag equals its demographic drag (−1.270 pp), since its TFP growth is at or below the frontier and there is no TFP transition component. Relative to Japan (−0.292 pp total), Hong Kong's situation is dramatically more severe despite its lower OADR, purely because of its steep projected dependency-ratio trajectory.

Table 10: Total Growth Drag, 2024–2100: Early-Aging Economies

Country	Dem Y/N	TFP Y/N	Total Y/N	**Country**	Dem Y/N	TFP Y/N	Total Y/N
Japan	−0.292	0.000	−0.292	Belgium	−0.238	0.000	−0.238
Finland	−0.216	−0.026	−0.243	Hungary	−0.217	−0.489	−0.706
Portugal	−0.225	0.000	−0.225	Spain	−0.397	0.000	−0.397
Italy	−0.341	0.108	−0.234	Netherlands	−0.267	−0.001	−0.268
Greece	−0.275	0.000	−0.275	Austria	−0.316	0.000	−0.316
Croatia	−0.355	−0.363	−0.717	Romania	−0.308	−0.274	−0.582
France	−0.174	0.000	−0.174	United Kingdom	−0.202	0.000	−0.202
Germany	−0.240	0.000	−0.240	Poland	−0.498	−1.264	−1.762
Serbia	−0.331	0.000	−0.331	Lithuania	−0.463	−0.330	−0.793
Latvia	−0.314	−0.617	−0.931	Switzerland	−0.295	0.000	−0.295
Bulgaria	−0.250	2.314	2.064	Canada	−0.207	0.000	−0.207
Slovenia	−0.274	−0.722	−0.996	Norway	−0.257	0.000	−0.257
Estonia	−0.326	−0.744	−1.070	USA	−0.161	0.000	−0.161
Sweden	−0.201	−0.265	−0.466	Ukraine	−0.456	0.653	0.198
Denmark	−0.225	0.000	−0.225	Slovakia	−0.367	−1.126	−1.493
Hong Kong	−1.270	0.000	−1.270	Australia	−0.162	−0.028	−0.190
Czechia	−0.224	−0.930	−1.153	New Zealand	−0.157	0.000	−0.157
Mean −0.309	−0.121	−0.430					

Notes: Low fertility, UN WPP 2024. Dem. Y/N = Shapley demographic drag on per-capita growth. TFP Y/N = Shapley TFP-path component (above-frontier TFP converges to $g^* = 1.11\%$ by 2045; below-zero TFP converges to zero, generating a positive component). Total Y/N = sum of both Shapley components on per-capita GDP. Under the fixed-working-age-share counterfactual, aggregate and per-capita Shapley drag are equal; baseline aggregate GDP growth g_Y is reported separately in Table 6. Negative = headwind; positive = tailwind. $N = 34$; sorted by 2024 OADR (descending).

Table 11 covers the 69 late-aging economies and shows a qualitatively different pattern. China faces the largest total per-capita drag among late-aging economies: −4.228 pp/yr, combining a demographic component of −0.813 pp/yr with a TFP-path component of −3.415 pp/yr. Korea also faces large pressure on both margins, with total per-capita drag of −1.208 pp/yr (−0.815 pp demographic plus −0.394 pp TFP-path component), but several other late-aging economies have larger total per-capita drags because of the TFP-path component: Kazakhstan (−1.550), Ireland (−1.431), and India (−1.400). Iraq records both the largest TFP-path component (−5.798 pp/yr) and the largest total per-capita drag of any country (−5.606 pp/yr) owing to its exceptional historical TFP growth rate, but it is not representative of the broader late-aging group. At the other end, economies such as Pakistan, Uganda, and Ethiopia have positive demographic tailwinds and no negative TFP-path component, so their total per-capita drag is close to zero or positive. The decomposition therefore separates two challenges: a demographic problem concentrated in rapidly aging economies such as Korea, Singapore, and China, and a TFP-transition problem concentrated in fast-catching-up economies such as China, India, Kazakhstan, and Ireland. The two problems coincide most clearly in China and Korea, which face headwinds from both channels simultaneously.

Table 11: Total Growth Drag, 2024–2100: Late-Aging Economies

Country	Dem Y/N	TFP Y/N	Total Y/N	**Country**	Dem Y/N	TFP Y/N	Total Y/N
South Korea	−0.815	−0.394	−1.208	Bangladesh	−0.125	0.000	−0.125
Belarus	−0.390	−0.154	−0.544	Paraguay	−0.060	0.000	−0.060
Russia	−0.146	0.000	−0.146	South Africa	−0.012	0.000	−0.012
Uruguay	−0.364	−0.490	−0.854	Cambodia	0.013	0.000	0.013
Ireland	−0.283	−1.148	−1.431	Uzbekistan	0.023	1.647	1.670
Iceland	−0.368	−0.298	−0.667	Bolivia	0.039	0.000	0.039
Israel	0.028	0.000	0.028	Philippines	−0.051	0.000	−0.051
Thailand	−0.426	0.000	−0.426	Egypt	0.068	0.000	0.068
China	−0.813	−3.415	−4.228	Mongolia	0.012	−2.193	−2.181
Chile	−0.514	0.000	−0.514	Guatemala	0.019	0.000	0.019
Argentina	−0.228	0.000	−0.228	Pakistan	0.250	0.000	0.250
Sri Lanka	−0.244	0.000	−0.244	Rwanda	0.254	−1.117	−0.863
Singapore	−0.610	−0.031	−0.641	Jordan	−0.020	0.000	−0.020
Costa Rica	−0.537	0.000	−0.537	Zimbabwe	0.353	0.000	0.353
Brazil	−0.348	0.000	−0.348	Honduras	−0.034	0.115	0.081
Türkiye	−0.364	0.255	−0.109	Senegal	0.226	0.000	0.226
Panama	−0.162	0.109	−0.053	Ghana	0.196	−1.150	−0.954
Tunisia	−0.310	−0.386	−0.696	Tanzania	0.349	0.000	0.349
Kazakhstan	0.011	−1.562	−1.550	Ethiopia	0.271	0.000	0.271
Peru	−0.213	0.000	−0.213	Iraq	0.193	−5.798	−5.606
Colombia	−0.365	0.000	−0.365	Nigeria	0.358	−2.238	−1.880
Viet Nam	−0.201	0.464	0.263	Angola	0.398	0.000	0.398
Ecuador	−0.248	−0.035	−0.283	Sudan	0.411	−0.286	0.125
Morocco	−0.196	0.000	−0.196	Niger	0.525	−0.703	−0.178
Mexico	−0.161	0.373	0.212	Mozambique	0.470	0.000	0.470
El Salvador	−0.240	0.000	−0.240	Mali	0.509	−2.809	−2.300
Dominican Rep.	−0.133	−0.901	−1.034	Cameroon	0.352	0.000	0.352
Azerbaijan	−0.136	7.513	7.377	Kenya	0.255	0.178	0.433
Iran	−0.305	0.000	−0.305	Burkina Faso	0.404	0.000	0.404
Malaysia	−0.205	0.000	−0.205	Malawi	0.352	−1.877	−1.525
Indonesia	−0.128	0.000	−0.128	Côte d'Ivoire	0.318	0.000	0.318
Myanmar	−0.072	1.499	1.426	Uganda	0.335	0.000	0.335
India	−0.224	−1.175	−1.400	Saudi Arabia	−0.020	3.163	3.142
Algeria	−0.059	0.094	0.035	Zambia	0.326	−1.033	−0.707
Nepal	−0.035	0.000	−0.035				
Mean	−0.041	−0.200	−0.241				

Notes: Low fertility, UN WPP 2024. Dem. Y/N = Shapley demographic drag on per-capita growth. TFP Y/N = Shapley TFP-path component. Total Y/N = sum of both Shapley components on per-capita GDP. See Table 10 notes for the relationship to aggregate baseline growth. Negative = headwind; positive = tailwind. $N = 69$; sorted by 2024 OADR (descending).

4.7 Growth Drag and Fiscal Adjustment

The Solow results can now be compared with the fiscal adjustment measure from Section 3.6. The comparison should be interpreted as a correlation between two summary statistics, not as a causal effect of growth on retirement ages. The FRA measure asks how much the retirement boundary would have to move in order to hold each country's 2024 OADR fixed through 2100. The growth-drag measures ask how much projected aging and TFP-path transitions change growth relative to transparent counterfactuals. Both are driven by demographic structure, but they capture different margins of adjustment.

Two patterns are useful. First, aging speed is informative about fiscal urgency: countries that move from OADR 25% to 50% in fewer years require larger FRA postponements to stabilize the 2024 OADR. Second, the growth-drag measures are less tightly related to aging speed because they depend on the remaining decline in working-age population shares after

2024 and, for TFP-path component, on each country's recent productivity growth. Thus the fiscal and growth results capture distinct margins of the demographic transition: China and Korea are severe cases on both margins, while some economies have large FRA adjustments but modest near-term Solow drag, and others have sizable TFP-path component even though their aging transition is less advanced.

The orthogonality result is useful for interpretation. Table 12 reports the correlations between compression speed and the fiscal and growth statistics. The speed measure for the critical OADR 25–50 percent range ($\rho = -0.69$) is strongly related to the required FRA increase: faster compression is associated with larger required retirement-age adjustments. By contrast, the same speed measure is nearly unrelated to aging drag ($\rho = 0.14$), TFP-path component ($\rho = 0.04$), or total drag ($\rho = 0.07$) in the Solow exercise. The earlier OADR 12.5–25 percent transition is slightly more correlated with the TFP-path component ($\rho = 0.07$) than the 25–50 percent transition ($\rho = 0.04$), consistent with the fact that many fast early-transition economies are also fast-converging economies, though the difference is small. The speed-column samples differ because not every country crosses both thresholds within 1950–2100: the effective sample is $N = 100$ for the $12.5\% \to 25\%$ transition and $N = 80$ for the $25\% \to 50\%$ transition, with countries that never reach the relevant upper threshold excluded from that column and countries already above the lower threshold in 1950 assigned the earliest available crossing year. The main message is that fiscal urgency and growth headwinds are distinct dimensions of the aging problem.

Table 12: Compression Speed, Fiscal Adjustment, and Growth Drag

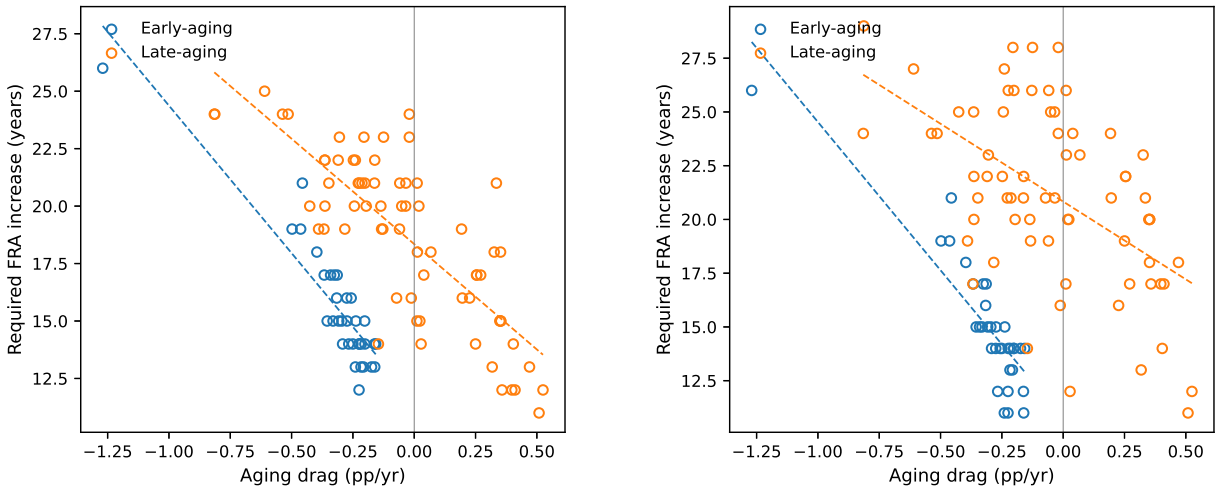
	Years between OADR thresholds	
Variable	$12.5\% \to 25\%$	$25\% \to 50\%$
OADR 65 in 2024	0.13	0.54
Required FRA increase to maintain 2024 OADR	−0.30	−0.69
Required FRA increase to reach Japan 2024 OADR	−0.15	−0.12
Required FRA increase to reach Japan 2050 OADR	−0.13	−0.24
Aging drag on $g_{Y/N}$	0.12	0.14
TFP-path component on $g_{Y/N}$	0.07	0.04
Total drag on $g_{Y/N}$	0.09	0.07

Notes: Pearson correlations across countries, low-fertility baseline. Only $g_{Y/N}$ correlations are reported because aggregate and per-capita components coincide under the Section 4.3 decomposition. Smaller speed values indicate faster compression; negative FRA correlations mean faster compression is associated with larger required adjustments. $N = 100$ ($12.5\% \to 25\%$) and $N = 80$ ($25\% \to 50\%$); see text.

Thus, the same demographic transition can create fiscal urgency without a proportionate Solow growth drag, or a large growth drag without being summarized by the retirement-age statistic alone.

Figure 5 provides the visual counterpart. Within each group the relationship is strong: the correlation between demographic drag and the required increase from age 65 is −0.89 among early-aging and −0.79 among late-aging economies (and −0.87 and −0.54, respectively, from statutory baselines)—countries with larger headwinds require larger adjustments. The pooled correlations are much weaker (−0.49 and −0.18) because the two groups occupy

different regions of the drag–FRA plane: late-agers combine modest drag with large required increases ahead of their OADR ascent. The relationship is therefore systematic within groups but not mechanical across them. This is why the paper presents OADR and FRA adjustments first, then introduces the Solow model before discussing growth headwinds and their correlations with fiscal pressure.



(a) FRA increase from age 65

(b) FRA increase from statutory FRA

Figure 5: Required FRA Increases and Aging Drag Under Low Fertility

Notes: Aging drag is the Shapley demographic component of Section 4.3, in percentage points per year; under the fixed-2024 working-age-share counterfactual the aggregate and per-capita components coincide. Negative values are growth headwinds; positive values are demographic tailwinds. Required FRA increases maintain 2024 OADRs through 2100. Panel (a) measures from a uniform age-65 baseline under low fertility; Panel (b) measures increases from each country's current statutory FRA under low fertility. Blue circles: the early-aging economies; orange circles: the late-aging economies. Dashed lines show within-group OLS fits; the corresponding correlations are −0.89 (early) and −0.79 (late) in Panel (a) and −0.87 (early) and −0.54 (late) in Panel (b). Data: UN WPP 2024 low-fertility variant, OECD *Pensions at a Glance* 2024, PWT 11.0.

4.8 Sensitivity to Alternative Working-Age Definitions

All baseline calculations use ages 20–64 as working age and 65+ as retirement age. To assess robustness, Appendix E replicates the analysis using ages 20–69 as working age and 70+ as retirement age. This five-year extension represents scenarios where countries successfully implement comprehensive policies extending working lives.

Table 13 presents a summary of key statistics under baseline (65+/20–64) and alternative (70+/20–69) age boundary specifications.

Table 13: Sensitivity Analysis: Alternative Age Boundaries (65+ vs. 70+ as Old Age)

	Baseline (65+/20–64)			**Alternative (70+/20–69)**		
Measure	Overall	Early	Late	Overall	Early	Late
Panel A: Correlations						
ρ(FRA inc., Drag)	−0.49	−0.89	−0.79	−0.49	−0.92	−0.78
ρ(OADR, FRA inc.)	−0.24	−0.20	0.40	−0.19	−0.28	0.42
Panel B: Mean FRA Inc. (yrs, Low)						
From baseline	17.7	15.5	18.7	16.6	15.0	17.4
Gap (Late − Early)		3.2			2.4	
Panel C: Mean Drag (pp, Low)						
Mean |drag|	0.27	0.31	0.25	0.25	0.27	0.24
Gap (Late − Early)		−0.06			−0.03	
Panel D: Range (yrs, Low)						
Minimum		Mali (11)			Mali (10)	
Maximum		Hong Kong (26)			Hong Kong (25)	
Panel E: Selected Countries						
China		24 (29)			21 (31)	
Korea		24 (24)			23 (28)	
Japan		14 (14)			14 (19)	
United States		13 (11)			14 (17)	

Notes: Baseline (65+/20–64) vs. alt. (70+/20–69) age boundaries. **Low** fertility, UN WPP 2024. N=34 early-aging, N=69 late-aging. ρ(FRA, Drag) uses the signed Shapley demographic drag (headwinds negative), consistent with Figure 5; Panel C reports its mean absolute value. The 70+ drag is from a re-simulation with ages 20–69 as labor input. Parentheses in Panel E: increase from statutory FRA (70-based under the alternative boundary). The within-group FRA–drag correlations are strong and significant (p<0.001) under both boundaries; the pooled correlation is attenuated because late-aging economies combine modest drag with large required increases. Singapore ties Hong Kong at 25 under the 70+ boundary. Medium fertility variant in Table 31, Appendix E.

Three findings emerge robustly. First, the within-group FRA–drag correlation is strong under both boundary definitions—−0.89 (early) and −0.79 (late) at the 65+ boundary, and −0.92 and −0.78 at 70+—so within each group, countries with larger demographic headwinds require larger retirement-age adjustments. The pooled (103-country) correlation is weaker (−0.49 under both boundaries), not because the relationship fails within the late-aging group but because the two groups occupy different regions of the drag–FRA plane: late-aging economies combine still-modest near-term drag with large required increases ahead of their OADR ascent. The association is therefore systematic within groups but not mechanical across them. Second, moving to the 70+ boundary changes mean required FRA increases only modestly (17.7 to 16.6 years overall), and the late-minus-early gap narrows from 3.2 to 2.4 years; the burden of required adjustment remains larger for late-agers under either definition. Third, mean |drag| falls only from 0.27 to 0.25 pp and country rankings are unchanged. Late-aging economies such as Korea (24–23 years) and China (24–21 years) face large FRA requirements under either boundary definition, and they must implement these adjustments within 14–25-year compression windows—the compressed-timeline conclusion is

robust.

4.9 The Chinese GDP Series

The baseline calibration uses PWT 11.0 throughout. For one country this choice is consequential. Beginning with version 11.0, PWT reports China on its official national accounts rather than the Maddison/Wu adjusted series used through version 10.01. Because the Solow residual is computed as $\log A = \log Y - \theta \log K - (1-\theta)\log L$, a revision to the output series passes directly into measured TFP growth: China's g_A over 1991–2019 is 3.84% on the official series, against a frontier growth rate of $g^* = 1.11\%$. The convergence drag reported in Table 7 is therefore larger for China than for any other economy in the sample, and it is worth asking how much of that reflects the output series rather than China's position relative to the frontier.

Table 14 recomputes the decomposition under the alternative series. Stripping 2.53 percentage points per year from the output path—the gap between the two vintages—and rescaling the capital stock proportionally lowers g_A to 2.37% and the convergence drag from -3.42 to -1.56. Holding the capital stock at its baseline values, which bounds the case in which only measured output is revised, lowers the drag further to -0.25.

Table 14: China's drag decomposition under alternative GDP series

Chinese GDP series	g_A	Demographic	TFP-path	Total
Official (PWT 11.0, baseline)	3.84%	−0.81	−3.42	−4.23
Maddison/Wu, K rescaled	2.37%	−0.79	−1.56	−2.36
Maddison/Wu, K unrevised	1.31%	−0.78	−0.25	−1.02

Note: drag components in annualized percentage points of per-capita output growth, averaged over 2025–2100, low-fertility variant. g_A is the Solow residual over 1991–2019; the frontier is $g^* = 1.11\%$ (United States) and all three rows lie above it, so the convergence branch of equation (6) applies in each case and the comparison is not affected by the piecewise structure of the TFP path. The Maddison/Wu rows strip 2.53 percentage points per year from the output path, the difference between the two PWT vintages in China's annualized per-capita growth over 1990–2020. The second row rescales the capital stock proportionally, on the grounds that PWT constructs capital stocks by perpetual inventory from investment measured as a share of the same output series; it is the more realistic of the two. The third row holds the capital stock at its baseline values and bounds the case in which only measured output is revised. Only China's calibration is altered; all other countries and all demographic inputs are as in the baseline.

The demographic drag is -0.81, -0.79, and -0.78 across the three rows. A fourteen-fold change in the convergence drag moves it by three hundredths of a percentage point. The reason is structural rather than coincidental: the demographic component is identified by the difference between the projected working-age share and the share locked at its 2024 value, and both paths are taken from the UN projections, which contain no output data at all. The output series affects the level of the growth path along which the demographic counterfactual is evaluated, but it enters baseline and counterfactual symmetrically and cancels in the difference.

The substantive conclusion of Section **??** for China survives in weakened form. Convergence remains the larger of the two channels, but by roughly two to one rather than four

to one, and the total drag is closer to −2.4 than to −4.2. More generally, the exercise locates the sensitivity precisely: what depends on the contested Chinese output series is the TFP-path component, and what does not is the demographic component that the paper's central comparison rests on. Notably, Hayashi (2026) makes the opposite baseline choice—retaining the **?**) series for China rather than the official PWT 11.0 figures, on the ground that autocracies tend to overstate measured growth—which sharpens his China–U.S. growth comparison but leaves the present paper's demographic conclusion unaffected, precisely because that conclusion rests on the component the output series does not touch.

4.10 Policy Illustration: Automatic Adjustment and Unfunded Obligations

The cross-country exercises above deliberately avoid modeling each country's pension system in detail. They instead summarize fiscal pressure with required retirement-age adjustments and summarize growth pressure with aging and TFP-path components. Appendix F converts these pressures into a common stock measure—a balanced-2023 demographic gap for OASI systems—across the broader set of economies for which expenditure data are available, while Appendix G uses the United States and Japan to illustrate the same stock-measure logic in more institutional detail. Neither exercise is intended as a full cross-country pension accounting model. Rather, both illustrate the fiscal value of early automatic adjustment. Japan's 2004 macroeconomic slide substantially reduces projected unfunded obligations by linking benefit growth to demographic conditions. In a stylized U.S. exercise, applying a similar cost-side adjustment beginning in 2024 reduces projected OASI unfunded obligations from $23.2 trillion to $11.2 trillion, or from 83.8 percent to 40.6 percent of 2023 GDP. These calculations reinforce the main message of the paper: automatic mechanisms are most valuable when adopted before dependency ratios reach extreme levels.

5 Conclusion

This paper distinguishes three dimensions of population aging: its endpoint, the speed of the transition, and its effect on growth. Its main contribution is to show that these dimensions cannot be summarized by a single measure. In particular, the calendar time available for adjustment is central to fiscal urgency but is nearly orthogonal to the demographic growth effect in a standard Solow accounting.

The first result is that late-aging economies face a compressed transition. Early-aging economies such as Japan and much of Western Europe moved through high OADR thresholds gradually. Many late-aging economies start from lower OADRs in 2024 but reach extreme levels by 2100 under low fertility. Korea and China are the clearest cases, but Brazil, Türkiye, Thailand, Chile, Colombia, and several other middle-income economies also face large increases before they reach the institutional and income levels at which earlier aging countries implemented major reforms.

The second result is that the implied adjustment is very large when expressed as a demographically equivalent retirement boundary. Reproducing 2024 OADRs in 2100 yields boundary changes that exceed historical experience for many late-aging economies. Because

the calculation abstracts from health, employment, hours, and productivity at advanced ages, these values are accounting equivalents rather than feasible policy targets. Extreme values demonstrate that retirement-age changes alone cannot stabilize the support ratio; the adjustment must also operate through contributions, benefits, general revenues, participation, immigration, and other margins. The point of the calculation is comparability. It shows that the countries with the most compressed transitions also have the least time to spread adjustment across cohorts.

The third result concerns growth. The demographic growth effect captures the contribution of projected working-age shares relative to a locked-age-structure counterfactual. The separate TFP-normalization effect is a scenario for productivity convergence, not a causal effect of aging. For above-frontier economies it is a headwind from recent TFP growth converging toward the U.S. frontier rate; for below-zero economies it is a tailwind from historical TFP growth converging up to zero. The combined calculation identifies cases in which demographic compression may coincide with the normalization of catch-up growth, without attributing that normalization to aging itself.

The fourth result is that fiscal pressure and growth pressure capture distinct margins of the demographic transition. The speed of aging from OADR 25 percent to 50 percent strongly predicts the retirement-boundary adjustment, but is close to orthogonal to Solow demographic drag. For early-aging economies this transition lies in the past, so growth drag over 2024–2100 is subsequent to the transition window. For late-aging economies such as Korea and China, however, the 25–50 percent transition overlaps substantially with the projection period; the orthogonality therefore describes contemporaneous differences between fiscal urgency and the demographic growth effect, not a temporal sequence. The OADR and retirement-boundary tables measure the scale and urgency of pension-system adjustment. The Solow tables separately measure the demographic growth effect and the TFP-normalization scenario. China and Korea are severe cases on both dimensions, but the dimensions need not move one-for-one across the full sample.

The policy implication is not that all countries should respond with the same instrument. Pension institutions, labor markets, health conditions, informality, and political constraints differ widely. The implication is instead that late adjustment is costly. Japan's 2004 macroeconomic slide illustrates the value of adopting automatic adjustment rules before dependency ratios become extreme: Appendix G shows that the slide reduces Japan's projected unfunded pension obligations by roughly 50 percentage points of GDP, and a stylized version applied to U.S. Social Security would cut projected unfunded obligations from 84 to 41 percent of GDP. Countries that wait until OADRs approach Japan's current level will have less room for gradual indexation and will need sharper changes in benefits, contributions, or retirement ages.

Several limitations remain. The paper does not solve a full overlapping-generations model for each country, does not model behavioral responses to retirement-age changes, and abstracts from distributional consequences within countries. It also treats the Solow model as an accounting device rather than as a complete theory of aging and growth. These limitations reflect the paper's goal of cross-country comparability rather than country-specific precision. The central conclusion is robust: many late-aging economies face large fiscal adjustments with unusually little calendar time in which to distribute them. Some fast-converging economies may simultaneously experience slower productivity catch-up, but this

is not a universal implication of late aging. The relevant policy question is therefore not whether aging countries must adjust, but how early they adopt automatic mechanisms that spread the adjustment across cohorts before demographic compression makes gradual reform politically and fiscally harder.

References

Acemoglu, D. and P. Restrepo (2017). Secular stagnation? the effect of aging on economic growth in the age of automation. *American Economic Review 107*(5), 174–179.

Aksoy, Y., H. S. Basso, R. P. Smith, and T. Grasl (2019). Demographic structure and macroeconomic trends. *American Economic Journal: Macroeconomics 11*(1), 193–222.

An, C.-B. and S.-H. Jeon (2006). Demographic change and economic growth: An inverted-U shape relationship. *Economics Letters 92*(3), 447–454.

Auerbach, A. J. and L. J. Kotlikoff (1987). *Dynamic Fiscal Policy*. Cambridge, UK: Cambridge University Press.

Bloom, D. E., D. Canning, G. Fink, and J. E. Finlay (2007, November). Fertility, female labor force participation, and the demographic dividend. Working Paper 13583, National Bureau of Economic Research.

Braun, R. A. and D. H. Joines (2015). The implications of a graying Japan for government policy. *Journal of Economic Dynamics and Control 57*, 1–23.

Congressional Budget Office (2025). The demographic outlook: 2025 to 2055. Technical report, Congressional Budget Office, Washington, DC.

Cutler, D. M., J. M. Poterba, L. M. Sheiner, and L. H. Summers (1990). An aging society: Opportunity or challenge? *Brookings Papers on Economic Activity 1990*(1), 1–73.

De Nardi, M., S. İmrohoroğlu, and T. J. Sargent (1999). Projected u.s. demographics and social security. *Review of Economic Dynamics 2*(3), 575–615.

European Commission, Directorate-General for Economic and Financial Affairs (2024). The 2024 ageing report: Economic and budgetary projections for the eu member states (2022–2070). European Economy Institutional Paper 279, European Commission, Brussels.

Eurostat (2025). Pension expenditure by function (ESSPROS). European System of Integrated Social Protection Statistics, online data code `spr_exp_pens`. Old-age and survivors functions, % of GDP, reference year 2023.

Feenstra, R. C., R. Inklaar, and M. P. Timmer (2015). The next generation of the Penn World Table. *American Economic Review 105*(10), 3150–82.

Fernández-Villaverde, J., L. Ohanian, and W. Yao (2026, January). The neoclassical growth of china. Unpublished manuscript.

Fernández-Villaverde, J., G. Ventura, and W. Yao (2025). The wealth of working nations. *European Economic Review 173*, 104962.

Fernández-Villaverde, J. (2025). The demographic future of humanity: Facts and consequences. Working Paper, University of Pennsylvania.

GBD 2021 Fertility and Forecasting Collaborators (2024). Global fertility in 204 countries and territories, 1950–2021, with forecasts to 2100: A comprehensive demographic analysis for the global burden of disease study 2021. *The Lancet 403*(10440), 2057–2099.

Hansen, G. and S. İmrohoroğlu (2016). Fiscal reform and government debt in japan: A neoclassical perspective. *Review of Economic Dynamics 21*, 201–224.

Hansen, G. D. and S. İmrohoroğlu (2023, October). Demographic change, government debt and fiscal sustainability in japan: The impact of bond purchase by the bank of japan. *Review of Economic Dynamics 50*, 88–105.

Hayashi, F. (2026). The root cause of japan's 30-year stagnation: Implications for china, the u.s., and other mature economies. Working Paper, GRIPS, Tokyo.

Holzmann, R., E. Palmer, and D. Robalino (2017). *Nonfinancial Defined Contribution Pension Schemes in a Changing Pension World: Volume 2, Gender, Politics, and Financial Stability*. Washington, DC: World Bank Publications.

Huang, H., S. İmrohoroğlu, and T. J. Sargent (1997). Two computations to fund social security. *Macroeconomic Dynamics 1*(1), 7–44.

İmrohoroğlu, S., S. Kitao, and T. Yamada (2016). Achieving fiscal balance in Japan. *International Economic Review 57*(February), 117–154.

İmrohoroğlu, S. and N. Sudo (2011). Productivity and fiscal policy in Japan: Short-term forecasts from the standard growth model. *Monetary and Economic Studies, Institute for Monetary and Economic Studies, Bank of Japan 29*(November), 73–106.

International Monetary Fund (2025, April). Fiscal monitor: Fiscal policy under uncertainty. Technical report, International Monetary Fund, Washington, DC.

Jones, G. W. (2019). Ultra-low fertility in east asia: policy responses and challenges. *Asian Population Studies 15*(2), 131–149.

Kearney, M. S. and P. B. Levine (2022). The puzzle of falling US birth rates since the Great Recession. *Journal of Economic Perspectives 36*(1), 151–176.

Kitao, S. (2015). Fiscal cost of demographic transition in japan. *Journal of Economic Dynamics and Control 54*, 37–58.

Kotlikoff, L. J. (1997). Privatizing social security in the united states: Why and how. In A. J. Auerbach (Ed.), *Fiscal Policy: Lessons from Economic Research*, pp. 213–248. Cambridge, MA: MIT Press.

Kotlikoff, L. J., K. Smetters, and J. Walliser (1999). Privatizing social security in the U.S.: Comparing the options. *Review of Economic Dynamics 2*(3), 531–573.

Kotschy, R. and D. E. Bloom (2023). Population aging and economic growth: From demographic dividend to demographic drag? Working Paper 31585, National Bureau of Economic Research.

Kwon, Y., S. Lee, and G. A. Pouliot (2024). Group Shapley value and counterfactual simulations in a structural model.

Lee, R. and A. Mason (Eds.) (2011). *Population Aging and the Generational Economy: A Global Perspective*. Cheltenham, UK and Northampton, MA: Edward Elgar Publishing.

Maestas, N., K. J. Mullen, and D. Powell (2023). The effect of population aging on economic growth, the labor force, and productivity. *American Economic Journal: Macroeconomics 15*(2), 306–332.

OECD (2023). *Pensions at a Glance 2023: OECD and G20 Indicators*. Paris: OECD Publishing.

OECD (2025). *Pensions at a Glance 2025: OECD and G20 Indicators*. Paris: OECD Publishing.

Shapley, L. S. (1953). A value for n-person games. In H. W. Kuhn and A. W. Tucker (Eds.), *Contributions to the Theory of Games, Volume II*, Number 28 in Annals of Mathematics Studies, pp. 307–317. Princeton, NJ: Princeton University Press.

Shorrocks, A. F. (2013). Decomposition procedures for distributional analysis: a unified framework based on the shapley value. *The Journal of Economic Inequality 11*(1), 99–126.

Social Security Administration, Office of the Chief Actuary (2024). The long-range demographic assumptions for the 2024 trustees report. Technical report, Social Security Administration, Baltimore, MD.

United Nations, Department of Economic and Social Affairs, Population Division (2024). World population prospects 2024: Online edition. United Nations Population Division. Accessed January 2025. Data files downloaded for old-age dependency ratio (population 65+/population 20-64) projections.

Appendix roadmap. The appendix collects sample details, calibration information, and robustness checks that support the main text. Appendix A lists the countries in the 103-economy sample and shows the early- and late-aging classification used throughout the paper. Appendix B compares the UN WPP fertility variants with alternative fertility projections and explains why the low-fertility variant is used as the baseline, while the medium-fertility variant is reported as an optimistic benchmark. Appendix C reports the calibrated Solow parameters for all countries and describes the construction of depreciation rates, capital shares, investment rates, and historical TFP growth rates from Penn World Table data. Appendix D examines the implications of using working-age population rather than employment as the labor input, and documents the robustness of the growth-accounting exercise to this choice. Appendix E reports the medium-fertility counterparts to the main low-fertility results, including the medium-fertility OADR, retirement-age, growth-drag, and age-boundary sensitivity tables. Appendix F converts the demographic pressure into a simple cross-country balanced-2023 demographic-pension gap for the economies with available public pension expenditure data. Appendix G provides the more detailed United States and Japan unfunded-obligation calculations, including the fiscal effect of Japan's macroeconomic slide and the stylized U.S. automatic-adjustment exercise.

A Country Sample and Early/Late-Aging Classification

The sample comprises 103 economies spanning all major world regions and levels of economic development. Countries are classified using their 2024 old-age dependency ratio (OADR), defined in Section 3 as the population aged 65 and above relative to the population aged 20–64: countries with a 2024 OADR of 30 percent or higher are classified as *early-aging* (34 countries, Table 15), and countries with a 2024 OADR below 30 percent are classified as *late-aging* (69 countries, Table 16). As discussed in Section 3, this 30 percent cutoff produces a level-based taxonomy rather than a direct measure of transition speed, and the paper's main findings are robust to alternative cutoffs of 28 and 32 percent. Within each table, countries are listed in the same order as Tables 1 and 2 (2024 OADR, descending).

Table 15: Early-Aging Economies (34 Countries)

Japan	Germany	Denmark	Austria	Norway
Finland	Serbia	Hong Kong	Romania	United States
Portugal	Latvia	Czechia	United Kingdom	Ukraine
Italy	Bulgaria	Belgium	Poland	Slovakia
Greece	Slovenia	Hungary	Lithuania	Australia
Croatia	Estonia	Spain	Switzerland	New Zealand
France	Sweden	Netherlands	Canada	

Notes: Ordered by 2024 OADR (descending), reading down each column before proceeding to the next, consistent with Table 1.

Table 16: Late-Aging Economies (69 Countries)

South Korea	Brazil	Iran	Egypt	Angola
Belarus	Türkiye	Malaysia	Mongolia	Sudan
Russia	Panama	Indonesia	Guatemala	Niger
Uruguay	Tunisia	Myanmar	Pakistan	Mozambique
Ireland	Kazakhstan	India	Rwanda	Mali
Iceland	Peru	Algeria	Jordan	Cameroon
Israel	Colombia	Nepal	Zimbabwe	Kenya
Thailand	Viet Nam	Bangladesh	Honduras	Burkina Faso
China	Ecuador	Paraguay	Senegal	Malawi
Chile	Morocco	South Africa	Ghana	Côte d'Ivoire
Argentina	Mexico	Cambodia	Tanzania	Uganda
Sri Lanka	El Salvador	Uzbekistan	Ethiopia	Saudi Arabia
Singapore	Dominican Republic	Bolivia	Iraq	Zambia
Costa Rica	Azerbaijan	Philippines	Nigeria	

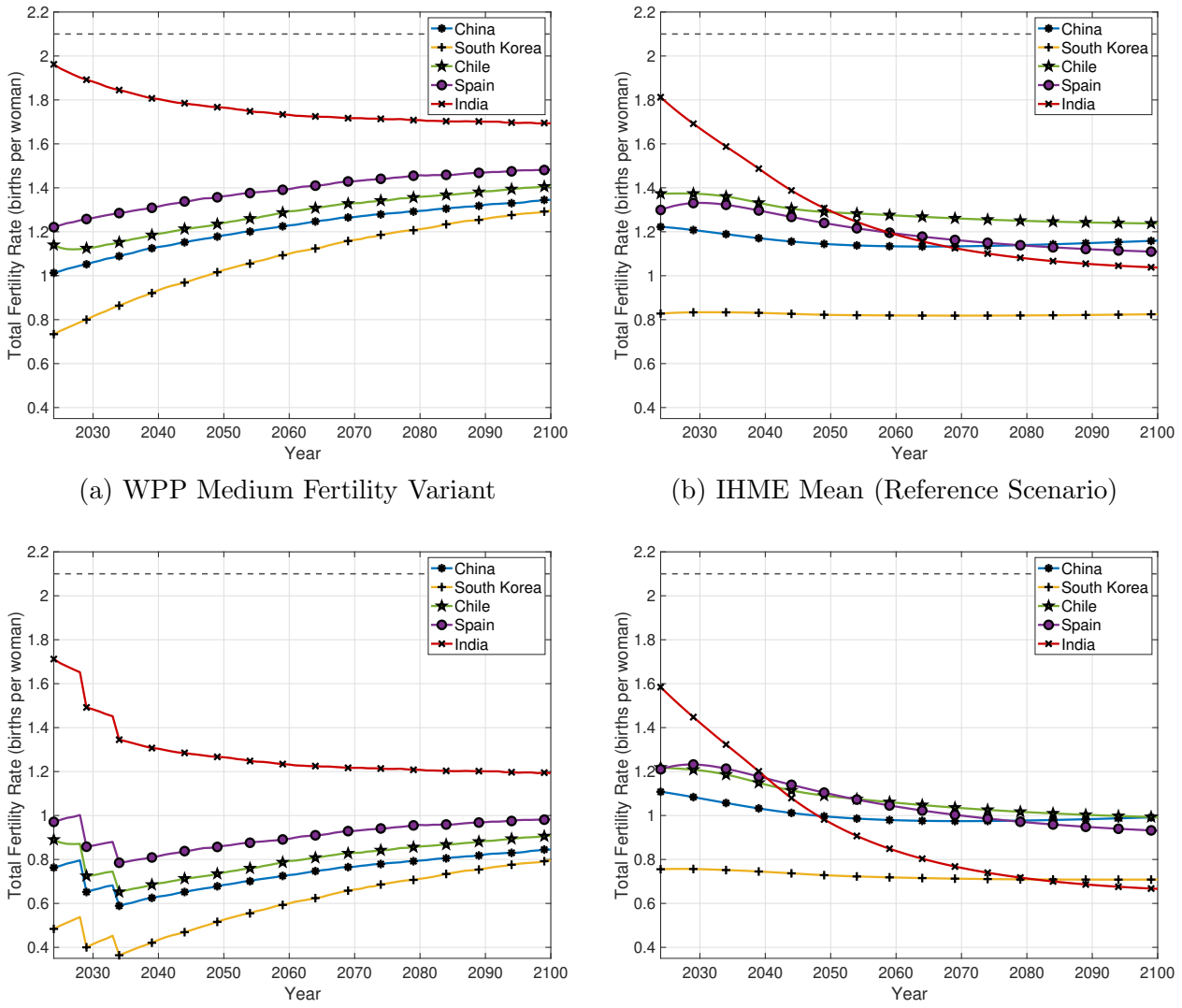
Notes: Ordered by 2024 OADR (descending), reading down each column before proceeding to the next, consistent with Table 2.

B Fertility Projection Comparison

The choice of fertility scenario has large consequences for projected old-age dependency ratios. Because fertility determines the size of the working-age cohorts entering the labour market from 2040 onward, a difference of even 0.3–0.5 in the assumed long-run total fertility rate (TFR) compounds into dramatically different OADR levels by 2080–2100. This appendix compares the four scenarios used to bound uncertainty in the main analysis: the UN World Population Prospects (WPP 2024) medium and low variants, and the Institute for Health Metrics and Evaluation (IHME) Global Burden of Disease reference-scenario mean and lower-bound projections.

The WPP medium variant assumes that below-replacement countries gradually recover fertility toward intermediate levels—typically 1.4–1.7 children per woman for East Asia and 1.6–1.9 for Southern Europe—by mid-century. The WPP low variant, by contrast, holds long-run fertility roughly half a child below the medium path, which the UN defines probabilistically as the 20th percentile of its demographic model. The IHME projections are methodologically independent: they use a socio-demographic regression framework rather than the UN's cohort-component method, and they incorporate education, female labour-force participation, and access to contraception as explicit drivers of fertility change. The IHME lower bound represents the pessimistic tail of the IHME uncertainty distribution, corresponding broadly to scenarios where female empowerment and economic development accelerate fertility decline beyond what the reference model projects.

Figure 6 plots projected TFRs for five illustrative economies: China, South Korea, Chile, Spain, and India. These span a wide range of current fertility levels and cover the key analytical cases discussed below. The horizontal dashed line at 2.1 marks replacement-level fertility.



(a) WPP Medium Fertility Variant

(b) IHME Mean (Reference Scenario)

(c) WPP Low Fertility Variant

(d) IHME Lower Bound

Figure 6: Total Fertility Rate Projections for Selected Countries (2024–2100). Panel (a) shows the UN World Population Prospects medium fertility variant. Panel (b) shows the IHME reference-scenario mean projection. Panel (c) shows the WPP low fertility variant. Panel (d) shows the IHME lower-bound projection. The horizontal dashed line at 2.1 indicates replacement-level fertility.

Several patterns stand out.

Korea: the pessimistic case. South Korea recorded a TFR of approximately 0.72 in 2023—the lowest ever measured for any large economy. The WPP medium variant embeds a substantial recovery toward 1.4–1.5 by 2050. The IHME reference scenario is considerably more pessimistic, remaining closer to 0.9–1.0 for Korea through mid-century, consistent with observed trends and the social dynamics driving delayed marriage and childlessness in East Asian societies. The divergence between WPP medium and IHME reference is largest for Korea, and it is precisely this divergence that accounts for the largest differences in projected

OADRs shown in the main tables: under WPP medium Korea's OADR reaches 105.9% by 2100, while under WPP low it reaches 196.2%. The IHME reference sits closer to WPP low, suggesting that WPP low—the main paper's baseline—is the better "central" case for these economies rather than an extreme pessimistic scenario.

China: structural break from the one-child era. China's TFR fell from around 1.7 in the early 2010s to an estimated 1.0–1.1 by 2022–2023, despite the reversal of the one-child policy in 2016 and the pronatalist incentives introduced since 2021. WPP medium assumes a gradual recovery to approximately 1.4 by 2050. The IHME reference is notably lower, projecting little rebound and sustained fertility below 1.2 through 2050. Because China's working-age population is already declining, the difference between these paths matters acutely: moving from WPP medium to WPP low raises China's 2100 OADR from 106% to 207%—a doubling of the old-age burden that depends almost entirely on the fertility assumptions made for the 2025–2050 birth cohorts.

India: intermediate trajectory. India currently has a TFR around 2.0, close to but still slightly above replacement. All four scenarios agree on continued gradual decline, with WPP medium and IHME reference projecting convergence toward 1.6–1.8 by mid-century. The divergence between scenarios is moderate compared to East Asia. India's aging trajectory therefore lies between the extremes: a meaningful long-run increase in the OADR, but at a pace closer to Western Europe than to Korea or China.

Chile and Spain: mid-range low fertility. Chile and Spain both have TFRs around 1.5–1.6, below replacement but substantially higher than East Asia. The WPP medium and low variants bracket a moderate range, with the IHME reference generally sitting between them for these economies. The consequence is that their projected OADR outcomes are less sensitive to scenario choice than Korea or China, though both face substantial aging under any scenario.

High-fertility economies (not shown in figure). For Sub-Saharan African economies such as Nigeria, Niger, Mali, and Uganda, TFRs of 4.5–7.0 remain far above replacement across all four scenarios through mid-century. All scenarios agree on a downward trajectory, but differ on pace. Even under the WPP low variant, Sub-Saharan Africa retains TFRs well above replacement through mid-century, which is why these economies show demographic *tailwinds* in the Solow model: their working-age populations continue expanding rapidly regardless of which scenario is used.

United States and Western Europe (not shown in figure). The United States, France, and Sweden have TFRs of 1.6–1.8—below replacement but substantially higher than East Asia. For these economies, the WPP medium and low variants are close, and the IHME reference scenario sits between them. The consequence is that US and Western European projected OADRs are relatively insensitive to the choice of scenario: the gap between WPP medium and WPP low OADRs in 2100 is on the order of 15–25 percentage points for these economies, compared with 80–100 percentage points for Korea and China.

Why WPP low is the baseline. The comparison supports the main text's choice to use WPP low fertility as the primary baseline for three reasons. First, for the economies with the most severe projected aging—Korea, China, Japan—the IHME reference scenario is closer to WPP low than to WPP medium, meaning that WPP medium embeds a more optimistic fertility rebound than the independent IHME methodology endorses. Second, realised fertility in 2020–2023 has surprised on the downside relative to WPP 2019 medium projections in virtually all low-fertility countries: WPP 2024 has already revised the medium path downward for Korea, China, and Japan compared with earlier editions. Third, because the fiscal and growth-drag results are most consequential for the scenarios that place the heaviest burden on pension systems, presenting the WPP low results as the central case and the WPP medium results as the optimistic alternative is the more appropriate framing for a policy audience.

This rationale applies most forcefully to the ultra-low-fertility economies (Korea, China, Japan) where the two scenarios diverge most dramatically. For high-fertility Sub-Saharan African and South Asian economies, where both WPP scenarios project fertility well above replacement through mid-century, the low-fertility variant is better interpreted as a stress scenario applied uniformly for cross-country comparability rather than as a central demographic forecast. The medium-fertility tables in Appendix E provide the counterpart results, and for high-fertility economies the two scenarios yield broadly similar conclusions about demographic drag direction and the relative ordering of countries.

The comparison shows why the WPP medium variant is best interpreted as an optimistic benchmark rather than as the only central case. WPP medium assumes a gradual rebound in fertility, while the IHME reference scenario is closer to WPP low for several economies where observed fertility has recently surprised on the downside. The discrepancy is especially relevant for China and Korea, where projected OADRs are highly sensitive to the size of cohorts born over the next several decades. The figures therefore support the main text's choice to use WPP low fertility as the baseline and to place WPP medium results in Appendix E.

C Calibrated Parameters

Table 18 reports the four model parameters calibrated from Penn World Table 11.0 data over 1991–2019 for all 103 economies in the sample. The full calibrated parameters for all 103 economies appear as Table 18 in the appendix. This appendix describes the calibration procedure, discusses cross-country heterogeneity in each parameter, and flags notable outliers.

Depreciation rate $\widehat{\delta}$. The depreciation rate is computed as the average of the PWT variable `delta` (economic depreciation of the capital stock) over 1991–2019. Across the 103 economies, $\widehat{\delta}$ ranges from 2.5% (Ukraine, Latvia) to 7.9% (Myanmar), with a cross-country mean of 4.3%. Advanced economies cluster in the 3.5–4.5% range, consistent with the standard macroeconomic calibration of approximately 4–5% per year. Several transition economies (Ukraine, Latvia) have unusually low estimated depreciation, possibly reflecting underreported retirement of Soviet-era capital stock during the 1990s. High values

for Myanmar (7.9%), Pakistan (7.6%), and Romania (7.3%) reflect more rapid turnover of shorter-lived capital assets in manufacturing-intensive or rapidly industrializing economies.

Capital share $\widehat{\theta}$. The capital share is computed as $\widehat{\theta} = 1 - \overline{\text{labsh}}$, where $\overline{\text{labsh}}$ is the PWT average labour compensation share of GDP over 1991–2019. To prevent implausibly high capital shares driven by measurement error or resource-sector income, $\widehat{\theta}$ is winsorized to the interval $[0.25, 0.65]$. The upper bound of 0.65 binds for 31 economies, predominantly resource-dependent countries (Algeria, Angola, Iraq, Saudi Arabia) and several low-income Sub-Saharan African economies where labour income is difficult to measure separately from mixed agricultural income. The lower bound of 0.25 does not bind for any economy in the sample. Conditional on not being winsorized, the capital share ranges from 0.259 (Rwanda) to 0.647 (Mexico), with a mean of approximately 0.47. Canada (0.336), Portugal (0.373), and the United States (0.394) have relatively low capital shares, consistent with their high labour compensation ratios. Korea (0.459) and China (0.422) are in the middle of the distribution.

Investment (saving) rate $\widehat{s}$. The saving rate is the average of the PWT investment-to-GDP ratio `csh_i` over 1991–2019. Across the 103 economies, $\widehat{s}$ ranges from 6.6% (Zimbabwe) to 40.0% (Singapore), with a mean of 22.1%. The East Asian high savers stand out: Singapore (40.0%), China (37.5%), and South Korea (37.3%) all have saving rates roughly double the sample mean, consistent with the well-documented East Asian saving puzzle. At the low end, Zimbabwe (6.6%), Côte d'Ivoire (9.6%), and Egypt (10.5%) reflect periods of severe economic and political instability that suppressed domestic investment over the calibration window. The saving rate matters for the Solow projection because it determines how quickly the capital stock adjusts to shocks in working-age population; economies with high $\widehat{s}$ accumulate replacement capital faster when labour supply contracts.

TFP growth rate $\widehat{g}_A$. The TFP growth rate is the centrepiece of the calibration. It is computed as the average annual log-difference of the Hicks-neutral Solow residual $A_t = Y_t/(K_t^{\widehat{\theta}} N_{w,t}^{1-\widehat{\theta}})$ over 1991–2019, where $N_{w,t}$ is WPP 2024 working-age population (ages 20–64) rather than PWT employment (see Appendix D).

The resulting $\widehat{g}_A$ values span a wide range: from -6.35% per year (Azerbaijan) to $+4.24\%$ per year (Iraq), with a cross-country mean of 0.81%. The negative values deserve particular attention.[9] Azerbaijan's $\widehat{g}_A = -6.35\%$ reflects the severe disruption of the 1991–1995 post-Soviet collapse and subsequent dependence on oil revenues whose GDP contribution is highly volatile; similarly, Saudi Arabia's -2.17% and Uzbekistan's -1.37% reflect resource-sector volatility and transition costs. Bulgaria (-1.87%) experienced deep output contraction in the late 1990s following the 1996–97 banking crisis. These economies have

[9]Because $\widehat{g}_A$ is a Solow residual, it turns negative whenever measured inputs grow faster than output, not only when technology regresses. In Saudi Arabia, the working-age population roughly tripled over 1991–2019 and oil revenue financed steady capital accumulation, while real output was constrained by OPEC quantity restraint rather than productivity, so the residual declines mechanically. Azerbaijan combines the 1991–95 post-Soviet output collapse with an oil boom in which extraction capital and labor grew rapidly against volatile constant-price oil output; Uzbekistan and Bulgaria reflect transition disruption, the latter culminating in the 1996–97 banking crisis. The zero-growth floor of Section 4.3 prevents these episode-driven residuals from being extrapolated over a 75-year horizon.

$\widehat{g}_A < 0$; under the model's convergence rule, their baseline TFP growth converges upward to zero by 2045, while the no-transition counterfactual would keep TFP growth at the (negative) historical rate. The baseline therefore *improves* relative to the counterfactual, generating a *positive* TFP-path component (a tailwind) for these economies, as reflected in Table 11 for Azerbaijan, Myanmar, and similar cases. The large positive TFP entry for Azerbaijan in that table (TFP $Y/N = +7.513$) reflects the severity of its historically negative TFP growth rate (-6.35%) and the large gain from convergence to zero.

Table 17 lists all $N = 14$ economies in the 103-country sample with $\widehat{g}_A < 0$, together with their calibrated historical TFP growth rates and the resulting Shapley TFP-path tailwinds. Under the model's convergence rule, each of these economies is assumed to converge linearly from its historical rate up to zero TFP growth by 2045 and to remain at zero thereafter, so the magnitude of the tailwind is increasing in the severity of historical TFP decline.

Table 17: Economies with Negative Historical TFP Growth ($\widehat{g}_A < 0$)

Country	Group	$\hat{g}_A$ (%)	TFP Y/N	**Country**	Group	$\hat{g}_A$ (%)	TFP Y/N
Azerbaijan	Late	−6.35	7.513	Mexico	Late	−0.27	0.373
Saudi Arabia	Late	−2.17	3.163	Türkiye	Late	−0.18	0.255
Bulgaria	Early	−1.87	2.314	Kenya	Late	−0.13	0.178
Uzbekistan	Late	−1.37	1.647	Honduras	Late	−0.09	0.115
Myanmar	Late	−0.95	1.499	Panama	Late	−0.08	0.109
Ukraine	Early	−0.69	0.653	Italy	Early	−0.09	0.108
Viet Nam	Late	−0.31	0.464	Algeria	Late	−0.06	0.094

Notes: $\hat{g}_A$ = calibrated 1991–2019 TFP growth (Solow residual). TFP Y/N = Shapley TFP-path component, low fertility, from Tables 10–11. $N = 14$; sorted by TFP-path component (descending).

At the upper end, Iraq (4.24%) and China (3.84%) record the highest TFP growth rates, both driven by rapid capital-efficient output expansion over the period. Mali (2.58%), Nigeria (2.52%), and Mongolia (2.45%) follow, all reflecting either commodity-driven productivity gains or strong catch-up from a low base. The frontier economy is the United States at $g^* = 1.11\%$ per year; economies above this threshold account for 36 of the 103 countries and face a TFP-path component in the Solow projection as their TFP growth converges to g^* by 2045. Japan's $\widehat{g}_A = 0.33\%$ sits well below the frontier, so it carries no negative TFP-path component and its total growth headwind comes entirely from the demographic channel. South Korea's $\widehat{g}_A = 1.42\%$ exceeds the frontier by 0.31 percentage points, generating a TFP-path component of -0.39 pp/yr that is roughly half its demographic drag (-0.815 pp/yr), making Korea an economy where both channels impose large but unequal burdens.

Table 18: Calibrated Parameters by Country (All 103 Economies)

Country	$\hat{\delta}$	$\hat{\theta}$	$\hat{s}$	$\hat{g}_A$ (%)	Country	$\hat{\delta}$	$\hat{\theta}$	$\hat{s}$	$\hat{g}_A$ (%)
Algeria	0.040	0.650	0.298	−0.0623	Lithuania	0.033	0.484	0.171	1.3793
Angola	0.042	0.650	0.369	0.3520	Malawi	0.058	0.650	0.161	2.1080
Argentina	0.034	0.558	0.161	0.4793	Malaysia	0.052	0.650	0.300	0.3293
Australia	0.030	0.406	0.265	1.1293	Mali	0.066	0.650	0.144	2.5799
Austria	0.039	0.387	0.297	0.6781	Mexico	0.035	0.647	0.193	−0.2702
Azerbaijan	0.061	0.645	0.159	−6.3467	Mongolia	0.042	0.614	0.263	2.4540
Bangladesh	0.045	0.650	0.210	0.2675	Morocco	0.047	0.491	0.282	0.6513
Belarus	0.039	0.443	0.187	1.2368	Mozambique	0.047	0.497	0.254	0.9603
Belgium	0.041	0.373	0.300	0.6445	Myanmar	0.079	0.650	0.162	−0.9483
Bolivia	0.056	0.488	0.139	0.8690	Nepal	0.035	0.650	0.213	0.0306
Brazil	0.047	0.450	0.193	0.0737	Netherlands	0.039	0.394	0.228	1.1066
Bulgaria	0.060	0.518	0.145	−1.8666	New Zealand	0.032	0.451	0.221	1.0019
Burkina Faso	0.044	0.497	0.151	0.8447	Niger	0.032	0.533	0.168	1.6026
Cambodia	0.037	0.650	0.213	0.0885	Nigeria	0.030	0.650	0.205	2.5189
Cameroon	0.049	0.365	0.130	0.3561	Norway	0.042	0.494	0.232	0.5010
Canada	0.035	0.336	0.246	0.7823	Pakistan	0.076	0.650	0.123	1.0428
Chile	0.034	0.548	0.258	0.7260	Panama	0.046	0.600	0.251	−0.0774
China	0.054	0.422	0.375	3.8377	Paraguay	0.036	0.538	0.208	0.6085
Colombia	0.034	0.521	0.200	0.5857	Peru	0.040	0.543	0.217	0.8499
Costa Rica	0.052	0.435	0.181	0.6149	Philippines	0.045	0.571	0.181	0.7245
Côte d'Ivoire	0.043	0.577	0.096	0.9654	Poland	0.046	0.398	0.179	2.1674
Croatia	0.042	0.364	0.213	1.4282	Portugal	0.029	0.373	0.273	0.3983
Czechia	0.041	0.487	0.259	1.8200	Romania	0.073	0.513	0.201	1.2982
Denmark	0.040	0.362	0.255	0.8912	Russia	0.033	0.486	0.189	0.9719
Dominican Rep.	0.039	0.484	0.225	1.8001	Rwanda	0.047	0.259	0.113	2.1510
Ecuador	0.038	0.492	0.214	1.1332	Saudi Arabia	0.053	0.650	0.294	−2.1723
Egypt	0.059	0.625	0.105	0.7009	Senegal	0.043	0.512	0.160	0.0321
El Salvador	0.049	0.518	0.145	0.0933	Serbia	0.033	0.376	0.163	0.8435
Estonia	0.039	0.410	0.250	1.7374	Singapore	0.049	0.556	0.400	1.1276
Ethiopia	0.039	0.650	0.154	0.9359	Slovakia	0.043	0.494	0.238	1.9629
Finland	0.037	0.413	0.276	1.1284	Slovenia	0.037	0.339	0.278	1.7567
France	0.033	0.358	0.238	0.8065	South Africa	0.047	0.441	0.160	0.4832
Germany	0.035	0.358	0.231	0.8435	South Korea	0.047	0.459	0.373	1.4209
Ghana	0.055	0.650	0.277	1.7419	Spain	0.035	0.381	0.278	0.4935
Greece	0.029	0.465	0.229	0.2815	Sri Lanka	0.065	0.576	0.231	0.8687
Guatemala	0.038	0.542	0.151	0.3665	Sudan	0.039	0.304	0.138	1.3657
Honduras	0.056	0.421	0.223	−0.0930	Sweden	0.039	0.391	0.259	1.3310
Hong Kong	0.030	0.501	0.271	0.9942	Switzerland	0.048	0.342	0.317	0.4402
Hungary	0.036	0.400	0.221	1.5269	Türkiye	0.051	0.577	0.247	−0.1834
Iceland	0.033	0.356	0.284	1.3735	Tanzania	0.041	0.534	0.245	0.8316
India	0.047	0.442	0.250	2.0272	Thailand	0.062	0.541	0.273	0.9318
Indonesia	0.040	0.492	0.253	0.6525	Tunisia	0.047	0.485	0.185	1.3992
Iran	0.040	0.607	0.263	0.0328	USA	0.039	0.394	0.239	1.1061
Iraq	0.045	0.650	0.197	4.2366	Uganda	0.047	0.650	0.170	0.2692
Ireland	0.042	0.518	0.288	1.9294	Ukraine	0.025	0.449	0.142	−0.6916
Israel	0.042	0.467	0.308	0.9067	United Kingdom	0.037	0.406	0.213	0.9098
Italy	0.036	0.464	0.260	−0.0938	Uruguay	0.031	0.490	0.196	1.4979
Japan	0.039	0.434	0.293	0.3280	Uzbekistan	0.041	0.575	0.132	−1.3653
Jordan	0.035	0.520	0.281	0.9055	Viet Nam	0.051	0.650	0.229	−0.3079
Kazakhstan	0.043	0.536	0.178	2.1843	Zambia	0.041	0.578	0.239	1.7721
Kenya	0.049	0.504	0.132	−0.1343	Zimbabwe	0.043	0.467	0.066	0.7945
Latvia	0.025	0.456	0.223	1.6459					

Notes: $\widehat{\delta}$ = average depreciation rate; $\widehat{\theta}$ = capital share (1 − labor share); $\widehat{s}$ = average investment rate; $\widehat{g}_A$ = compound annual TFP growth rate. All computed as 1991–2019 averages from Penn World Table 11.0.

Alternative Calibration: Recovering the Implied Real Saving Rate

To perfectly align the valuation units of the investment flow with the Penn World Table constant-price capital stock (*rnna*) and constant-price real GDP (*rgdpna*), we can

back out the implied real saving rate directly from the capital accumulation identity rather than using current-price shares.

Based on the discrete-time capital law of motion, the real investment flow required to generate the observed change in the empirical capital stock is the difference between next year's capital and the undepreciated portion of this year's capital. Let $K_{i,t}$ be the constant-price capital stock, $Y_{i,t}$ be constant-price real GDP, and $\delta_{i,t}$ be the depreciation rate for country i in year t. The implied real saving rate $s_{i,t}$ solves the identity:

$$s_{i,t}\, Y_{i,t} = K_{i,t+1} - (1 - \delta_{i,t})\, K_{i,t} \tag{8}$$

Dividing by real output isolates the implied real saving rate for that specific year:

$$s_{i,t} = \frac{K_{i,t+1} - (1 - \delta_{i,t})\, K_{i,t}}{Y_{i,t}} \tag{9}$$

The calibrated, country-specific constant-price saving rate $\hat{s}_i$ applied uniformly over the projection period is then the time-series average of this implied rate over the 1991–2019 horizon:

$$\hat{s}_i = \frac{1}{2019 - 1991 + 1} \sum_{t=1991}^{2019} \left(\frac{rnna_{i,t+1} - (1 - \delta_{i,t})\, rnna_{i,t}}{rgdpna_{i,t}} \right) \tag{10}$$

Using this derived $\hat{s}_i$ guarantees that the forward-simulated capital path remains strictly valuation-consistent with the empirical 2023 initial conditions.

As a robustness check, we compute $\hat{s}_i$ for four focal economies and compare it to the baseline current-price investment share $\bar{s}_i = \overline{csh_i}$ used throughout the paper. Table 19 reports the two saving rates and the resulting Shapley demographic drag on per-capita GDP growth under each calibration.

Table 19: Baseline vs. Implied Real Saving Rate: Four Focal Economies

Country	$\bar{s}_i$	$\hat{s}_i$	Drag $g_{Y/N}$, base	Drag $g_{Y/N}$, alt	Diff (pp)
USA	0.2394	0.2136	−0.1610	−0.1607	0.0003
Japan	0.2934	0.2828	−0.2917	−0.2912	0.0005
China	0.3746	0.5863	−0.8128	−0.8159	−0.0031
South Korea	0.3735	0.4625	−0.8147	−0.8195	−0.0047

Notes: $\bar{s}_i$ = mean current-price investment share (*csh_i*) over 1991–2019, used as the baseline throughout the paper. $\hat{s}_i$ = mean implied real saving rate recovered from the capital accumulation identity (equations above) using *rnna* and *rgdpna*. Drag $g_{Y/N}$ = Shapley demographic drag on per-capita GDP growth, low fertility, 2024–2100. Diff = alternative minus baseline drag.

For the USA and Japan the two measures agree closely (within 1–2 percentage points), and the implied drag difference is negligible (≤ 0.001 pp). For China and South Korea the implied real saving rate is substantially higher—58.6% and 46.3% versus 37.5% and 37.4%—reflecting that the PWT constant-price capital series embeds larger real investment volumes

than the current-price investment share suggests. The discrepancy arises from the index-number construction of constant-price series in the Penn World Tables: for fast-growing economies, the deflation procedure can embed different real investment volumes than the nominal share implies. Even so, the effect on the demographic drag estimate is negligible in both cases (≤ 0.005 pp over the 76-year projection horizon), confirming that the main results are insensitive to this calibration choice. We therefore retain the standard current-price investment share throughout.

D Labor-Input Choice: WPP Working Age vs. PWT Employment

This paper calibrates TFP growth using WPP 2024 working-age population (ages 20–64) as the labour input, consistently with the projection period. An alternative standard in the literature Fernández-Villaverde, Ventura, and Yao (2025) uses PWT 11.0 employment ($emp_{i,t}$) as the labour input in their growth-accounting framework; the production-function structure adopted here follows their insight that working-age population is the appropriate denominator for GDP-per-worker comparisons, but departs from their calibration by using WPP working-age population throughout for internal consistency with the demographic projection. The two calibrations diverge where employment rates trended over 1991–2019. In Japan and Korea, employment-to-working-age ratios rose, so the WPP-consistent TFP rates exceed the employment-based ones (0.33% versus 0.06% for Japan, 1.42% versus 1.23% for Korea); in China, the working-age population grew faster than employment, so the ordering reverses (3.84% versus 4.23%). Table 20 reports both calibrations for six economies, with the alternative fully recalibrated: TFP growth and the 2023 TFP level use employment as the labour input, the frontier rate becomes $g^* = 1.07\%$ (versus 1.11%), and projections hold each country's 2023 employment-to-working-age ratio constant along the WPP low-fertility path, leaving $\widehat{\theta}$, $\widehat{\delta}$, $\widehat{s}$, and K_{2024} unchanged. Three results stand out. First, for the United States, Japan, and Russia the TFP-path component is zero under both calibrations—each economy's TFP growth lies below the frontier on either basis—so total drag is purely demographic and identical to the second decimal (-0.16, -0.29, and -0.15 pp/yr). Second, China's convergence penalty is large under either calibration and somewhat larger on the employment basis (-3.95 versus -3.42 pp/yr; total -4.77 versus -4.23), whereas Korea's is about twice as large on the WPP basis (-0.39 versus -0.19 pp/yr). Third, Türkiye's negative-TFP convergence tailwind shrinks from $+0.26$ to $+0.05$ pp/yr under the employment basis. The demographic component is essentially invariant to the labour-input choice (differences are at most 0.01 pp/yr across the six economies), and the qualitative ranking of countries by severity of total drag is preserved across both calibrations.

Table 20: TFP-path component: WPP Working-Age (Baseline) vs. PWT Employment Calibration (Low Fertility, Selected Economies)

	TFP growth (%)		TFP-path component (pp/yr)		Total drag (pp/yr)	
Country	**WPP N_w**	**PWT emp**	**WPP N_w**	**PWT emp**	**WPP N_w**	**PWT emp**
United States	1.11	1.07	+0.00	+0.00	−0.16	−0.16
Japan	0.33	0.06	+0.00	+0.00	−0.29	−0.29
China	3.84	4.23	−3.42	−3.95	−4.23	−4.77
Russia	0.97	1.05	+0.00	+0.00	−0.15	−0.15
South Korea	1.42	1.23	−0.39	−0.19	−1.21	−1.00
Türkiye	−0.18	−0.04	+0.26	+0.05	−0.11	−0.31

Notes: WPP N_w = baseline (this paper): labour input is the WPP working-age population in calibration (1991–2019) and projection. PWT emp = alternative: TFP growth and the 2023 TFP level are recalibrated with PWT 11.0 employment; projections hold each country's 2023 employment-to-working-age ratio constant along the WPP low-fertility path. $\widehat{\theta}$, $\widehat{\delta}$, $\widehat{s}$, and K_{2024} are identical across calibrations. Frontier rates: $g^* = 1.11\%$ (WPP), 1.07% (PWT emp). TFP-path component and total drag are Shapley components on $g_{Y/N}$, pp/yr, low fertility.

E Medium Fertility Variant Tables

Under the UN WPP 2024 medium-fertility variant, total fertility converges to near-replacement levels by 2100, yielding smaller working-age population declines and correspondingly smaller dependency-ratio increases than the low-fertility baseline. Country rankings by OADR, required FRA postponement, and demographic drag are preserved across scenarios. Quantitatively, required FRA postponements are 3–7 years shorter for the most demographically stressed economies (Korea, China, and Southern Europe), and per-capita demographic drag magnitudes are typically 30–45% smaller under medium than under low fertility. The TFP-path component is nearly invariant to the fertility scenario: the TFP convergence schedule to $g^* = 1.11\%$ by 2045 depends only on each economy's calibrated TFP growth rate, so the component varies across fertility variants only through the Shapley interaction with capital accumulation (differences are below 0.05 pp/yr; see Tables 8 and 9).

The early-aging group ($N = 34$) and late-aging group ($N = 69$) are identical to those in the main text (Tables 1 and 2): the 30% OADR threshold is applied to 2024 values, which do not vary across fertility projections.

Required FRA Postponements (Medium Fertility)

Tables 21 and 22 replicate Tables 4 and 5 under medium fertility, reporting the 2024 OADR together with required FRA increases from the uniform age-65 baseline and from each country's current statutory retirement age. For Japan, the required increase from age 65 falls from 14 years (low) to 7 years (medium)—the sharpest drop in the early-aging group—because Japan's projected OADR is highly sensitive to the fertility path given its already-extreme age structure. Hong Kong's requirement falls from 26 to 23 years. Spain drops from 18 to 14 years and Ukraine from 21 to 16 years. New Zealand, the youngest early-aging

economy at OADR = 30.2%, requires 10 years from age 65 under medium fertility (14 years under low).

Among late-aging economies, Korea's requirement falls from 24 to 21 years and China's from 24 to 21 years under medium fertility. Singapore falls from 25 to 21 years. Russia (OADR = 28.6%, 9 years) and Belarus (OADR = 29.1%, 15 years) are included in the late-aging table, consistent with their 2024 dependency ratios below the 30% threshold.

Table 21: Required Full Retirement Age Postponements: Early-Aging Economies (Medium Fertility)

		FRA Increase (years)				FRA Increase (years)	
Country	OADR 2024	From age 65	From stat. FRA	**Country**	OADR 2024	From age 65	From stat. FRA
Japan	54.9	7	7	Belgium	35.7	10	10
Finland	42.8	8	8	Hungary	35.4	8	8
Portugal	42.5	7	6	Spain	34.9	14	14
Italy	42.0	11	9	Netherlands	34.8	10	8
Greece	41.6	10	8	Austria	34.1	11	11
Croatia	40.3	10	10	Romania	34.1	10	10
France	40.2	8	9	United Kingdom	34.0	10	9
Germany	39.8	8	6	Poland	33.7	15	15
Serbia	39.1	10	10	Lithuania	33.5	14	14
Latvia	37.9	12	12	Switzerland	33.3	11	11
Bulgaria	37.7	8	8	Canada	33.2	9	9
Slovenia	37.3	10	10	Norway	31.9	12	10
Estonia	37.1	12	12	USA	30.8	9	7
Sweden	36.8	10	10	Ukraine	30.7	16	16
Denmark	36.3	9	7	Slovakia	30.6	13	13
Hong Kong	36.0	23	23	Australia	30.2	10	8
Czechia	35.7	9	9	New Zealand	30.2	10	10

Notes: As Table 4 but under the UN WPP 2024 **medium**-fertility variant. $N = 34$; sorted by 2024 OADR (descending).

Table 22: Required Full Retirement Age Postponements: Late-Aging Economies (Medium Fertility)

Country	OADR 2024	FRA Increase (years) From age 65	FRA Increase (years) From stat. FRA	Country	OADR 2024	FRA Increase (years) From age 65	FRA Increase (years) From stat. FRA
South Korea	29.3	21	21	Bangladesh	11.7	20	25
Belarus	29.1	15	15	Paraguay	11.6	16	16
Russia	28.6	9	9	South Africa	11.3	13	13
Uruguay	27.3	16	16	Cambodia	11.3	15	20
Ireland	27.1	15	14	Uzbekistan	10.6	13	18
Iceland	26.1	15	13	Bolivia	10.2	14	21
Israel	24.1	10	8	Philippines	9.7	18	23
Thailand	24.0	16	21	Egypt	9.5	16	21
China	23.1	21	26	Mongolia	9.4	19	24
Chile	22.5	20	20	Guatemala	9.1	18	18
Argentina	21.3	17	17	Pakistan	8.8	12	17
Sri Lanka	20.9	16	21	Rwanda	8.3	14	19
Singapore	19.8	21	23	Jordan	8.2	21	26
Costa Rica	19.8	21	21	Zimbabwe	8.2	12	17
Brazil	17.7	17	17	Honduras	8.0	19	19
Türkiye	16.8	20	20	Senegal	7.7	14	14
Panama	16.2	18	18	Ghana	7.4	14	19
Tunisia	16.1	19	19	Tanzania	7.0	13	18
Kazakhstan	16.0	13	15	Ethiopia	6.9	15	15
Peru	15.8	18	18	Iraq	6.9	16	21
Colombia	15.7	19	22	Nigeria	6.8	10	15
Viet Nam	15.0	18	23	Angola	6.8	11	16
Ecuador	14.3	19	19	Sudan	6.6	10	15
Morocco	14.1	17	17	Niger	6.6	11	11
Mexico	14.0	19	19	Mozambique	6.6	11	16
El Salvador	14.0	18	23	Mali	6.5	9	9
Dominican Rep.	13.8	16	16	Cameroon	6.2	13	18
Azerbaijan	13.7	17	17	Kenya	6.1	15	20
Iran	13.2	21	21	Burkina Faso	6.0	12	12
Malaysia	12.4	20	25	Malawi	5.8	16	16
Indonesia	12.2	16	23	Côte d'Ivoire	5.7	11	11
Myanmar	12.1	13	18	Uganda	5.1	19	19
India	12.0	19	24	Saudi Arabia	4.5	22	22
Algeria	11.9	19	24	Zambia	4.3	16	21
Nepal	11.8	17	22				

Notes: As Table 5 but under the UN WPP 2024 **medium**-fertility variant. $N = 69$; sorted by 2024 OADR (descending).

Required FRA Postponements from an Age-70 Boundary

Tables 23 and 24 report the corresponding required increases when the retirement boundary is age 70 and the working-age population is defined as ages 20–69, the alternative specification of Section 4.8. The age-70 boundary leaves average required increases nearly unchanged—about one year lower under low fertility (16.6 versus 17.7 years) and essentially identical under medium fertility (14.4 versus 14.3)—because the much lower 2024 age-70 dependency ratios constitute correspondingly more stringent maintenance targets. The cross-country ordering is preserved, and the late-minus-early gap narrows but remains positive.

Table 23: Required FRA Postponements from Age 70: Early-Aging Economies

	FRA Increase (years)			FRA Increase (years)	
Country	Low	Med	**Country**	Low	Med
Japan	14	9	Belgium	15	12
Finland	14	10	Hungary	13	10
Portugal	12	9	Spain	17	14
Italy	16	12	Netherlands	14	11
Greece	15	12	Austria	15	12
Croatia	15	11	Romania	14	11
France	14	10	United Kingdom	14	11
Germany	13	10	Poland	18	15
Serbia	15	11	Lithuania	17	14
Latvia	15	12	Switzerland	14	12
Bulgaria	13	9	Canada	14	11
Slovenia	15	12	Norway	16	13
Estonia	16	13	USA	14	11
Sweden	14	11	Ukraine	19	16
Denmark	13	10	Slovakia	16	14
Hong Kong	25	22	Australia	14	11
Czechia	14	11	New Zealand	14	11

Notes: Postponements (years) beyond age 70 required to maintain each country's 2024 age-70 dependency ratio (population 70+ relative to population 20–69; see Section 3.6) through 2100, under the UN WPP 2024 low- and medium-fertility variants. $N = 34$; sorted by 2024 OADR_{65} (descending).

Table 24: Required FRA Postponements from Age 70: Late-Aging Economies

	FRA Increase (years)			FRA Increase (years)	
Country	Low	Med	**Country**	Low	Med
South Korea	23	20	Bangladesh	21	19
Belarus	17	15	Paraguay	18	16
Russia	14	12	South Africa	16	13
Uruguay	19	16	Cambodia	16	15
Ireland	18	15	Uzbekistan	15	13
Iceland	18	15	Bolivia	15	13
Israel	13	11	Philippines	19	17
Thailand	20	17	Egypt	17	16
China	21	19	Mongolia	19	18
Chile	22	20	Guatemala	18	17
Argentina	19	16	Pakistan	14	12
Sri Lanka	18	16	Rwanda	16	14
Singapore	25	22	Jordan	21	20
Costa Rica	22	20	Zimbabwe	14	12
Brazil	19	17	Honduras	20	18
Türkiye	20	18	Senegal	15	14
Panama	20	18	Ghana	15	14
Tunisia	20	18	Tanzania	14	12
Kazakhstan	15	14	Ethiopia	16	15
Peru	20	18	Iraq	17	15
Colombia	21	19	Nigeria	11	9
Viet Nam	20	18	Angola	12	11
Ecuador	20	18	Sudan	11	10
Morocco	19	17	Niger	11	10
Mexico	20	18	Mozambique	11	10
El Salvador	20	17	Mali	10	9
Dominican Rep.	18	16	Cameroon	14	13
Azerbaijan	19	18	Kenya	16	14
Iran	21	19	Burkina Faso	13	12
Malaysia	21	20	Malawi	16	15
Indonesia	17	16	Côte d'Ivoire	12	11
Myanmar	15	13	Uganda	20	18
India	20	18	Saudi Arabia	23	21
Algeria	19	18	Zambia	16	15
Nepal	18	16			

Notes: Postponements (years) beyond age 70 required to maintain each country's 2024 age-70 dependency ratio (population 70+ relative to population 20–69; see Section 3.6) through 2100, under the UN WPP 2024 low- and medium-fertility variants. $N = 69$; sorted by 2024 OADR_{65} (descending).

Tables 25 and 26 replicate the demographic drag decomposition of Tables 6 and 7 under the medium-fertility variant, and the comparison isolates how much of the growth headwind depends on the fertility path. Mean demographic drag among early-agers falls by roughly a third, from −0.309 pp/yr under low fertility to −0.203 pp/yr under medium, while mean drag among late-agers, already small under low fertility (−0.041 pp/yr), essentially vanishes (−0.006 pp/yr). The largest proportional relief accrues to the most rapidly aging economies: Hong Kong's drag falls from −1.270 to −0.708 pp/yr, South Korea's from −0.815 to −0.529, China's from −0.813 to −0.479, and Japan's from −0.292 to −0.170. By contrast, economies whose headwind is modest under low fertility change little (the United States moves from −0.161 to −0.128 pp/yr; Israel's small tailwind of +0.028 is unchanged), and the set of demographic-tailwind economies is nearly identical across variants. The baseline growth columns shift for a different reason: under medium fertility, mean population growth among late-agers turns positive ($g_N = +0.41$ versus −0.10%/yr under low) and the early-aging mean population decline halves (−0.38 versus −0.86%/yr), raising mean baseline

aggregate growth by roughly 0.4–0.5 pp/yr in both groups. Country rankings by drag are, however, essentially preserved, so the early/late taxonomy and the cross-country patterns discussed in Section 4 are robust to the fertility variant; what changes is the magnitude of the headwind, which is uniformly smaller when fertility recovers toward the medium path.

Table 25: Demographic Drag Decomposition, 2024–2100: Early-Aging Economies (Medium Fertility)

Country	g_Y	g_N	Dem. drag	**Country**	g_Y	g_N	Dem. drag
Japan	0.05	−0.63	−0.170	Belgium	0.79	−0.08	−0.166
Finland	1.33	−0.26	−0.133	Hungary	1.17	−0.34	−0.159
Portugal	0.29	−0.23	−0.166	Spain	0.15	−0.49	−0.282
Italy	−0.71	−0.68	−0.232	Netherlands	1.50	−0.05	−0.196
Greece	−0.21	−0.62	−0.179	Austria	0.67	−0.28	−0.239
Croatia	0.66	−0.78	−0.210	Romania	0.82	−0.75	−0.190
France	1.09	0.04	−0.111	United Kingdom	1.34	0.09	−0.142
Germany	1.02	−0.23	−0.179	Poland	1.06	−0.91	−0.303
Serbia	0.28	−0.79	−0.197	Lithuania	0.72	−1.13	−0.267
Latvia	0.86	−0.93	−0.170	Switzerland	0.60	0.03	−0.234
Bulgaria	−1.50	−0.85	−0.162	Canada	1.40	0.39	−0.173
Slovenia	1.16	−0.34	−0.191	Norway	0.87	−0.04	−0.192
Estonia	1.04	−0.66	−0.198	USA	2.11	0.26	−0.128
Sweden	1.75	0.09	−0.138	Ukraine	−1.75	−1.20	−0.234
Denmark	1.18	−0.03	−0.160	Slovakia	1.30	−0.62	−0.257
Hong Kong	0.02	−1.67	−0.708	Australia	2.32	0.56	−0.141
Czechia	1.48	−0.35	−0.159	New Zealand	2.48	0.56	−0.138
Mean	0.80	−0.38	−0.203				

Notes: As Table 6 but under UN WPP 2024 **medium** fertility. See Table 6 for column definitions. $N = 34$; sorted by 2024 OADR (descending).

Table 26: Demographic Drag Decomposition, 2024–2100: Late-Aging Economies (Medium Fertility)

Country	g_Y	g_N	Dem. drag	**Country**	g_Y	g_N	Dem. drag
South Korea	0.75	−1.13	−0.529	Bangladesh	0.92	0.24	−0.067
Belarus	0.52	−0.96	−0.231	Paraguay	1.50	0.35	−0.036
Russia	0.96	−0.18	−0.116	South Africa	1.03	0.51	−0.029
Uruguay	1.51	−0.54	−0.217	Cambodia	0.78	0.33	0.018
Ireland	2.67	0.01	−0.200	Uzbekistan	−0.48	0.94	0.008
Iceland	1.40	−0.10	−0.257	Bolivia	1.66	0.47	0.040
Israel	2.96	0.98	0.028	Philippines	1.28	−0.02	−0.014
Thailand	0.96	−0.60	−0.311	Egypt	2.21	0.72	0.059
China	1.12	−1.06	−0.479	Mongolia	3.38	0.61	0.014
Chile	1.31	−0.51	−0.348	Guatemala	1.02	0.45	0.046
Argentina	0.68	−0.23	−0.140	Pakistan	3.38	0.93	0.214
Sri Lanka	1.32	−0.11	−0.159	Rwanda	2.92	1.10	0.235
Singapore	2.08	−0.44	−0.473	Jordan	2.27	0.81	−0.009
Costa Rica	0.34	−0.40	−0.355	Zimbabwe	2.00	1.06	0.320
Brazil	−0.43	−0.34	−0.245	Honduras	0.45	0.60	−0.007
Türkiye	0.02	−0.38	−0.245	Senegal	1.20	1.23	0.199
Panama	0.20	0.35	−0.120	Ghana	4.57	0.89	0.160
Tunisia	1.67	−0.19	−0.202	Tanzania	3.67	1.77	0.299
Kazakhstan	2.93	0.65	0.009	Ethiopia	4.05	1.35	0.235
Peru	1.55	0.14	−0.147	Iraq	5.11	1.03	0.168
Colombia	1.21	−0.15	−0.262	Nigeria	2.83	0.94	0.313
Viet Nam	0.17	−0.13	−0.150	Angola	4.33	1.81	0.340
Ecuador	1.62	0.07	−0.161	Sudan	2.76	0.91	0.362
Morocco	1.36	−0.01	−0.122	Niger	3.98	1.59	0.474
Mexico	0.35	−0.01	−0.107	Mozambique	3.28	1.45	0.416
El Salvador	−0.73	−0.29	−0.129	Mali	5.36	1.66	0.448
Dominican Rep.	1.96	0.03	−0.076	Cameroon	2.24	1.47	0.306
Azerbaijan	−2.13	−0.04	−0.110	Kenya	1.10	0.81	0.222
Iran	−0.17	−0.18	−0.226	Burkina Faso	3.15	0.99	0.361
Malaysia	1.40	0.28	−0.173	Malawi	6.54	1.32	0.309
Indonesia	0.90	0.05	−0.098	Cote d'Ivoire	2.97	1.55	0.261
Myanmar	−1.33	−0.12	−0.060	Uganda	2.11	1.16	0.314
India	2.11	0.05	−0.153	Saudi Arabia	0.38	0.97	−0.059
Algeria	1.22	0.42	−0.038	Zambia	4.10	1.46	0.278
Nepal	1.01	0.09	0.005				
Mean	1.76	0.41	−0.006				

Notes: As Table 7 but under UN WPP 2024 **medium** fertility. See Table 6 for column definitions. $N = 69$; sorted by 2024 OADR (descending).

Table 27: FRA Increases and Demographic Drag: Early-Aging Economies (Low Fertility)

Country	Stat.	FRA↑	Dem. drag	**Country**	Stat.	FRA↑	Dem. drag
Japan	65	14	−0.292	Belgium	65	15	−0.238
Finland	65	14	−0.216	Hungary	65	13	−0.217
Portugal	66	12	−0.225	Spain	65	18	−0.397
Italy	67	17	−0.341	Netherlands	67	14	−0.267
Greece	67	16	−0.275	Austria	65	16	−0.316
Croatia	65	15	−0.355	Romania	65	15	−0.308
France	64	13	−0.174	United Kingdom	66	15	−0.202
Germany	67	13	−0.240	Poland	65	19	−0.498
Serbia	65	15	−0.331	Lithuania	65	19	−0.463
Latvia	65	17	−0.314	Switzerland	65	15	−0.295
Bulgaria	65	14	−0.250	Canada	65	13	−0.207
Slovenia	65	15	−0.274	Norway	67	16	−0.257
Estonia	65	17	−0.326	USA	67	13	−0.161
Sweden	65	14	−0.201	Ukraine	65	21	−0.456
Denmark	67	14	−0.225	Slovakia	65	17	−0.367
Hong Kong	65	26	−1.270	Australia	67	14	−0.162
Czechia	65	14	−0.224	New Zealand	65	14	−0.157

Notes: UN WPP 2024 **low** fertility. FRA↑ = years beyond age 65 to maintain 2024 OADR through 2100. Stat. = statutory retirement age (OECD *Pensions at a Glance* 2024 and national legislation). Dem. drag = Shapley demographic component of per-capita growth drag (Section 4.3); aggregate and per-capita components coincide under the fixed-working-age-share counterfactual. $N = 34$; sorted by 2024 OADR (descending).

Table 28: FRA Increases and Demographic Drag: Late-Aging Economies (Low Fertility)

Country	Stat.	FRA↑	Dem. drag	**Country**	Stat.	FRA↑	Dem. drag
South Korea	65	24	−0.815	Bangladesh	60	23	−0.125
Belarus	65	19	−0.390	Paraguay	65	19	−0.060
Russia	65	14	−0.146	South Africa	65	16	−0.012
Uruguay	65	20	−0.364	Cambodia	60	18	0.013
Ireland	66	19	−0.283	Uzbekistan	60	15	0.023
Iceland	67	19	−0.368	Bolivia	58	17	0.039
Israel	67	14	0.028	Philippines	60	20	−0.051
Thailand	60	20	−0.426	Egypt	60	18	0.068
China	60	24	−0.813	Mongolia	60	21	0.012
Chile	65	24	−0.514	Guatemala	65	20	0.019
Argentina	65	21	−0.228	Pakistan	60	14	0.250
Sri Lanka	60	20	−0.244	Rwanda	60	17	0.254
Singapore	63	25	−0.610	Jordan	60	23	−0.020
Costa Rica	65	24	−0.537	Zimbabwe	60	15	0.353
Brazil	65	21	−0.348	Honduras	65	21	−0.034
Türkiye	65	22	−0.364	Senegal	65	16	0.226
Panama	65	21	−0.162	Ghana	60	16	0.196
Tunisia	65	22	−0.310	Tanzania	60	15	0.349
Kazakhstan	63	15	0.011	Ethiopia	65	17	0.271
Peru	65	21	−0.213	Iraq	60	19	0.193
Colombia	62	22	−0.365	Nigeria	60	12	0.358
Viet Nam	60	21	−0.201	Angola	60	12	0.398
Ecuador	65	22	−0.248	Sudan	60	12	0.411
Morocco	65	20	−0.196	Niger	65	12	0.525
Mexico	65	22	−0.161	Mozambique	60	13	0.470
El Salvador	60	22	−0.240	Mali	65	11	0.509
Dominican Rep.	65	19	−0.133	Cameroon	60	15	0.352
Azerbaijan	65	20	−0.136	Kenya	60	17	0.255
Iran	65	23	−0.305	Burkina Faso	65	14	0.404
Malaysia	60	23	−0.205	Malawi	65	18	0.352
Indonesia	58	19	−0.128	Cote d'Ivoire	65	13	0.318
Myanmar	60	16	−0.072	Uganda	65	21	0.335
India	60	21	−0.224	Saudi Arabia	65	24	−0.020
Algeria	60	21	−0.059	Zambia	60	18	0.326
Nepal	60	20	−0.035				

Notes: As Table 27. $N = 69$; sorted by 2024 OADR (descending).

Table 29: FRA Increases and Demographic Drag: Early-Aging Economies (Medium Fertility)

Country	Stat.	FRA↑	Dem. drag	**Country**	Stat.	FRA↑	Dem. drag
Japan	65	7	−0.170	Belgium	65	10	−0.166
Finland	65	8	−0.133	Hungary	65	8	−0.159
Portugal	66	7	−0.166	Spain	65	14	−0.282
Italy	67	11	−0.232	Netherlands	67	10	−0.196
Greece	67	10	−0.179	Austria	65	11	−0.239
Croatia	65	10	−0.210	Romania	65	10	−0.190
France	64	8	−0.111	United Kingdom	66	10	−0.142
Germany	67	8	−0.179	Poland	65	15	−0.303
Serbia	65	10	−0.197	Lithuania	65	14	−0.267
Latvia	65	12	−0.170	Switzerland	65	11	−0.234
Bulgaria	65	8	−0.162	Canada	65	9	−0.173
Slovenia	65	10	−0.191	Norway	67	12	−0.192
Estonia	65	12	−0.198	USA	67	9	−0.128
Sweden	65	10	−0.138	Ukraine	65	16	−0.234
Denmark	67	9	−0.160	Slovakia	65	13	−0.257
Hong Kong	65	23	−0.708	Australia	67	10	−0.141
Czechia	65	9	−0.159	New Zealand	65	10	−0.138

Notes: As Table 27 but under UN WPP 2024 **medium** fertility. $N = 34$.

Table 30: FRA Increases and Demographic Drag: Late-Aging Economies (Medium Fertility)

Country	Stat.	FRA↑	Dem. drag	**Country**	Stat.	FRA↑	Dem. drag
South Korea	65	21	−0.529	Bangladesh	60	20	−0.067
Belarus	65	15	−0.231	Paraguay	65	16	−0.036
Russia	65	9	−0.116	South Africa	65	13	−0.029
Uruguay	65	16	−0.217	Cambodia	60	15	0.018
Ireland	66	15	−0.200	Uzbekistan	60	13	0.008
Iceland	67	15	−0.257	Bolivia	58	14	0.040
Israel	67	10	0.028	Philippines	60	18	−0.014
Thailand	60	16	−0.311	Egypt	60	16	0.059
China	60	21	−0.479	Mongolia	60	19	0.014
Chile	65	20	−0.348	Guatemala	65	18	0.046
Argentina	65	17	−0.140	Pakistan	60	12	0.214
Sri Lanka	60	16	−0.159	Rwanda	60	14	0.235
Singapore	63	21	−0.473	Jordan	60	21	−0.009
Costa Rica	65	21	−0.355	Zimbabwe	60	12	0.320
Brazil	65	17	−0.245	Honduras	65	19	−0.007
Türkiye	65	20	−0.245	Senegal	65	14	0.199
Panama	65	18	−0.120	Ghana	60	14	0.160
Tunisia	65	19	−0.202	Tanzania	60	13	0.299
Kazakhstan	63	13	0.009	Ethiopia	65	15	0.235
Peru	65	18	−0.147	Iraq	60	16	0.168
Colombia	62	19	−0.262	Nigeria	60	10	0.313
Viet Nam	60	18	−0.150	Angola	60	11	0.340
Ecuador	65	19	−0.161	Sudan	60	10	0.362
Morocco	65	17	−0.122	Niger	65	11	0.474
Mexico	65	19	−0.107	Mozambique	60	11	0.416
El Salvador	60	18	−0.129	Mali	65	9	0.448
Dominican Rep.	65	16	−0.076	Cameroon	60	13	0.306
Azerbaijan	65	17	−0.110	Kenya	60	15	0.222
Iran	65	21	−0.226	Burkina Faso	65	12	0.361
Malaysia	60	20	−0.173	Malawi	65	16	0.309
Indonesia	58	16	−0.098	Cote d'Ivoire	65	11	0.261
Myanmar	60	13	−0.060	Uganda	65	19	0.314
India	60	19	−0.153	Saudi Arabia	65	22	−0.059
Algeria	60	19	−0.038	Zambia	60	16	0.278
Nepal	60	17	0.005				

Notes: As Table 28 but under UN WPP 2024 **medium** fertility. $N = 69$.

Age-Boundary Sensitivity (Medium Fertility)

Table 31 replicates the age-boundary sensitivity analysis of Table 13 under medium fertility. The three headline findings are preserved. First, $\rho(\text{FRA}, |\text{drag}|)$ is small overall (0.07 at the 65+ boundary, −0.12 at 70+) but 0.87–0.88 within the early-aging group, confirming that the tight association between fiscal pressure and growth headwinds is a within-group phenomenon regardless of fertility scenario; within the late-aging group the correlation is mildly negative (−0.13 to −0.38). Second, the 70+ boundary leaves mean FRA requirements essentially unchanged under medium fertility (14.3 versus 14.4 years overall), in contrast to the modest reduction under low fertility. Third, the late-minus-early gap (5.3 years baseline, 3.7 years alternative) remains substantial. In Panel D, the minimum required increase under medium fertility is Japan (7 years from age 65, tied with Portugal; 9 years from age 70), and the maximum is Hong Kong under both definitions (23 and 22 years).

Table 31: Sensitivity Analysis: Alternative Age Boundaries (65+ vs. 70+ as Old Age, Medium Fertility)

	Baseline (65+/20–64)			**Alternative (70+/20–69)**		
Measure	Overall	Early	Late	Overall	Early	Late
Panel A: Correlations						
ρ(FRA inc., |Drag|)	0.07	0.88	−0.13	−0.12	0.87	−0.38
ρ(OADR, FRA inc.)	−0.50	−0.38	0.22	−0.41	−0.43	0.31
Panel B: Mean FRA Inc. (yrs, Med)						
From baseline	14.3	10.7	16.0	14.4	11.9	15.6
Gap (Late − Early)		5.3			3.7	
Panel C: Mean Drag (pp, Med)						
Mean |drag|	0.20	0.20	0.19	0.19	0.19	0.19
Gap (Late − Early)		−0.01			0.00	
Panel D: Range (yrs, Med)						
Minimum		Japan (7)			Japan (9)	
Maximum		Hong Kong (23)			Hong Kong (22)	
Panel E: Selected Countries						
China		21 (26)			19 (29)	
Korea		21 (21)			20 (25)	
Japan		7 (7)			9 (14)	
United States		9 (7)			11 (14)	

Notes: Baseline (65+/20–64) vs. alt. (70+/20–69) age boundaries. **Medium** fertility, UN WPP 2024. N=34 early-aging, N=69 late-aging. Panel C reports the mean absolute Shapley demographic drag; the 70+ drag is from a re-simulation with ages 20–69 as labor input. Parentheses in Panel E: increase from statutory FRA (70-based under the alternative boundary). China statutory FRA = 60: required retirement age in 2100 under medium fertility = 65+21 = 86; increase from statutory = 86−60 = 26 years. Ties in Panel D: Portugal at 7 (65+); Portugal, Bulgaria, Mali, and Nigeria at 9 (70+).

TFP-Path Component (Medium Fertility)

Tables 8 and 9 (in the main text) report the Shapley TFP-path component under both fertility variants side by side. The component is nearly invariant across the low- and medium-fertility baselines because the TFP convergence schedule depends only on calibrated historical TFP growth rates; the small differences (below 0.05 pp/yr) reflect the Shapley interaction with capital accumulation. The 14 above-frontier early-aging economies and 22 above-frontier late-aging economies are the same sets under both fertility variants; in particular, the early-aging group contains Finland, Croatia, Latvia, Slovenia, Estonia, Sweden, Czechia, Hungary, Netherlands, Romania, Poland, Lithuania, Slovakia, and Australia—and does *not* include Russia, Belarus, USA, Serbia, Ukraine, or Hong Kong.

F A Cross-Country Demographic-Pension Gap Calculation

The unfunded-obligation calculations for the United States and Japan in Section G rest on detailed national projections of scheduled benefits and contributions. This appendix places the two economies in a broader cross-section by applying a deliberately simple, common accounting exercise to every country for which the required 2023 data exist. The object is the *balanced-2023 demographic gap*: the present value of the old-age and survivors' (OASI) primary deficit that the projected change in age structure alone opens up, assuming each system is exactly balanced in 2023. Because it conditions on a balanced starting point, the measure isolates the incremental fiscal pressure of future demographic change and requires no cross-country contribution series—sidestepping the fact, discussed below, that pension-specific contribution revenue is not comparably measured across countries.

F.1 Data and method

Let E_i be country i's 2023 ratio of public OASI expenditure to GDP, and G_i the corresponding ratio of OASI contribution revenue to GDP. For the European economies E_i is the 2023 ESSPROS figure for the old-age and survivors functions Eurostat (2025); for the remaining OECD economies it is the latest available year (2021–2023) in OECD (2025), Table 8.2. I assume each system is balanced in 2023, so that $G_i = E_i$ (contributions equal benefits). Let $R_{i,t}$ and $W_{i,t}$ be the populations aged 65 and over and 20–64 in year t, from the United Nations World Population Prospects 2024 low- and medium-fertility variants United Nations, Department of Economic and Social Affairs, Population Division (2024). Holding the 2023 benefit per retiree and contribution per worker fixed as shares of GDP, the primary deficit in year t as a share of 2023 GDP is

$$d_{i,t} \;=\; E_i \frac{R_{i,t}}{R_{i,2023}} - G_i \frac{W_{i,t}}{W_{i,2023}} \;=\; E_i \left[\frac{R_{i,t}}{R_{i,2023}} - \frac{W_{i,t}}{W_{i,2023}} \right], \tag{11}$$

where the second equality uses the 2023 balance assumption $G_i = E_i$, and the balanced-2023 demographic gap is its discounted sum,

$$\mathrm{UO}_i^{\mathrm{bal}} \;=\; \sum_{t=2024}^{2100} \frac{d_{i,t}}{(1+r)^{\,t-2023}}, \qquad r = 0.02. \tag{12}$$

Only the population ratios vary over time, so the entire gap is driven by the projected rise in retirees relative to workers. Holding E_i fixed as a share of GDP while discounting at 2% is equivalent to assuming benefits and the contribution base grow with the economy and that 2% is the real discount rate net of growth.

Following the present-value accounting of Section G, let $C_{i,t}$ and $I_{i,t}$ be country i's OASI cost and contribution income in year t. Holding the 2023 ratios of cost per retiree and income per worker to GDP fixed and scaling them by the projected populations gives, as shares of t_0 GDP ($t_0 = 2023$),

$$C_{i,t} = E_i \, \frac{R_{i,t}}{R_{i,t_0}}, \qquad I_{i,t} = G_i \, \frac{W_{i,t}}{W_{i,t_0}}, \tag{13}$$

so that $UO_i = PV[\text{Cost}]_i - PV[\text{Income}]_i$ as in equation (15). Under the 2023 balance assumption $G_i = E_i$ and with the trust fund set to zero, this specialises to

$$UO_{i,t_0} = E_i \sum_{t=t_0}^{t_n} \frac{(R_{i,t}/R_{i,t_0}) - (W_{i,t}/W_{i,t_0})}{(1+r)^{\,t-t_0}}, \tag{14}$$

with r the real discount rate, $t_n = 2100$, and $PV[\text{Cost}]_i = \sum_{t=t_0}^{t_n} C_{i,t}/(1+r)^{t-t_0}$, $PV[\text{Income}]_i = \sum_{t=t_0}^{t_n} I_{i,t}/(1+r)^{t-t_0}$.

F.2 Results

Table 32 reports UO_i^{bal} under the low- and medium-fertility variants. The pattern restates the paper's demographic taxonomy in fiscal terms. Gaps are uniformly positive and large, averaging about 140% of 2023 GDP across the early-aging economies and close to 200% across the late-aging economies under low fertility (about 125% and 185% under medium fertility). That the late-aging group carries the *larger* gap is the central point: the early-aging economies have already absorbed much of their demographic transition by 2023, so less incremental deterioration remains over 2024–2100, whereas the late-aging economies face the bulk of their ageing ahead. The same logic orders countries within the early-aging group—Japan, the most-aged economy in the sample, records one of the smallest gaps (93% of GDP), below the United States (132%), precisely because its transition is largely complete. The largest gaps arise where high current benefit levels combine with severe projected ageing: Colombia (320%), Mexico (289%), Spain (272%), Austria (271%) and Costa Rica (242%); the smallest are in economies that are either young or already old with modest benefits, such as Estonia (73%), Hungary (76%) and Australia (77%). New Zealand is instructive: it operates no contributory pension, yet its balanced demographic gap is a substantial 115% of GDP, since the measure captures the demographic burden regardless of how the system is financed. Moving from the low- to the medium-fertility variant reduces every gap, by roughly 10 to 20 percentage points of GDP on average, as a larger future workforce widens the contribution base.

The simplified measure also provides a benchmark for the detailed national calculations of Section G. The balanced-2023 gap is, by construction, the demographic component of the obligation: it abstracts from each system's starting fiscal position. The national figures add that starting position—the existing OASI trust fund for the United States and the current primary balance for Japan. Read this way, the demographic increments of 132% (United States) and 93% (Japan) are directly comparable to the national numbers once the latter are placed on the same no-reserve, balanced footing, and the agreement in magnitude indicates that the constant-structure approximation captures the bulk of the demographic pressure. The cross-country figures should accordingly be read as comparable orders of magnitude for the demographic burden, not as system-specific forecasts.[10]

[10]We do not tabulate net obligations under explicit contribution measures because no pension-specific contribution-revenue series is comparable across countries, and the available proxies overstate OASI financing. Reconstructing contributions from statutory mandatory rates (PAG 2025, Table 8.1, times the labour share) credits countries for funded occupational pillars and disability insurance, while total social security

Table 32: Balanced-2023 Demographic Gap of OASI Systems: PV of the Demographic Deficit, 2024–2100 (% of 2023 GDP, 2% discount)

Country	OASI	Low	Med	**Country**	OASI	Low	Med
Early-aging							
Spain	11.4	272	251	Finland	12.0	131	104
Austria	12.9	271	245	Denmark	8.9	130	108
Italy	13.0	229	206	Czechia	8.1	118	102
Switzerland	9.4	216	195	Canada	5.9	117	102
Greece	13.6	201	176	New Zealand	5.1	115	101
Poland	9.8	190	173	United Kingdom	7.1	114	96
Belgium	10.7	184	159	Romania	7.7	103	89
France	13.5	175	141	Lithuania	5.9	99	89
Netherlands	9.5	167	144	Japan	9.2	93	75
Slovakia	7.4	158	145	Latvia	7.4	92	79
Portugal	11.2	153	131	Serbia	7.9	90	76
Germany	10.4	149	128	Bulgaria	7.9	88	75
Norway	6.7	148	132	Croatia	6.5	82	70
Slovenia	8.5	144	127	Australia	3.4	77	67
Sweden	9.5	143	119	Hungary	6.5	76	63
USA	7.3	132	113	Estonia	4.9	73	64
Late-aging							
Colombia	5.7	320	306	Chile	3.7	150	143
Mexico	5.3	289	274	South Korea	3.8	131	125
Costa Rica	5.1	242	231	Ireland	3.7	105	96
Türkiye	4.7	228	218	Israel	4.5	92	75
Iceland	7.4	221	203				

Notes: Present value at end-2023, discounted at 2%, of the OASI primary deficit that opens over 2024–2100 from demographic change alone, as a percentage of 2023 GDP. Each system is assumed balanced in 2023 (contributions equal to benefits); the gap is $E_{2023}\sum_t[(R_t/R_{2023}) - (W_t/W_{2023})](1+r)^{-(t-2023)}$, where E_{2023} is OASI expenditure (and contributions) (% of GDP), R_t the population 65+ and W_t the population 20–64 under the WPP 2024 low- and medium-fertility variants. "OASI" is 2023 expenditure (% of GDP). Positive = the demographic shift opens a financing gap. For the United States, this OECD-based figure (7.3% of GDP) reflects a broader concept of public old-age and survivors spending than the Social Security Administration's OASI program alone ($1,227.4bn, about 4.4% of 2023 GDP, used in Appendix G); the two should not be conflated when comparing this table with Table 33.

F.3 Caveats

The exercise's simplicity carries clear limitations, all working in interpretable directions. It holds the 2023 benefit structure fixed and embeds no policy response, so it measures the pressure a system would face *absent* reform rather than a forecast of outcomes; the retirement-age adjustments quantified in Section 4.8 are precisely the kind of reform that

contributions (Revenue Statistics 2025) additionally include health and unemployment. Both produce implausible net surpluses for economies with large funded second pillars or broad social insurance—under the statutory-rate measure the Netherlands, the United Kingdom and Israel all appear to run sizeable OASI surpluses. Where the proxies align reasonably with OASI the net present values are informative—about 165–180% of GDP for the United States and 190–270% for Greece—but across the full sample they are dominated by measurement rather than economics, which is why only the contribution-free balanced gap is reported.

would close part of the gap. It conditions on budget balance in 2023, so it excludes any pre-existing surplus or deficit—a system already in deficit (as several late-aging schemes are) faces a larger total obligation than the demographic increment reported here. The non-European expenditure figures are the latest available rather than strictly 2023, and the horizon is truncated at 2100, which omits obligations accruing thereafter and so understates the gap. Finally, the cross-country numbers use the common constant-ratio method rather than the national benefit formulas underlying the United States and Japan figures; the benchmark comparison above is the appropriate gauge of how much is lost in the simplification.

G Unfunded Pension Obligations: United States and Japan

The paper demonstrated that maintaining 2024 dependency ratios through 2100 requires retirement age increases ranging from 12 years (Portugal) to 24 years (China and Korea). For late-aging economies, these adjustments approach or exceed political and social feasibility bounds—China and Korea's required increase would push retirement ages toward 80s. Moreover, even feasible FRA increases address only one margin of pension system adjustment. Countries must simultaneously manage contribution rates, replacement rates, indexation rules, and eligibility criteria, all while demographic drag reduces the GDP base from which revenues are drawn and against which pension expenditures are measured.

This raises a critical question: what is the total fiscal burden that pension systems face under demographic aging? Quantifying this burden requires moving beyond flow measures (annual deficits or dependency ratios) to stock measures that capitalize the entire stream of future obligations net of projected revenues. Unfunded obligations—the present value of promised benefits minus expected contributions and existing reserves—provide precisely this metric. By expressing the full fiscal challenge as a stock relative to current GDP, unfunded obligations make transparent both the magnitude of adjustment required and the time sensitivity of reform.

The timing of reform matters critically. Japan's experience with the macroeconomic slide mechanism, introduced in 2004, illustrates how early indexation adjustments can substantially reduce long-term obligations while spreading adjustment costs gradually across cohorts. Countries that delay reform until demographic pressures peak face starker trade-offs: larger benefit cuts, higher tax increases, or both, concentrated in shorter timeframes when fiscal capacity is most strained. For late-aging economies approaching their demographic inflection points, the window for gradual adjustment is narrowing rapidly.

This section quantifies unfunded pension obligations for United States and Japan. I begin with the United States Social Security system, whose official actuarial methodology provides a transparent template, then extend the framework to Japan.

G.1 Calculating Unfunded Obligations of SSA

According to the Office of the Chief Actuary, Social Security Administration (2024), the value of unfunded obligations in year t_0, UO_{t_0}, over the valuation period (e.g., from year

t_0 to year t_n) is:

$$UO = PV[\text{Cost}] - PV[\text{Income}] - \text{Trust Fund}_{t_0} \tag{15}$$

where $PV[\text{Cost}] = \sum_{t=t_0}^{t_n} \frac{C_t}{(1+r)^{t-t_0}}$ is the present value of projected Social Security costs, $PV[\text{Income}] = \sum_{t=t_0}^{t_n} \frac{I_t}{(1+r)^{t-t_0}}$ is the present value of projected non-interest income (payroll taxes, income taxes on benefits), Trust Fund_{t_0} is the trust fund balance at the beginning of the valuation period, r is the real discount rate, C_t is total cost (benefits + administrative expenses) in year t and I_t is total non-interest income in year t.

In the 2024 Trustees Report, one of the long-range evaluation periods is the 75-year period from 2024 to 2098. Since I have data through 2100, I apply formula (15) from 2024 through 2100, taking into account the $2.6 trillion Trust Fund as of 2023.

I abstract from revenue from taxation of benefits and interest earnings on the Trust Fund in calculating income, and ignore administrative expenses to calculate costs. On the cost side, I assume all beneficiaries claim benefits at age 65, although a significant fraction (perhaps 50%) claim between ages 62 and 64. The direction of the resulting bias is ambiguous: the 2023 per-capita cost is constructed from total OASI benefits (which already include payments to early claimants) divided by the 65+ population, and projecting this loaded average with future 65+ population may over- or under-state costs depending on the relative growth of the 62–64 and 65+ age groups and on the actuarial benefit adjustments for early claiming. Finally, I consider only the Old-Age and Survivors Insurance (OASI) program, excluding Disability Insurance (DI) and Medicare (HI) programs.

The SSA's detailed methodology incorporates time-varying assumptions for interest rates, inflation, productivity, labor market dynamics, and demographic change. My estimates abstract from these complexities in favor of simplicity and transparency, allowing straightforward application to Japan's pension system using the same framework.

I begin with total net payroll tax income of $1,054.1 billion and total scheduled benefits of $1,227.4 billion reported for the OASI program in 2023.[11]

Using SSA estimates of the working-age population (ages 20–64) at 197.995 million and retirement-age population (ages 65 and older) at 60.877 million for 2023, I calculate the per capita income contribution from workers as $5,324, and the per capita benefit cost to retirees as $20,162. Since I evaluate unfunded obligations in 2023 dollars, I assume the per-person income and cost values in 2023 dollars remain constant through 2100.[12] This allows me to isolate time-variation in income and cost purely from changes in the old-age dependency ratio.

Applying these per-person income and cost estimates to SSA's intermediate population projections from 2024 through 2100, I compute annual total income and benefit cost streams. I then calculate the present value (as of 2023) of these streams using a constant real discount rate of 2.0%, and subtract the present value of total income (payroll taxes) and the OASI Trust Fund balance at end-2023 ($2.6 trillion) from the present value of total costs (benefits), following equation (15). This yields an estimate of unfunded obligations of $23.2

[11] See the 2024 Trustees Report Table II.B1, page 7.

[12] This is equivalent to assuming that both nominal income and nominal cost grow at the same rate as average nominal wages, so that the real per-person values are unchanged. The calculation therefore isolates time-variation in aggregate income and costs from changes in population age structure alone, holding the real benefit and contribution levels fixed at 2023 levels.

trillion as of 2023, which is 83.8% of 2023 GDP. This simple estimate is broadly consistent with the 2024 Trustees Report, which places the 75-year open-group unfunded obligations of the OASI program at $23.7 trillion.[13] The numerical closeness should be treated cautiously: the simplified calculation holds 2023 per-person income and cost values fixed and uses a coarse age-65 cost base, while SSA's estimate incorporates wage growth, benefit adjustment rules, and detailed beneficiary dynamics. The match is useful as an overall check that the order of magnitude is correct, but it should not be interpreted as evidence that the simplified model reproduces SSA's structural assumptions—several simplifications that raise the estimate (e.g., ignoring benefit claiming before age 65) are likely offset by others that lower it (e.g., ignoring benefit growth with wages).

Table 33 reports the impact of using different demographic projections, keeping the 2023 per-person income and cost values unchanged.

Table 33: Unfunded Obligations of SSA Under Alternative Demographic Projections

SSA	low cost	intermediate	high cost
	$16.8	$23.2	$30.7
	60.7%	83.8%	110.8%
UN	high TFR	medium TFR	low TFR
	$24.3	$27.4	$29.9
	87.6%	99.0%	108.1%
CB	medium	low	zero
	$25.7	$26.0	$26.7
	92.7%	94.0%	96.6%

$ trillion; as a percentage of 2023 GDP

Notes: All calculations use 2% real discount rate and 2023 per-person income ($5,324) and cost ($20,162). Valuation period: 2024–2100. 2023 GDP = $27.7 trillion. Trust Fund balance end-2023 = $2.6 trillion.

SSA's own population forecasts yield enormous range. The difference between 'low cost' and 'high cost' unfunded obligations exceeds 50% of GDP—nearly $14 trillion. This reflects fundamental uncertainty about future fertility, mortality, and immigration.

SSA projections are markedly more optimistic than Census Bureau or UN. CB's and UN's medium population projections produce approximately 9 and 15 percentage points of GDP higher unfunded obligations, respectively, compared to SSA's intermediate projections. This stems primarily from fertility assumptions. SSA projects U.S. TFR will rise from 1.7 in 2024 to 1.9 by 2031 and remain at that level—a substantial recovery given that U.S. fertility has been below 1.9 since 2009. In contrast, CB and UN assume fertility stabilizes near 1.6.

This 0.3 difference in TFR compounds over 75 years to produce dramatically different age structures. If SSA's fertility assumptions prove too optimistic—as recent trends suggest—the actual fiscal gap could be $4–6 trillion larger than officially projected, or 15–20 percentage points of GDP.

[13] See page 76, Table IV.B6 in the 2024 Trustees Report.

Immigration assumptions matter but less than fertility. The CB projections show that moving from the medium to the zero immigration scenario increases unfunded obligations by about 4 percentage points of GDP—substantial but far less than the fertility effect.

The range of UN projections is surprisingly narrow on the fiscal metric. Under the UO calculation, the UN high-TFR versus low-TFR spread for the U.S. is about 20 percentage points of GDP ($24.3 trillion to $29.9 trillion in Table 33). For reference, under the OADR metric Japan's UN high/low scenarios differ by roughly 60 percentage points; the corresponding UO fiscal spread for Japan under UN high versus low (no-slide, no-subsidy) is about 27 percentage points of GDP, so the two countries are more comparable in fiscal sensitivity than in demographic sensitivity. The relatively narrow U.S. UO spread reflects the fact that U.S. fertility variation across UN scenarios is smaller than Japan's, whose already-extreme age structure amplifies even modest fertility differences into large OADR gaps.[14]

These findings underscore substantial fiscal sensitivity of pension obligations to underlying demographic forecasts and highlight the importance of considering multiple projection sources in fiscal planning.

G.2 Unfunded Obligations of Japan's Public Pension System

The Japanese public pension system is organized in a two-tier structure combining universal coverage with earnings-related benefits. At its foundation is the National Pension (*Kokumin Nenkin*), which all residents of Japan between ages 20 and 59 are required to join. The National Pension provides the Basic Pension (*Kiso Nenkin*), a flat-rate benefit that serves as the common core of the system. The Basic Pension is financed by fixed monthly contributions, central and local government subsidies, and investment income. It ensures every resident meeting minimum coverage requirements is entitled to old-age, disability, or survivors' benefits. The Old-age Basic Pension is normally payable from age 65, subject to at least ten years of insured participation, with adjustments possible for earlier or later receipt.

On top of this universal system, salaried private sector workers and public employees are covered by Employees' Pension Insurance (*Kōsei Nenkin*). This scheme requires contributions proportional to wages, shared equally between employers and employees. In addition to the Basic Pension provided through the National Pension, Kōsei Nenkin pays an earnings-related benefit calculated from the insured's average salary and length of coverage. Thus, participants in Employees' Pension Insurance receive both the flat-rate Basic Pension and an additional wage-linked pension, while the self-employed, students, and non-salaried residents rely on the National Pension alone.

Japan's 2004 Macroeconomic Slide In 2004, the Japanese government undertook a pension reform with three important elements: 1) the contribution rate was raised from 13.58% gradually to 18.3% by 2017, 2) the central government promised to subsidize the

[14]When I ignore the $2.6 trillion trust fund, the unfunded obligations using the UN WPP medium and low variants are 108.5% and 117.6%, respectively. These are quite similar to 113% and 132% calculated using a different methodology in Section F as shown in Table 32.

basic National Pension by 50%, and 3) a macroeconomic slide mechanism was introduced to limit future nominal benefit increases to 0.2%—an amount calculated as an average increase in nominal wages of 1.1% minus 0.9% representing the decline in the labor force and the increase in longevity. In a positive-wage-growth environment, the 0.2% figure therefore represents the nominal floor on benefit growth; in real terms (deflating by actual price inflation), this mechanism results in a decline in the real value of benefits when inflation exceeds 0.2%.

Put differently, as long as nominal wages increased, this would be less than fully reflected as an increase in new and existing public pension benefits due to the macroeconomic slide. It was expected that the replacement rate would decline by about 15 percentage points over approximately 20 years from 2004 to 2023, and continue declining to about 2047.

However, Japan experienced deflation for many years with limited or negative nominal wage growth, and as a result the full slide was rarely implemented until about 2015, when 2.3% wage growth was reduced by the full 0.9% slide plus a 0.5% special adjustment to result in only a 0.9% increase in benefits—a 1.4% decline in real terms. Further reductions in real terms occurred in fiscal years 2019, 2020, 2021, 2023, 2024, and 2025, ranging from 0.1% to the full 0.9% slide.[15]

In my calculations, I start from actual 2023 public pension income and cost values and assume the macroeconomic slide on the cost side is implemented every year from 2024 through 2050, leading to a 0.8% annual decline in the real value of benefits.[16] I also show unfunded obligations in counterfactual cases of no macroeconomic slide and with the slide extended through 2100.

Data and Calculations In fiscal year 2023, Japan collected ¥40.7 trillion in premiums (paid by individuals and employers across the Employees' Pension and National Pension systems). Subsidies from central and local government's general tax revenues amounted to ¥13.4 trillion, bringing total income of the public pension system to ¥54.1 trillion.[17]

Dividing total revenue by the number of 20–64 year olds in 2023, 67.45 million, gives per-person income of ¥595,530 excluding government subsidies and ¥791,297 including transfers.[18] In the baseline accounting exercise, the government transfer is treated as a tax-financed revenue stream calibrated to its 2023 level and projected forward with the same real per-person convention as contributions—that is, constant in real per-worker terms. It should therefore be interpreted as an accounting subsidy flow, not as a full institutional model of the statutory 50 percent Basic Pension subsidy (which would vary with benefit costs). This convention means the "with subsidy" UO estimates measure how much fiscal

[15]See İmrohoroğlu, Kitao, and Yamada (2016) for estimates of the decline in replacement ratio in Japan as a consequence of implementing the 2004 macroeconomic slide.

[16]The 0.2% figure in the institutional description represents the minimum nominal benefit growth when the slide is triggered in a positive-wage-growth environment (average wage growth of 1.1% minus the 0.9% slide). The −0.8% used in my calculations reflects the realized annual *real* benefit change under the slide during the post-2015 period of moderate nominal wage growth (approximately 1%–2%) and positive inflation, when the full 0.9% slide applied. These two numbers are consistent: one describes nominal benefit growth under the mechanism, the other the real decline in purchasing power under observed macroeconomic conditions.

[17]See Annual Actuarial Report on the Public Pension Plans in Japan, Fiscal Year 2023, Pension Actuarial Subcommittee of the Social Security Council, Ministry of Health, Labour and Welfare, Japan.

[18]IPSS estimates for 2023: 20–64 population = 68.368 million; 65+ population = 36,347,900.

space the government transfer provides given 2023 income levels, not the actuarial present value of the government's open-ended statutory commitment.

Japan's total public pension benefits disbursed—combining both National Pension (basic) and Employees' Pension Insurance—amounted to approximately ¥54.0 trillion in FY 2023, about 9.1% of GDP. Dividing by the number of individuals 65 and older (36,347,900) gives per-person public pension benefit of ¥1,485,643.

Given per-person cost and income, I now calculate UO using various population projections, taking into account the Government Public Investment Fund (GPIF). Table 34 shows estimates (as percentage of 2023 GDP) using official IPSS and UN population projections.

Table 34: Unfunded Public Pension Obligations in Japan Under Alternative Scenarios

		no subsidy	w/subsidy
IPSS worst	No Slide	119.0%	58.1%
	Slide to 2050	65.9%	5.0%
	Slide to 2100	45.4%	−15.5%
IPSS medium	No Slide	99.4%	36.8%
	Slide to 2050	48.5%	−14.1%
	Slide to 2100	29.0%	−33.6%
IPSS best	No Slide	78.9%	14.4%
	Slide to 2050	30.2%	−34.3%
	Slide to 2100	11.8%	−52.7%
UN low	No Slide	111.7%	54.9%
	Slide to 2050	62.4%	5.6%
	Slide to 2100	44.7%	−12.1%
UN medium	No Slide	102.2%	41.4%
	Slide to 2050	52.1%	−8.8%
	Slide to 2100	33.8%	−27.0%
UN high	No Slide	84.4%	19.4%
	Slide to 2050	34.8%	−30.2%
	Slide to 2100	16.8%	−48.3%

As a percentage of 2023 GDP.

Notes: As percentage of 2023 GDP. "No Subsidy" excludes government transfers (¥13.4 trillion annually); "With Subsidy" includes 50% basic pension subsidy. "Slide to 2050" assumes 0.8% annual real benefit decline through 2050 (as legislated), then constant benefits. "Slide to 2100" extends mechanism through 2100. Negative values indicate fiscal surplus—present value of revenues exceeds present value of obligations.

Japan's macroeconomic slide is extraordinarily effective. Using IPSS medium population projections, unfunded obligations are −14.1% of GDP with the slide to 2050—meaning a positive balance of the public pension system in 2100. Without the slide, unfunded obligations would be +36.8% of GDP. The slide thus creates fiscal space equivalent to 51 percentage points of GDP.[19]

[19]When I ignore the GPIF, the macroeconomic slide, and the government subsidy, the unfunded obligations

Automatic adjustment eliminates fiscal risk. Under UN medium projections, the UO is −8.8% of GDP with the slide—also indicating positive balance. This demonstrates Japan is well-positioned to address public pension challenges with help from the 2004 reforms.

Extending the slide magnifies effectiveness. If the slide continues beyond 2050 to 2100, fiscal space expands further—to −34% of GDP (IPSS medium) or −27% (UN medium). This represents substantial reduction in the fiscal burden of public pensions.

Early reform matters enormously. Japan implemented the macroeconomic slide in 2004 when its OADR was 45%. This gave the mechanism 20 years to accumulate effects before demographic pressure peaked. Countries delaying reform until dependency ratios exceed 60–70% face much steeper adjustment paths.

Interpreting Negative Unfunded Obligations A negative UO indicates that under stated assumptions, the present value of future income (payroll taxes plus government subsidies) exceeds the present value of future benefit costs. Note that the Japan calculation does not subtract existing pension reserve assets, analogously to the treatment in the U.S. calculation where the OASI Trust Fund *is* subtracted. Japan's Government Pension Investment Fund (GPIF) held approximately ¥224 trillion at end-FY2023; including these reserves would make Japan's UO more negative across all scenarios. The estimates in Table 34 should therefore be interpreted as a conservative upper bound on Japan's net pension liability under the stated scenarios.

This finding has several interpretations. First, it signals Japan's 2004 reforms are likely to be successful—perhaps even more aggressive than necessary—in restoring long-run sustainability. Second, it suggests that if demographic outcomes prove better than medium projections (higher fertility or immigration), Japan could afford modest benefit increases or contribution rate reductions after 2050. Even under the worst IPSS projections, the UO of public pensions is only 5% of GDP. Third, it highlights that the macroeconomic slide, while politically contentious due to its gradual erosion of replacement rates, has been extraordinarily effective at creating fiscal space.

G.3 Comparing U.S. and Japan: What if the U.S. Adopted a Macroeconomic Slide?

If the U.S. Social Security Administration undertook a macroeconomic slide like Japan's—starting in 2024 and reducing cost per retiree by 0.8% annually until 2050—unfunded liability using SSA's intermediate population projections would decrease from $23.2 trillion to $11.2 trillion (from 83.8% to 40.6% of 2023 GDP).[20] Extending this slide to 2100 would deliver a UO of only $7.7 trillion (27.8% of 2023 GDP).

Put differently, reforming U.S. Social Security along the lines of Japan's 2004 macroeconomic slide (only on the cost side, without raising the payroll taxes) would help postpone

using the UN WPP medium and low variants are 143.8% and 153.3%, respectively. These are much higher than 75% and 93% calculated using a different methodology in Section F as shown in Table 32.

[20]The 0.8% annual reduction applied to the U.S. case is a stylized benchmark—equal in magnitude to Japan's realized slide—to illustrate the fiscal value of early automatic adjustment. It does not represent a specific proposed U.S. policy rule; optimal U.S. parameters would depend on domestic wage growth, inflation, and demographic projections.

Trust Fund insolvency substantially and reduce long-run fiscal pressure dramatically. Combined with modest contribution rate increases, the system could achieve sustainability without dramatic benefit cuts or retirement age increases.