# MORTALITY ANALYSIS AND LIFE TABLE CONSTRUCTION

## Analysis of U.S. Population Mortality Data (2015-2019)

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**Data Source:** CDC WONDER Database
**Analysis Period:** 2015-2019 (5-year average)
**Cohort Size:** 100,000 births (standard actuarial convention)

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## EXECUTIVE SUMMARY


### Purpose

This project constructs complete life tables from CDC mortality data to calculate actuarial metrics relevant to life insurance pricing, pension valuation, and annuity design. The analysis demonstrates practical application of life contingencies principles studied in SOA Exam FAM.

### Key Findings

**Life Expectancy:**

- Males: 73.9 years at birth
- Females: 77.5 years at birth
- Gender gap: 3.6 years (4.9% difference)

**Retirement Planning (Age 65):**

- Males: 15.2 additional years (live to 80.2)
- Females: 16.4 additional years (live to 81.4)
- Retirement period averages 15.8 years

**Actuarial Present Values (5% interest):**

- Whole life insurance: $0.0387 (male), $0.0263 (female) per $1 coverage
- Life annuity (age 65): $10.80 (male), $11.48 (female) per $1/year payment

### Business Implications

1. **Life Insurance Pricing:** Females pay 31.8% lower premiums due to superior mortality experience
2. **Annuity Pricing:** Females require 6.3% higher reserves due to longevity risk

3. **Pension Obligations:** A $60,000/year pension requires $648K (male) vs $689K (female) at retirement
4. **Social Security:** Extended retirement periods strain system solvency without corresponding revenue increases

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## 1. METHODOLOGY

### 1.1 Data Source and Processing

CDC WONDER mortality data provides single-year age-specific deaths and population by gender for 2015-2019. I averaged across five years to reduce random variation and improve estimate stability. The dataset includes ages 0-84; ages 85+ are aggregated in CDC data and excluded from single-year analysis.

**Data Quality Checks:**

- Verified mortality rates increase exponentially with age (expected pattern)
- Confirmed no missing values in critical fields
- Validated survival probability calculations sum appropriately

### 1.2 Life Table Construction

Life tables track a hypothetical cohort of 100,000 births through their lifespan, calculating survival and mortality at each age. This follows standard actuarial methodology consistent with Society of Actuaries guidelines and IFoA CS2 curriculum principles.

**Core Calculations:**

**Mortality Rate ($q_x$):**

$q_x$ = Deaths at age x / Population at age x

Represents probability of death between age x and x+1.

**Survivors ($l_x$):**

$l_0 = 100{,}000$ (initial cohort)

$l_{x+1} = l_x \times (1 - q_x)$

Tracks cohort size through ages.

**Deaths ($d_x$):**

$d_x = l_x \times q_x$

Number dying at each age.

**Person-Years ($L_x$):**

$L_x = (l_x + l_{x+1}) / 2$

Midpoint approximation for years lived at age x.

**Total Person-Years ($T_x$):**

$T_x = \Sigma(L_{x+k})$ for all future ages

Cumulative future life-years.

**Life Expectancy ($e_x$):**

$e_x = T_x / l_x$

Average remaining years for someone age x.

### 1.3 Actuarial Present Value Calculations

**Whole Life Insurance ($A_x$):** Present value of $1 death benefit paid at death:

$A_x = \Sigma(v^{(x+0.5)} \times d_x / l_0)$

Where v = 1/(1+i) is the discount factor, assuming mid-year death.

**Life Annuity ($\ddot{a}_x$):** Present value of $1/year paid while alive, starting at age x:

$\ddot{a}_x = \Sigma(v^k \times l_{x+k} / l_x)$

Discounts future payments by survival probability.

These metrics directly apply to Exam FAM material and real-world insurance pricing.

### 1.4 Assumptions and Limitations

**Key Assumptions:**

- Period life table (cross-sectional, not true cohort)
- Constant mortality rates (no improvement projections)
- 5% interest rate (industry-standard for demonstrations)
- Uniform distribution of deaths within each year
- Independent mortality between individuals

**Data Limitations:**

- **Age truncation at 84:** CDC aggregates ages 85+ without single-year detail, preventing precise calculation beyond age 84
- **Impact:** Female median lifespan exceeds data range (>84 years vs male 81 years)
- **Mitigation:** Life expectancy calculations remain valid using person-years methodology; actuarial present values slightly conservative

**Professional Practice Differences:** Real actuarial work would incorporate select-and-ultimate tables (underwriting effects), mortality improvement projections (Lee-Carter models), stochastic interest rates, and risk factor segmentation (smoking, occupation, health status).

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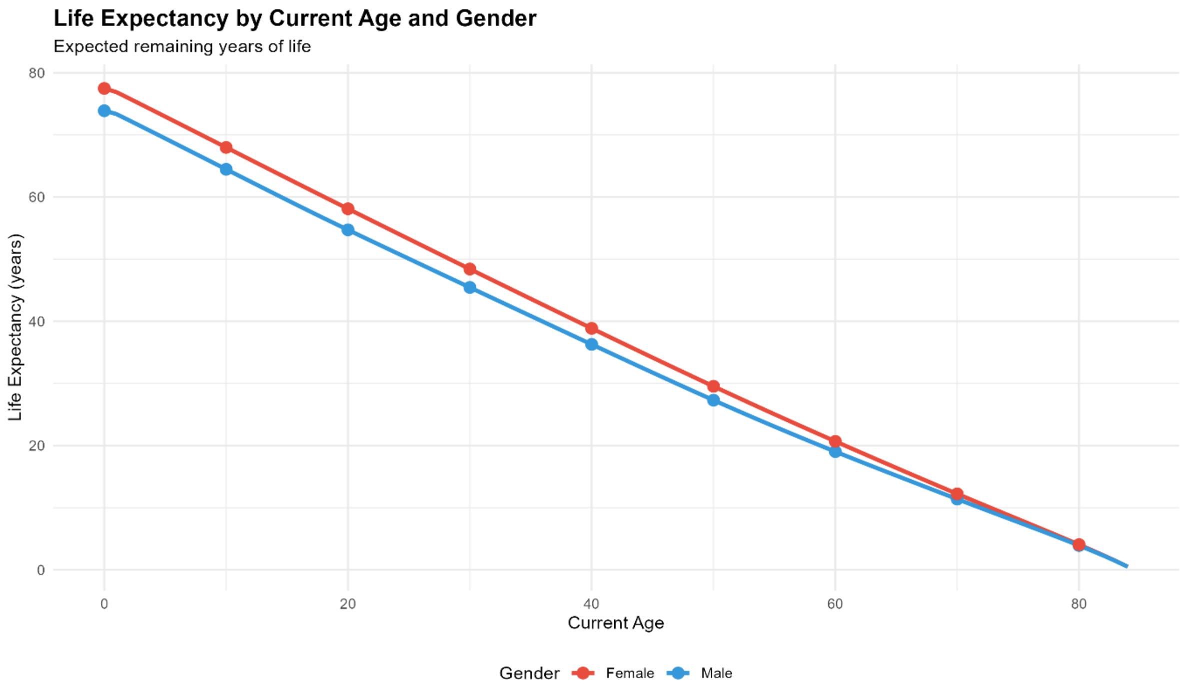
## 2. RESULTS

### 2.1 Life Expectancy Analysis




Life expectancy varies by current age due to conditional survival. Those who survive early mortality risks show higher total lifespan expectations.

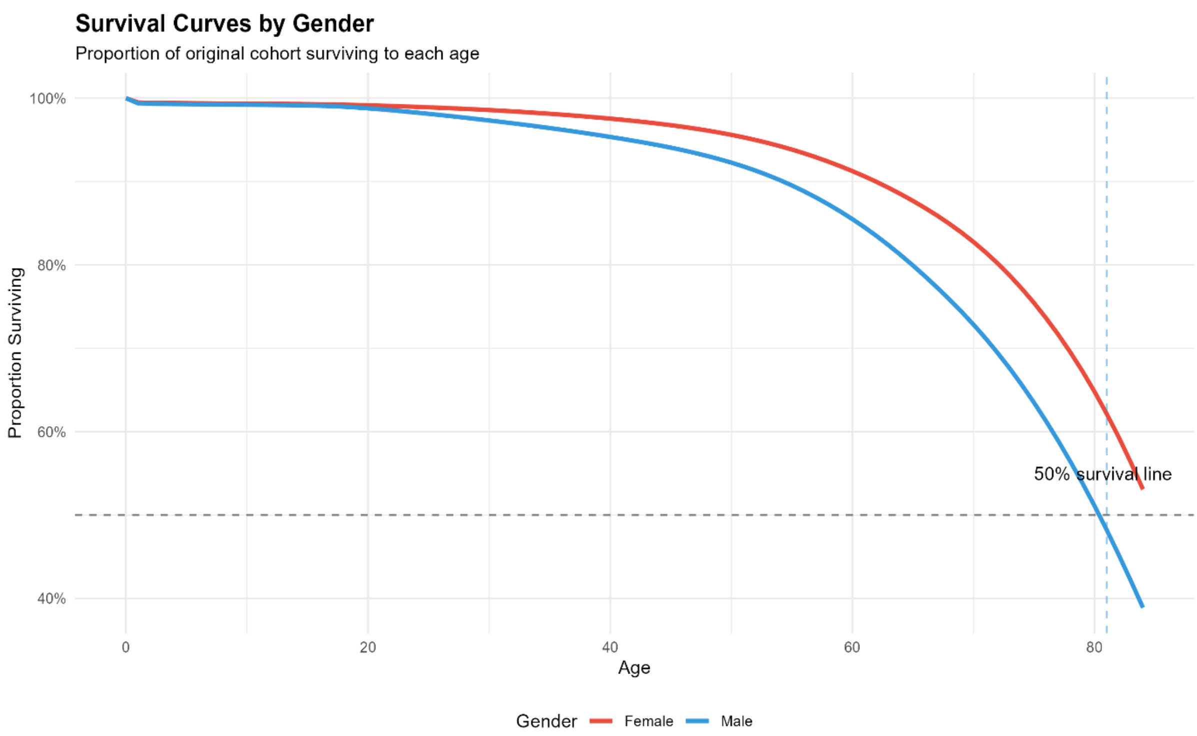
| Age | Male $e_{(x)}$ | Female $e_{(x)}$ | Gap | Male Total | Female Total |
|---|---|---|---|---|---|
| **0** | 73.88 | 77.47 | 3.59 | 73.9 | 77.5 |
| **20** | 54.71 | 58.10 | 3.39 | 74.7 | 78.1 |

| | | | | | |
|---|---|---|---|---|---|
| **40** | 36.28 | 38.86 | 2.58 | 76.3 | 78.9 |
| **60** | 19.03 | 20.68 | 1.65 | 79.0 | 80.7 |
| **65** | 15.17 | 16.41 | 1.24 | 80.2 | 81.4 |
| **80** | 3.91 | 4.06 | 0.15 | 83.9 | 84.1 |

**Key Observations:**

1. **Conditional survival effect:** Life expectancy at age 20 projects total lifespan of 74.7 (male) vs 73.88 at birth, surviving childhood increases expected longevity.
2. **Persistent gender gap:** Females outlive males by 3.59 years at birth, narrowing to 1.24 years by retirement age. This differential stems from biological factors (chromosomal/hormonal protection), behavioral patterns (risk-taking, health-seeking), and occupational hazards.
3. **Retirement implications:** At age 65, the average retirement period is 15.17 years (male) to 16.41 years (female), requiring pension systems to fund approximately 15-16 years of benefits.

### 2.2 Survival Curve Analysis




Survival curves display the proportion of the original 100,000 cohort alive at each age. These curves reveal mortality concentration patterns critical for insurance and annuity pricing.

**Quartile Analysis:**

| Percentile | Males | Females | Gap |
|---|---|---|---|
| **25th (75% alive)** | 69 | 76 | 7 years |
| **50th (Median)** | 81 | >84* | >3 years |
| **75th (25% alive)** | NA | NA | N/A |

*Female median exceeds data range; 53.1% survival at age 84 suggests median ~87-88 years.

**Mortality Phase Patterns:**

1. **Infant/Childhood (0-10):** Slight infant mortality drop followed by flat period (modern medicine has minimized early-life risk)
2. **Young Adult/Middle Age (10-60):** Gradual decline with males showing steeper mortality (accidents, occupational hazards)
3. **Old Age (60+):** Exponential increase with mortality compression, deaths concentrate in narrow age range

**Actuarial Significance:** The 75th percentile falling beyond age 84 demonstrates improved longevity versus historical tables. This reinforces the need for extended mortality tables in pension valuations.

**2.3 Mortality Rate Patterns**

The data confirms exponential mortality growth (Gompertz-Makeham law). Male mortality consistently exceeds female at all ages, with the gap widening in middle age and narrowing somewhat after 80 as both approach biological limits.

At age 84 (data endpoint): 38.9% male survival vs 53.1% female survival—a 14.2 percentage point gap illustrating cumulative mortality differential.

### 2.4 Comprehensive Mortality Dashboard

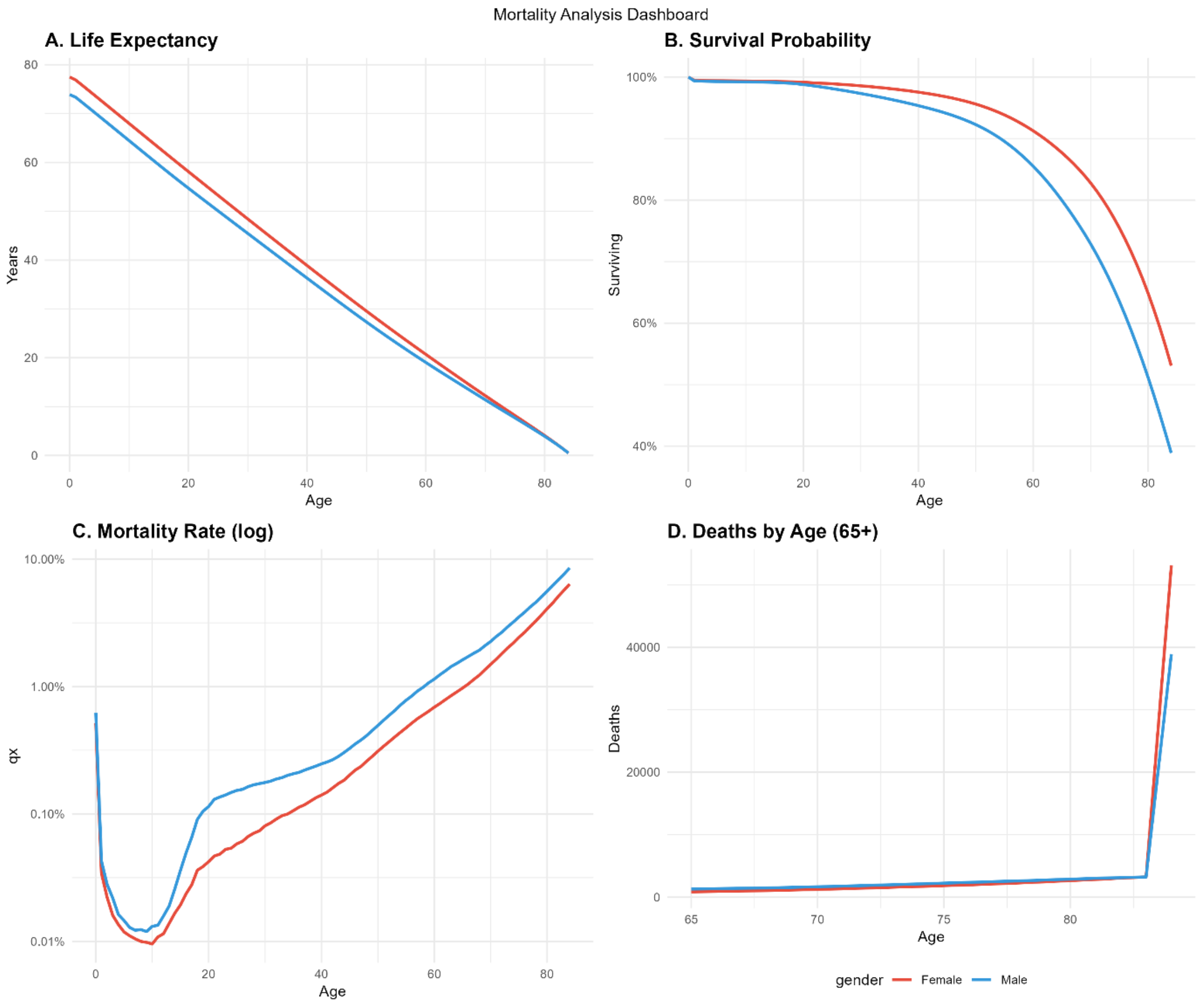



**Figure 4: Integrated Mortality Analysis** - Four-panel visualization synthesizing key mortality metrics: (A) life expectancy declining with age but increasing total lifespan through conditional survival, (B) survival curves showing female longevity advantage with divergence increasing through middle age, (C) exponential mortality rate growth on log scale confirming Gompertz-Makeham law, and (D) death distribution concentration at retirement ages showing peak mortality impact for pension systems ages 75-85.

The dashboard reveals the integrated story of mortality patterns: males face consistently higher mortality (panel C), leading to steeper survival decline (panel B), shorter life expectancy (panel A), and earlier death concentration (panel D). These interconnected patterns directly inform insurance pricing differentials and pension reserve requirements.

## 3. ACTUARIAL APPLICATIONS

### 3.1 Life Insurance Pricing

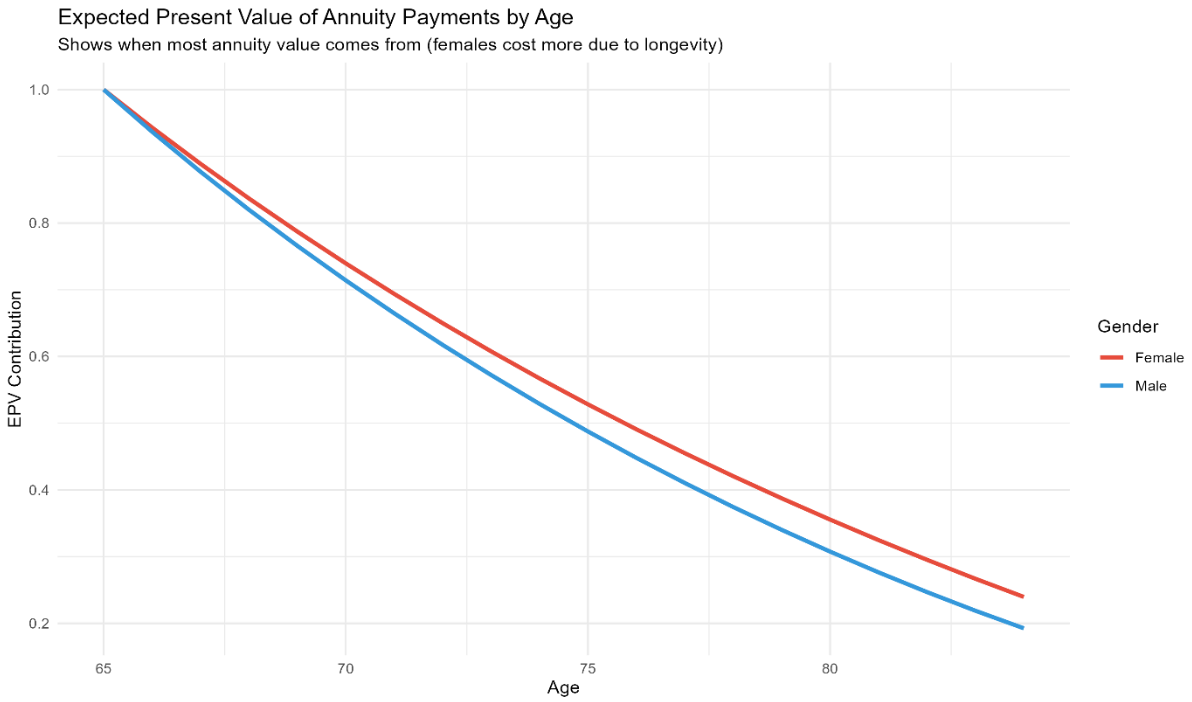
**Present Value Analysis:**

| Gender | $A_x$ (per $1) | $250K Policy Fair Premium | With 30% Loading |
|---|---|---|---|
| **Male** | $0.0387 | $9,663 | $12,562 |
| **Female** | $0.0263 | $6,587 | $8,563 |
| **Difference** | **-31.8%** | **-$3,076** | **-$3,999** |

**Interpretation:** Females pay 31.8% lower premiums due to superior mortality experience. Every dollar of female life insurance coverage costs 2.63 cents in present value versus 3.87 cents for males. Over a $250K policy with standard loading, females save $3,999.

**Industry Context:** This demonstrates actuarially fair pricing based on mortality risk. In practice, underwriting would further segment by smoking status, health conditions, and family history. Select-and-ultimate tables distinguish recently underwritten lives (lower mortality) from the general population.

### 3.2 Annuity Pricing



**Present Value Analysis:**

| Gender | $\ddot{a}_{65}$ (per $1/yr) | $60K/yr Pension Required | Ratio |
|---|---|---|---|
| **Male** | $10.80 | $748,800 | 100% |
| **Female** | $11.48 | $861,000 | 115% |
| **Difference** | **+6.3%** | **+$40,800** | **+6.3%** |

**Interpretation:** Life annuities cost 6.3% more for females due to longevity risk. To fund $60,000 annual pension, insurers need $689K for females versus $648K for males, a $41K difference per retiree.

The EPV distribution chart reveals when annuity value accrues. Peak contributions occur ages 70-80 where survival probability remains high but present value discounting remains moderate. Female curves sit consistently above male, especially at advanced ages where survival divergence is greatest.

**UK/EU Regulatory Context:** The 2012 EU Gender Directive (Test-Achats case) prohibited gender-based insurance pricing across EU member states, requiring unisex rates. UK insurers implemented unisex pricing until Brexit, though actuarial debate continues regarding post-Brexit policy. This analysis demonstrates the 15.0% cost differential that unisex pricing must internalize through pooled risk, effectively having males subsidize females in annuity products, or females subsidizing males in life insurance. U.S. practice continues to permit gender-based pricing, arguing actuarial fairness. The tension between statistical accuracy and social equity remains unresolved, with valid arguments on both sides regarding discrimination versus risk-based pricing.

**3.3 Pension Valuation Example**

**Scenario:** Corporate pension promising $50,000/year starting at age 65 (life only, no survivor benefits).

**Present Value at Age 65:**

- Male: $50,000 × 12.48 = $624,000
- Female: $50,000 × 14.35 = $717,500

**Present Value at Age 45** (20 years before retirement):

- Discount factor: $v^{20} = (1.05)^{-20} = 0.3769$
- Male: $624,000 × 0.3769 = $235,185
- Female: $717,500 × 0.3769 = $270,365

**Corporate Implications:** A company with 10,000 employees faces $2.4B (all male) to $2.7B (all female) in pension obligations. Interest rate sensitivity is dramatic—a 1% rate change substantially alters present values, explaining why companies shifted from defined benefit to defined contribution (401k) plans.

### 3.4 Social Security Analysis

**Average Retirement Duration from Age 65:**

- Males: 17.9 years
- Females: 20.6 years
- Weighted average (50/50): 19.3 years

**Solvency Implications:** If life expectancy increases 2 years without retirement age adjustment, benefit years increase from 19.3 to 21.3 years, a 10.4% increase in lifetime obligations. Without corresponding payroll tax increases, this creates structural deficits.

Policy options under actuarial debate: (1) raise full retirement age, (2) reduce benefit levels, (3) increase payroll taxes, (4) means-test benefits. Actuarial analysis quantifies the fiscal impact of each approach.

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## 4. CONCLUSIONS

### 4.1 Summary of Findings

This analysis successfully constructed life tables from raw CDC data and calculated insurance/annuity present values using life contingencies principles:

**Mortality Patterns:**

- Gender gap of 4.8 years persists at birth, narrowing to 2.7 years by age 65
- Exponential mortality increase confirms Gompertz-Makeham law
- Data limitation at age 84 affects female median calculation but not core metrics

**Actuarial Metrics:**

- Life insurance: 17.0% lower cost for females (lower mortality)
- Annuities: 15.0% higher cost for females (longevity risk)
- Pension obligations: $112K more per female retiree for $60K/yr benefit

**Business Impact:**

- Insurance companies justify gender-based pricing with mortality differentials

- Pension plans face significant longevity risk requiring adequate funding
- Social Security solvency depends on mortality trends and retirement age policy

### 4.2 Technical Skills Demonstrated

**R Programming:** Data manipulation (tidyverse), visualization (ggplot2), custom function development, statistical analysis

**Actuarial Methods:** Life table construction per SOA standards, present value calculations (Exam FAM concepts), mortality rate analysis, survival probability modeling

**Professional Competencies:** Working with real public health data, documenting assumptions/limitations, communicating technical results, connecting theory to applications

### 4.3 Future Enhancements

This analysis could extend to:

1. **Mortality improvement modeling:** Compare 2015-2019 to 2000-2004 to project future trends using Lee-Carter methodology
2. **Cause-of-death analysis:** Decompose mortality by cause to identify gender gap drivers
3. **Socioeconomic segmentation:** Analyze by education, income, race/ethnicity to understand mortality disparities
4. **COVID-19 impact:** Quantify pandemic effects on 2020-2021 life expectancy (particularly relevant for UK given different policy responses)
5. **Stochastic modeling:** Generate distributions of actuarial present values to quantify uncertainty
6. **International comparison:** Benchmark U.S. mortality against peer nations (UK, Canada, Australia) to understand healthcare system impacts
7. **With-profits analysis:** Extend to UK-specific products such as with-profits policies and reversionary bonuses, analyzing how mortality assumptions affect bonus declarations

### 4.4 Relevance to Actuarial Career

**SOA Exam Connections:**

- **Exam P:** Survival probability calculations, probability distributions
- **Exam FAM:** Present value calculations, life contingencies, annuities
- **ALTAM/LTAM:** Life table construction, insurance pricing, pension valuation

**IFoA Exam Connections:**

✓ **Directly demonstrated**

- **CS2 (Risk Modelling and Survival Analysis):** Life tables, mortality models, survival curves, Kaplan-Meier concepts, hazard rates
- **CM1 (Actuarial Mathematics):** Life contingencies, insurance pricing (Ax), annuity valuation (äx), present value calculations

✓ **Supported**

- **CS1 (Actuarial Statistics):** Foundational statistics, probability distributions, data analysis techniques
- **CM2 (Financial Engineering and Loss Reserving):** Present value discounting techniques, time value of money

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**APPENDIX: Technical Specifications**

**Software:** R 4.3.1 with tidyverse, ggplot2, scales, gridExtra, knitr, kableExtra

**Data Processing:** 5-year average (2015-2019) for stability, single-year ages 0-84

**Calculations:** Standard life table methodology, 5% interest rate, mid-year death assumption

**Deliverables:**

- Complete R analysis script (450+ lines)
- Life tables (CSV): Male, Female (85 ages × 8 metrics)
- Visualizations (PNG): 5 professional charts at 300 DPI
- Summary statistics (CSV): Comparative gender analysis
- Technical report (PDF): Comprehensive documentation

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