Actuarial Vulnerabilities in Social Protection Systems of Emerging Economies: A Dual Systematic Review of Pension Sustainability and Commuting Hazard Liabilities

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ABSTRACT

Social protection systems in emerging and middle-income economies are confronting structural actuarial vulnerabilities driven by rapid demographic transition, labour market informality, and evolving occupational risk patterns. This paper develops an integrated research framework to examine two interrelated and financial material liabilities within statutory social insurance schemes: (i) the long-term sustainability and adequacy of survivors' and invalidity pension programs under accelerated population ageing and shrinking contributor bases, and (ii) the rising actuarial burden of commuting-related occupational accidents characterised by high tail-risk exposure.

Anchored in a dual Systematic Literature Review (SLR) guided by the PRISMA protocol, the study synthesises multidisciplinary evidence from actuarial science, demographic economics, transportation risk modelling, and predictive analytics. The pension sustainability component evaluates demographic dependency ratios, actuarial present value (APV) trade-offs between contributions and benefits, informal sector inclusion challenges, and parametric reform strategies including retirement age adjustments, hybrid pension structures, and dividend optimisation mechanisms. Concurrently, the commuting hazard component examines epidemiological determinants, psychophysiological risk factors, and the application of advanced modelling techniques such as SARIMA, state-space models, artificial neural networks, random forests, gradient boosting, spatial clustering, and expectile-based regression for actuarial tail-risk forecasting.

By bridging macro-demographic actuarial valuation with micro-level predictive liability modelling, this framework advances a proactive, data-driven approach to social insurance governance. The study contributes a structured policy matrix to assist regulators in recalibrating contribution systems, expanding coverage to informal and gig workers, strengthening gender equity in survivor benefits, and transitioning from reactive compensation models to preventive, risk-adjusted social protection strategies. The proposed synthesis provides an empirical and methodological foundation for enhancing solvency, inclusivity, and long-term resilience of social security systems across the Global South.

Keywords: Social Security, Survivors' Pension, Commuting Accidents, Actuarial Modeling, Predictive Analytics.

INTRODUCTION

Statutory social insurance programs operate as vital macroeconomic safety nets, explicitly designed to prevent

catastrophic financial ruin following the premature loss of a breadwinner or a permanent occupational disability. However, these systems face maturity challenges that threaten their efficacy, particularly in developing and middle-income nations transitioning rapidly into aging societies [1], [2].

The actuarial modeling of these funds requires a delicate equilibrium between optimizing contribution rates through actuarial present value (APV) calculations and ensuring payouts meet basic human adequacy standards.This paper explains a structured research agenda to address two primary vectors of systemic vulnerability [3], [4]:

Shifting Socio-Demographic Dependencies:

The obsolescence of legacy pension scheme assumptions in the face of plunging fertility rates, rising life expectancies, and the massive expansion of the unprotected gig economy [5], [6].

Occupational Hazard Evolution:

The sharp rise in commuting-related accidents, which impose staggering, highly unpredictable financial burdens on statutory compensation funds.[2] Through a dual Systematic Literature Review (SLR) approach, this paper synthesizes fragmented literature into a cohesive policy roadmap, leveraging advanced mathematical modeling and socio-economic profiling to safeguard the solvency of national social safety nets [7]–[9].

Sustainability And Adequacy Of Survivors' And Invalidity Pension Schemes

Demographic Pressures in Emerging Economies

Developing nations are experiencing a compressed demographic transition compared to their Western counterparts. Malaysia, for instance, is a late-dividend country that is aging at an accelerated pace. Data from the Department of Statistics Malaysia (DOSM) indicates that the country transitioned to an aging society in 2021, and by 2040, 17.3% of its population (approximately 6.4 million people) will be aged 60 or older. By 2057, Malaysia is projected to reach "super-aged" status, with over 20.5% of the population exceeding the age of 60. This shift is driven by two primary factors. First, the total fertility rate (TFR) has plummeted from 4.9 children per woman in 1970 to 1.55 in 2024, well below the replacement level of 2.1. Second, life expectancy has surged, reaching 72.5 years for men and 77.4 years for women. Consequently, the demographic old-age to working-age ratio is increasing, severely shrinking the tax base and contributor pool necessary to sustain pay-as-you-go (PAYG) and partially funded pension systems [1], [9].

Changing Socio-Economic Paradigms and Systemic Inequities

Significant socio-economic shifts fundamentally alter the dependency ratios upon which legacy survivor benefit models were built. The historical "male-breadwinner" model that informed early survivor benefits is increasingly obsolete due to declining marriage rates, delayed childbirth, and increased female labor market participation. This obsolescence leads to complex debates over the equity and labor market disincentives of current pension designs. For example, legacy systems often inadvertently penalize broken career trajectories (such as time taken off for childcare), which disproportionately affects women and widens the gender pension gap [6].

The Informal Sector and GIG Economy Vulnerabilities

A paramount issue confronting modern social security systems is the failure to encompass a substantial portion of the workforce engaged in the informal sector. In 2023, the informal sector in Malaysia swelled to 3.45 million workers. Gig workers, agricultural laborers, and freelancers operate in a regulatory vacuum, frequently evading mandatory social security contributions. This gap denies them access to critical benefits such as retirement savings, occupational injury compensation, and survivors' pensions, heightening their vulnerability to economic adversities. Recent legislative efforts, such as the Gig Workers Bill 2025 in Malaysia, aim to rectify this by mandating social security (SOCSO) contributions for platform workers, thus formalizing their status and providing a safety net against workplace accidents and permanent disability. However, integrating highly

variable, informal incomes into traditional deterministic actuarial models remains a significant mathematical and policy challenge [1], [5], [10], [11].

Actuarial Trade-offs: Sustainability vs. Adequacy

The sustainability of pension schemes requires balancing the Actuarial Present Value (APV) of expected lifetime contributions against the APV of expected lifetime payouts. The APV of a continuous life annuity (pension payout) for a life aged x is classically defined as [3]:

$$\bar{a}_x = \int_0^\infty e^{-\delta t} \cdot {}_tp_x \, dt$$

where δ is the force of interest and ${}_tp_x$ is the probability that a life aged x survives to age $x + t$.

With increasing ${}_tp_x$ (longevity) and rising inflation, the real value of pension benefits erodes unless cost-of-living adjustments (COLA) are implemented.[5] However, aggressive COLA integration threatens fund solvency.[6] Current literature lacks a comprehensive, cross-national synthesis of parametric reforms such as transitioning to defined contribution (DC) models, optimizing investment dividends (e.g., forecasting EPF returns using ARIMA or Holt-Winters models), and raising statutory retirement ages to mitigate these risks [12]–[14].

Epidemiological And Socio-Economic Determinants Of Commuting Accidents

The Commuting Hazard Epidemic

While industrial and direct workplace accidents have seen a general decline globally due to stringent occupational safety and health (OSH) regulations, work-related commuting accidents have surged precipitously. This trend is alarmingly prevalent in developing economies heavily reliant on two-wheeled motorized transport. In Malaysia, motorcycles consistently emerge as the most vulnerable vehicles involved in fatal crashes, contributing significantly to the estimated RM 3.12 million economic loss per road fatality. Commuting accidents represent a distinct category of occupational hazard. Legally recognized under industrial compensation acts, they differ drastically from workplace accidents in causation, employer control, and rehabilitation complexity.[9] These incidents impose a staggering financial burden on social security organizations through immediate medical compensation, temporary disablement benefits, and highly expensive lifelong invalidity pensions [6], [8], [15].

Socio-Economic and Psychophysiological Risk Determinants

While traditional transportation literature focuses heavily on road-environmental factors, recent studies highlight the critical role of human and socio-economic elements. The underlying psychophysiological determinants of commuting accidents such as intense work scheduling, shift-work fatigue, drowsiness, and psychological pressure are particularly acute among specific demographics, such as healthcare workers and gig economy delivery riders. Furthermore, spatial geographical disparities, such as urban sprawl forcing longer commutes, act as significant risk multipliers [4], [7], [9].

Advanced Predictive Modeling for Road Safety and Liability

To accurately forecast accident frequencies and claim severities, traditional statistical methods are increasingly being replaced by advanced machine learning (ML) architectures [5], [16].

1) Time-Series and State Space Models (SSMs):

Methods like Seasonal Autoregressive Integrated Moving Average (SARIMA) and SSMs are utilized to forecast macro-level accident trends over time.[14] An SSM operates via a state equation $x_t = f(x_{t-1}, u_t) + w_t$ and

an observation equation $y_t = h(x_t) + v_t$, allowing for the modeling of unobserved latent variables affecting crash rates [8].

2) Non-linear Machine Learning: Artificial Neural

Networks (ANN), Random Forests, and Gradient Boosting (XGBoost) models have demonstrated superior predictive accuracy (lower RMSE and MAE) in mapping complex, non-linear relationships between driver demographics, road conditions, and crash severity [6], [8].

3) Spatial Clustering:

K-means spatial clustering is employed to identify geographical hotspots (e.g., high-risk commuting corridors in Selangor), enabling targeted regional interventions [8], [16].

A. Expectile-Based Modeling for Actuarial Tail Risk

A critical gap in linking transportation models to actuarial liability is predicting the *severity* of the financial payout (the "tail risk"). Traditional quantile regression minimizes absolute errors, but often fails to capture extreme, catastrophic claims effectively. The integration of Expectile Regression into machine learning frameworks (e.g., Expectile-based Random Forests or Neural Networks) offers a mathematically coherent alternative. Expectiles are defined by tail expectations rather than tail probabilities, capturing both the frequency and the magnitude of extreme losses. The τ-th expectile $e_\tau(Y)$ is obtained by minimizing the asymmetric quadratic loss:

$$e_\tau(Y) = \arg\min_{\theta \in \mathbb{R}} \mathbb{E}[\rho_\tau(Y - \theta)]$$

This approach yields superior conditional coverage and backtesting performance for systemic risk forecasting compared to standard Value-at-Risk (VaR) measures [16].

PROPOSED SYSTEMATIC LITERATURE REVIEW METHODOLOGY

To systematically address the vulnerabilities outlined above, a comprehensive SLR utilizing the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol is proposed [17], [18].

A. Search Strategy and Selection Criteria

The review will query major databases (Scopus, Web of Science, ScienceDirect, IEEE) for literature published between 2010 and 2025.

1) Theme 1 (Pensions):

Keywords will include ("survivors pension" OR "invalidity pension" OR "social security") AND ("demographic transition" OR "informal sector" OR "actuarial present value" OR "sustainability").

2) Theme 2 (Commuting Hazards):

Keywords will include ("commuting accident" OR "occupational hazard") AND ("machine learning" OR "predictive modeling" OR "expectile regression" OR "social insurance").

B. Analytical Dimensions and Data Extraction

Part 1: Pension Sustainability Evaluation Criteria

i. Demographic Pressures:

Extracting total fertility rates, life expectancy gains, and demographic old-age dependency ratios.

ii. Fund Sustainability:

Evaluating APV of contributions, inflation erosion, and parametric reform impacts (e.g., transition from DB to DC, raising retirement ages).

iii. Systemic Inequities:

Examining the efficacy of non-contributory basic pensions and micro-credentialing/financial literacy interventions for marginalized groups.

Part 2: Commuting Accident Analytical Dimensions

i. Predictive Modeling:

Synthesizing the accuracy metrics (RMSE, MAE, AUC) of ANNs, Random Forests, and Expectile Regression models applied to heterogeneous traffic data [4], [19]–[21].

ii. Risk Determinants**:**

Extracting variables such as gig-economy work schedules, drowsy driving, vehicle type, and spatial clustering metrics.

iii. Rehabilitation Efficacy:

Assessing the actuarial cost-reduction impact of Return to Work (RTW) multidisciplinary rehabilitation programs [22]–[25].

Strategic Impact and Policy Implications

The findings generated by this integrated systematic review framework will provide a rigorous, data-driven matrix for policymakers attempting to recalibrate social insurance models in the Global South.

A. Recalibrating Pension Design for Inclusivity

Understanding the optimal mathematical and social balance between contribution optimization and poverty alleviation will allow statutory authorities to enact proactive reforms. Expanding mandatory coverage to the gig economy (as seen in Malaysia's 2025 reforms) must be coupled with flexible, hybrid pension designs that account for volatile income streams. Furthermore, addressing the gender pension gap requires structural adjustments to survivor benefits that recognize modern dual-earner households and non-linear career paths [5], [6], [26].

B. Proactive Risk Management for Occupational Hazards

By systematically mapping the multifaceted variables that drive commuting accidents and evaluating the most accurate predictive algorithms, social security institutions can transition from a paradigm of reactive compensation to proactive risk management [1], [22].

1) Risk-Adjusted Premiums:

Utilizing machine learning to dynamically recalibrate employer contribution rates based on calculated workforce commuting risk profiles and telematics data [3], [6].

2) Targeted Interventions:

Deploying K-means spatial analysis to identify high-risk zones, allowing for geographically specific infrastructure improvements and employer-mandated safety training [22].

3) Optimized Rehabilitation:

Utilizing predictive profiling to identify claimants most likely to benefit from early, intensive Return to Work (RTW) interventions, thereby reducing the long-term dependency on invalidity pensions [21], [27].

CONCLUSION

The intersection of rapid demographic aging, the expansion of the unprotected gig economy, and the surge in commuting-related fatalities present an existential threat to the sustainability of social protection funds in emerging economies. Traditional deterministic models are no longer sufficient to navigate this highly volatile risk landscape. By executing the proposed dual Systematic Literature Review, researchers and policymakers can harness the power of advanced predictive analytics specifically expectile-based machine learning and spatial clustering to accurately forecast tail risks. Simultaneously, it provides the empirical foundation necessary to design inclusive, equitable, and mathematically sustainable pension frameworks capable of protecting the most vulnerable populations in the 21st century [4], [7]–[9], [27].

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Any remaining limitations are solely the responsibility of the authors.

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