

Beyond Income: The Independent Contributions of Health Expenditure and Digital Infrastructure to Population Longevity

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Beyond Income: The Independent Contributions of Health Expenditure and Digital Infrastructure to Population Longevity

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Abstract

Does government health expenditure independently contribute to longer lives, or does its longevity dividend reflect income and governance conditions that enable high spending? Using data for 261 countries over 2000–2024 (6,525 observations), this paper quantifies the independent contributions of health investment, digital infrastructure, income, and governance to population longevity, with implications for health system design and SDG 3 policy. The analysis combines LMG variance decomposition, which attributes cross-country longevity variation to each predictor simultaneously in an ordering-invariant manner, with TWFE panel regressions estimating within-country associations between changes in health investment and longevity outcomes. The main finding challenges income dominance. In a joint six-predictor model, government health expenditure (23.0%) and GDP per capita (22.4%) are statistically indistinguishable leading predictors of cross-national life expectancy differences, with EGDI (21.3%) close behind. Out-of-pocket spending contributes only 3.6%, despite its importance for health equity and financial protection. Within countries, a 10% increase in per capita government health expenditure is associated with approximately 0.8% lower infant mortality, 0.75% lower under-5 mortality, and 0.9% lower neonatal mortality the following year. Associations with adult life expectancy are statistically inconclusive, suggesting longer cumulative lag structures. Digital infrastructure (specifically the telecommunication infrastructure sub-index) is independently associated with lower child mortality, suggesting a logistics channel through vaccine supply chains and community health worker connectivity. These findings carry implications for health budget prioritization, universal health coverage policy, and public health system design.

Keywords: health expenditure; life expectancy; child mortality; digital infrastructure; e-government; health systems; health equity; population health; SDG 3

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1 Introduction

A child born in Japan today can expect to live 84 years. One born in Sierra Leone, around 62 [1]. That gap of more than two decades, compressed into the accident of birthplace, is among the starkest inequalities on Earth and yet one that has narrowed consistently since 1990 [2]. The narrowing itself is instructive. Sub-Saharan Africa gained nearly a decade of life expectancy between 2000 and 2019 [2], a period of substantial investments in maternal and child health, infectious disease control, and health system strengthening. But the gains have been uneven, fragile, and difficult to attribute cleanly to any single policy lever. As countries now reorient development strategies around SDG 3 targets (ending preventable child and maternal deaths, achieving universal health coverage, ensuring healthy lives for all ages by 2030), a fundamental empirical question re-emerges: *among the investments governments can make, which ones are associated with longer lives, and how much does each one independently contribute?*

The literature has converged on three broad channels linking policy to longevity, but has rarely quantified their independent contributions in a unified framework. The most extensively studied channel is *health investment*. Cross-national evidence broadly documents associations between higher government health expenditure per capita and lower child mortality and higher life expectancy, even after controlling for income, though magnitudes and robustness vary by context and specification [3, 4]. Yet the channel is not simple. The composition of spending matters as much as its level. Out-of-pocket (OOP) spending, which accounts for more than 40% of total health expenditure in many low- and middle-income countries [1], functions as a regressive barrier to care rather than a productive investment, with well-documented consequences for catastrophic spending, care-seeking, and poverty traps [5]. The empirical challenge is that health expenditure levels are tightly correlated with national income and governance quality, making it difficult to isolate how much independent longevity leverage health budgets actually provide.

The second channel is *economic development and governance*. Income per capita expands the resources available for health investment, nutrition, housing, and sanitation, all of which are determinants of longevity that pre-date modern health systems [6]. Beyond income, institutional quality shapes the efficiency with which resources translate into outcomes. Well-governed health systems achieve lower child mortality at equivalent spending levels than poorly-governed ones, because accountability, anti-corruption enforcement, and administrative capacity determine whether budgets reach frontline services [7]. This creates a fundamental confounding problem in cross-national analysis. Countries that spend more on health also tend to be richer and better governed. Correlations between health spending and longevity observed across countries will therefore overstate the independent contribution of spending if income and governance are not separately accounted for.

The third channel, *digital infrastructure*, has attracted growing policy attention but remains incompletely integrated into quantitative longevity analyses. Digital investment generates economic dividends through improved information, market efficiency, and state capability, but gains are contingent on complementary institutional foundations [8]. In health specifically, digital infrastructure operates through logistics, service delivery, and administrative channels that determine whether health inputs reach populations in need [9, 10]. The

UN E-Government Development Index (EGDI), which captures government-wide readiness across online services, telecommunication infrastructure, and human capital, has expanded from 190 to nearly universal country coverage since 2003 [11], providing a rare multi-decade global panel of digital infrastructure that enables panel estimation alongside cross-sectional analysis.

Despite this three-channel framework, the empirical literature rarely estimates all three sets of determinants simultaneously in a way that quantifies independent contributions. Studies examining health expenditure typically control for income but not for digital infrastructure. Studies of digital health focus on specific interventions rather than macro-level longevity outcomes; and governance analyses seldom jointly decompose the variance shared with spending and connectivity. This matters for two reasons. First, multicollinearity among the three channels is severe. Government health expenditure, GDP per capita, governance quality, and EGDI all correlate strongly with each other and with life expectancy (pairwise $r = 0.78\text{--}0.92$; Table A2), so bivariate associations are highly misleading about independent leverage. Second, cross-sectional studies, which dominate this literature, cannot distinguish whether health expenditure independently contributes to longevity or is a proxy for the underlying income and institutional conditions. Within-country panel evidence, exploiting changes within the same country over time, is required to address this question, but is complicated by the slow-moving nature of longevity outcomes and the long lag structures between investment and impact.

This paper addresses those gaps through two complementary analyses applied to one of the most comprehensive global panels assembled for this question: 261 countries over 2000–2024 (6,525 country-year observations), integrating World Bank WDI, WHO GHQ, UN EGDI, and Worldwide Governance Indicators data. The *primary analysis* applies LMG (Lindemann–Merenda–Gold) variance decomposition [12], an ordering-invariant method that attributes cross-country longevity variance to each predictor simultaneously regardless of entry order (Section 5.1). The *secondary analysis* uses two-way fixed effects (TWFE) panel regressions with country and year fixed effects to ask whether *within-country* changes in health expenditure and digital infrastructure are associated with longevity improvements, absorbing time-invariant country heterogeneity and common global shocks (Section 5.2).

In the pooled descriptive analysis, the three dominant predictors of life expectancy (government health expenditure, GDP per capita, and EGDI) each independently account for approximately 21–23% of explained variance. Health expenditure and GDP are statistically indistinguishable co-leaders. EGDI is close but carries a modestly smaller share than health expenditure, a difference confirmed by bootstrap inference, placing digital infrastructure among the leading predictors of cross-national longevity differences. OOP share, despite its strong theoretical importance, carries only a 3.6% independent share once the other predictors are jointly controlled. Within countries over time, a 10% increase in lagged government health expenditure is associated with approximately 0.8% lower infant mortality, 0.75% lower under-5 mortality, and approximately 0.9% lower neonatal mortality in the following year. EGDI gains are associated with child mortality reductions, most strongly through the telecommunication infrastructure sub-component (TTI), indicating that connectivity improvements support vaccine logistics, supply chains, and frontline health worker reach.

The paper makes three contributions to this literature. It provides, to the author’s

knowledge, a systematic LMG variance decomposition of the global longevity gradient across health investment, income, governance, and digital infrastructure predictors jointly, a scope and predictor set not previously addressed in this combination. It also documents that digital infrastructure carries broadly comparable but modestly smaller independent explanatory power than health spending in cross-national variance decomposition, confirmed by bootstrap inference, which challenges the implicit hierarchy treating digital investment as a secondary concern to direct health spending. Finally, it documents within-country associations using TWFE that separate short-run child mortality responsiveness to health spending from the slower dynamics of adult life expectancy, providing an empirically grounded basis for calibrating expectations about when health investments produce observable population-level returns.

Section 2 reviews the literature. Section 3 develops the conceptual framework. Section 4 presents the data. Section 5 outlines the empirical strategy. Section 6 reports results. Section 7 discusses how the evidence informs three standing debates, addresses alternative explanations, states limitations, and draws policy implications. Section 8 concludes.

2 Related Literature

2.1 Government Health Investment: Returns and Financing Composition

A substantial body of cross-national evidence documents positive associations between government health spending and longevity outcomes, but the magnitude and independence of these effects remain contested. Influential early work documented associations between health expenditure and lower child mortality beyond what income alone predicts [13, 14]. Synthesis evidence from meta-regression analysis confirms that cross-country panel studies broadly document negative associations between government health spending and child mortality after controlling for income, with a pooled mortality elasticity near -0.13 , though magnitudes depend on country context and specification [3, 15]. Yet a competing strand of evidence, prominently associated with Filmer and Pritchett [16], argues that the strength of governance and institutional capacity dwarfs the contribution of public spending levels. In their account, *how* a government spends matters far more than *how much* it spends. Filmer and Pritchett found that income and institutional conditions explained far more cross-country child mortality variation than public spending, igniting a debate that two decades of richer panel data have not fully resolved.

More recent evidence has nuanced this picture. Panel studies exploiting within-country variation over longer time horizons find that health expenditure associations are present but heterogeneous. They are larger in low-income settings, in countries with stronger governance, and for child mortality outcomes than for adult life expectancy [4, 14]. This pattern is theoretically coherent. Child survival is acutely sensitive to public goods (vaccination campaigns, maternal care, oral rehydration) that government budgets fund directly, whereas adult longevity responds to chronic disease management, lifestyle factors, and cumulative nutrition with longer lag structures.

A distinct dimension of health investment is its financing structure. The share of health

expenditure paid out-of-pocket by households, rather than pooled through government budgets or insurance schemes, has well-documented adverse consequences for both access and health outcomes. Xu et al. [5] established using household survey data from 59 countries that approximately 150 million people face catastrophic health expenditure annually, and that nearly all are in countries where OOP spending accounts for more than 15–20% of total health expenditure. High OOP burdens deter care-seeking, particularly for preventive services among poorer households, and create poverty traps in which illness triggers impoverishment that in turn deepens health deprivation across generations. The empirical challenge is that OOP share and government expenditure are simultaneously determined by the same underlying conditions of fiscal capacity, governance quality, and institutional development, making it difficult to isolate the independent contribution of financing structure from the structural conditions that generate it [15].

2.2 Income, Governance, and the Confounding Problem

The relationship between national income and life expectancy, the *Preston curve* [6], is a robust empirical regularity in development economics. Richer countries consistently live longer, yet the curve has shifted upward over successive decades. Countries achieve higher life expectancy at constant income levels, indicating that something beyond income accounts for a large fraction of longevity improvement. Subsequent work reinterpreted this shift as driven primarily by the diffusion of public health knowledge and technology (vaccines, antibiotics, oral rehydration therapy), with income playing an important but secondary facilitating role [17].

This insight creates a central challenge for cross-national studies. Government health expenditure, governance quality, and longevity are all strongly correlated with income, making it extremely difficult to isolate their independent contributions. Countries that spend more on health per capita are also richer, better governed, more urbanized, and more institutionally capable. Observed correlations between health spending and longevity will therefore confound the effect of spending with the effect of all the development conditions that accompany it. Governance quality is a particularly important moderator. Kruk et al. [7] show that health system quality (encompassing competence, safety, and responsiveness) mediates the translation of health coverage into mortality reductions, implying that the returns to spending are themselves a function of institutional capacity. The upshot is that simple bivariate correlations between health expenditure and longevity overstate the independent contribution of spending, while studies that control for income but not governance produce intermediate estimates that are still confounded. A joint decomposition that simultaneously controls for income, governance, and connectivity is required to produce credible estimates of how much independent longevity leverage health investment provides.

2.3 Digital Infrastructure as a Health System Determinant

Digital infrastructure has emerged as a third major channel from policy to longevity, but remains incompletely integrated into quantitative health economics analyses. Digital systems enable supply chain management for medicines and vaccines, remote health worker

supervision, real-time disease surveillance, insurance enrolment and claims processing, and community health worker connectivity in areas without facility access [9, 10, 8].

Despite this strong theoretical case, macroeconomic evidence on digital infrastructure’s independent contribution to longevity outcomes (as distinct from its correlation with income and governance) remains sparse. Most published analyses either focus on specific digital health interventions at the program level [9], or examine e-government and connectivity broadly without isolating health outcomes. A growing review literature [18] concludes that digital health initiatives in low- and middle-income countries have shown promise for child survival and UHC outcomes, but that macro-level evidence from conservative panel designs is limited. EGDI, covering virtually all countries since 2003 across online services, telecommunication infrastructure, and human capital [11], provides a rare multi-decade global series that enables panel estimation of digital infrastructure’s contribution to longevity alongside health spending and income, with sub-indices that allow decomposition of which dimension drives observed associations.

2.4 Methodological Gaps: Joint Decomposition and Panel Identification

Three methodological gaps remain underaddressed across these literatures. First, to the author’s knowledge, no study has applied an ordering-invariant variance decomposition method (such as LMG [12]) to jointly quantify the independent contributions of health expenditure, income, governance, and digital infrastructure to cross-country longevity variation. Existing work estimates one or two channels at a time, and because predictors are highly correlated, bivariate associations systematically misattribute variance. The unique contribution of each input can only be recovered through a joint decomposition. Second, panel evidence on within-country health expenditure effects over a *long* horizon is limited. Most TWFE analyses use panels of five to ten years, better suited to detecting child mortality responses than adult survival changes with lag structures measured in decades [4]. Third, the income-group heterogeneity of spending and digital infrastructure effects has rarely been examined simultaneously using both decomposition and panel methods, leaving it unclear whether pooled global findings generalise to the high-, middle-, and low-income sub-populations where policy challenges differ most.

3 Conceptual Framework

3.1 A Health Production Function

The analysis is organized around a health production function in the tradition of Grossman [19], adapted to the cross-national macro setting. Let H_{it} denote a longevity outcome (life expectancy, healthy life expectancy (HALE), maternal, under-5, infant, or neonatal mortality, or UHC coverage) for country i in year t . It is modeled as a function of three classes of inputs:

$$H_{it} = f(G_{it}, D_{it}, A_{it}; \theta_{it}) \quad (1)$$

where G_{it} is government health investment (government health expenditure per capita and its financing structure via OOP share), D_{it} is digital infrastructure (EGDI and its sub-components), A_{it} is the structural development environment (GDP per capita, governance quality, institutional capacity), and θ_{it} captures unobserved efficiency. The production function is assumed to be increasing in G and D , and decreasing in OOP share, with the marginal returns to all inputs increasing in A . Better-governed, wealthier countries extract more longevity from each unit of health spending and digital investment, because their administrative, logistical, and institutional infrastructure converts inputs into outputs more efficiently.

Two features of equation (1) are central to the paper’s empirical strategy. First, the three input classes are positively correlated: countries that invest more in health also tend to be richer, better governed, and more digitally connected, so any single-equation regression omitting one class conflates its channel with those of the omitted inputs; a joint decomposition across all three is required to separate their contributions. Second, the inputs enter with different lag structures: child survival responds primarily to recurrent public health spending within one to three years, whereas adult life expectancy reflects decades of cumulative investment in chronic disease management, motivating the separate analysis of child mortality and life expectancy outcomes.

3.2 Two Conceptual Channels for Digital Infrastructure

Within the production function, digital infrastructure operates through two economically distinct mechanisms that correspond to different sub-indices of EGDI.

Logistics and supply chain efficiency. Telecommunication infrastructure (TTI) determines whether physical health system inputs (vaccines, medicines, diagnostic equipment) reach frontline facilities reliably and on schedule. Cold chains for immunization, stock management for essential medicines, and remote supervision of health workers all depend on connectivity. This mechanism generates returns to existing health spending: a given budget achieves more child survival where telecommunications are strong because inputs are wasted less in transit and delivered more reliably. Digital infrastructure acts as an efficiency multiplier for health expenditure rather than a substitute for it.

Administrative capacity and coverage expansion. Online service delivery (OSI) and government digital readiness enable insurance enrolment at scale, electronic claims processing, and data systems for identifying uncovered populations. These mechanisms primarily affect the breadth of health financing coverage rather than specific clinical service delivery, and are most consequential for reducing the OOP share through enrolment of informal-sector and rural populations into risk-pooling schemes.

3.3 The Confounding Structure and What Identification Requires

The central challenge for measuring the independent contributions of G , D , and A is that all three are simultaneously determined by underlying development conditions. A country with high GDP per capita will tend to spend more on health, have better digital infrastructure, and have stronger governance, not because any of these causes the others, but because all three are produced by the same underlying development process. This generates a *common*

factor structure in which a single latent development factor drives the observed correlation among all three input classes and between each of them and longevity outcomes.

Figure 1 illustrates the confounding structure. Development conditions (A) affect longevity both directly and indirectly, by enabling G and D to be higher and more productive, so naive bivariate estimates of either channel are inflated by the shared A pathway. The analysis addresses this in two complementary ways. The LMG decomposition partitions R^2 across all inputs simultaneously in a pooled cross-section, making each predictor’s unique contribution explicit; TWFE absorbs time-invariant A via country fixed effects to estimate within-country associations net of fixed omitted factors.

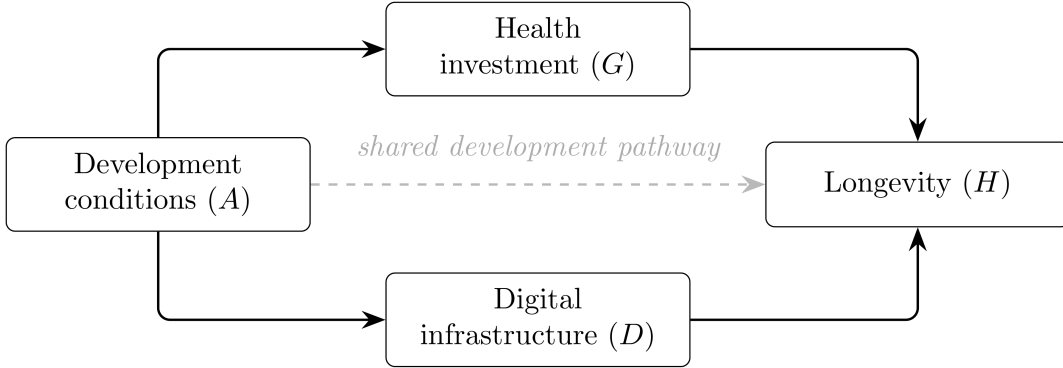


Figure 1: Confounding structure: background development conditions (A) jointly shape health investment (G), digital infrastructure (D), and longevity (H), so naive bivariate associations overstate the independent role of each channel.

3.4 Testable Predictions

Four predictions follow from this framework.

Prediction 1. Bivariate associations between health expenditure and longevity, and between EGDI and longevity, will attenuate once development controls enter simultaneously. In the joint LMG decomposition, health expenditure, GDP per capita, and EGDI will each carry meaningful, co-leading shares of explained longevity variance.

Prediction 2. Within-country TWFE estimates will be larger and more precisely estimated for child mortality than for life expectancy, whose cumulative lag structure extends beyond what a 25-year panel can fully identify.

Prediction 3. Among EGDI sub-indices, the telecommunication infrastructure component (TTI) will dominate child mortality associations, reflecting its role in vaccine logistics and health worker connectivity. The online service (OSI) and human capital (HCI) sub-indices will show weaker associations with child mortality.

Prediction 4. OOP share will contribute a small unique share of explained longevity variance in the LMG decomposition, owing to its co-determination with income, governance, and health spending levels. Within-country TWFE associations may be more detectable for outcomes sensitive to financial access barriers.

4 Data

4.1 Panel Construction

The analysis draws on a global country-year panel assembled from five primary sources covering 2000–2024. *Health outcomes* – life expectancy at birth, maternal mortality ratio, under-5 mortality rate, infant mortality rate, and neonatal mortality rate – are drawn from the World Bank World Development Indicators (WDI) [1]. Healthy life expectancy (HALE) is sourced from the WHO Global Health Observatory [2], covering years through 2021. *Health investment variables* – government health expenditure per capita and OOP share of current health expenditure – are from WDI [1]. *UHC service coverage* is measured using the WHO/World Bank UHC service coverage index [1]. *Digital infrastructure* is measured using the UN E-Government Development Index (EGDI) and its three sub-components: the Online Service Index (OSI), Telecommunication Infrastructure Index (TTI), and Human Capital Index (HCI) [11]. EGDI is published biennially; values for intervening years are linearly interpolated, a standard practice for slowly-varying index variables. *Development controls* – GDP per capita (PPP, constant 2017 international dollars), government effectiveness, rule of law, physician density, and urban population share – are drawn from WDI and the Worldwide Governance Indicators (WGI) [20, 1].

4.2 Sample

The full panel covers 261 countries and 6,525 country-year observations over 2000–2024. Coverage varies by variable: life expectancy is available across all panel years for most countries; government health expenditure for 85.8% of observations; EGDI for 73.9%; and HALE through 2021 only (62.4% of observations). The TWFE estimation sample is smaller due to the requirement for complete cases on the full control vector – 2,487 country-year observations and 181 countries for the preferred specification with government health expenditure as the main regressor. The LMG cross-sectional sample is 3,943 observations and 181 countries. Both samples over-represent higher-income countries relative to the global panel. Results should not be extrapolated to low-income, data-sparse settings.

4.3 Variable Construction

Government health expenditure per capita is log-transformed to account for its right-skewed distribution. OOP share is retained in percentage-point units (0–100). Mortality outcomes (maternal mortality ratio, under-5, infant, and neonatal mortality rates) are similarly log-transformed; life expectancy and HALE are used in levels (years). The UHC service coverage index is on a 0–100 scale and is used without transformation.

Development controls enter as follows: log GDP per capita (PPP, constant 2017 international dollars); government effectiveness and rule of law as continuous WGI scores ranging approximately from -2.5 (weakest) to $+2.5$ (strongest); physician density in physicians per 1,000 population; and urban population as a percentage share of total population.

EGDI and its three sub-components (OSI, TTI, HCI) are on a 0–1 scale. As noted above, EGDI is published biennially; annual values are linearly interpolated and used without

further transformation. In the TWFE specifications, the main regressors (log government health expenditure and EGDI) are lagged one year to partially address reverse causality. The rationale is developed in Section 5.

Summary statistics are presented in Table 1. The within-country standard deviation column is particularly relevant for the TWFE results, which identify exclusively from within-country variation over time.

Table 1: Summary Statistics — Longevity Panel (2000–2024)

Variable	<i>N</i>	Mean	SD	Within-SD	Min	Max
Life expectancy at birth (years)	6,525	70.65	8.56	2.492	14.66	86.50
Healthy life expectancy (years)	4,070	70.15	8.63	2.426	39.96	84.66
Maternal mortality (per 100,000)	5,712	185.51	250.64	74.733	1.00	1662.00
Under-5 mortality (per 1,000)	6,000	38.50	40.08	15.991	1.30	489.30
Infant mortality (per 1,000)	6,000	27.77	24.69	9.231	1.20	239.90
UHC service coverage index (0–100)	4,824	62.84	18.45	5.442	13.00	92.00
Gov. health exp. per capita (US\$)	5,600	643	1,240	389	0.2	7,937
OOP share (% of health exp.)	5,620	33.85	18.81	5.828	0.04	87.90
EGDI overall (0–1)	4,825	0.48	0.23	0.112	0.00	0.98
Internet users (% of population)	5,470	39.41	31.57	21.589	0.00	100.00
GDP per capita, PPP (2017 US\$)	6,009	22,462	23,927	4,927	703	174,570
Government effectiveness (WGI)	4,470	-0.02	0.99	0.230	-2.44	2.47
Rule of law (WGI)	4,545	-0.02	1.00	0.206	-2.59	2.12
Physician density (per 1,000)	2,974	2.03	1.58	0.436	0.01	9.54
Urban population (%)	6,525	58.22	23.02	3.426	8.04	100.00

Notes: Country-year panel, 2000–2024, up to 261 countries. Within-SD is the standard deviation after removing country means, indicating the within-country variation available for TWFE estimation. EGDI is the UN E-Government Development Index (0–1 scale, biennial, linearly interpolated). Governance indicators from the Worldwide Governance Indicators (WGI), standardised approximately (−2.5, +2.5).

5 Empirical Strategy

The empirical strategy uses two complementary approaches that exploit different sources of variation and address different questions. The primary analysis, LMG variance decomposition, asks how much of the variation in longevity across countries is independently associated with each input, net of all others. The secondary analysis, two-way fixed effects, asks whether *within-country* changes in health investment and digital infrastructure predict within-country longevity improvements over time. The two methods are not substitutes. The first quantifies relative explanatory power in the pooled country-year sample. The second tests whether the associations are driven by time-varying investment dynamics or by persistent structural differences across countries.

5.1 Primary Analysis: LMG Variance Decomposition

Let $\mathbf{x} = (x_1, \dots, x_p)$ be a vector of p predictors. The LMG (Lindemann–Merenda–Gold) contribution of predictor j is defined as its average marginal R^2 increment across all $p!$ orderings of the predictor set [12]:

$$\text{LMG}_j = \frac{1}{p!} \sum_{\pi \in \mathcal{S}_p} \left[R^2(S_\pi^j \cup \{j\}) - R^2(S_\pi^j) \right], \quad (2)$$

where $\mathcal{S}_p$ is the set of all $p!$ orderings and S_π^j is the subset of predictors entering before j in ordering π . LMG contributions are non-negative, invariant to entry order, and sum exactly to the total model R^2 . With $p = 6$ predictors ($6! = 720$ orderings), the computation is exact.¹

The decomposition is estimated on a pooled country-year sample with complete cases on all six predictors: log government health expenditure per capita, OOP share, log GDP per capita (PPP), government effectiveness, EGDI, and internet users (%). LMG shares are computed from the unclustered pooled OLS regression. Standard errors on the sequential coefficient ladder are clustered at country level. For each predictor we report its LMG share and its *last-in* R^2 , the marginal increment when the predictor enters after all others.

LMG shares are descriptive and do not recover causal effects. When predictors share a common omitted variable, shares reflect that confounding. The decomposition is interpreted throughout as relative explanatory power, not causal attribution.

5.2 Secondary Analysis: Two-Way Fixed Effects

The within-country specification is:

$$Y_{it} = \alpha_i + \gamma_t + \beta X_{i,t-1} + \boldsymbol{\delta}' \mathbf{Z}_{it} + \varepsilon_{it}, \quad (3)$$

where Y_{it} is a longevity outcome for country i in year t ; α_i are country fixed effects that absorb all time-invariant country characteristics (geography, historical disease burden, long-run institutional development); γ_t are year fixed effects that absorb common global shocks (including the COVID-19 pandemic disruption visible in 2020–2022 data) as well as secular global trends in pharmaceutical innovation and public health technology diffusion; $X_{i,t-1}$ is the main regressor of interest *lagged one year* (log government health expenditure per capita or EGDI); and $\mathbf{Z}_{it}$ is a vector of contemporaneous time-varying controls comprising log GDP per capita (PPP), government effectiveness, rule of law, urban population share, and physician density. Standard errors are clustered at the country level using the Arellano [21] sandwich estimator, which is robust to arbitrary serial correlation within countries over the 25-year panel.

A one-year lag on X is motivated by the temporal structure of health production. Health expenditure at time t triggers procurement, hiring, and training processes that translate into

¹Sequential ΔR^2 (hierarchical partitioning) assigns credit based on entry order, producing results that depend entirely on the analyst’s chosen sequence. LMG averages across all $p!$ orderings, so no predictor benefits from entering first.

delivered services over the following year. A contemporaneous specification would instead capture the correlation between spending increases and concurrent mortality crises that motivate those increases, conflating reverse causality with the productive investment channel. The lag partially severs this feedback loop. The one-year horizon is conservative with respect to adult life expectancy, which responds to cumulative multi-decade investment. A single-year lag will miss most of that cumulative channel, and life expectancy effects in TWFE are therefore expected to be small and imprecisely estimated.

Both regressors carry sufficient within-country variation to power the estimates (Table 1, Within-SD column).

5.3 Identification, Threats, and Caveats

All TWFE estimates are within-country associations, not causal effects. Three threats to identification warrant discussion.²

Reverse causality. Governments may increase health expenditure in response to observed mortality deterioration, for example following a disease outbreak or a drought-induced nutrition crisis. This would generate a spurious positive correlation between spending increases and subsequent mortality increases, attenuating or even reversing the estimated $\hat{\beta}$. The inclusion of country and year fixed effects mitigates this concern partly by absorbing common health shocks (via year effects) and country-specific long-run spending trajectories (via country effects). It cannot fully resolve acute within-country, within-year reverse causality.

Parallel trends. TWFE requires that countries with different spending trajectories would have followed parallel longevity trends absent those changes.³ Year fixed effects absorb global trend shocks, including the COVID-19 disruption and secular pharmaceutical improvements. The control vector spans the main within-country confounders. The staggered-treatment concerns raised by Callaway and Sant’Anna [22] and de Chaisemartin and D’Haultfoeuille [23] apply most acutely to binary treatment settings with heterogeneous timing; with continuous regressors (spending levels, EGD scores), their decomposition is not directly applicable. Income-group splits serve as a partial check on whether pooled estimates mask heterogeneous associations.

Time-varying confounders. Variables that change within countries over time and simultaneously affect both the regressor and the outcome could bias TWFE estimates. Aid inflows to the health sector, structural adjustment programs, and debt-relief initiatives are the most plausible examples. Log GDP per capita and governance indicators are included as time-varying controls to absorb the component of these confounders that operates through macroeconomic and institutional channels. Residual confounding from idiosyncratic shocks remains a limitation.

²Formally, TWFE requires strict exogeneity: $E[\varepsilon_{it} \mid X_{i1}, \dots, X_{iT}, \alpha_i, \gamma_t] = 0$. This rules out feedback from past outcomes to current regressors, a stronger condition than the sequential exogeneity assumed in GMM estimators.

³This assumption cannot be tested directly without a credible control group. Three observations support its plausibility: (i) year fixed effects absorb global trend shocks, including the COVID-19 disruption and secular improvements in pharmaceutical technology; (ii) the control vector spans the main drivers of time-varying confounding: GDP growth, governance change, urbanization, and physician supply; (iii) health expenditure increases over 2000–2024 were driven largely by fiscal capacity improvements common to countries at similar income levels, not by idiosyncratic mortality shocks.

Measurement error in EGDI. The EGDI is published biennially and linearly interpolated to annual frequency for the panel. Interpolated values introduce mechanical smoothing that attenuates within-country variation and biases $\hat{\beta}$ toward zero. TWFE estimates for EGDI are likely lower bounds in magnitude; the bias compresses but does not reverse the sign.⁴

5.4 Functional Form, Controls, and Specification Ladder

Functional form. Government health expenditure per capita is log-transformed throughout, so $\hat{\beta}$ is a semi-elasticity. For mortality outcomes also log-transformed (maternal, under-5, infant, and neonatal), $\hat{\beta}$ becomes a log-log elasticity. For life expectancy and HALE in levels, it is measured in years per unit log-spending. The log-log specification amplifies percentage reductions at low absolute mortality levels, where public health spending has the largest marginal impact. This helps explain why child mortality TWFE effects tend to exceed life expectancy effects.

Control set rationale. The five time-varying controls serve distinct roles. Log GDP per capita absorbs income-driven changes in both health investment capacity and longevity-relevant consumption (nutrition, housing quality, water and sanitation access) that would otherwise confound the health expenditure coefficient. Government effectiveness and rule of law capture how efficiently budgets translate into delivered services. Physician density controls for health workforce supply. Urban population share controls for the epidemiological and access effects of urbanization.

Specification ladder. For each outcome–regressor pair, three nested specifications are reported: (1) country fixed effects only, no controls; (2) country fixed effects plus time-varying controls, no year effects; (3) the preferred specification with country effects, year effects, and full controls.

5.5 Income Group Heterogeneity and Sub-Index Robustness

The preferred TWFE specification is estimated separately for high-income (HIC), upper-middle income (UMC), lower-middle income (LMC), and low-income (LIC) country groups, following World Bank income classifications. Separate estimation is preferred over interaction terms because the theoretical prediction (from Section 3) is that the production function parameters themselves differ across groups, not merely the mean level of outcomes. Within-group samples are necessarily smaller, reducing statistical power. These results are exploratory and should be interpreted with caution.

Sub-index robustness replaces the overall EGDI score with its three components (the Online Service Index (OSI), Telecommunication Infrastructure Index (TTI), and Human Capital Index (HCI)) in separate regressions. This decomposition tests Prediction 3 from Section 3: that the logistics channel (TTI) rather than the administrative capacity channel (OSI) or the human capital channel (HCI) drives the child mortality effects. Each sub-index regression uses the same country and year fixed effects, time period, and control vector as the preferred TWFE specification, so differences in coefficients across sub-indices isolate the mechanism rather than specification differences.

⁴In interpolated years $t \in (t_0, t_1)$, $\text{EGDI}_{it} = \text{EGDI}_{it_0} + \frac{t-t_0}{t_1-t_0}(\text{EGDI}_{it_1} - \text{EGDI}_{it_0})$, so within-country variation in those years is smooth and carries no independent signal beyond the biennial endpoints.

6 Results

The results are organized to directly test the four predictions from Section 3. The LMG variance decomposition (§6.1) provides cross-sectional evidence on Predictions 1 and 4. The TWFE specification ladder (§6.2) tests Prediction 2 and examines within-country associations for all three main regressors. The sub-index decomposition (§6.3) tests Prediction 3. Income-group heterogeneity (§6.4) examines whether pooled estimates mask meaningful variation in the health production function parameters across development levels.

6.1 Cross-Sectional Variance Decomposition

Table 2 reports LMG decomposition results for life expectancy at birth as the primary longevity outcome. The six-predictor model explains 74.6% of pooled variation ($R^2 = 0.746$). Government health expenditure (23.0%) and GDP per capita (22.4%) are co-leaders; EGDI (21.3%) is close behind, a modestly smaller share. Government effectiveness (15.1%) and internet users (14.6%) are secondary; OOP share carries 3.6%.

Table 2: Variance Decomposition of Life Expectancy: LMG Method

Predictor	LMG (R^2 share)	Share of R^2 (%)	95% CI
Gov. health expenditure (log)	0.1719	23.0%	[22.3, 23.7]
GDP per capita, PPP (log)	0.1673	22.4%	[21.6, 23.3]
E-Gov. readiness (EGDI)	0.1590	21.3%	[20.5, 22.1]
Government effectiveness	0.1123	15.1%	[14.5, 15.6]
Internet users (%)	0.1086	14.6%	[14.0, 15.2]
OOP share (%)	0.0270	3.6%	[3.3, 3.9]
<i>Total model R^2</i>	0.7461	100.0%	
Marginal R^2 : gov. health exp. (last-in)	0.0150	2.0%	[1.10, 1.91]
Marginal R^2 : EGDI (last-in)	0.0142	1.9%	[1.03, 1.83]
Marginal R^2 : OOP share (last-in)	0.0091	1.2%	[0.62, 1.27]

Notes: Pooled OLS on complete-case country-year observations ($N = 3,943$; 181 countries). Dependent variable: life expectancy at birth (years). LMG (Lindemann–Merenda–Gold) decomposes total model R^2 into each predictor’s average marginal contribution across all 720 orderings of the six-predictor set. 95% confidence intervals are bootstrap percentile intervals ($B = 999$; RNG seed 2026). “Marginal R^2 (last-in)” reports the increment in R^2 from adding each predictor after all others are included.

The income hierarchy is flatter than the Preston curve tradition implies. The canonical view, grounded in Preston [6] and reinforced by the dominant role of GDP in bivariate regressions, holds that income is the primary determinant of cross-country longevity differences. The LMG decomposition challenges this directly. After jointly conditioning on governance, digital infrastructure, and health financing structure, income’s dominant position in bivariate regressions disappears. The independent contribution of GDP per capita (22.4%) is statistically indistinguishable from that of government health expenditure (23.0%), and EGDI (21.3%) is close behind, indistinguishable from GDP but carrying a smaller share than health expenditure alone (bootstrap pairwise CIs: Table 2). Health expenditure and GDP

emerge as co-equal leaders; EGDI is a near-peer. No input commands the field once the full set of determinants is jointly controlled.

Both health expenditure and EGDI retain unique explanatory power after full conditioning. Government health expenditure, entered last, contributes 1.5 percentage points of additional explained variance (2.0% of total $R^2 = 0.746$, Table 2); EGDI contributes 1.4 percentage points (1.9%); OOP share contributes 0.91 percentage points (1.2%). The near-symmetry in last-in contributions (1.5 vs. 1.4 percentage points) confirms that health expenditure and EGDI each carry information about cross-country longevity not captured by any other predictor in the model.

OOP share carries limited unique variance despite its theoretical importance. Its 3.6% LMG share is the lowest in the model. The Xu et al. [5] mechanism remains intact. High OOP burdens deter care and generate poverty traps. The low LMG share reflects the well-known collinearity between OOP share and the structural development conditions that simultaneously determine it. Countries with low OOP share are also richer, better governed, and spend more on health publicly, so the *independent* signal from OOP share, once those conditions are jointly controlled, is necessarily attenuated. Its 0.91 percentage point last-in contribution (1.2% of explained variance, Table 2) shows the other five predictors account for virtually all the longevity variation that OOP share could explain alone.

6.2 Within-Country TWFE Results

Table 3 reports TWFE results for lagged log government health expenditure across seven health-system outcomes, following the three-specification ladder described in Section 5.4.

Table 3: TWFE Estimates: Government Health Expenditure and Longevity Outcomes

Outcome	(1) Bivariate		(2) + Controls		(3) Preferred TWFE		N
	Coef.	SE	Coef.	SE	Coef.	SE	
Life expectancy	2.774***	(0.135)	1.228***	(0.221)	-0.036	(0.236)	2487
HALE	2.648***	(0.167)	1.338***	(0.244)	0.023	(0.262)	2288
ln(Maternal mort.)	-0.263***	(0.017)	-0.056*	(0.032)	0.022	(0.042)	2487
ln(Under-5 mort.)	-0.376***	(0.014)	-0.184***	(0.019)	-0.075***	(0.024)	2487
ln(Infant mort.)	-0.350***	(0.013)	-0.176***	(0.019)	-0.078***	(0.023)	2487
ln(Neonatal mort.)	-0.305***	(0.015)	-0.155***	(0.020)	-0.092***	(0.026)	2487
UHC index	6.783***	(0.368)	2.630***	(0.482)	0.248	(0.569)	2487

Notes: Two-way fixed effects (country + year) panel estimates, 2000–2024. Main regressor: log government health expenditure per capita, *lagged one year* ($t - 1$) to allow spending to transmit through procurement, deployment, and service delivery before affecting outcomes. Specification (1): entity FE only, no controls. Specification (2): entity FE + controls (log GDP per capita PPP, government effectiveness, rule of law, urban population %, physician density). Specification (3): preferred — entity + time FE + full controls. Controls are contemporaneous. Standard errors clustered at country level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

What the specification ladder reveals about confounding. For infant and under-5 mortality, the outcomes with the strongest associations, the negative coefficient on lagged health expenditure is present already in column (1) and remains directionally consistent through

columns (2) and (3), with modest attenuation as controls absorb confounding. Stability across the full ladder shows that the child mortality associations are robust to the inclusion of time-varying controls and to the modelling of global time trends via year fixed effects. In particular, near-identical estimates in columns (2) and (3) are consistent with common global health shocks during 2000–2024 (including COVID-19 disruption and secular diffusion of pharmaceutical and vaccine technology) not confounding the within-country spending–child mortality relationship. By contrast, for life expectancy and HALE, point estimates are negligible and imprecise across all three specifications, suggesting the null for adult longevity is not an artefact of over-controlling but is consistent throughout the specification ladder.

Government health expenditure: child mortality responds; life expectancy does not. In the preferred specification, lagged log government health expenditure is negatively associated with infant mortality ($\hat{\beta} = -0.078$, $\text{SE} = 0.023$, $p < 0.01$) and under-5 mortality ($\hat{\beta} = -0.075$, $\text{SE} = 0.024$, $p < 0.01$). In log-log terms, a within-country 10% increase in per capita government health spending is associated with approximately a 0.8% lower infant mortality rate and 0.75% lower under-5 mortality rate in the following year, conditional on GDP growth, governance changes, physician supply, and urbanization. Neonatal mortality, in a parallel specification with identical country and year fixed effects, controls, and sample ($N = 2,487$), shows the same pattern. $\hat{\beta} = -0.092$ ($p < 0.01$) corresponds to 0.9% lower neonatal mortality per 10% spending increase. Associations with life expectancy ($\hat{\beta} = -0.036$, $\text{SE} = 0.236$) and HALE ($\hat{\beta} = 0.023$, $\text{SE} = 0.262$) are negligible. The response appears concentrated in a one-year horizon. Year-over-year increases in health spending are associated with child mortality reductions the following year. Adult life expectancy, shaped by cumulative multi-decade investment in chronic disease management, nutrition, and occupational health, does not register within a 25-year panel using a single-year lag. The null for life expectancy is consistent with lag structure and panel length constraints, and does not necessarily indicate the absence of long-run investment returns. Within-country life expectancy variation is limited ($\text{SD} = 2.5$ years over the 25-year panel), constraining TWFE power for adult mortality outcomes regardless of the underlying return to investment. Figure 2 summarises this concentration of significant associations in child mortality.

EGDI child mortality associations are robust; the UHC result requires qualification. With lagged EGDI as the main regressor, the pattern mirrors that for health expenditure in child outcomes (Table A3). EGDI is associated with lower under-5 mortality ($\hat{\beta} = -0.430$, $\text{SE} = 0.131$, $p < 0.01$) and lower infant mortality ($\hat{\beta} = -0.534$, $\text{SE} = 0.134$, $p < 0.01$). Associations with life expectancy and HALE are negligible, as with health expenditure. One result requires specific discussion. Lagged EGDI is negatively associated with the UHC service coverage index ($\hat{\beta} = -5.60$, $\text{SE} = 2.38$, $p < 0.05$). This sign is counterintuitive. Digital infrastructure gains would not ordinarily be expected to reduce health service coverage, and is most plausibly a measurement artefact of the biennial interpolation discussed in Section 5.3. Outcomes with genuine annual dynamics can generate spurious short-run associations when regressed on a mechanically smoothed regressor. The UHC result should not be read as evidence that digital infrastructure investment reduces service coverage.

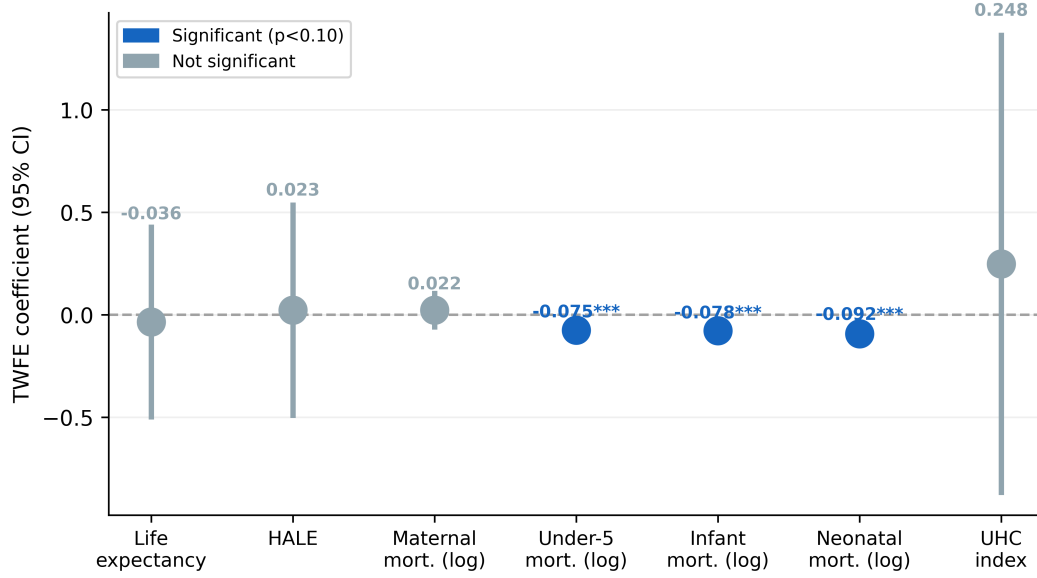


Figure 2: TWFE associations across outcomes (lagged government health expenditure). Preferred specification with country and year fixed effects and full controls. Blue markers indicate associations significant at $p < 0.10$; grey markers are not statistically significant. For visual clarity, the figure uses a binary significance indicator; Table 3 reports the full three-tier significance notation ($*p < 0.10$, $**p < 0.05$, $***p < 0.01$). Significant associations are concentrated in child mortality outcomes (infant, under-5, and neonatal mortality).

Within-country OOP associations are undetectable in a 25-year panel. Lagged OOP share shows no statistically significant within-country association with any longevity outcome in the preferred specification (Table A4). The within-country standard deviation of OOP share is only 5.8 percentage points against a cross-country standard deviation of 18.8 points. Health financing structures change slowly within countries, and a 25-year panel offers limited power to detect within-country OOP associations against a backdrop of predominantly structural variation. OOP share is co-determined by long-run development rather than year-to-year fiscal decisions. The within-country estimator’s identification window is too narrow to capture a mechanism operating through structural health system transformation.

6.3 EGDI Sub-Index Robustness

Table 4 decomposes the overall EGDI association by replacing it with its three sub-components (the Telecommunication Infrastructure Index (TTI), the Online Service Index (OSI), and the Human Capital Index (HCI)) in separate regressions using the same country and year fixed effects, time period, and control vector as the preferred TWFE specification. The question is which of physical connectivity (TTI) and service digitization (OSI, HCI) is most strongly associated with the child mortality outcome, given vaccine cold chains, supply routing, and real-time health worker supervision are plausible pathways most proximate to child survival.

Telecommunications infrastructure is most strongly associated with child mortality; online services and human capital contribute less. TTI is significantly and negatively associated with both under-5 mortality ($\hat{\beta} = -0.335$, $SE = 0.105$, $p < 0.01$) and infant mortality ($\hat{\beta} = -0.399$,

SE= 0.111, $p < 0.01$), producing the largest child mortality associations among the sub-indices. OSI also yields significant child mortality associations ($\hat{\beta} = -0.158$ for under-5; $\hat{\beta} = -0.196$ for infant), suggesting an administrative coverage channel. Online service capacity is consistent with supporting insurance enrolment and benefit delivery, potentially reducing financial barriers to antenatal care and facility delivery. The human capital component (HCI) produces a marginally significant infant mortality association but no robust relationship with under-5 mortality. The ranking, $TTI > OSI > HCI$, places physical connectivity as the primary channel through which digital infrastructure reaches child health outcomes.

Table 4: EGDI Sub-Index Robustness: Digital Infrastructure and Longevity (TWFE)

IV	Life exp.	ln(Mat. mort.)	ln(U5 mort.)	ln(Inf. mort.)
EGDI overall	-1.073 (1.172)	0.135 (0.227)	-0.465*** (0.114)	-0.561*** (0.118)
Online Service Index (OSI)	0.044 (0.603)	0.123 (0.112)	-0.158*** (0.059)	-0.196*** (0.060)
Telecom Infrastructure (TTI)	-2.300* (1.193)	0.057 (0.234)	-0.335*** (0.105)	-0.399*** (0.111)
Human Capital Index (HCI)	-0.471 (0.922)	0.048 (0.116)	-0.179 (0.118)	-0.228* (0.123)

Notes: TWFE estimates for 2000–2024. Sub-index variables are entered contemporaneously rather than with a one-year lag, so coefficient magnitudes are not directly comparable to the lagged overall EGDI specification in Table A3. All regressions include country and year fixed effects and the full control set. 181 countries; clustered standard errors in parentheses. HALE and UHC index are omitted because HALE coverage ends in 2021 and the UHC–EGDI association appears to reflect biennial interpolation (see Section 6.2). * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

TTI, OSI, and HCI: plausible channels and limitations. The TTI result is consistent with physical connectivity enabling the delivery logistics most proximate to child survival: vaccine cold chains, essential medicine stock management, and remote supervision of community health workers. OSI also yields significant child mortality associations, suggesting a complementary administrative pathway operating through insurance enrolment and benefit delivery. The HCI result (weakest among the three) reflects human capital’s high collinearity with income and governance, so that its independent child mortality signal is largely absorbed by the time-varying controls. The sub-index hierarchy indicates that physical logistics and administrative capacity, not general human capital, are plausible pathways through which digital infrastructure reaches child health outcomes.

Table 4 uses contemporaneous rather than one-year lagged EGDI sub-components, so coefficient magnitudes are not directly comparable to the lagged overall EGDI specification.

6.4 Income Group Heterogeneity

Table 5 asks whether the health spending–longevity association varies by income group, using life expectancy as the outcome. Life expectancy captures aggregate longevity returns to

sustained multi-year investment, though its limited within-country variation in high-income settings constrains identification at the sub-group level.

The pooled null is consistent with underlying heterogeneity of uncertain direction. Figure 3 and Table 5 report estimates by income group. No within-group estimate reaches conventional significance levels. Within-group samples range from 52–60 countries for HIC and UMC to 20–48 for LIC and LMC, substantially reducing statistical power relative to the pooled specification. The pooled estimate ($\hat{\beta} = -0.036$, not significant) is near zero, but income-group point estimates are dispersed around it. HIC and UMC show positive point estimates ($\hat{\beta} = 0.408$ and 0.415 respectively); LMC shows a negative estimate ($\hat{\beta} = -0.473$); LIC is imprecise and sign-indeterminate ($\hat{\beta} = 0.143$, $SE = 0.629$).

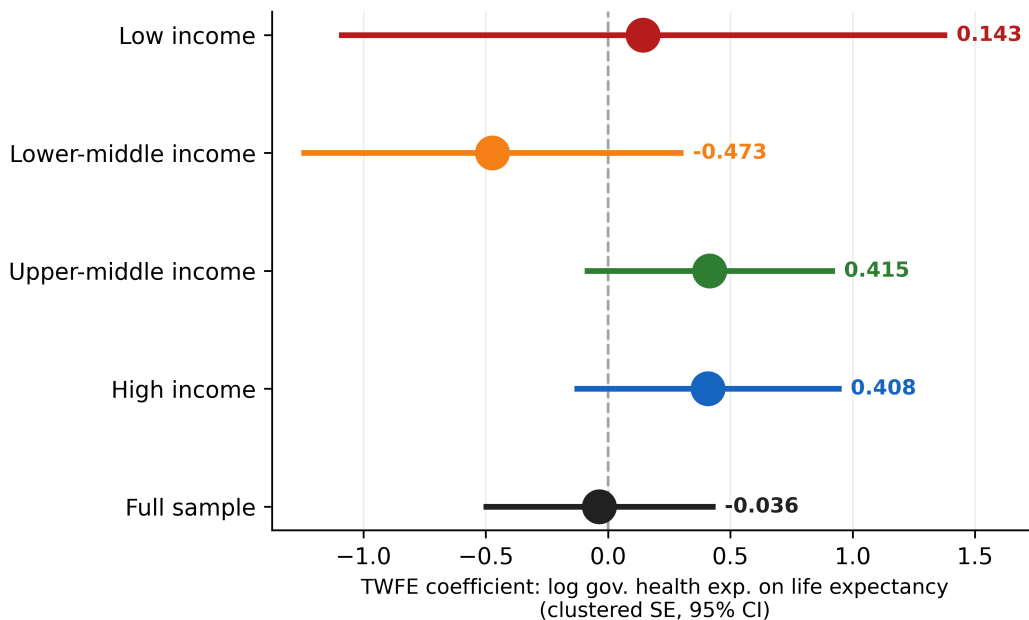


Figure 3: Income-group heterogeneity in TWFE associations between lagged government health expenditure and life expectancy. Points show preferred-specification estimates; horizontal lines indicate 95% confidence intervals. No within-group estimate is statistically significant.

Positive HIC and UMC coefficients may reflect reverse causality rather than structural effects. The positive point estimates for high- and upper-middle-income countries are not a structural finding. The most plausible interpretation is confounding. In high-income settings, health spending increases are frequently driven by population ageing, rising chronic disease burdens, and pandemic responses, precisely the conditions that also suppress life expectancy growth within a one-year window. These positive coefficients may reflect a form of within-group reverse causality, where spending responds to deteriorating or stagnating health trajectories rather than generating them. This pattern reflects the lag structure argument. A one-year horizon is insufficient to detect positive longevity returns to health investment in settings where the primary challenge is chronic disease management over decades, not acute infectious disease mortality.

The LMC sign reversal and absorptive capacity. The negative LMC point estimate ($\hat{\beta} = -0.473$) aligns with the pooled child mortality results and with the prior literature

finding that health spending associations are concentrated in lower-income settings [4, 14]. Lower-middle-income countries are in a range of health system development where recurrent government expenditure on vaccination, maternal care, and child nutrition translates into near-term survival improvements, even if significance is not achieved at the sub-group sample size. The reversal from negative (LMC) to positive (UMC, HIC) is consistent with an absorptive capacity gradient. Lower-middle-income countries are still accumulating the health system infrastructure, including facilities, supply chains, and workforce, where marginal public spending has a visible near-term longevity return. Higher-income countries face chronic disease dynamics where the relevant investment returns operate over much longer horizons.

Income-group results are underpowered for life expectancy; child mortality is a sharper test. These exploratory results are inconclusive. The difficulty is both statistical and conceptual. Statistically, within-country life expectancy variance is extremely limited in high-income countries, providing little identification variation at the sub-group level. Conceptually, life expectancy is an inappropriate TWFE outcome for testing short-run spending returns where chronic disease dominates. Whether higher-income countries extract more longevity from health spending is better tested using child mortality across income groups, where within-country variation is larger and the lag structure is shorter. That analysis is left for future work.

Table 5: Income Group Heterogeneity: Health Expenditure and Life Expectancy (TWFE)

Income group	Coef.	SE	Sig	<i>N</i>	Countries	R^2 (within)
Full	-0.0356	0.2360		2487	181	0.0912
HIC	0.4079	0.2726		1037	60	0.1916
UMC	0.4153	0.2551		670	52	0.1125
LMC	-0.4732	0.3926		528	48	0.0513
LIC	0.1427	0.6285		238	20	0.0945

Notes: Split-sample TWFE estimates by World Bank income group. Dependent variable: life expectancy at birth. Main regressor: log government health expenditure per capita. Controls and fixed effects mirror the preferred specification (Table 3). HIC = High income; UMC = Upper-middle income; LMC = Lower-middle income; LIC = Low income. Standard errors clustered at country level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

7 Discussion

7.1 Implications for Three Standing Debates

The results bear on three debates in the cross-national health economics literature identified in Section 2. Taken together, they move each debate a step forward without resolving it definitively.

The Filmer–Pritchett debate: spending versus governance. The influential finding of Filmer and Pritchett [16], that income, female education, and ethno-linguistic fragmentation explain child mortality variation far better than government health spending once institutional factors are controlled, has underwritten two decades of skepticism about the returns to health budget expansions. The LMG decomposition offers a partial reconciliation. Governance and institutional quality (government effectiveness, 15.1% LMG share) are genuine

contributors to the cross-country longevity gradient, confirming the Filmer–Pritchett finding that institutions matter. But government health expenditure (23.0%) carries a *larger* independent share than governance in a joint decomposition that simultaneously includes digital infrastructure. The difference is partly methodological. Filmer and Pritchett estimated spending effects in the presence of income and education controls but without digital infrastructure, which was not measurable at global scale in the late 1990s. When digital infrastructure enters the decomposition as a joint predictor, government spending retains a distinct and substantial share. The TWFE results reinforce this within countries. Lagged health expenditure is associated with lower child mortality even after absorbing country-level governance differences through country fixed effects. The spending-versus-governance opposition may be less stark than the literature implies. The evidence here suggests both channels operate independently, with health spending carrying at least as much independent explanatory power as governance quality in a globally comprehensive joint decomposition.

The Preston curve and the income-dominance assumption. The Preston (1975) finding that richer countries live longer, with the income–longevity curve shifting upward over decades as public health knowledge diffuses, has anchored an implicit view that income is the primary longevity determinant and health policy is secondary. The LMG decomposition challenges this hierarchy. In a joint six-predictor model spanning 261 countries and 25 years, health expenditure and income emerge as statistically indistinguishable co-leaders, with digital infrastructure close behind but carrying a modestly smaller independent share (Section 6.1; Table 2). This does not overturn the Preston curve. The income–longevity relationship is robust and well-established. What the decomposition reveals is that the independent explanatory power of income, once jointly conditioned on health spending, digital infrastructure, and governance, is no larger than those inputs’ independent shares. The non-income sources of cross-country longevity differences appear to be distributed across health investment and digital infrastructure, each carrying comparable independent explanatory power, rather than concentrated in a single residual factor. If health spending and connectivity carry independent predictive power for longevity comparable to income, health and digital budget decisions need not be treated as secondary to macroeconomic growth policy when estimating expected population health benefits.

Digital infrastructure as a macro-level longevity determinant. The quantitative health economics literature has largely treated digital infrastructure as a program-level intervention (mobile health applications, telemedicine, electronic health records) with evidence concentrated on specific technology deployments in specific contexts. The results document EGDI as a cross-national predictor of longevity comparable in cross-sectional explanatory power to income, and close behind health spending. Within countries over time, EGDI gains are significantly associated with lower child mortality, with the sub-index analysis suggesting that the telecommunication infrastructure component (TTI) is most strongly associated with these outcomes rather than the online services or human capital components. This points to a logistics mechanism. Connectivity may enable the physical delivery of health inputs (vaccines, essential medicines, supervision of community health workers) that are central to child survival at scale. The finding carries an important complementarity implication. If the mechanism operates through the efficiency of health input delivery, digital infrastructure would raise the return to government health spending rather than substituting for it. A country that increases its health budget without simultaneously investing in the connectivity

infrastructure to deliver those inputs reliably may realize lower returns than one investing in both. The broadly comparable LMG shares of the two inputs, each carrying significant independent explanatory power, are consistent with this complementarity interpretation.

7.2 Alternative Explanations and Residual Threats

Section 5.3 addressed the principal identification threats systematically. Two residual concerns merit additional discussion here, as they are not fully resolved by the design.

Program timing as the primary unmeasured confounder. The most substantive threat to the within-country TWFE associations is the coincident timing of major global health programs. Between 2000 and 2020, GAVI (the Vaccine Alliance) expanded immunization financing to dozens of low- and middle-income countries; PEPFAR scaled antiretroviral treatment across sub-Saharan Africa; and the Global Fund to Fight AIDS, Tuberculosis and Malaria transferred substantial resources to recipient country health budgets. These programs simultaneously increased government health expenditure in recipient countries (through direct co-financing requirements and by crowding in domestic health budget commitments) and reduced child and maternal mortality through the interventions they funded. Year fixed effects absorb the global-average trajectory of these programs, but country-specific rollout timing (when a country entered GAVI co-financing, when it reached PEPFAR treatment saturation) is not absorbed and constitutes a genuine time-varying confounder. The direction of this bias is negative. Program entry spuriously correlates spending increases with mortality reductions, making the negative $\hat{\beta}$ estimates potentially overstated in magnitude. The practical significance of this threat is, however, bounded. The pooled child mortality associations are stable from the bivariate within-country specification (column 1) through the fully controlled preferred specification (column 3), suggesting that the year-fixed-effects model already absorbs a large share of the program-timing variation.

Sample selection and the direction of attenuation. The TWFE estimation sample overrepresents higher-income countries with more complete administrative data records. If, as the sub-group analysis suggests, health expenditure associations with child mortality are concentrated in lower-middle-income settings (where the public health system is the primary delivery mechanism for vaccination and maternal care, and where marginal spending faces less diminishing returns) then the pooled $\hat{\beta}$ understates the child mortality responsiveness in the settings where the policy question is most urgent. The pooled infant mortality estimate (Table 3) therefore likely understates the within-country child mortality response to health spending in the low- and lower-middle-income settings where the longevity deficit is greatest.

7.3 Limitations

Five limitations bound the scope of the conclusions.

Panel length. The 25-year panel is among the longest available at global scale but remains short relative to the lag structures governing adult longevity. Detecting the cumulative return to health investment in life expectancy requires multi-decadal evidence in which chronic disease management, occupational health improvements, and nutritional transitions accumulate. The null associations for life expectancy in TWFE should be read as a reflection of this

panel-length constraint rather than as evidence that adult health investment yields no return. Longer panels, as they become available from the post-2024 EGDI series and extended WHO GHO data, will allow more powerful tests of the life expectancy channel.

Scope of EGDI. EGDI captures government-wide digital readiness across online services, telecommunications, and human capital. It is not a health-sector-specific digital investment index. The child mortality associations attributed to EGDI (particularly through the TTI sub-index) may partly operate through economic and administrative channels (improved logistics for the economy broadly, better government data systems for social program delivery) rather than exclusively through health service delivery mechanisms. TTI’s child mortality association is *consistent with* the logistics mechanism but does not rule out alternative pathways through general economic connectivity improvements. Health-sector-specific digital investment data, where available at country scale, would provide a sharper test.

Income-group power. The income-group TWFE estimates are underpowered for life expectancy and use an outcome whose lag structure makes it inappropriate for detecting year-to-year spending returns in high-income settings. Estimates are exploratory and the positive HIC and UMC point estimates likely reflect within-group reverse causality rather than a structural negative return to health spending. Conclusions about income heterogeneity should be drawn from the full-sample child mortality results, where power and lag structure are both more favorable.

Causal identification. Both methods (LMG decomposition and TWFE) reflect associations, not causal effects. The TWFE specification addresses reverse causality and time-invariant confounding but cannot eliminate time-varying confounders or program-timing coincidences. Moving from the descriptive benchmark established here to credible causal estimates requires quasi-experimental designs, including fiscal shocks to health budgets (oil windfalls, IMF conditionality), natural experiments in connectivity rollout (cable landings, spectrum auctions), or staggered health system reforms with credible control groups. This paper establishes the magnitudes that such causal designs should be powered to detect.

OOP and detection horizons. The low LMG share for OOP (3.6%) does not invalidate OOP reduction as a financial protection target, but the paper cannot speak to its longevity effects within the TWFE framework. OOP financing structures change slowly within countries. The within-country standard deviation is only 5.8 percentage points, against a cross-country standard deviation of 18.8 points, so a 25-year panel with a one-year lag window cannot detect the cumulative longevity benefits of shifting toward prepaid, pooled financing. Those benefits, operating through reduced catastrophic spending, improved care-seeking, and poverty-trap avoidance [5], accumulate over decades. Governments undertaking OOP reforms should evaluate them against financial protection benchmarks (catastrophic spending incidence, impoverishment rates) rather than near-term longevity improvements detectable in the TWFE framework.

7.4 Policy Relevance

Two implications for health and development finance follow from the findings, stated with appropriate caution given the descriptive nature of the analysis.

The LMG decomposition shows that countries at equivalent income levels and governance quality are associated with meaningfully different longevity outcomes depending on

their health budget allocation. This is directly relevant to fiscal prioritization decisions in ministries of finance and treasury departments where health spending competes with other budget claims. The within-country TWFE associations (approximately 0.8% lower infant mortality per 10% increase in per capita government health spending) provide an order-of-magnitude benchmark for evaluating the child survival dividend from health budget expansions. At mean sample spending levels (\$643 per capita), a 10% increase represents roughly \$64 per capita, subject to the identification caveats above and the assumption that the pooled association generalises to the country’s specific context.

The sub-index analysis shows that TTI drives the child mortality associations attributed to EGDI overall, rather than the online service delivery (OSI) or human capital (HCI) sub-indices. This has implications for infrastructure investment sequencing. The evidence here is consistent with prioritizing physical connectivity infrastructure (mobile towers, broadband backbones, rural network extension) over administrative digitization platforms or e-government portals when the primary goal is health system efficiency. Physical connectivity appears to support vaccine logistics, supply chain management, and real-time community health worker coordination, the specific pathways most consequential for child mortality at the margin. OSI (administrative capacity) may be a productive next investment once basic connectivity is established, given its partial confirmation in the sub-index results.

8 Conclusion

This paper begins from a more-than-two-decade longevity gap between the world’s longest- and shortest-lived populations and asks which investments are most strongly associated with that gap once income, governance, and digital infrastructure are considered jointly. The evidence does not support a simple hierarchy. In a joint ordering-invariant decomposition of the cross-country longevity gradient spanning 261 countries and 25 years, no single input dominates. Government health expenditure (23.0%) and national income (22.4%) are statistically indistinguishable co-leaders. Digital infrastructure as measured by EGDI (21.3%) is close behind, a result that challenges both the income-dominance view embedded in the Preston curve tradition and the spending-skepticism view associated with Filmer–Pritchett. OOP share, theoretically important as a financial protection variable, contributes only 3.6% of explained variance once structural development conditions are jointly controlled, suggesting it is largely a proxy for the development conditions already captured by the other predictors.

The within-country evidence reinforces the cross-sectional picture from a different identification angle. Within countries over time, government health spending and digital infrastructure gains translate into measurable improvements concentrated in child outcomes. A 10% within-country increase in per capita government health expenditure is associated with approximately 0.8% lower infant mortality and 0.75% lower under-5 mortality in the following year, while EGDI gains are significantly associated with child mortality reductions, with the TTI sub-index showing the strongest association. Both associations are negligible for adult life expectancy, not because health investment is irrelevant to adult survival, but because the cumulative lag structures governing life expectancy exceed what a 25-year panel with a one-year regressor lag can detect. The concentration of within-country responsiveness in child outcomes, and specifically through the logistics mechanism that TTI captures

(vaccine cold chains, supply routing, real-time supervision of community health workers) is consistent with digital infrastructure operating as an efficiency multiplier for recurrent health spending rather than as a substitute for it.

The decomposition result carries a methodological implication for prior work and a practical implication for policy. Methodologically, studies that estimate health spending or income effects without jointly controlling for digital infrastructure risk misattributing variance. The broadly comparable LMG shares across all three inputs, and the bootstrapped last-in contributions of health expenditure and EGDI in particular, indicate that each carries unique explanatory power not captured by the others. Partial models, which dominate the literature for data availability reasons, may systematically overstate the contribution of whichever inputs they include and understate those they omit. Practically, the result suggests that health spending, income growth, and digital infrastructure should be treated as jointly important inputs in health and development planning rather than as a sequence in which macroeconomic growth comes first and health budgets follow. The three inputs may be complements rather than substitutes. Neither income growth, health investment, nor connectivity alone delivers the longevity dividends that their joint deployment appears to provide.

Three specific extensions would most productively build on this foundation. First, the causal status of the associations documented here requires quasi-experimental variation (fiscal shocks to health budgets from oil windfalls or IMF conditionality, natural experiments in connectivity rollout from submarine cable landings or spectrum auctions, staggered health system reforms with credible comparison groups). This paper provides the coefficient magnitudes and outcome-specific response patterns that such designs should be powered to detect. Second, longer panels (as HALE data extend beyond 2021 and the EGDI series accumulates beyond 2024) will permit tests of the adult life expectancy channel whose lag structure exceeds the current horizon. Third, and most important for the policy argument, directly testing the complementarity hypothesis (whether the marginal child mortality return to health spending rises with EGDI level) requires interaction specifications or stratified analyses that current within-group sample sizes constrain. If confirmed, complementarity would strengthen the case for treating connectivity infrastructure as a prerequisite investment that raises the productivity of health expenditure, with implications for the sequencing of SDG 3 financing across national development programmes.

Until causal identification is achieved, this paper provides a precise descriptive benchmark. The global longevity gradient is associated in roughly equal shares with health investment, national income, and digital infrastructure, together accounting for about two-thirds of explained cross-country variance, with governance and internet penetration contributing a further quarter between them. The race to close the more-than-two-decade longevity gap that divides the world's populations is not primarily a race to grow richer, though income matters. It is equally a race to build health systems that spend effectively and digital infrastructure that makes that spending productive.

Appendix

A Variable Definitions and Data Sources

Table A1 lists all variables used in the analysis, their exact sources, World Bank indicator codes where applicable, sample coverage, and transformations applied.

Table A1: Variable Definitions and Data Sources

Variable	Source	Indicator / Code	Coverage	Transformation
<i>Longevity outcomes</i>				
Life expectancy at birth	WDI	SP.DYN.LE00.IN	2000–2024	Levels
Healthy life exp. (HALE)	WHO GHO	WHOSIS_000001	2000–2021	Levels
Maternal mortality ratio	WDI	SH.STA.MMRT	2000–2020	Log
Under-5 mortality rate	WDI	SH.DYN.MORT	2000–2024	Log
Infant mortality rate	WDI	SP.DYN.IMRT.IN	2000–2024	Log
Neonatal mortality rate	WDI	SH.DYN.NMRT	2000–2024	Log
UHC service coverage index	WB UHC	UHC.SCI.OVRL	2000–2021	Levels (0–100)
<i>Health investment</i>				
Gov. health exp. per capita	WDI	SH.XPD.GHED.PC.CD	2000–2022	Log (USD)
OOP share of health exp.	WDI	SH.XPD.OOPC.CH.ZS	2000–2022	Levels (%)
<i>Digital infrastructure</i>				
EGDI (overall)	UN DESA	E-Gov Survey	2003–2024	Levels (0–1); biennially interpolated
EGDI: Online Services (OSI)	UN DESA	E-Gov Survey	2003–2024	Levels (0–1); biennially interpolated
EGDI: Telecom Infra. (TTI)	UN DESA	E-Gov Survey	2003–2024	Levels (0–1); biennially interpolated
EGDI: Human Capital (HCI)	UN DESA	E-Gov Survey	2003–2024	Levels (0–1); biennially interpolated
<i>Development controls</i>				
GDP per capita (PPP)	WDI	NY.GDP.PCAP.PP.KD	2000–2024	Log (2017 intl. USD)
Gov. effectiveness	WGI	GE.EST	2000–2023	Levels (–2.5 to +2.5)
Rule of law	WGI	RL.EST	2000–2023	Levels (–2.5 to +2.5)
Physician density	WDI	SH.MED.PHYS.ZS	2000–2022	Levels (per 1,000 pop.)
Urban population share	WDI	SP.URB.TOTL.IN.ZS	2000–2024	Levels (%)
Internet users	WDI	IT.NET.USER.ZS	2000–2024	Levels (% of pop.)

Notes: WDI = World Bank World Development Indicators; WHO GHO = WHO Global Health Observatory; WGI = Worldwide Governance Indicators; UN DESA = United Nations Department of Economic and Social Affairs. Only variables used in the reported LMG decomposition, TWFE regressions, or appendix robustness tables are listed here. EGDI and sub-indices are published biennially and linearly interpolated in intervening years. WGI indicators are standardised on an approximately (–2.5, +2.5) scale. Health investment variables are available through 2022 in the WDI extract used; with one-year lagging, health-expenditure TWFE models therefore use outcome years 2001–2023.

B Pairwise Correlation Matrix

Table A2 reports pairwise correlations among the main analysis variables. The high collinearity among health expenditure, GDP per capita, EGDI, and governance (pairwise $r = 0.78$ – 0.92) motivates the LMG ordering-invariant decomposition in Section 5.1: sequential ΔR^2 methods assign different shares depending on entry order, whereas LMG averages across all 720 orderings to produce allocation that is invariant to this choice.

Table A2: Pairwise Correlation Matrix of Main Analysis Variables

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
(1) Life expectancy	1.00									
(2) ln(Under-5 mort.)	-0.92	1.00								
(3) ln(Infant mort.)	-0.90	0.99	1.00							
(4) ln(Maternal mort.)	-0.88	0.92	0.92	1.00						
(5) Gov. health exp. (log)	0.82	-0.90	-0.89	-0.83	1.00					
(6) OOP share (%)	-0.34	0.44	0.45	0.36	-0.59	1.00				
(7) GDP pc (log, PPP)	0.82	-0.87	-0.86	-0.83	0.92	-0.39	1.00			
(8) Gov. effectiveness	0.73	-0.79	-0.80	-0.72	0.82	-0.48	0.79	1.00		
(9) EGDI	0.81	-0.87	-0.87	-0.81	0.84	-0.40	0.83	0.78	1.00	
(10) Internet users (%)	0.72	-0.78	-0.78	-0.69	0.79	-0.39	0.74	0.66	0.86	1.00

Notes: Pearson correlation coefficients, complete-case cross-sectional sample ($N = 3,943$ country-year observations). The high pairwise correlations among health expenditure, GDP per capita, EGDI, and governance (0.78–0.92) illustrate the multicollinearity that makes ordering-sensitive variance decomposition methods unreliable and motivates the LMG approach.

C TWFE Results: EGDI and OOP Share as Main Regressors

Tables A3 and A4 report the full TWFE specification ladder for EGDI and OOP share as the main regressors, respectively. These results are discussed in Section 6.2 but tabulated here for completeness and to allow direct comparison with the health expenditure results in Table 3. The specification columns are identical across all three tables. They are (1) country FE only, (2) country FE plus time-varying controls, and (3) the preferred specification with country and year FE and full controls.

The most notable feature of Table A3 is the large sign reversal and collapse from column (1) to column (3) for life expectancy and HALE. The bivariate within-country EGDI association is large and positive (+11.6 and +12.4 years per unit EGDI respectively), but reverses sign and becomes insignificant (−1.36 and −1.09) in the preferred specification. The reversal (and roughly 90% shrinkage in absolute magnitude) indicates that the cross-sectional EGDI–life expectancy gradient is driven primarily by persistent country-level characteristics (geography, institutional history, long-run development trajectory) absorbed by country fixed effects, rather than by year-to-year within-country EGDI improvements. Child mortality outcomes show substantially less attenuation, suggesting a genuine within-country

logistics mechanism responsive to EGDI changes at the annual frequency.

Table A3: TWFE Estimates: EGDI and Longevity Outcomes

Outcome	(1) Bivariate		(2) + Controls		(3) Preferred TWFE		N
	Coef.	SE	Coef.	SE	Coef.	SE	
Life expectancy	11.639***	(0.933)	4.884***	(0.925)	-1.358	(1.055)	2,502
HALE	12.368***	(1.082)	4.799***	(1.009)	-1.093	(1.150)	2,302
ln(Maternal mort.)	-1.017***	(0.130)	-0.062	(0.170)	0.177	(0.212)	2,502
ln(Under-5 mort.)	-1.735***	(0.114)	-0.945***	(0.096)	-0.430***	(0.131)	2,502
ln(Infant mort.)	-1.633***	(0.111)	-0.936***	(0.103)	-0.534***	(0.134)	2,502
UHC index	27.389***	(2.379)	8.499***	(2.245)	-5.600**	(2.381)	2,502

Notes: TWFE panel estimates, 2000–2024, main regressor EGDI (0–1 scale) lagged one year ($t - 1$). Specification (1): country FE only. Specification (2): country FE + time-varying controls. Specification (3): country + year FE + full controls (log GDP per capita PPP, government effectiveness, rule of law, urban population %, physician density). SEs clustered at country level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. EGDI is published biennially and linearly interpolated to annual frequency; this attenuates within-country variation, biasing TWFE estimates toward zero. The negative UHC coefficient in specification (3) is a measurement artefact of this interpolation (see Section 6) and should not be interpreted structurally.

Table A4 shows the analogous pattern for OOP share. Bivariate within-country associations (column 1) are consistent in sign with the financial protection mechanism (higher OOP share is associated with worse longevity outcomes) but attenuate sharply once controls absorb income and governance, and are statistically insignificant in the preferred specification (column 3) for all outcomes. This confirms the interpretation in Section 6.2. OOP financing structures change slowly within countries, and annual within-country variation in OOP share is insufficient to power the TWFE estimator over a 25-year horizon.

Table A4: TWFE Estimates: OOP Share and Longevity Outcomes

Outcome	(1) Bivariate		(2) + Controls		(3) Preferred TWFE		N
	Coef.	SE	Coef.	SE	Coef.	SE	
Life expectancy	-0.137***	(0.016)	-0.029*	(0.015)	-0.009	(0.012)	2,487
HALE	-0.117***	(0.019)	-0.037**	(0.016)	-0.019	(0.013)	2,288
ln(Maternal mort.)	0.008***	(0.002)	-0.003	(0.003)	-0.004	(0.003)	2,487
ln(Under-5 mort.)	0.017***	(0.002)	0.003**	(0.001)	0.001	(0.001)	2,487
ln(Infant mort.)	0.015***	(0.002)	0.003*	(0.001)	0.000	(0.001)	2,487
UHC index	-0.328***	(0.037)	-0.082**	(0.032)	-0.041	(0.026)	2,487

Notes: TWFE panel estimates, 2000–2024, main regressor OOP share (percentage points) lagged one year ($t - 1$). Specification (1): country FE only. Specification (2): country FE + time-varying controls. Specification (3): country + year FE + full controls (log GDP per capita PPP, government effectiveness, rule of law, urban population %, physician density). SEs clustered at country level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Within-country SD of OOP share is 5.8 pp (31% of the cross-country SD of 18.8 pp), limiting within-country identification power. The bivariate specification (1) picks up the large cross-country OOP gradient; this attenuates substantially once controls absorb income and governance.

Declarations

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Author contributions: H.S.Y. conceptualized the study, assembled the panel dataset, conducted all statistical analyses, and wrote the manuscript in its entirety.

Ethics declaration: This study uses only publicly available, anonymized aggregate country-level data obtained from the World Bank, WHO, and United Nations. No individual-level data, human participants, or biological material were involved. Ethics approval and informed consent were not required.

Data availability: All data used in this study are publicly available. World Bank WDI and WGI indicators: <https://data.worldbank.org>. WHO GHO data: <https://www.who.int/data/gho>. UN EGDI data: <https://publicadministration.un.org/egovkb>. The replication dataset and analysis code are available from the corresponding author upon reasonable request.

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