International Journal of Advanced Trends in Engineering and Technology (IJATET)
International Peer Reviewed - Refereed Research Journal, Website: www.dvpublication.com
Impact Factor: 5.965, ISSN (Online): 2456 - 4664, Volume 10, Issue 2, July - December, 2025

ECONOMIC CONDITIONS AND ANTIRETROVIRAL THERAPY COVERAGE AMONG PEOPLE LIVING WITH HIV: EVIDENCE FROM PANEL DATA

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Cite This Article: Kannan Vishwanath & Lloyd Zulu, "Economic Conditions and Antiretroviral Therapy Coverage Among People Living with HIV: Evidence from Panel Data", International Journal of Advanced Trends in Engineering and Technology, Volume 10, Issue 2, July - December, Page Number 193-202, 2025.
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DOI: https://doi.org/10.5281/zenodo.24040302

Abstract:

This analysis examines whether distinct economic conditions explain differences in antiretroviral therapy coverage across resource constrained economies, informing international debates on economic development and treatment access. An unbalanced panel of 754 annual observations across 59 economies from 2010 through 2023 combines World Development Indicators with UNAIDS coverage estimates. Ordinary least squares models include economy and year fixed effects, with standard errors clustered by economy. A 10 percent increase in real GDP per capita is associated with 1.39 percentage points higher coverage, with a 95 percent confidence interval from 0.62 to 2.17. Annual growth and aggregate trade exhibit imprecise conditional associations. The positive income relationship persists under alternative income scaling, economy specific trends, exclusion of recorded zero trade values, and balanced panel estimation. These findings distinguish economic resource levels from contemporaneous expansion and international exchange without identifying causal transmission pathways. The contribution refines resource based explanations by separating economic dimensions that provide different information about treatment access. International financing assessments should therefore combine economic capacity indicators with direct coverage monitoring.

Key Words: Antiretroviral Therapy; Economic Development; Treatment Coverage; Trade Openness; Panel Data.

1. Introduction:

Expanding antiretroviral therapy requires sustained access to treatment, yet economic progress does not necessarily translate into wider coverage. The UNAIDS Global AIDS Update published in 2023 estimated that 29.8 million of the 39.0 million people living with HIV globally received antiretroviral therapy in 2022, equivalent to 76 percent coverage. These estimates demonstrate the scale of treatment provision alongside the remaining access gap. Understanding whether different economic conditions are associated with treatment coverage matters for governments and international partners assessing financing capacity, comparing programme performance, and planning service expansion. Income level, economic growth, and trade openness represent distinct conditions under which treatment programmes operate. Income level captures economic resources per person, growth captures changes in real output, and trade openness captures international exchange relative to domestic production. Treating these measures as interchangeable can obscure whether treatment access relates more closely to the level of available resources, annual economic expansion, or participation in international markets. A health systems perspective provides the conceptual basis for separating these relationships. Bigdeli et al. in 2013 explain that access to medicines emerges through interactions among financing, institutions, service delivery, and household circumstances. National economic indicators can describe the context surrounding these processes without directly measuring their operation.

The closest financing research establishes that economic resources and treatment commitments must be considered together. Resch et al. in 2015 examine domestic AIDS spending in twelve countries and construct financing scenarios based on economic conditions, health spending priorities, and disease burden. Remme et al. in 2016 distinguish potential fiscal capacity from resources likely to become available through observed government financing responses. Their empirical analysis includes expenditure information from 92 governments in low income and middle-income settings. These contributions clarify why economic capacity does not automatically become programme financing. They do not, however, directly establish whether income levels and annual economic growth retain distinct associations with treatment coverage when evaluated alongside aggregate trade in a common annual panel. International supply provides a separate reason to examine trade. Waning et al. in 2010 document the role of Indian generic manufacturers in supplying affordable antiretroviral medicines to developing countries. Holmes et al. in 2010 associate greater generic procurement within supported treatment programmes with increased procurement volumes and estimated cost savings. This evidence establishes the relevance of international medicine markets, but it does not make aggregate trade openness a direct measure of pharmaceutical access. Exports and imports include activities unrelated to treatment, while procurement arrangements determine which medicines become available and at what cost. The relationship between aggregate trade and treatment coverage therefore requires empirical examination rather than inference from evidence about generic medicine supply.

Treatment coverage also requires a precise interpretation. The outcome measures the percentage of all people living with HIV who receive antiretroviral therapy. It captures treatment access rather than viral suppression, continuity of adherence, or survival. These distinctions matter because programme inputs and population outcomes answer different questions. Bendavid et al. in 2012 examine HIV development assistance and adult mortality across African settings, demonstrating the importance of evaluating programme exposure against a defined health outcome. The present analysis instead examines whether national economic conditions are associated with the reach of treatment provision. Its outcome remains an estimated annual coverage measure, whose interpretation depends on the surveillance, demographic information, and modelling procedures described by Stover et al. in 2019. The reviewed evidence leaves a bounded empirical question: whether income level, annual economic growth, and aggregate trade openness have distinct conditional relationships with antiretroviral therapy coverage across resource

constrained economies. Resolving this question requires separating the three economic dimensions while accounting for stable differences across economies and common annual influences. The contribution concerns comparative measurement and empirical differentiation rather than the identification of financing or procurement mechanisms. Distinguishing these relationships can clarify whether broad macroeconomic indicators provide similar information about treatment access or whether their interpretation must remain separate.

This analysis aims to estimate the conditional associations between these three economic dimensions and antiretroviral therapy coverage. It asks whether higher real GDP per capita is associated with wider coverage, how annual real GDP growth relates to coverage, and whether aggregate trade openness contributes a separate association. The dataset contains 754 complete annual observations across 59 economies from 2010 through 2023. Resource constrained economies are operationalized through the fixed low income and lower middle-income classifications recorded in the supplied sampling frame. The analysis combines World Development Indicators with UNAIDS treatment coverage estimates and applies regression with economy and year fixed effects. This design distinguishes changes within economies from stable differences between them, while remaining associational. The completed analysis identifies a positive income association: a 10 percent increase in real GDP per capita corresponds to approximately 1.39 percentage points higher treatment coverage, with a 95 percent confidence interval from 0.62 to 2.17 percentage points. The positive direction persists under alternative income scaling, additional economy specific trends, exclusion of recorded zero trade values, and restriction to a balanced panel. Growth and trade estimates remain imprecise around zero. The findings therefore differentiate income levels from annual growth and aggregate international exchange without establishing that either of the latter relationships is absent. For international treatment planning, this distinction supports assessing economic resources alongside direct coverage measures rather than assuming that macroeconomic expansion or greater trade necessarily signals improved treatment access. The evidence applies to the observed economies and does not establish a universal relationship across income groups.

2. Theory, Conceptual Framework and Research Question Development:

Antiretroviral therapy coverage depends on how economic resources translate into sustained access to treatment. Governments finance services, procurement agencies purchase medicines, providers deliver care, and individuals face costs when seeking treatment. These interdependent activities make coverage a system outcome rather than a direct consequence of national income. Bigdeli et al. in 2013 locate access to medicines within relationships among financing, service delivery, institutions, and household resources. This analysis applies that perspective to three observed economic dimensions: income level, economic growth, and trade openness. The outcome is the percentage of people living with HIV who receive antiretroviral therapy. Income level represents the economic resources available per person and is measured through real GDP per capita. Under a resource constraint framework, greater income can expand the resources available for treatment provision and reduce the relative burden of accessing services. The expected relationship is positive because sustained treatment requires recurrent expenditure rather than a single purchase. Nevertheless, national income measures neither the allocation of public resources to HIV services nor the resources available to individual patients.

The distinction between resources and treatment capacity matters because delivering antiretroviral therapy requires medicines, personnel, laboratory services, and supporting infrastructure. Galárraga et al. in 2011 documented substantial variation in treatment delivery costs across resource settings. Their evidence supports treating economic resources as relevant to service provision, but it does not establish that higher national income necessarily produces wider coverage. The theoretical expectation therefore concerns a conditional association rather than an automatic conversion of income into treatment access. This analysis measures income level through the natural logarithm of real GDP per capita. The transformation expresses income differences proportionately without constructing a composite index. Within the country and year fixed effects specification, the hypothesis concerns whether changes in income within an economy are associated with changes in coverage, conditional on economic growth and trade openness.

H1: Higher real GDP per capita is positively associated with antiretroviral therapy coverage, conditional on economic growth, trade openness, country effects, and year effects.

Economic growth captures the annual rate of expansion in real output and differs conceptually from income level. An economy can have a low-income level while growing rapidly, or a higher income level while contracting. Growth may ease resource constraints, but an annual increase in output need not coincide with an immediate expansion in treatment provision. Budget decisions, procurement commitments, and service capacity can prevent economic improvements from translating into coverage within the same year. Competing mechanisms make a directional prediction less secure for growth than for income level. Economic expansion may strengthen the resources available to sustain treatment, while established programmes may maintain coverage during periods of weak growth. Conversely, fiscal responses to economic disruption may intensify barriers to care. Ruckert and Labonté in 2017 argue that austerity and social protection choices shape the distribution of health consequences following economic crises. Their analysis indicates that policy responses condition the relationship between economic performance and health access, rather than establishing a uniform relationship between annual growth and treatment coverage. The available measure records annual GDP growth rather than fiscal responses or programme financing. Accordingly, this analysis evaluates the conditional relationship without assigning a predetermined sign. This formulation permits positive, negative, and inconclusive results while keeping the question aligned with the observed indicator.

RQ1: How is annual real GDP growth associated with antiretroviral therapy coverage, conditional on income level, trade openness, country effects, and year effects?

Trade openness captures the scale of exports and imports relative to GDP. Its theoretical relevance arises from the international organization of medicine production and supply. Access to external producers can widen procurement options and make affordable treatment inputs available to economies with limited domestic production. Waning et al. in 2010 documented the central role of Indian generic manufacturers in supplying antiretroviral medicines to developing countries. This evidence establishes the importance of international supply relationships, but it does not establish that a higher aggregate trade ratio produces greater treatment coverage. The affordability mechanism depends on what countries purchase and the conditions under

which procurement occurs. Holmes et al. in 2010 found that greater use of generic antiretroviral medicines within supported treatment programmes accompanied increased procurement and estimated cost savings. These findings connect procurement choices to treatment resources. However, aggregate trade includes goods and services unrelated to HIV care, so it cannot identify generic procurement, medicine prices, or the composition of pharmaceutical imports. This measurement distinction prevents a defensible directional hypothesis for trade openness. A higher trade ratio may reflect stronger access to international supply, but it may also reflect changes in unrelated exports, imports, or domestic output. This analysis therefore treats trade openness as an observed economic condition and asks whether it has a conditional association with coverage.

RQ2: How is trade openness associated with antiretroviral therapy coverage, conditional on income level, economic growth, country effects, and year effects?

The conceptual framework links the three observed economic dimensions directly to observed antiretroviral therapy coverage. Economic conditions serve as an organizing concept, not a latent variable or a constructed index. Income level, economic growth, and trade openness enter the specification separately. Country effects account for stable differences across economies, while year effects account for common annual influences. The framework evaluates associations using 807 complete observations across 59 economies. The proposed mechanisms explain the theoretical relevance of the predictors; they are not estimated mediating pathways. H1, RQ1, and RQ2 consequently concern measurable conditional relationships and permit unsupported or inconclusive outcomes.

3. Data:

This analysis establishes data provenance, constructs the estimation sample, and defines measures of economic conditions and antiretroviral therapy coverage.The resulting annual panel supports descriptive comparisons and estimation of conditional associations across resource constrained economies.

3.1 Data Sources, Population, and Sample Construction:

The dataset combines four series from the World Bank World Development Indicators, database identifier 2. National statistical agencies, central banks, and international statistical organizations supply the national accounts information, while UNAIDS supplies antiretroviral therapy coverage estimates. The series identifiers and stable source links appear in Table 3. Data were retrieved through the World Bank Indicators API and consolidated by economy and year. The indicator pages specify the Creative Commons Attribution 4.0 licence. The archived workbook records the extraction and release timestamps separately from observation years. This provenance distinction follows the emphasis on traceable data reuse in the World Bank report published in 2021. The target population comprises resource constrained economies. The accessible frame operationalizes this population as the 72 economies classified as low income or lower middle income in the country metadata accompanying the supplied workbook. This fixed classification defines the cohort throughout the analysis; it does not represent income classification in each historical year. The frame contains 25 low-income economies and 47 lower middle-income economies. Eligibility requires an identifiable economy, an observation year from 2010 through 2023, and availability of the four study indicators for inclusion in regression analysis.

The unit of analysis is the economy observed annually. Economic measures cover national production and international trade, while the health measure covers people living with HIV who receive antiretroviral therapy. Annual GDP and trade originate from economic flows over an accounting period. GDP per capita expresses annual output relative to population, GDP growth measures the annual change in real output, and treatment coverage measures the proportion receiving therapy rather than treatment initiations during the year. The observation window and complete observation rule were applied before estimating the manuscript specifications. Restricting the supplied panel to the analysis window removed 72 annual records. The remaining eligible frame contains 1,008 observations. Table 1 documents the subsequent exclusions using mutually exclusive missingness patterns. Reporting selection separately from estimation follows the transparency principles developed by Benchimol et al. in 2015.

Table 1: Sample construction

Stage	Economies	Observations	Reason or Rule
Eligible frame	72	1,008	Annual observations from 2010 through 2023
Exclusion: treatment coverage unavailable only	8 affected	110 removed	Economic indicators available
Exclusion: trade unavailable only	11 affected	100 removed	Other indicators available
Exclusion: income, growth, and trade unavailable	5 affected	29 removed	Treatment coverage available
Exclusion: all four indicators unavailable	1 affected	14 removed	No usable study measures
Exclusion: growth unavailable only	1 affected	1 removed	Other indicators available
Complete analysis sample	59 retained	754 retained	All four indicators available
Baseline regression	59	754	No additional transformation or estimator losses
Sensitivity using income in levels	59	754	Same observations as baseline
Sensitivity with economy specific linear trends	59	754	Same observations as baseline
Sensitivity excluding recorded zero trade values	59	752	Two source recorded zeros excluded
Balanced panel sensitivity	47	658	Fourteen complete annual observations per economy

Affected economy counts overlap across exclusion categories and therefore cannot be added. Observation exclusions are mutually exclusive. The retained panel is unbalanced. Forty-seven economies contribute all fourteen years, while twelve contribute between two and thirteen observations. Thirteen eligible economies contribute no complete observations. The retained sample includes 22 low-income economies and 37 lower middle-income economies. Treatment coverage is an estimated national indicator rather than a complete enumeration of patients. The reporting distinction follows Stevens et al. in 2016, while Stover et al. in 2019 explain how HIV indicators depend on surveillance, demographic inputs, and modelling assumptions. The GBD 2019

HIV Collaborators in 2021 further demonstrate the importance of estimation methods when interpreting international HIV measures. These publications inform interpretation of the outcome; their estimates were not merged into the dataset.

3.2 Data Integration, Cleaning, and Quality Assurance:

Integration used the three-letter economy identifier and observation year as the joint key. Each indicator contributed one record for every eligible economy and year, including records with unavailable values. Within the eligible frame, each source series contained 1,008 unique keys. No duplicate eligible keys, conflicting repeated values, or increases caused by repeated matching were identified. The complete sample reconstructed from the source panel matched the corresponding observations in the supplied analysis worksheet. The rectangular structure preserves one observation per row and one variable per column, following Wickham in 2014. All variables retain their source annual labels. No frequency conversion, temporal interpolation, local currency conversion, or additional inflation adjustment was performed. GDP per capita remains expressed in constant 2015 US dollars using the provider's adjustment. Growth, trade, and treatment coverage retain their published percentage scales. Missing values remain unavailable rather than becoming zeros. Across the eligible frame, GDP per capita has 43 missing observations across six economies, GDP growth has 44 across six economies, trade has 143 across seventeen economies, and treatment coverage has 124 across nine economies. These marginal counts overlap and exceed the 254 observations excluded through the joint completeness requirement. The supplied values do not distinguish structural inapplicability from other reasons for nonavailability. Table 2 reports missingness by year.

Table 2: Annual missingness and retained observations

Year	GDP Per Capita Missing	Growth Missing	Trade Missing	Treatment Coverage Missing	Complete Observations
2010	2	2	12	9	52
2011	2	2	11	9	53
2012	3	3	11	9	53
2013	2	3	9	9	54
2014	2	2	9	9	55
2015	2	2	9	9	55
2016	3	3	10	9	54
2017	3	3	10	9	54
2018	3	3	10	9	54
2019	4	4	11	9	53
2020	4	4	10	9	54
2021	4	4	10	9	54
2022	4	4	10	8	55
2023	5	5	11	8	54
Total	43	44	143	124	754

No imputation was performed. This preserves the distinction between published observations and constructed replacements, but it does not establish that exclusion is unrelated to the outcome. White and Carlin in 2010 and Hughes et al. in 2019 show that the validity of complete observation analysis depends on the missingness process rather than on the percentage missing alone. A descriptive comparison indicates that excluded observations with available treatment coverage have mean coverage of 39.05 percent, compared with 41.35 percent among retained observations. Available GDP per capita averages 1,848.45 US dollars among excluded observations and 1,632.76 among retained observations. These comparisons use different available subsets and do not establish the absence of selection bias.

Range checks confirmed positive GDP per capita, treatment coverage within zero to one hundred percent, and nonnegative trade ratios in the estimation sample. Trade values above one hundred percent were retained because combined exports and imports can exceed GDP. Two recorded zero trade values for Venezuela in 2010 and 2011 were flagged. The baseline preserves their published numeric values, while an exploratory sensitivity specification excludes them. No trimming or winsorization was applied. The analysis uses a revised historical snapshot rather than information demonstrably available at each observation date. It therefore supports retrospective association analysis rather than real time forecasting. Original values remain separate from the logarithmic transformation and regression calculations. Executable checks preserve this distinction, consistent with the reproducibility principles articulated by Sandve et al. in 2013 and Peng in 2011.

3.3 Variable Measurement, Construction, and Validation:

Economic conditions comprise three separately observed dimensions: income level, economic growth, and trade openness. No latent score or composite index is constructed. This distinction prevents the organizing concept from acquiring measurement properties that the indicators do not establish, consistent with Flake and Fried in 2020. Treatment coverage remains a national access measure rather than a measure of medicine availability alone, reflecting the systems distinction developed by Bigdeli et al. in 2013.

Table 3: Variable dictionary

Variable	Analytical Role	Definition and Construction	Source and Identifier	Unit and Frequency	Transformation and Direction	Missing Value Rule	Coverage and Limitation
Antiretroviral therapy coverage	Outcome	People receiving therapy as a percentage of all people living with	UNAIDS through World Bank WDI	Percent; annual	Published level; higher values indicate wider coverage	Exclude incomplete observations	884 available frame observations; 754 retained; estimated coverage does not measure viral suppression

Variable	Analytical Role	Definition and Construction	Source and Identifier	Unit and Frequency	Transformation and Direction	Missing Value Rule	Coverage and Limitation
		HIV					
Real GDP per capita	Income predictor	Real GDP divided by population, as published	World Bank WDI	Constant 2015 US dollars per person; annual	Natural logarithm in baseline; higher values indicate greater output per person	Exclude unavailable values; logarithm requires positive values	965 available; 754 retained; national average does not measure household resources
Real GDP growth	Growth predictor	Published annual percentage change in real GDP	World Bank WDI	Percent; annual	No transformation; negative values retained	Exclude unavailable values	964 available; 754 retained; does not measure growth in health expenditure
Trade openness	Trade predictor	Exports plus imports of goods and services expressed relative to GDP	World Bank WDI	Percent of GDP; annual	No transformation; higher values indicate greater trade relative to output	Exclude unavailable values; retain recorded zeros in baseline	865 available; 754 retained; aggregate trade does not identify pharmaceutical imports

The income transformation is defined in Equation 1.

$$L_{it} = \ln I_{it}$$

Equation 1 defines L_{it} as logarithmic real GDP per capita and I_{it} as published real GDP per capita for economy i in year t. All 754 retained income observations are positive, so the transformation causes no additional loss. Coverage and trade are percentages rather than proportions stored between zero and one. A one-unit change in either measure represents one percentage point. GDP growth is a percentage change in real output; a one-unit difference in the growth variable represents one percentage point of growth. Income remains a level before logarithmic transformation. The indicators do not directly measure the mechanisms motivating their inclusion. Galárraga et al. in 2011 identify the resource requirements of treatment delivery, but GDP per capita does not measure those costs. Waning et al. in 2010 document international generic supply, while Holmes et al. in 2010 examine procurement and cost savings. Neither mechanism is equated with the aggregate trade ratio used here. Validation comprised identifier checks, reconciliation against the supplied analysis worksheet, missingness accounting, domain checks, and verification that the logarithmic transformation was defined. These checks establish internal consistency rather than independent validation of national estimates.

Table 4: Descriptive statistics for the estimation sample

Variable	Valid Observations	Mean	Standard Deviation	Median	Minimum	Maximum
Treatment coverage, percent	754	41.35	24.11	37.50	1.00	94.00
Real GDP per capita, constant US dollars	754	1,632.76	1,315.88	1,256.28	349.82	8,955.54
Logarithmic real GDP per capita	754	7.16	0.67	7.14	5.86	9.10
Real GDP growth, percent	754	3.40	5.97	4.33	−46.08	31.73
Trade, percent of GDP	754	67.24	37.61	57.88	0.00	320.94

Statistics give equal weight to each retained economy and year observation. They are not population weighted estimates of treatment coverage or economic conditions.

3.4 Analytical Framework, Identification, and Reproducibility:

The analysis estimates conditional associations rather than causal effects. The baseline uses ordinary least squares with economy and year fixed effects, as expressed in Equation 2.

$$C_{it} = \alpha_i + \lambda_t + \beta_1 L_{it} + \beta_2 G_{it} + \beta_3 T_{it} + \varepsilon_{it}$$

Equation 2 defines C_{it} as treatment coverage, α_i as the economy fixed effect, λ_t as the year fixed effect, L_{it} as logarithmic real GDP per capita, G_{it} as real GDP growth, and T_{it} as trade openness. The coefficients β_1, β_2, and β_3 represent partial associations, while ε_{it} represents unexplained variation. All explanatory variables refer to the same observation year as the outcome. Economy effects absorb stable differences across economies, and year effects absorb common annual influences. Estimation therefore uses changes within economies after accounting for common year patterns and the other predictors. Fixed effects do not remove changing omitted influences or establish temporal ordering. Imai and Kim in 2019 clarify the assumptions required for causal interpretations of unit fixed effects, while their analysis published in 2021 examines corresponding limitations of models containing both unit and time effects. Inference uses standard errors clustered by economy, with a finite sample correction and a reference distribution based on 58 degrees of freedom. This allows heteroskedasticity and dependence among observations within each of the 59 economies. The choice follows the cluster dependence considerations discussed by Cameron and Miller in 2015 and Abadie et al. in 2023. Clustering does not eliminate correlation across economies or correct bias in coefficient estimates.

Exploratory sensitivity checks address four specific features of the data. Replacing logarithmic income with income in levels examines functional form. Adding economy specific linear trends examines sensitivity to different underlying coverage trajectories. Restricting estimation to the 47 economies observed throughout the analysis window examines panel composition. Excluding the two recorded zero trade values examine their influence. The income and trend specifications use the same 754 observations as the baseline. Comparisons involving the balanced panel or zero trade exclusions use the smaller samples reported in Table 1. These checks were added during the present analytical audit and are exploratory. They do not constitute a formal assessment of all omitted confounding. Cinelli and Hazlett in 2020 distinguish sensitivity to observed specifications from sensitivity to unobserved confounders, a distinction retained when interpreting the estimates. The analysis preserves consistent identifiers, annual timing, source units, and missing value rules across all four indicators. The accompanying ART_reproducibility_2010_2023.py reconstructs the restricted sample, reports missingness by economy and variable, reproduces descriptive statistics, and estimates the baseline and sensitivity specifications from the supplied workbook.

4. Methods:

4.1 Research Design and Analytical Identification:

This analysis uses an observational annual panel to estimate conditional associations between economic conditions and antiretroviral therapy coverage across resource constrained economies. The unit of analysis is the economy observed in a calendar year. The estimands are the partial regression coefficients for income level, economic growth, and trade openness, conditional on the other predictors, economy effects, and year effects. The design evaluates contemporaneous relationships over 2010 through 2023. Useful variation arises from changes within economies after accounting for common annual influences. Economy effects absorb stable differences across economies, while year effects absorb influences shared across economies within each year. The resulting comparisons concern whether deviations in economic conditions accompany differences in treatment coverage beyond these fixed components. The design does not identify a treatment intervention or an externally assigned exposure. Changing institutions, programme financing, reverse relationships, and measurement error may affect the estimated associations. Fixed effects do not eliminate these possibilities. Imai and Kim in 2019 explain why adjustment for stable unit characteristics does not establish causal identification when dynamic relationships remain possible. Their analysis published in 2021 further clarifies the interpretive restrictions of models containing both unit and time effects. Accordingly, the coefficients are interpreted as conditional associations rather than causal effects.

4.2 Model Specification and Measurement Alignment:

The implemented baseline is Equation 2. Antiretroviral therapy coverage is regressed on logarithmic real GDP per capita, annual real GDP growth, and trade openness, together with economy and year fixed effects. All explanatory variables refer to the same observation year as the outcome. Table 3 defines their sources, units, and measurement limitations, while Equation 1 defines the income transformation. The baseline assumes an additive relationship with common slopes across retained economies. Each economic dimension enters separately, and the other two dimensions provide mutual statistical adjustment. These coefficients therefore describe partial relationships rather than total causal effects operating through an established sequence of economic changes. Income enters logarithmically to express its association in proportional terms. Growth and trade retain their published percentage scales, including negative growth values and recorded zero trade values. Coverage remains measured from zero to one hundred. Consequently, changes in fitted coverage are interpreted in percentage points.

Estimation uses an intercept, 58 economy indicators, thirteen-year indicators, and three economic predictors. The resulting design matrix contains 75 columns and has full column rank. The three predictors therefore remain jointly identifiable after inclusion of both sets of fixed effects. For substantive interpretation, the logarithmic income coefficient is multiplied by the natural logarithm of 1.10 to express the fitted coverage difference associated with a 10 percent income increase. Corresponding confidence limits receive the same transformation. Growth and trade contrasts are obtained by multiplying their coefficients and confidence limits by the specified percentage point change. These calculations preserve the distinction between proportional income changes and changes in variables already expressed as percentages.

4.3 Sample Processing, Estimation, and Inference:

Table 1 documents sample construction and model specific observation counts. The baseline contains 754 complete observations across 59 economies. The panel is unbalanced, with between two and fourteen observations per economy. Forty-seven economies contribute all fourteen years. The estimation sample represents the observed complete records within the eligible frame rather than a probability sample of all resource constrained economies. Processing first restricts the source panel to the observation window, converts the study fields to numeric values, and identifies records with all four indicators available. The income transformation is then calculated. Checks confirm unique economy and year identifiers, positive income values, coverage within its permitted range, and nonnegative trade ratios. Reconstructing the complete sample from the source panel reproduces the corresponding analysis worksheet.

Unavailable values are excluded through the joint completeness rule. No imputation, interpolation, trimming, or winsorization is applied. These preserves published observations but does not establish that exclusion is unrelated to treatment coverage. Hughes et al. in 2019 show why the suitability of complete observation analysis depends on the missingness process and model structure rather than the missing percentage alone. Coefficients are estimated through ordinary least squares using an explicit indicator representation of fixed effects. Every retained observation receives equal weight. Computation uses Python 3.12.14, NumPy 2.3.5, pandas 2.2.3, and SciPy 1.17.0. NumPy linear least squares estimate the coefficients, pandas construct the indicator variables and sample summaries, and SciPy supplies the reference distribution for inference.

Standard errors use an economy clustered sandwich covariance estimator. Residual contributions are summed within each economy before constructing the covariance matrix, allowing heteroskedasticity and dependence among observations from the same economy. The finite sample multiplier equals the number of clusters divided by one fewer cluster, multiplied by one fewer observation divided by observations minus estimated parameters. The parameter count includes the intercept and fixed effect indicators. Baseline inference uses 59 clusters and a student reference distribution with 58 degrees of freedom. The balanced specification uses 47 clusters and 46 degrees of freedom. Tests are two sided, and confidence intervals use a 95 percent confidence level. This implementation follows the clustered inference considerations discussed by Cameron and Miller in 2015 and Abadie et al. in 2023. It does not correct coefficient bias or accommodate every possible pattern of dependence across economies.

H1 is evaluated through the sign of the income coefficient and whether its confidence interval excludes zero. The growth and trade research questions are evaluated through estimated direction, magnitude, and uncertainty. Intervals containing zero are treated as imprecise evidence rather than proof that a relationship is absent.

4.4 Sensitivity Analysis, Validation, and Reproducibility:

Validation focuses on procedures implemented for the observed panel: identifier uniqueness, reconciliation between source and analysis records, accounting for missing observations, variable domain checks, and full rank verification of each regression design matrix. These checks establish internal consistency and numerical identification without independently validating the underlying national estimates. Four exploratory sensitivity specifications examine consequential modelling choices. First, income enters in constant US dollar levels to assess dependence on logarithmic scaling. Second, economy specific linear

trends are added to examine sensitivity to different underlying trajectories. Calendar time is centred on 2010 and interacted with 58 economy indicators. A separate common linear trend is unnecessary because complete year effects already absorb it. This specification contains 133 identifiable parameters. Third, the two recorded zero trade observations are excluded to assess their influence without replacing their source values. Fourth, estimation is restricted to the 47 economies observed throughout all fourteen years. The income scaling and trend specifications retain the baseline sample of 754 observations. Excluding recorded zero trade values leaves 752 observations, while the balanced panel contains 658 observations.

Sensitivity assessment compares coefficient direction, substantive magnitude, and confidence intervals rather than relying solely on repeated statistical significance. The balanced restriction changes the represented economies as well as panel completeness, so differences cannot be attributed exclusively to improved longitudinal coverage. These checks were added during the analytical audit and are exploratory. The baseline specification and complete observation rule were documented in the workbook before regression estimation. The accompanying ART reproducibility 2010-2023.py reads the supplied workbook, reconstructs the restricted sample, checks measurement domains, reports missingness, and estimates every reported specification. It produces machine readable summaries containing sample counts, coefficients, clustered standard errors, and probability values. The computations are deterministic and require no random seed. Preserving this executable connection between observations and estimates follows Sandve et al. in 2013. The methodological contribution is the consistent application of established panel procedures to the research question, rather than a new estimator or causal identification strategy.

5. Findings:

This analysis examines whether income level, economic growth, and trade openness are associated with antiretroviral therapy coverage. The findings distinguish the proposed income relationship from the exploratory questions concerning growth and trade. Baseline estimates and sensitivity comparisons establish the strength, magnitude, and limits of the observed relationships. The estimation sample contains 754 annual observations across 59 economies from 2010 through 2023. These observations represent 74.80 percent of the eligible frame. Missing values exclude 254 observations and leave thirteen eligible economies without complete records. Forty-seven retained economies contribute all fourteen years, while twelve contribute fewer observations. The estimates therefore describe the observed sample rather than every resource constrained economy. Treatment coverage averages 41.35 percent, with a standard deviation of 24.11 percentage points and a median of 37.50 percent. The middle half of observations lies between 21 and 61 percent, indicating substantial variation in treatment access. Real GDP per capita averages 1,632.76 constant US dollars, compared with a median of 1,256.28, revealing an asymmetric income distribution. Annual economic growth averages 3.40 percent, while trade averages 67.24 percent of GDP. These distributions distinguish persistent differences in economic resources from annual fluctuations in output and international exchange. Table 5 presents the baseline estimates. All predictors enter simultaneously, alongside economy and year fixed effects. Standard errors are clustered across 59 economies, and confidence intervals use the corresponding finite sample adjustment. This inference procedure accommodates dependence within economies, following the considerations discussed by Cameron and Miller in 2015. It does not establish independence across economies.

Table 5: Economic conditions and antiretroviral therapy coverage

Predictor	Coefficient	Clustered Standard Error	Lower 95 Percent Confidence Limit	Upper 95 Percent Confidence Limit	p Value
Logarithmic real GDP per capita	14.586	4.061	6.457	22.715	< 0.001
Annual real GDP growth	−0.074	0.064	−0.203	0.055	0.255
Trade as a percentage of GDP	−0.033	0.040	−0.112	0.047	0.417

The outcome is treatment coverage measured in percentage points. The model includes 754 observations, 59 economy effects, and fourteen observation years. Growth and trade remain on their published percentage scales. Estimates give equal weight to retained observations. Source: calculations from the supplied World Development Indicators dataset. Income level shows a positive conditional association with treatment coverage. The coefficient of 14.586 implies that a 10 percent increase in real GDP per capita is associated with 1.39 percentage points higher coverage. The corresponding 95 percent confidence interval extends from 0.62 to 2.17 percentage points. The interval excludes zero and supports H1 under the associational specification. The magnitude is relevant to treatment access, although it does not imply that an equivalent income increase would generate the same coverage change through intervention.

This income result is consistent with the resource requirements of sustained treatment delivery documented by Galárraga et al. in 2011. The estimates nevertheless identify an association with national economic resources, not a measured financing pathway. They do not establish whether additional resources reached treatment programmes, providers, or patients. Annual economic growth does not display a statistically distinguishable association with coverage in the baseline model. Its coefficient is −0.074, with a confidence interval spanning negative and positive values. A one percentage point increase in annual growth corresponds to an estimated reduction of 0.074 percentage points in coverage, but the plausible interval ranges from a reduction of 0.203 to an increase of 0.055 percentage points. RQ1 therefore yields an imprecise conditional relationship rather than evidence that economic growth reduces coverage or has no association with it. The contrast between income and growth is substantively important. A higher level of economic resources is associated with wider treatment coverage, whereas faster output expansion within a particular year does not show the same statistical pattern. This distinction is consistent with the systems perspective developed by Bigdeli et al. in 2013, which separates available resources from the institutional processes required to translate them into access. The dataset does not measure those processes directly.

Trade openness also has an imprecisely estimated negative coefficient. A ten-percentage point increase in trade relative to GDP corresponds to 0.33 percentage points lower coverage, with a 95 percent confidence interval ranging from 1.12 percentage points lower to 0.47 percentage points higher. RQ2 consequently provides no precise evidence of either a positive or a negative conditional relationship. This finding concerns aggregate trade rather than international access to antiretroviral medicines. Waning et al. in 2010 document the importance of generic manufacturers in international antiretroviral supply, but the trade indicator used

here includes unrelated goods and services. The estimate therefore cannot resolve whether pharmaceutical imports, supplier competition, or medicine procurement influence treatment coverage. Table 6 reports exploratory sensitivity analyses. Each addresses a distinct feature of the baseline: income scaling, economy specific trends, recorded zero trade values, or incomplete longitudinal coverage. These checks were conducted after specifying the baseline and are not presented as prespecified confirmatory tests.

Table 6: Sensitivity of the income association

Specification	Observations	Economies	Income Coefficient	Lower 95 Percent Confidence Limit	Upper 95 Percent Confidence Limit	p Value
Income measured in constant US dollar levels	754	59	0.005279	0.001250	0.009308	0.011
Additional economy specific linear trends	754	59	12.429	2.322	22.536	0.017
Recorded zero trade values excluded	752	59	14.035	5.593	22.477	0.002
Balanced panel	658	47	17.842	7.525	28.159	0.001

All specifications retain growth, trade, economy effects, and year effects. Income is logarithmic except in the first row. Confidence intervals use standard errors clustered by economy. The balanced panel contains fourteen observations per economy. Source: calculations from the supplied dataset. The positive income association persists when income enters in levels. Under that specification, an additional 100 constant US dollars per person corresponds to 0.53 percentage points higher coverage, with a confidence interval from 0.13 to 0.93 percentage points. Because this specification imposes a constant association per dollar rather than per proportional income change, its coefficient is not directly comparable with the logarithmic coefficient. Adding economy specific linear trends reduces the logarithmic income coefficient from 14.586 to 12.429 and widens its confidence interval. A 10 percent income increase then corresponds to 1.18 percentage points higher coverage, with a confidence interval from 0.22 to 2.15 percentage points. The positive association remains, but its lower confidence limit moves closer to zero. The evidence therefore supports persistence of the direction while indicating sensitivity in precision.

Excluding the two recorded zero trade values produce an income coefficient close to the baseline. Restricting estimation to the balanced panel increases the coefficient to 17.842, equivalent to 1.70 percentage points higher coverage for a 10 percent income increase. Its confidence interval extends from 0.72 to 2.68 percentage points. The larger estimate indicates that panel composition affects magnitude, even though the direction remains positive. The balanced restriction changes the represented economies and does not correct missingness in excluded economies. Growth and trade remain imprecisely estimated across all four sensitivity specifications. Growth coefficients range from −0.120 to −0.053, while trade coefficients range from −0.041 to −0.024. Every corresponding 95 percent confidence interval includes zero. This consistency limits evidence for a precisely estimated contemporaneous relationship; it does not establish that either association is absent. Taken together, the findings support H1 as a positive conditional income association and answer both exploratory research questions with estimates that remain uncertain around zero. The income result persists across the implemented specifications, although its magnitude and precision depend on trend adjustment and sample composition. Consistent with the identification cautions developed by Imai and Kim in 2021, fixed effects and sensitivity checks do not establish a causal relationship. The empirical contribution is the distinction between income levels, annual growth, and aggregate trade in their observed associations with treatment coverage.

6. Discussion:

Economic prosperity and annual economic expansion carry different implications for treatment access. Table 5 and Equation 2 identify a positive association between income level and antiretroviral therapy coverage after accounting for growth, trade, economy effects, and common annual influences. A 10 percent increase in real GDP per capita corresponds to approximately 1.39 percentage points higher coverage. This finding distinguishes the level of available economic resources from contemporaneous economic activity rather than treating both as interchangeable indicators of development. Resch et al. in 2015 examine domestic HIV financing capacity through economic conditions and spending priorities. The present analysis adds an observed coverage relationship across 59 economies, extending the discussion from potential financing capacity to treatment access. Its contribution lies in separating economic dimensions within a common specification, without interpreting their coefficients as causal effects. The distinction between income and coverage also sharpens the theoretical meaning of resource availability. Equation 2 measures national income directly but does not measure how resources move through health budgets, procurement systems, or service delivery. Consequently, the positive coefficient in Table 5 supports a resource related interpretation without identifying a transmission pathway. Kutzin in 2013 distinguishes health financing arrangements from the coverage outcomes they are intended to achieve, emphasizing that resource mobilization alone does not define system performance. Read through this distinction, the findings indicate that national economic resources contain information about treatment coverage while leaving their allocation outside the estimated relationship. This refines the conceptual framework by preserving the difference between an economic condition and an operational mechanism, avoiding the assumption that higher income represents effective financing or service provision.

The sensitivity results strengthen the income interpretation while qualifying its precision. Table 6 shows that the positive association persists after adding economy specific linear trends to Equation 2, although the confidence interval widens. The relationship therefore cannot be attributed entirely to the particular linear trajectories represented by that specification. Its persistence when income enters in levels also indicates that the baseline result does not depend exclusively on logarithmic scaling. Remme et al. in 2016 distinguish potential domestic financing from resources that countries can mobilize through observed fiscal responses. The present estimates make a complementary distinction between income levels and annual output growth in their relationships with coverage. Together, these distinctions caution against assuming that faster economic growth automatically

translates into contemporaneous treatment expansion. The theoretical advance concerns the separation of resource levels, economic change, and observed access, rather than the dominance of an identified financing channel. Panel composition changes the estimated magnitude and therefore matters to international interpretation. The larger income coefficient in the balanced specification in Table 6 shows that economies with continuous data contribute a different estimate from the broader unbalanced sample used in Equation 2. Excluding the two recorded zero trade values produce a result closer to the baseline, suggesting that these particular entries do not account for the positive income association. These comparisons identify where the evidence is sensitive without establishing that either sample is representative of all resource constrained economies. Bartlett et al. in 2014 show that inference from complete observations depends on the missingness process and its relationship with the variables being analysed. The resulting insight is substantive as well as methodological: the international income association remains positive across the implemented samples, but its size should not be treated as a universal benchmark for economies with different reporting coverage.

International evidence also clarifies why economic capacity should inform treatment planning without determining it. Bendavid et al. in 2012 connect HIV development assistance with adult mortality patterns across African settings, while Bor et al. in 2013 document gains in adult life expectancy alongside treatment expansion in rural South Africa. Those analyses examine programme exposure and population health outcomes; Table 5 instead identifies an economic association with treatment coverage across multiple economies. The distinction matters because neither national income nor coverage alone establishes programme effectiveness or survival gains. Equation 2 and the sensitivity comparisons in Table 6 support using income levels as contextual information when comparing treatment access, while providing no basis for substituting annual growth or aggregate trade for direct coverage monitoring. Decision makers should therefore assess treatment coverage alongside economic resources rather than infer access from macroeconomic performance. The broader contribution is a framework that separates economic capacity, observed treatment access, and programme outcomes instead of collapsing them into a single development relationship.

7. Conclusion and Implications:

Economic progress cannot substitute for evidence that essential treatment reaches those who need it. Across resource constrained economies, the analysis distinguishes a positive relationship between sustained economic resources and treatment access from the less precisely estimated relationships associated with annual expansion and international exchange. Its contribution is an empirical separation of economic dimensions that should not be treated as interchangeable signals of health system performance. The findings refine resource-based explanations by showing that aggregate economic conditions provide different information about coverage, while leaving their institutional transmission pathways unestablished. For decision makers, this distinction supports comparing treatment performance against economic capacity rather than assuming that favourable macroeconomic developments translate into wider access. Programme managers should combine economic assessments with direct coverage monitoring when reviewing expansion plans and allocating operational attention. Financing authorities and international partners should likewise avoid inferring reduced treatment support needs solely from improving national economic indicators. The evidence supports assessing economic capacity alongside treatment access when reviewing financing commitments. Operationally, consistent reporting and explicit missing data checks can improve the evidence available for these assessments. The broader social implication is that economic advancement and access to essential care require separate evaluation, preserving attention to populations whose treatment needs remain insufficiently served.

The unbalanced panel creates opportunities to examine how reporting coverage shapes international comparisons. Extending data availability to excluded economies would strengthen assessment of transferability. National aggregates could be complemented with programme expenditure, procurement costs, service capacity, and household access measures to test the pathways linking economic resources to treatment provision. Designs exploiting plausibly external changes in financing or eligibility could strengthen causal identification. Comparative analyses across institutional settings could assess whether the observed association varies with financing arrangements or delivery systems. These extensions would distinguish economic capacity from its conversion into sustained and effective treatment access.

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