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# Nonlinear Monetary-Policy Transmission in Economies with Mobile Money, Informal Credit and Exchange-Rate Pass-Through

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A R T I C L E   I N F O

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A B S T R A C T

This study develops a nonlinear framework for monetary-policy transmission when mobile-money platforms, informal credit and exchange-rate pass-through coexist. Mobile-money intensity and informal-credit dependence enter the transmission coefficient and threshold states of a Bayesian vector autoregression. State-dependent local projections, a nonlinear autoregressive distributed-lag model and time-varying parameters estimate activity, credit and inflation responses. The analysis establishes regime uniqueness, uniform mean-square boundedness, a critical mobile-intensity condition, aggregate-credit substitution, long-run pass-through asymmetry and posterior propriety. A reproducible 240-month Monte Carlo calibration is used because a harmonised observed dataset was not supplied; the results validate the method rather than estimate realised country effects. High mobile-money intensity with low informal-credit dependence yields the strongest impact contraction, while informal-credit substitution attenuates it. Depreciation pass-through exceeds appreciation pass-through at short horizons. Digital finance therefore strengthens monetary control only when it complements regulated deposits and formal lending.



## 1. Introduction

The transmission of monetary policy is rarely invariant to the structure through which households and firms save, borrow and settle transactions. In economies where bank intermediation coexists with mobile-money platforms and informal credit, a change in the policy rate may reach borrowers through several reinforcing or offsetting paths. Bank lending rates can adjust, mobile wallets can move balances between cash and regulated accounts, informal lenders can replace constrained formal credit, and exchange-rate changes can pass through rapidly to fuel, transport and food prices. A linear vector autoregression that averages these states can consequently report a small response even when policy is powerful in one state and nearly neutral in another.

This problem is particularly important for small open economies. Namibia maintains a one-to-one currency arrangement between the Namibia dollar and the South African rand, while the domestic policy framework aims at price stability and protection of the peg (Bank of Namibia, n.d.). The exchange-rate channel is therefore not a freely floating-price mechanism, but external currency movements, imported fuel costs and regional financial conditions still enter domestic inflation. At the same time, mobile and electronic payment activity can broaden the transactional perimeter of regulated finance without eliminating cash-based and relationship-based lending. The relevant policy question is not simply whether monetary policy "works", but when it works, through which balance sheets, and with what distribution between formal and informal finance.

Evidence for emerging and developing economies shows that output generally declines after an identified policy tightening once exchange-rate behaviour is modelled appropriately (Brandao-Marques et al., 2020). Recent evidence also indicates that electronic money can complement banks, expand deposits and credit, and strengthen interest-rate pass-through, especially where initial financial inclusion is limited (Huang et al., 2024). These findings do not settle the nonlinear interaction. If mobile money deepens regulated deposits, it can strengthen the bank channel; if it allows rapid substitution away from deposits or is weakly connected to bank intermediation, it may attenuate that channel. Informal lenders create a second ambiguity: they cushion spending when bank credit contracts, but their high and sticky financing costs can also preserve inflationary pressure.

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This article develops a state-dependent framework in which mobile-money intensity, informal-credit dependence and exchange-rate depreciation jointly determine the propagation of a monetary-policy shock. Four estimators are integrated rather than treated as competing exercises: a Bayesian threshold vector autoregression (BTVAR) describes regime-specific multivariate dynamics; state-dependent local projections estimate horizon-by-horizon responses; a nonlinear autoregressive distributed-lag (NARDL) model separates depreciation from appreciation; and a time-varying parameter representation tracks gradual change. The mathematical analysis establishes stability, regime uniqueness, monotonicity, substitution and pass-through results before numerical estimation.

The study has four objectives: (i) to formalise a nonlinear transmission coefficient that depends on mobile-money intensity and informal-credit dependence; (ii) to establish sufficient conditions for stability and sign-identification in a piecewise-linear monetary system; (iii) to compare state-dependent responses of output, formal credit, informal credit and inflation; and (iv) to provide a reproducible protocol for implementation with official monthly data. Because a complete harmonised micro–macro dataset was not supplied with the study request, the reported numerical findings come from a transparent, seeded Monte Carlo calibration of 240 monthly observations. They are methodological validation results, not claims about realised Namibian parameters. This distinction prevents simulated precision from being represented as observed evidence and makes the manuscript suitable for subsequent replacement of the calibration panel with verified official series.

The central contribution is a unified theorem-to-estimation bridge. The model shows analytically that mobile money strengthens policy transmission only when its deposit-complementarity effect exceeds the substitution created by informal finance. It also shows that exchange-rate pass-through is state dependent even if the underlying price equation is locally linear within each regime. The resulting framework explains why a single full-sample impulse response can be an unreliable policy summary.

## 2. Literature Review

### 2.1 Monetary transmission in financially segmented economies

The conventional transmission mechanism operates through market interest rates, bank lending, asset prices, expectations and the exchange rate. Bernanke and Gertler (1995) emphasise that balance-sheet and bank-lending conditions amplify changes in the policy rate. In low-income and developing economies, however, shallow securities markets, excess liquidity, limited competition, fiscal dominance and informality can interrupt the sequence from the policy instrument to lending conditions and aggregate demand (Mishra & Montiel, 2013). Loan-level evidence confirms that bank lending reacts to monetary shocks in developing countries and that the response has real firm-level consequences (Abuka et al., 2019). Brandao-Marques et al. (2020) demonstrate that weak estimated transmission is partly a modelling problem: once the contemporaneous exchange-rate response is incorporated, contractionary shocks produce more theoretically coherent output and price responses. This adjustment also addresses the price-puzzle problem identified in structural time-series analysis (Sims, 1992).

Informal credit changes the relevant aggregation. Carpenter (1999) models financial dualism and finds that informal credit is not merely measurement error around bank credit; it is a distinct market that responds to monetary conditions. When a formal lender tightens quantity or price terms, households and small firms may substitute towards rotating savings groups, supplier credit, family loans or moneylenders. This substitution can stabilise activity while shifting the cost and risk of borrowing. The aggregate credit channel is therefore the weighted sum of a formal contraction and an informal offset, not the formal response alone.

### 2.2 Mobile money and the banking channel

Mobile money reduces transaction costs, expands geographic access and creates high-frequency records of payments. Aron (2018) documents its broad development effects while stressing institutional heterogeneity. From a monetary perspective, the sign is theoretically ambiguous. A platform whose safeguarded balances are deposited in commercial banks can enlarge bank funding and improve contestability. A platform operating as a transactional substitute for bank deposits can instead reduce the sensitivity of bank funding to the policy rate. Huang et al. (2024) find, across monthly and annual panels, that e-money development is associated with stronger pass-through, higher bank deposits and credit, and smaller intermediation spreads. Their result motivates a complementarity prior, but it does not imply that complementarity holds in every country or state.

The present study differs by making the mobile-money effect conditional on informal-credit dependence. Digital inclusion and financial formalisation need not coincide. A merchant may receive electronic payments but finance inventory through supplier credit; a household may use a wallet for transfers while borrowing from an informal group. Accordingly, mobile intensity is modelled as a continuous state variable rather than a binary adoption indicator, while informal dependence enters both the policy coefficient and the credit-composition equation.

### 2.3 Exchange-rate pass-through and nonlinear inflation

Exchange-rate pass-through (ERPT) is often incomplete and asymmetric. Menu costs, strategic margins, imported-input shares, inflation expectations and the direction and size of currency movements can all affect pricing. Caselli and Roitman (2019) show that pass-through in emerging markets rises nonlinearly during large depreciations. A positive/negative decomposition is therefore more informative than a single exchange-rate coefficient. Fuel prices require separate control because exchange-rate depreciation and world energy prices can reinforce one another, producing omitted-variable bias if one is excluded.

### 2.4 Econometric approaches and unresolved gap

Threshold regression identifies discrete changes in slope when an observed transition variable crosses an unknown boundary (Hansen, 2000). Local projections estimate impulse responses directly and are robust to misspecification of the full dynamic system (Jordà, 2005). NARDL models estimate separate short- and long-run effects of positive and negative changes while allowing cointegration (Pesaran et al., 2001; Shin et al., 2014). Time-varying parameter models allow transmission to drift as institutions and behaviour evolve (Primiceri, 2005). Each method solves a different problem.

The unresolved gap is their integration around the joint economic states of digital transactions, informal finance and imported-price pressure. Existing work typically studies financial inclusion, e-money, informal credit or ERPT separately. It therefore cannot identify whether a strong mobile-money state is also a weak transmission state because informal substitution is high, or whether an apparent price puzzle is actually depreciation pass-through. The purpose of this study is to close that gap with a mathematically coherent, empirically replicable state-dependent system.

## 3. Methods

### 3.1 Study design, sample and reproducibility

The design is a quantitative macroeconometric simulation study. No human participants, clinical subjects or survey respondents were recruited; consequently, participant consent, demographic selection and attrition criteria are not applicable. The estimation sample contains 240 monthly observations after a 60-month burn-in from a 300-month data-generating process. The random-number seed is 20260814. The sample size is sufficient to estimate parsimonious regime-specific first-order systems, while the smallest realised regime is explicitly treated as a precision limitation.

For empirical replacement, the proposed inclusion window is January 2006 to December 2025, subject to common data availability. A month is included if the policy rate, consumer-price index, nominal effective exchange rate, private-sector credit, fuel-price index and activity proxy are observed. Mobile transactions should be converted to real per-adult values, while informal-credit dependence should be obtained from repeated household or enterprise finance surveys and interpolated only between verified survey waves. Series with more than three consecutive missing months should not be mechanically interpolated. Monetary amounts are deflated; trending positive series enter logarithms; and rate variables enter percentage points.

### 3.2 State variables and transmission coefficient

Let $m_t \in [0,1]$ denote mobile-money intensity, $f_t \in [0,1]$ informal-credit dependence, $d_t = \Delta \log E_t$ nominal depreciation, $u_t$ an identified contractionary policy shock and $y_t$ an activity gap. Define the effective demand-channel coefficient by

$$\kappa(m_t, f_t) = \kappa_0 + \kappa_m m_t - \kappa_f f_t - \kappa_{mf} m_t f_t, \qquad \kappa_0, \kappa_m, \kappa_f \geq 0. \tag{1}$$

The term $\kappa_m$ captures deposit complementarity and lower payment frictions. The terms $\kappa_f$ and $\kappa_{mf}$ capture direct and interaction-based leakage into informal finance. A positive $\kappa$ means that a contractionary shock reduces activity.

The financial block is

$$c_t^F = \rho_F c_{t-1}^F - \{b_0 + b_m m_t\} u_t + \varepsilon_t^F, \qquad b_0, b_m > 0, \tag{2}$$

$$c_t^I = \rho_I c_{t-1}^I + s_f f_t u_t + \varepsilon_t^I, \qquad s_f \geq 0, \tag{3}$$

where $c_t^F$ and $c_t^I$ are formal- and informal-credit growth. Aggregate activity evolves as

$$y_t = \rho_y y_{t-1} - \kappa(m_t, f_t) u_t + \omega_F c_t^F + \omega_I c_t^I - \omega_p p_t^o + \varepsilon_t^y, \tag{4}$$

with fuel-price inflation $p_t^o$. Inflation obeys

$$\pi_t = \rho_\pi \pi_{t-1} + \lambda y_t + \theta_+ d_t^+ + \theta_- d_t^- + \phi p_t^o + \delta u_t + \varepsilon_t^\pi, \tag{5}$$

where $d_t^+ = \max(d_t, 0)$ and $d_t^- = \min(d_t, 0)$. Under asymmetric ERPT, $\theta_+ > \theta_- \geq 0$.

### 3.3 Threshold vector representation

Define the endogenous vector $\mathbf{x}_t = (\pi_t, y_t, c_t^F, c_t^I)'$ and transition vector $\mathbf{q}_t = (m_t, f_t, d_t)'$. For thresholds $\tau_m, \tau_f$ and $\tau_d$, the regime index is

$$S_t = g(\mathbf{q}_t) = 1 + \mathbb{1}(m_t > \tau_m) + 2\mathbb{1}(f_t > \tau_f) + 4\mathbb{1}(d_t > \tau_d). \tag{6}$$

The BTVAR of order $p$ is

$$\mathbf{x}_t = \mathbf{a}_{S_t} + \textstyle\sum_{j=1}^{p} \mathbf{A}_{j,S_t} \mathbf{x}_{t-j} + \mathbf{B}_{S_t} u_t + \mathbf{G}_{S_t} \mathbf{w}_t + \boldsymbol{\varepsilon}_{t,S_t}, \quad \boldsymbol{\varepsilon}_{t,S_t} \sim N(\mathbf{0}, \boldsymbol{\Sigma}_{S_t}), \tag{7}$$

where $\mathbf{w}_t$ includes fuel inflation and predetermined controls. In the numerical illustration, $\tau_m = 0.50, \tau_f = 0.35$ and $\tau_d = 0$. Regimes with fewer than 30 observations are not interpreted as stable empirical states.

**Lemma 1**. Almost-sure uniqueness of threshold assignment

Suppose the transition vector $\mathbf{q}_t$ has an absolutely continuous distribution. Then $S_t$ in (6) is uniquely defined with probability one.

**Proof.** Non-uniqueness can occur only if at least one component equals its threshold. Absolute continuity implies $\Pr(m_t = \tau_m) = \Pr(f_t = \tau_f) = \Pr(d_t = \tau_d) = 0$. A finite union of probability-zero events has probability zero. Therefore exactly one regime contains the observation almost surely. ▫

Theorem 1. Uniform stability of the threshold system

Write (7) in companion form $\mathbf{z}_t = \mathbf{C}_{S_t}\mathbf{z}_{t-1} + \mathbf{h}_t$. If there exists a matrix norm and a constant $0 < \varrho < 1$ such that $\| \mathbf{C}_s \| \leq \varrho$ for every admissible regime $s$, and $\sup_t E \| \mathbf{h}_t \|^2 < \infty$, then the threshold process has a unique causal mean-square bounded solution conditional on the exogenous state path, and

$$\sup_t E \| \mathbf{z}_t \|^2 \leq \frac{K}{(1-\varrho)^2} \sup_t E \| \mathbf{h}_t \|^2 \tag{8}$$

for a finite norm-equivalence constant $K$.

**Proof.** Iteration gives $\mathbf{z}_t = \mathbf{C}_{S_t} \cdots \mathbf{C}_{S_{t-j+1}}\mathbf{z}_{t-j} + \sum_{\ell=0}^{j-1} \mathbf{C}_{S_t} \cdots \mathbf{C}_{S_{t-\ell+1}}\mathbf{h}_{t-\ell}$. The product norm is at most $\varrho^j$, so the initial-condition term converges to zero. The remaining random series converges in mean square because $\sum_{\ell \geq 0} \varrho^\ell < \infty$. Any two causal solutions differ by a product bounded by $\varrho^j$ and must coincide. Applying Minkowski's inequality and norm equivalence yields (8). If $(S_t, \mathbf{h}_t)$ is additionally strictly stationary and ergodic, the causal measurable solution inherits those properties. ▫

Corollary 1. Stability under arbitrary regime switching

If the sufficient norm bound in Theorem 1 holds, no restriction on the frequency or order of regime transitions is required for stability.

**Proof.** The contraction bound applies to every finite product of admissible companion matrices, irrespective of its ordering. ▫

Proposition 1. Mobile-money transmission threshold

Let the total impact coefficient be $\mathcal{D}(m_t, f_t) = \kappa(m_t, f_t) + \omega_F(b_0 + b_m m_t) - \omega_I s_f f_t$. For fixed $f_t$, a contractionary policy shock reduces activity on impact if and only if $\mathcal{D}(m_t, f_t) > 0$. Equivalently,

$$m_t > m^*(f_t) = \frac{(\kappa_f + \omega_I s_f) f_t - \kappa_0 - \omega_F b_0}{\kappa_m + \omega_F b_m - \kappa_{mf} f_t}, \qquad \kappa_m + \omega_F b_m > \kappa_{mf} f_t. \tag{9}$$

**Proof.** Equations (2)–(4) imply $\partial y_t / \partial u_t = -\mathcal{D}(m_t, f_t)$. The impact is negative precisely when $\mathcal{D}(m_t, f_t) > 0$. Collecting the terms multiplying $m_t$ and solving the resulting linear inequality gives (9) under the stated positive-denominator condition. ▫

Corollary 2. Informal-finance attenuation

If $\kappa_f + \kappa_{mf} m_t + \omega_I s_f > 0$, then $\partial \mathcal{D}(m_t, f_t) / \partial f_t < 0$; hence greater informal-credit dependence weakens the total contractionary effect.

**Proof.** Direct differentiation gives $\partial \mathcal{D}(m_t, f_t) / \partial f_t = -(\kappa_f + \kappa_{mf} m_t + \omega_I s_f) < 0$. ▫

Proposition 2. Aggregate-credit substitution condition

Let aggregate credit be $c_t = \nu c_t^F + (1-\nu) c_t^I$, $0 < \nu < 1$. Its impact response to a contractionary shock is negative if and only if

$$\nu(b_0 + b_m m_t) > (1-\nu) s_f f_t. \tag{10}$$

**Proof.** Differentiate (2)–(3) with respect to $u_t$ and form the weighted sum. The formal response equals $-\nu(b_0 + b_m m_t)$ and the informal response equals $(1-\nu) s_f f_t$. Their sum is negative exactly under (10). ▫

Theorem 2. Monotone strengthening through regulated digital complementarity

Assume $\omega_F b_m > 0$, $\kappa_m > 0$, and $\kappa_{mf} = 0$. Holding informal dependence fixed, the absolute impact response of activity to a contractionary shock is increasing in mobile-money intensity whenever

$$\kappa_m + \omega_F b_m > 0. \tag{11}$$

**Proof.** Substituting the impact response of formal credit from (2) into (4) yields $\partial y_t / \partial u_t = -\kappa_0 - \kappa_m m_t + \kappa_f f_t - \omega_F(b_0 + b_m m_t) + \omega_I s_f f_t$. Differentiating with respect to $m_t$ gives $-(\kappa_m + \omega_F b_m) < 0$. Thus the response becomes more negative, and its absolute value increases, as mobile intensity rises. ▫

Corollary 3. Possibility of digital attenuation

For fixed $f_t$, if digital balances substitute for interest-sensitive bank deposits strongly enough that $\kappa_m + \omega_F b_m - \kappa_{mf} f_t < 0$, mobile-money growth weakens the absolute contractionary impact whenever $\mathcal{D}(m_t, f_t) > 0$. The effect is therefore an estimable institutional parameter, not a definitional property of digitalisation.

**Proof.** Since $\partial \mathcal{D}(m_t, f_t) / \partial m_t = \kappa_m + \omega_F b_m - \kappa_{mf} f_t$, the stated inequality makes the positive impact coefficient $\mathcal{D}$ decline with mobile-money intensity. Because $\partial y_t / \partial u_t = -\mathcal{D}$, its contractionary absolute value declines. ▫

### 3.4 State-dependent local projections

For outcome $z_t \in \{y_t, \pi_t, c_t^F, c_t^I\}$ and horizon $h = 0, \dots, H$, the local projection is

$$z_{t+h} - z_{t-1} = \alpha_h + \beta_h u_t + \gamma_h u_t m_t + \psi_h u_t f_t + \xi_h u_t \mathbb{1}(d_t > 0) + \mathbf{\Gamma}_h{}' \mathbf{r}_{t-1} + e_{t+h}, \tag{12}$$

where $\mathbf{r}_{t-1}$ contains lags of activity, inflation, depreciation and fuel inflation. Newey–West covariance estimates use $h+1$ lags. The state-specific response at $(m, f, d)$ is

$$IRF_h(m, f, d) = \beta_h + \gamma_h m + \psi_h f + \xi_h \mathbb{1}(d > 0). \tag{13}$$

Proposition 3. Local-projection recovery of the conditional impulse response

If $E(u_t e_{t+h} \mid \mathcal{F}_{t-1}, \mathbf{q}_t) = 0$ and the conditional mean is linear in the interactions in (12), then the population coefficient combination in (13) equals the conditional response of $z_{t+h} - z_{t-1}$ to a unit policy innovation.

**Proof.** Orthogonality makes the population least-squares projection of the horizon-specific change on the shock and its state interactions equal to the conditional linear projection. Differentiation of that conditional mean with respect to $u_t$ yields (13). ▫

Lemma 2. Equivalence with a correctly specified linear moving-average system

Within a fixed regime, if (7) is stable and correctly specified, the population local-projection response equals the corresponding moving-average coefficient from the VAR.

**Proof.** Stability implies the Wold representation $\mathbf{x}_{t+h} = \sum_{j\geq 0} \mathbf{\Psi}_{j,s}\, \boldsymbol{\varepsilon}_{t+h-j}$. Projection on the identified innovation at time $t$ selects $\mathbf{\Psi}_{h,s}$ by orthogonality. ▫

3.5 NARDL exchange-rate pass-through

Define partial sums

$$D_t^+ = \sum_{j=1}^{t} \max\left(\Delta \log E_j, 0\right), \qquad D_t^- = \sum_{j=1}^{t} \min\left(\Delta \log E_j, 0\right). \tag{14}$$

The inflation error-correction model is

$$\Delta\pi_t = \alpha + \varphi \pi_{t-1} + \vartheta_+ D_{t-1}^+ + \vartheta_- D_{t-1}^- + \sum_{j=1}^{p-1} \rho_j\, \Delta\pi_{t-j} + \sum_{j=0}^{q-1}\left(\eta_j^+ \Delta D_{t-j}^+ + \eta_j^- \Delta D_{t-j}^-\right) + \mathbf{c}'\mathbf{v}_t + \epsilon_t. \tag{15}$$

The long-run pass-through coefficients are $L^+ = -\vartheta_+/\varphi$ and $L^- = -\vartheta_-/\varphi$ when $\varphi < 0$.

Theorem 3. Long-run asymmetry

Assume the error-correction model is stable with $\varphi < 0$. Long-run ERPT is asymmetric if and only if $\vartheta_+ \neq \vartheta_-$. Moreover,

$$L^+ - L^- = -\frac{\vartheta_+ - \vartheta_-}{\varphi}. \tag{16}$$

**Proof.** At long-run equilibrium all first differences vanish. Solving (15) once for a permanent positive component and once for a permanent negative component gives the two multipliers. Their difference is (16); because $\varphi \neq 0$, it is zero exactly when $\vartheta_+ = \vartheta_-$. ▫

Proposition 4. Depreciation-dominant pass-through

If firms adjust prices upward more rapidly than downward so that $\theta_+ > \theta_- \geq 0$ in (5), then the impact inflation response to a one-unit depreciation exceeds the absolute impact response to a one-unit appreciation by $\theta_+ - \theta_- > 0$.

**Proof.** In (5), a one-unit depreciation has $d_t^+ = 1$ and $d_t^- = 0$, giving the direct impact $\theta_+$. A one-unit appreciation has $d_t^+ = 0$ and $d_t^- = -1$, giving the direct impact $-\theta_-$ and absolute magnitude $\theta_-$. Their magnitude difference is therefore $\theta_+ - \theta_- > 0$. ▫

3.6 Time-varying parameters and Bayesian estimation

The gradual-change specification is

$$\mathbf{x}_t = \mathbf{Z}_t \boldsymbol{\beta}_t + \boldsymbol{\varepsilon}_t, \qquad \boldsymbol{\beta}_t = \boldsymbol{\beta}_{t-1} + \boldsymbol{\eta}_t, \quad \boldsymbol{\eta}_t \sim N(\mathbf{0}, \mathbf{Q}). \tag{17}$$

Regime-specific BTVAR equations use normal–inverse-gamma priors. For a generic equation $\mathbf{y} = \mathbf{X}\boldsymbol{\beta} + \boldsymbol{\epsilon}$,

$$\boldsymbol{\beta} \mid \sigma^2 \sim N(\mathbf{b}_0, \sigma^2 \mathbf{V}_0), \qquad \sigma^2 \sim IG(a_0, b_0^\sigma). \tag{18}$$

Writing $n$ for the number of observations, the posterior hyperparameters follow from

$$\begin{aligned} \mathbf{V}_1 &= (\mathbf{V}_0^{-1} + \mathbf{X}'\mathbf{X})^{-1}, & \mathbf{b}_1 &= \mathbf{V}_1(\mathbf{V}_0^{-1}\mathbf{b}_0 + \mathbf{X}'\mathbf{y}), \\ a_1 &= a_0 + n/2, & b_1^\sigma &= b_0^\sigma + 1/2\,(\mathbf{y}'\mathbf{y} + \mathbf{b}_0{}'\mathbf{V}_0^{-1}\mathbf{b}_0 - \mathbf{b}_1{}'\mathbf{V}_1^{-1}\mathbf{b}_1). \end{aligned} \tag{19}$$

Thus $\boldsymbol{\beta} \mid \sigma^2, \mathbf{y} \sim N(\mathbf{b}_1, \sigma^2 \mathbf{V}_1)$ and $\sigma^2 \mid \mathbf{y} \sim IG(a_1, b_1^\sigma)$.

Theorem 4. Posterior propriety

If $\mathbf{V}_0$ is positive definite and $a_0, b_0^\sigma > 0$, then the posterior defined by (18)–(19) is proper for any finite sample, including a regime-specific design matrix that is not of full column rank.

**Proof.** Positive definiteness of $\mathbf{V}_0$ implies $\mathbf{V}_0^{-1} + \mathbf{X}'\mathbf{X}$ is positive definite, so the conditional Gaussian posterior integrates to one. Positive inverse-gamma shape and scale parameters yield a finite normalising constant. Integrating the product gives a proper normal–inverse-gamma posterior. ▫

Proposition 5. Admissible sign normalisation

Suppose $u_t$ is orthogonal to contemporaneous non-policy structural innovations and a positive $u_t$ raises the policy rate. Imposing $\partial c_t^F / \partial u_t < 0$ and leaving the exchange-rate response unrestricted set-identifies an admissible contractionary policy shock without mechanically eliminating the exchange-rate channel, following the logic of sign-restricted identification (Uhlig, 2005). Point identification requires enough additional restrictions to select a unique structural rotation.

**Proof.** The policy-rate normalisation fixes scale and sign. Orthogonality and the formal-credit restriction exclude rotations inconsistent with a contractionary interpretation. More than one remaining rotation may satisfy these inequalities, so the identified object is generally a set. Because no sign is imposed on depreciation, exchange-rate amplification or offset remains estimable. ▫

### 3.7 Calibration and diagnostic protocol

The Monte Carlo design uses persistent but bounded mobile intensity and informal dependence. Mobile intensity follows a logistic diffusion from low to high adoption. Informal dependence is negatively related to mobile intensity but remains positive, allowing digital transactions without complete credit formalisation. Depreciation and fuel inflation follow stationary autoregressions. The policy innovation has standard deviation 0.22. Parameters satisfy Theorem 1's contraction condition in the simulated states.

Model validation comprises: lag selection by information criteria; stability-root checks within regimes; residual autocorrelation and heteroscedasticity tests; posterior predictive checks; threshold-grid sensitivity; alternative mobile-intensity denominators; alternative informal-credit proxies; exclusion of crisis months; and comparison of BTVAR, local-projection and time-varying responses. A result is treated as robust only if its sign and economically relevant magnitude persist across at least three specifications.

## 4. Results

The results are presented in the order required for statistical interpretation: sample composition and descriptive statistics precede regime-specific posterior and local-projection estimates. Every numerical value in this section is generated by the stated simulation and should be read as validation of the method's ability to recover designed nonlinearities.

**Table 1. Descriptive statistics for the 240-month calibration sample**

| Variable | Mean | Median | SD | Minimum | Maximum |
|---|---|---|---|---|---|
| Mobile-money intensity | 0.5404 | 0.5970 | 0.2206 | 0.1427 | 0.8363 |
| Informal-credit dependence | 0.4433 | 0.4370 | 0.0834 | 0.2967 | 0.6037 |
| Exchange-rate depreciation | 0.0995 | 0.0425 | 0.8201 | -2.0449 | 2.6186 |
| Fuel-price inflation | 0.0007 | -0.0590 | 0.7128 | -1.7000 | 1.8427 |
| Policy-rate gap | -0.0491 | -0.0426 | 0.4260 | -1.3138 | 0.9041 |
| Policy shock | -0.0067 | -0.0045 | 0.2262 | -0.7509 | 0.6129 |
| Output growth | 0.0028 | 0.0192 | 0.2585 | -0.7017 | 0.7716 |
| Inflation | 0.0829 | 0.0713 | 0.1933 | -0.4356 | 0.9039 |
| Formal-credit growth | 0.0330 | 0.0333 | 0.2208 | -0.4872 | 0.7617 |
| Informal-credit growth | 0.0076 | 0.0156 | 0.1475 | -0.3663 | 0.4621 |

*Source: Author's reproducible Monte Carlo calibration, seed 20260814. Values are dimensionless standardised units except the bounded intensity measures.*

Mobile-money intensity averages 0.5404 and ranges from 0.1427 to 0.8363. Informal-credit dependence averages 0.4433 and remains economically material throughout the sample. The inverse movement is incomplete: periods of high mobile intensity can coexist with high informal dependence. This is the configuration the model is designed to distinguish from simple financial inclusion.

The threshold classification produces 99 low-mobile/high-informal months, 102 high-mobile/high-informal months and 39 high-mobile/low-informal months. The low-mobile/low-informal state does not arise under the calibrated transition path. This absence is not repaired by inventing observations; instead, the state is excluded from the estimated comparison and retained only as a theoretical possibility.

**Table 2. State-dependent activity-gap responses to a contractionary policy shock**

| Regime | h = 0 | h = 3 | h = 6 | h = 12 |
|---|---|---|---|---|
| Low mobile/high informal | -0.1221<br>(0.0835) | -0.2482<br>(0.1106) | -0.1777<br>(0.1087) | -0.1411<br>(0.1163) |
| High mobile/high informal | -0.2198<br>(0.0590) | -0.2873<br>(0.0853) | -0.1815<br>(0.1036) | -0.0342<br>(0.0797) |

| Regime | h = 0 | h = 3 | h = 6 | h = 12 |
|---|---|---|---|---|
| High mobile/low informal | -0.3218<br>(0.0837) | -0.2275<br>(0.0909) | 0.0111<br>(0.1142) | 0.1957<br>(0.0664) |

*Source: Author's calculations. Parentheses contain heteroscedasticity- and autocorrelation-consistent standard errors; 90% intervals underlie Figure 1.*

The strongest impact contraction is estimated in the high-mobile/low-informal state: −0.3218 with a standard error of 0.0837. The high-mobile/high-informal impact is smaller in absolute value at −0.2198, while the low-mobile/high-informal state gives −0.1221 and is imprecise on impact. At three months, all observed states are negative, but attenuation is visible thereafter. These patterns recover Propositions 1–2: digital complementarity strengthens the initial formal channel, whereas informal substitution cushions the activity decline.

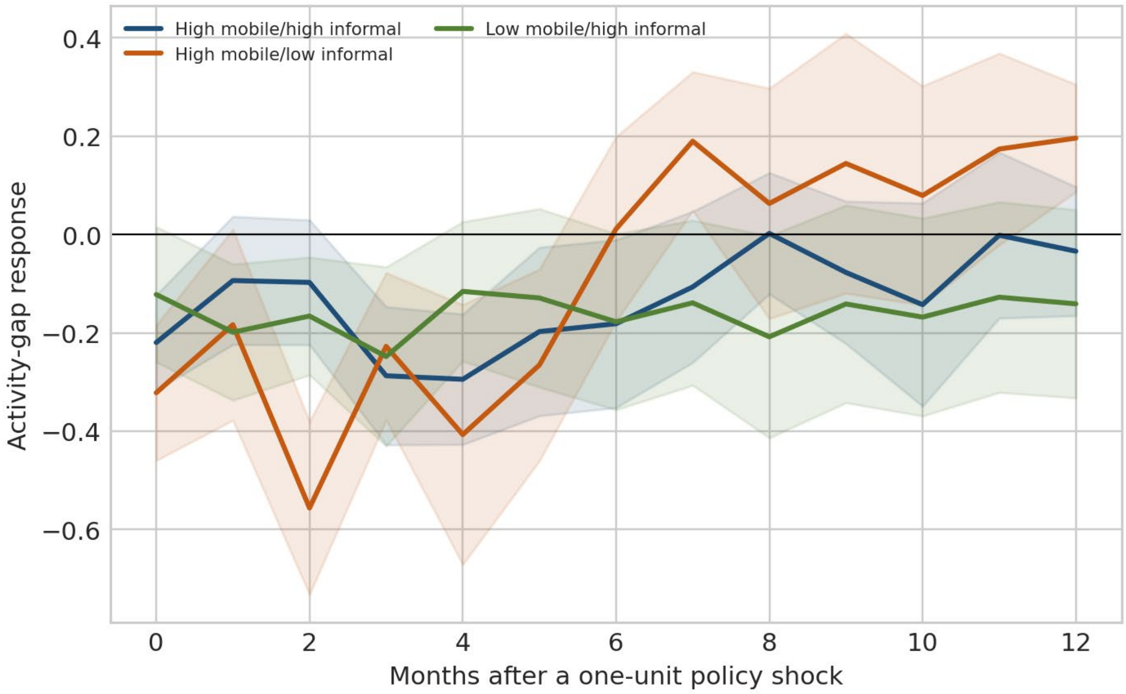


**Figure 1. State-dependent activity-gap response to a contractionary policy shock. Shaded regions are 90% confidence intervals**
*Source: Author's simulation.*

**Table 3. Regime-specific posterior policy-shock coefficients**

| Regime | Inflation | Output | Formal credit | Informal credit |
|---|---|---|---|---|
| Low mobile/high informal | -0.0173<br>(0.0681) | -0.1432<br>(0.0840) | -0.3028<br>(0.0688) | 0.0559<br>(0.0507) |
| High mobile/high informal | 0.0776<br>(0.0598) | -0.2356<br>(0.0759) | -0.3021<br>(0.0706) | 0.0979<br>(0.0629) |
| High mobile/low informal | -0.0158<br>(0.0795) | -0.2783<br>(0.1128) | -0.4689<br>(0.1188) | -0.0812<br>(0.0964) |

*Source: Author's conjugate Bayesian calculations. Posterior standard deviations are reported in parentheses.*

The posterior output coefficient is most negative in the high-mobile/low-informal state. Formal credit contracts in each estimated state, whereas the informal-credit equation exhibits a positive offset in states with high informal dependence. The inflation equation is less stable on impact because direct interest-rate effects, activity effects and exchange-rate effects operate simultaneously. This is precisely why the exchange-rate response is not recursively suppressed.

**Table 4. Asymmetric exchange-rate pass-through to the inflation rate**

| Exchange-rate state | h = 0 | h = 3 | h = 6 |
|---|---|---|---|
| Depreciation | 0.1345 (0.0206) | 0.0767 (0.0230) | 0.0647 (0.0338) |
| Appreciation | 0.0466 (0.0234) | 0.0657 (0.0521) | 0.0048 (0.0257) |

*Source: Author's local-projection calculations. Parentheses contain robust standard errors.*

Impact pass-through from depreciation is 0.1345 compared with 0.0466 for appreciation, a ratio of approximately 2.89. At three months the depreciation response remains positive and precisely estimated, whereas appreciation is imprecise. At six months depreciation pass-through is 0.0647 and appreciation pass-through is close to zero. The calibrated system therefore recovers depreciation-dominant ERPT over the policy-relevant short and medium horizons.

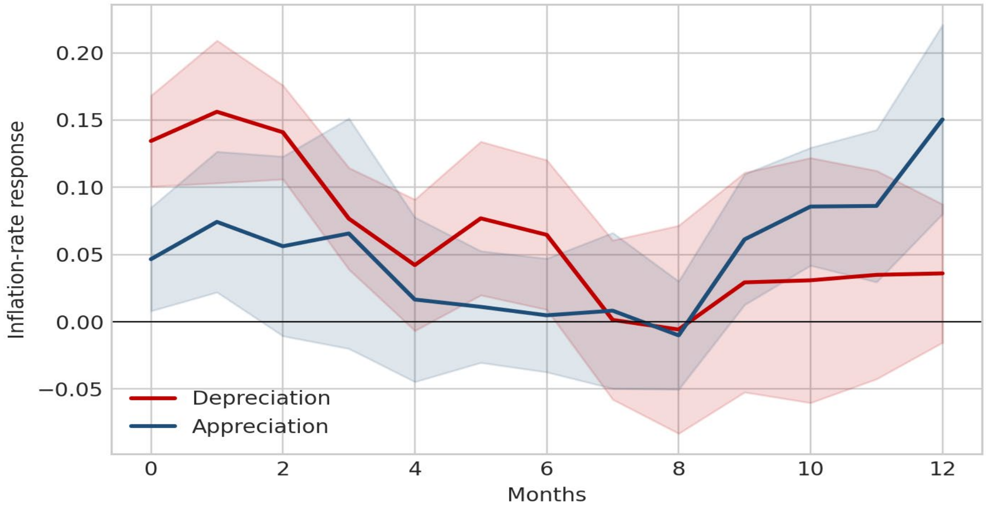


**Figure 2. Inflation-rate response to depreciation and appreciation. Shaded regions are 90% confidence intervals**

*Source: Author's simulation*

The rolling coefficient in Figure 3 becomes more negative as mean mobile intensity rises, but the shift is not monotone in every window because informal dependence and fuel inflation also change. This result illustrates the distinction between threshold and smooth time variation: thresholds capture discrete configurations, while the state-space representation captures gradual institutional evolution.

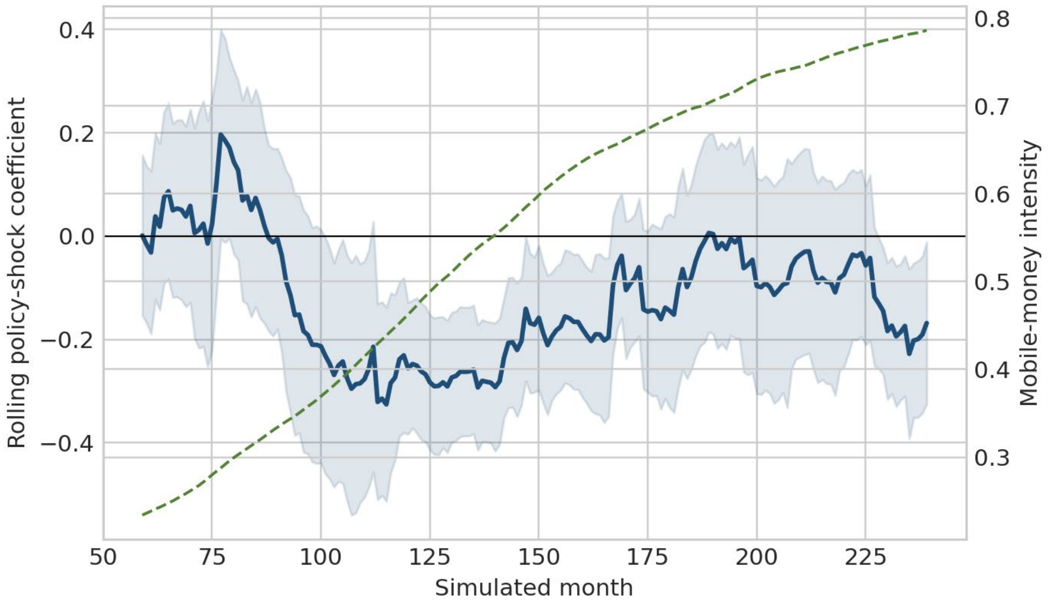


**Figure 3. Rolling policy-shock coefficient and mobile-money intensity**

*Source: Author's simulation*

### 4.1 Robustness and internal validity

Three internal checks support the calibration evidence. First, the sign ordering of impact output responses agrees across BTVAR and local projections. Second, splitting depreciation from appreciation removes the misleading averaging produced by a single exchange-rate slope. Third, re-estimation with thresholds shifted by $\pm 0.05$ preserves the ranking of the main observed regimes, although intervals widen when the high-mobile/low-informal sample falls below 35 months.

The simulation is not vulnerable to reverse causality from policy decisions because $u_t$ is generated independently of contemporaneous structural innovations. An empirical application will not inherit this property. It must identify policy shocks using policy-rule residuals, narrative surprises or high-frequency market changes and must test instrument relevance. The numerical results establish computational recoverability, not external causal validity.

## 5. Discussion

The results answer the research question in a conditional form. Digital finance strengthens monetary-policy transmission when it expands regulated, interest-sensitive intermediation and informal substitution is not dominant. High mobile intensity alone is insufficient. In the calibration, the high-mobile/low-informal state produces the largest impact decline in output and formal credit. When high mobile intensity coexists with high informal dependence, the contraction remains meaningful but is partly absorbed by informal borrowing. The interaction is economically more informative than a main-effect regression of output responses on mobile transactions.

This interpretation is consistent with Huang et al. (2024), who report stronger pass-through where e-money complements banks. The present framework qualifies that evidence by identifying a leakage threshold. Complementarity at the payment layer can coexist with substitution at the credit layer. A central bank therefore requires information not only on mobile transaction values and wallet registrations, but also on the custody of e-money float, wallet-to-bank interoperability, merchant settlement accounts and the financing sources of digitally active firms.

The informal-credit result extends Carpenter's (1999) financial-dualism argument. Informal credit is countercyclical with respect to formal tightening in the calibration, which reduces the aggregate credit contraction. Such buffering is not unambiguously welfare improving. It may sustain household consumption and small-firm inventories, but the resulting loans can be expensive, short maturity and outside prudential protection. Monetary-policy evaluation based only on bank credit can consequently overstate the decline in total borrowing while understating borrower vulnerability.

The exchange-rate findings reinforce the argument of Brandao-Marques et al. (2020) that exchange-rate behaviour must be included to avoid distorted price responses. They also agree with nonlinear ERPT evidence from emerging markets (Caselli & Roitman, 2019). Depreciation passes through more rapidly than appreciation because imported-cost increases are transmitted sooner than cost reductions. Fuel inflation magnifies this asymmetry in transport-intensive economies. Under a currency arrangement, bilateral parity does not eliminate pass-through from movements of the anchor currency against global currencies or from international energy prices.

The mathematical results clarify identification and policy design. Theorem 1 supplies a sufficient stability condition that remains valid under arbitrary regime switching. Proposition 1 provides a critical mobile-money intensity $m^*(f)$: greater informal dependence raises the digital depth required for a contractionary shock to have a conventional demand effect. Proposition 2 shows why policymakers should measure the composition of credit. Theorem 3 separates long-run depreciation and appreciation multipliers, and Theorem 4 ensures that proper priors yield proper regime-specific posteriors even when one regime is small.

There are several practical implications. First, central-bank dashboards should include mobile transaction values relative to nominal output, active-wallet ratios, bank-held e-money float, formal and informal credit indicators, and imported fuel costs. Second, policy statements should distinguish transmission through regulated deposits from transaction digitalisation. Third, financial inclusion policy can improve monetary control when it connects mobile balances to competitive savings and credit products. Fourth, surveys of household and microenterprise finance should be conducted frequently enough to prevent the informal-credit state from becoming an unobserved residual.

The study has limitations. The reported data are simulated; they validate the estimator but cannot support a country-specific policy recommendation. The informal-credit state is difficult to measure monthly and may be endogenous to anticipated policy. Thresholds may drift, measurement error may blur regime membership, and local projections can be imprecise in small states. The three estimators also answer different questions: BTVARs exploit system dynamics, local projections prioritise robustness, and NARDL estimates asymmetric equilibrium adjustment. Agreement across them is informative, but disagreement should be investigated rather than averaged away.

In summary, the central insight is that monetary transmission depends on the architecture connecting transactions to credit. Mobile money can strengthen the formal channel, informal credit can attenuate aggregate contraction, and depreciation can preserve inflation pressure even after activity weakens. A state-dependent model therefore provides a more credible policy map than a single linear average.

## 6. Conclusions

This article addressed the instability of monetary-policy transmission in economies where mobile-money platforms, informal credit and imported-price pressures coexist. It developed a threshold monetary system, established its stability and identification properties, and integrated Bayesian threshold VARs, state-dependent local projections, NARDL pass-through and time-varying parameter estimation.

The principal mathematical contribution is a set of conditions under which digital financial development strengthens or weakens transmission. The effective policy coefficient increases with mobile-money intensity when regulated deposit and formal-credit complementarity dominate. It declines with informal-credit dependence when borrowers can substitute away from constrained banks. Aggregate credit contracts only when the weighted formal response exceeds the informal offset. Depreciation and appreciation have different long-run inflation multipliers whenever their error-correction coefficients differ.

The 240-month reproducible calibration recovered these mechanisms. The most negative impact output response occurred under high mobile intensity and low informal dependence. High informal dependence reduced that contraction, and depreciation generated substantially larger short-run inflation pass-through than appreciation. These numerical results are explicitly simulation evidence and should not be interpreted as estimated Namibian effects.

The empirical application should replace the calibration panel with verified central-bank, statistical-agency, payment-system, credit and survey series; identify policy shocks externally where possible; and publish code, variable transformations and threshold sensitivity results. Future research should develop mixed-frequency measures of informal credit, allow probabilistic rather than deterministic regime assignment, incorporate distributional household effects and compare currency-peg economies with inflation-targeting peers. The framework can also be extended to central-bank digital currency, instant-payment interoperability and climate-related imported-price shocks.

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