

The Exchange Rate Effects of a Singaporean Closed-Border Retail Central Bank Digital Currency: A Counterfactual Analysis



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Abstract: Central bank digital currencies (CBDCs) are heralded as the next innovation in currency usage. Their unique architecture provides both liquidity and remuneration to investors. This paper aims to assess the exchange rate changes caused by differing plausible implementations of CBDCs due to changes in portfolio allocations of investors. Furthermore, the paper also aims to identify the ideal form of CBDC implementation.

This study uses a novel aggregated uncovered interest parity equation to connect interest rate differentials between Singaporean and international assets to estimate exchange rate differentials. Three counterfactual CBDC regimes are modelled over the period between 2000 Q1 and 2024 Q4, namely the Baseline Rule (no interest rate on CBDCs), the Markdown Rule (a discounted rate on CBDCs), and the Taylor Rule (interest rate set as per inflation and output gaps). These regimes are compared with the non-CBDC counterfactual which is modelled using the standard uncovered interest parity equation.

The criteria for comparison are path fidelity and volatility of the exchange rate. It was found that the Markdown Rule is the ideal form of CBDC implementation. Furthermore, it was also found that the Singapore dollar appreciates 35.8% to 80.4% across CBDC regimes. These findings are of great importance to the Monetary Authority of Singapore, as they can significantly affect its unique exchange-rate-targeting monetary policy.

Keywords: central bank digital currencies; closed border CBDC; small open economy; uncovered interest parity; portfolio allocation; liquidity premium; counterfactual analysis; path fidelity; exchange rate volatility.

JEL Classification: F41; F31; E52; E42.

Introduction

Playing a massive role in the future of monetary policy considerations, CBDCs are digital currencies issued by a country's central bank. The central bank controls the supply of CBDCs, which are equivalent to the country's fiat currency. CBDCs can be divided into wholesale and retail CBDCs. A wholesale CBDC is also a digital form of fiat currency, but one that is only accessible to large financial institutions, such as commercial banks (Reserve Bank of Australia 2015). On the other hand, a retail CBDC (used in this paper) is available to the public, similar to cash (in a digital form).

Since retail CBDC implementation in Singapore (the geography the model is calibrated to) is a purely hypothetical scenario, this study makes assumptions about the other properties of CBDCs in a potential implementation. Firstly, the paper assumes that the CBDC is not cross-border tradable by individuals globally, *i.e.*, foreign investors cannot hold it. This assumption is in opposition to those made by Popescu (2022) and Ferrari, Mehl, and Stracca (2020), and is similar to the assumption made in George, Xie, and Alba (2020). Bank for International Settlements (2022) also finds that cross-border use is highly unlikely, at least in the near future due to

capital flow volatility concerns. The model also assumes that bonds (foreign and domestic) and CBDCs are the only tradable financial assets available to investors. Note that due to the paper's assumption of a closed-border CBDC, foreign individuals can only invest in foreign bonds and Singaporean bonds. At the same time, domestic investors can choose between the domestically exclusive CBDC and both foreign and domestic bonds. It is also important to note that, regardless of the CBDC being "closed border", the economy is considered open since foreign individuals can invest in Singaporean assets and vice versa (other than CBDCs, which are unavailable to foreigners).

This paper contributes to the growing literature on the effects of deploying CBDCs with various characteristics in small open economies like Singapore. The paper focuses on the exchange rate effects of three differing CBDC implementations in Singapore and then simulates exchange rate changes as a counterfactual. These counterfactuals are compared with each other (between CBDC regimes) and with the exchange rate data without a CBDC to determine (i) the general effects of the CBDC on exchange rate volatility and path and (ii) ideal CBDC implementation from an exchange rate perspective. These findings address a clearly identified gap in existing literature. While prior studies have examined CBDC effects in open economies – Ferrari, Mehl, and Stracca (2020) focus on cross border-CBDCs in two-country DSGE models, and George, Xie, and Alba (2020) model interest-bearing CBDCs in small open economies calibrated to New Zealand – no study has specifically analyzed the exchange rate path and volatility implications of alternative closed-border retail CBDCs that have been calibrated to Singapore and consider its unique exchange-rate targeting monetary policy framework. The distinction is significant as Singapore does not use an interest-rate instrument but instead manages a nominal effective exchange rate band, making the portfolio channel of any CBDC design particularly consequential and understudied. This paper fills that gap by combining a closed-border CBDC assumption with a novel portfolio-weighted uncovered interest parity framework, generating quantitative counterfactual estimates of exchange rate effects under three distinct remuneration regimes across 100 quarterly observations (2000 Q1–2024 Q4).

1. Literature Review

The current literature can be divided into four strands, which are (i) the implications on the financial sector, (ii) the implications on the domestic economy, (iii) the implications on monetary policy transmission, and (iv) the implications internationally.

1.1. Financial Sector

In the literature on CBDC and its impacts on portfolio allocation, there has been a heavy focus on modelling bank disintermediation, bank runs, and other financial sector concerns in the domestic economy, such as Agur, Ari, and Dell'Ariccia (2019), Brunnermeier and Niepelt (2019), Andolfatto (2021), Chiu and Davoodalhosseini (2023), and Niepelt (2020).

The implications of bank disintermediation and CBDC design preferences show a range of interpretations. Agur, Ari, and Dell'Ariccia (2019) suggest that CBDC design (like whether it should bear interest) can influence disintermediation, presenting a tradeoff between interest-bearing and non-interest-bearing options. Brunnermeier and Niepelt (2019) note that the impact of CBDCs on bank disintermediation largely depends on the associated monetary policy. They argue that a strong commitment from the central bank could allow CBDCs to replace bank deposits. Andolfatto (2021) believes disintermediation isn't guaranteed, as banks could raise deposit rates to compete with interest-bearing CBDCs. Chiu and Davoodalhosseini (2023) share a similar view but are more optimistic, suggesting that CBDCs can enhance lending and intermediation, estimating a 7% increase in borrowing post-CBDC implementation. Niepelt (2020) argues that the substitution of deposits for CBDCs may not have significant macroeconomic effects.

Another point of focus in this strand is financial stability and bank runs. Fernández-Villaverde et al. (2020) provide a model that features three banking institutions: investment banks, commercial banks, and the central bank. In the model, commercial banks have both short-term and long-term saving technologies, investment banks have only long-term technologies, and central banks have only short-term saving technologies. Consequently, central banks allocate a portion of their deposits to investment banks to invest in long-term technologies. Thus, the central bank is more flexible and stable than commercial banks, assuming that the contract between investment banks and central banks is rigid. Depositors internalise this feature, and the central bank arises as a deposit monopolist, attracting all deposits away from the commercial banking sector. They note that this can deter runs but also point out that the lack of competition in the deposit market can discourage the central bank from delivering the socially optimal amount of maturity transformation.

1.2. Domestic Economy

Some papers propose models of CBDCs that aim to capture the domestic implications. Barrdear and Kumhof (2016) take an initial stock of CBDC equal to 30% of GDP and calibrate their model to match the pre-crisis US. They find that such a CBDC issuance against government bonds can lead to reductions in real interest rates, distortionary taxes, and monetary transaction costs, collectively resulting in a permanent increase in GDP of up to 3%.

More recent work has extended these domestic macroeconomic findings. Auer, Cornelli, and Frost (2020) provide a comprehensive database of CBDC development efforts across countries and find that retail CBDC work is more advanced in economies with larger informal sectors and higher digital capacity, cautioning against universal calibrations. For Singapore specifically, the Monetary Authority of Singapore's Project Orchid (MAS, 2023) has investigated tokenized money use cases, suggesting that the infrastructure and demand dynamics for a digital SGD in Singapore's highly digitized economy may differ from assumptions in earlier theoretical models.

1.3. Monetary Policy Transmission

Some papers also discuss the impact that CBDCs can have on the domestic implementation of monetary policy. Das et al. (2023) explain how CBDCs can strengthen and enhance the effectiveness of existing economic policy. Hemingway (2023) demonstrates how interest-bearing CBDCs enhance competition for deposits, thereby weakening bank market power, which in turn strengthens the interest rate transmission channel and makes it more potent, as affirmed by Drechsler, Savov, and Schnabl (2021). Vollmar and Wening (2024) also show that the majority of deposit-dependent banks examined likely faced funding issues and profit losses if a CBDC had been implemented in most years since 2000. The study suggests that banks may turn to wholesale funding after the introduction of CBDCs, which is more sensitive to changes in the policy rate than retail deposits, resulting in larger variations in funding costs. To stay profitable, banks adjust lending rates more sensitively to these fluctuations, thereby strengthening monetary policy transmission.

Furthermore, Tan (2024) demonstrates that issuing a CBDC enhances financial inclusion through efficient transactions and increased anonymity. Thus, Das et al. (2023) explain that financial inclusion leads to a greater proportion of the economy making intertemporal decisions that are directly affected by monetary policy, thereby widening the effects of monetary policy.

Third, introducing CBDCs, especially in developing economies, can enhance monetary sovereignty by promoting the use of domestic currencies over foreign stable currencies, such as the dollar. Thus, Fan, Walker, and Wright (2025) write that implementing CBDCs reduces reliance on the US dollar and decreases dollarisation. The paper also comments that as dollarisation decreases, the country can implement monetary policy more effectively. However, this may not always be the case. In some scenarios, CBDCs drive higher "digital dollarisation." If a CBDC from a stable currency is used across borders and widely adopted, the country adopting it may experience devaluation of its fiat currency. Thus, European Central Bank (2021) explains that dollarisation is plausible in less developed economies with unstable currencies, and that while this may help currencies like the US dollar retain reserve status, it may also undermine the strength of monetary policy in developing economies.

Subsequent work has further refined this strand. Abad, Nuño, and Thomas (2024) introduce CBDC into a New Keynesian model with heterogeneous banks and a frictional interbank market calibrated to the euro area, showing that even substantial CBDC adoption has a relatively modest effect on bank lending because the reduction in deposits is absorbed by a fall in excess reserves. Their results suggest that the operational framework of monetary policy (and specifically whether the central bank operates a floor or corridor system) mediates the macroeconomic impact of CBDC adoption.

1.4. Open Economy

George, Xie, and Alba (2020) developed an open economy model with an interest-bearing CBDC as a second monetary policy instrument to analyze its impact on welfare. They find that a flexibly remunerated CBDC (using a Taylor Rule) improves economic stability. Furthermore, they also model a flat interest rate regime and a quantity rule regime calibrated to New Zealand data. It is worth noting that they limit the CBDC to domestic usage (closed border CBDC), which is the same assumption made in this paper, to make the implementation more realistic.

Furthermore, Benigno, Schilling, and Uhlig (2022) model a two-country economy digital currency; however, it models a cryptocurrency which is not as reputable or as safe as a CBDC. The third paper, by Ferrari, Mehl, and Stracca (2020), also models a two-country model with differing remuneration regimes. They find that the presence of a CBDC increases the sensitivity of international spillovers of domestic shocks due to the increased interconnectedness that CBDCs cause. However, they do note that this finding depends on the remuneration regimes, frictions in access to the CBDC, and other miscellaneous features. This paper's model leverages their

model specifically to quantify the liquidity markup placed on CBDCs and also is similar to the uncovered interest parity conditions in their model. However, their model is fundamentally different, as it provides a full-fledged foreign economy, whereas this paper presents the domestic economy (Singapore) and the foreign economy (all other countries). Furthermore, they also model a cross border CBDC, while this paper models a closed-border CBDC.

As noted above, Bank for International Settlements (2022) documents that cross-border CBDC use remains unlikely in the near term due to capital flow volatility concerns - a finding that directly motivates this paper's closed-border assumption.

1.5. Summary of Relevant Literature

AUTHORS	ECONOMY	CBDC TYPE	METHOD	KEY FINDING	LIMITATION
Ferrari, Mehl & Stracca (2020)	Two-country DSGE	Cross-border, multiple regimes	Two-country DSGE	CBDC amplifies international spillovers; design matters for volatility	Cross-border assumption limits applicability to closed-border cases
George, Xie & Alba (2020)	Small open economy (NZ calibration)	Closed-border, interest-bearing (Taylor Rule)	Small open economy DSGE	Flexible remuneration improves stability; CBDC as second policy lever	Calibrated to NZ; exchange-rate targeting regimes not addressed
Bardear & Kumhof (2016)	Closed economy (US calibration)	Retail CBDC against govt. bonds	Closed-economy DSGE	Up to 3% permanent GDP gain from CBDC issuance	Closed-economy assumption; no exchange rate implications
Agur, Ari & Dell'Ariccia (2019)	Generic closed economy	Interest-bearing vs. non-interest-bearing	Theoretical/calibration model	CBDC design drives disintermediation tradeoff	No open economy or exchange rate dimension
Andolfatto (2021)	Generic closed economy	Interest-bearing retail CBDC	Partial equilibrium model	Banks raise deposit rates; disintermediation not inevitable	No exchange rate channel; closed economy only
Chiu & Davoodalhosseini (2023)	Generic economy	Cash-like retail CBDC	Macroeconomic calibration model	CBDCs enhance intermediation; 7% borrowing increase	Contradicts Andolfatto (2021); calibration-sensitive
Fan, Walker & Wright (2025)	Small open economies (general)	Retail CBDC (multiple designs)	Open economy structural model	CBDC affects exchange rate via portfolio channel; modest effects	Does not isolate specific exchange rate-targeting regimes
Kumhof & Noone (2021)	Generic open economy	Design principles framework	Conceptual framework	Identifies design features needed for financial stability	Conceptual framework; no quantified exchange rate estimates
This Paper	Singapore (exchange-rate targeting)	Closed-border retail CBDC (3 regimes)	Reduced-form portfolio-weighted UIP counterfactual	Quantifies exchange rate path and volatility effects of three closed-border retail CBDC remuneration regimes using a portfolio-weighted UIP framework calibrated to Singapore (2000 Q1–2024 Q4)	Reduced-form UIP; limited asset classes; no general equilibrium

Source: Author's compilation. The table summarizes the main contributions relevant to this paper across the four literature strands, highlights the key methodological difference of each study, and positions this paper's contribution relative to prior work.

2. Method

2.1. CBDC Interest Rates Time Series Counterfactual

This study generated three separate counterfactual time series for CBDC interest rates under distinct remuneration regimes. However, the CBDC rules that are assessed follow Ferrari, Mehl, and Stracca (2020). The data were collected at quarterly observations from 2000 Q1 to 2024 Q4 for data availability reasons, and because they encompass the 2008 recession and COVID-19 (analyzed later).

In the baseline scenario, the model assumed that CBDCs are not remunerated. Thus, CBDCs acted nearly identically to cash but are calibrated as being 10% more liquid. This rule is referred to as “Baseline” or “Baseline Rule” throughout the paper.

In the second scenario, a Taylor Rule was used to simulate the central bank’s control over the interest rate on CBDCs. This is particularly interesting, as Singapore relies solely on exchange rate monetary policy. However, they may choose to use the traditional Taylor Rule to control interest rates on CBDCs for financial stability, and thus, it is an appropriate extension of the model. A Taylor Rule with its calibrated parameters (calibrated to Singapore) is seen in Equation (1) (Chow, Lim, and McNelis 2014).

$$\log (R_t) = \rho^r \log (R_{t-1}) + (1 - \rho^r) \rho^\pi \log \left(\frac{\Pi_t^c}{\Pi^c} \right) + (1 - \rho^r) \rho^y \log \left(\frac{Y_t}{Y_t^{flex}} \right) \quad (1)$$

The Taylor Rule defines the interest rate in period t (R_t) as being a function of R_{t-1} (the interest rate in the previous period), the difference between target inflation and current inflation, and the output gap. The parameters are also calibrated to Singaporean data in the same paper. The Taylor Rule was used to generate a time series of CBDC interest rate data using previous CBDC interest rates and quarterly data of Singapore's inflation differences, and output gaps from 2000 Q1 to 2024 Q4. To find the long-term GDP trend for the output gap, the Hodrick-Prescott filter was used (Hodrick and Prescott 1997). It is also important to note that the interest rate for this regime may be negative and must be lower than the bond interest rate.

To set R_{t-1} for the first period, this study used the estimates from Chiu and Davoodalhosseini (2023). In their calibration, they found that a CBDC expands bank intermediation if its interest rate is between 0.30% and 1.49%. Taking the mean of this ideal range, around 0.895%, is a reasonable starting point for the CBDC interest rate. Therefore, R_{t-1} in time $t=1$ is 1.00895 (gross returns). This remuneration regime is referred to as the “Taylor Rule” throughout the paper.

For the third regime, a Markdown interest rate on CBDCs was taken, as seen in Ferrari, Mehl, and Stracca (2020). Essentially, the interest rate on CBDCs was set at a constant percentage below the policy rate (and thus less attractive). This markdown on returns can be interpreted as a trade-off or penalty for the liquidity benefit of the CBDC.

$$R_t^{DC} = R_t - R_{markdown}^{DC} \quad (2)$$

In Equation (2), $R_{markdown}^{DC}$ was a constant that is calibrated to 0.005, as per Bindseil (2022). This means that the interest rate on CBDC (R_t^{DC}) is always 0.5% less than the policy rate (R_t). Note that the interest rate here can be negative in certain quarters when the bond interest rate is below 0.5%. This regime is referred to as the “Markdown Rule” throughout the paper.

2.2. Standard Uncovered Interest Parity

Now, since the monetary return on CBDCs (R_t^{DC}) and bonds (R_t) is defined, this paper can compare the investor’s utility of holding the two assets in the portfolio to make predictions on the ideal portfolio allocations. Then, as per the allocations made, the paper can use the link between the interest rate differential and exchange rates that is defined in the UIP condition to see the impact of the portfolio allocation on Singaporean exchange rates. The Control UIP for Singapore (no CBDC implementation) is seen in Equation (3).

$$r_t^* - r_t = E_t \text{ner}_{t+1} - \text{ner}_t \quad (3)$$

In Equation (3), r_t is the log gross return on the home risk-free asset, r_t^* is the log gross return on the foreign risk-free asset, and ner_t is the log nominal exchange rate, defined as the USD/SGD exchange rate (if ner_t decreases, that means the Singapore currency has depreciated). $E_t \text{ner}_{t+1}$ defines the expected exchange rate in the following time period. This arbitrage equation (control UIP) is used to set the counterfactual exchange rate path in Singapore between 2000 Q1 and 2024 Q4 if no CBDC is implemented. The exchange rate path that is

generated using this is referred to as the “Control UIP” or just the “Control,” as it means that there is no CBDC in the regime.

2.3. Modified Uncovered Interest Parity

The Control UIP is then modified to fit CBDC implementation in Singapore. Control UIP condition is used to connect the interest rate differential between the foreign asset and the home asset to the impact on the exchange rate. However, if CBDCs are implemented, the model will need to consider the two separate asset options, bonds as well as CBDCs, in the UIP condition. To do so, the model estimates the ratio of investment into bonds versus CBDCs due to the substitution effect that the CBDC will have. When the CBDC is rolled out, a percentage of domestic bond investment is likely to be moved into CBDC, and, in later periods, vice versa. Thus, a CBDC UIP equation is derived for the model.

Since the CBDC is closed border (to be specific to Singapore), there are two arbitrage equations. Equation (4) is the first arbitrage equation (between foreign bonds and domestic CBDCs). The exchange rate change that occurs due to the interest rate differential is specific to the arbitrage of foreign bonds and domestic CBDCs only.

$$r_t^* - r_t^{DC} = E_t [\Delta e_{t+1}] \quad (4)$$

Equation (5) is the second arbitrage equation, which is between foreign bonds and domestic bonds. The exchange rate change that occurs due to the interest rate differential is purely due to the arbitrage between foreign bonds and domestic bonds.

$$r_t^* - r_t = E_t [\Delta e_{t+1}] \quad (5)$$

Next, the weightage variable, w_t , is defined in Equation (6).

$$w_t = \frac{dc_t}{dc_t + b_t} \quad (6)$$

In Equation (6), dc_t is the holdings of CBDC in the domestic economy (endogenously derived in the model later), while b_t is the holdings of bonds in the domestic economy (exogenous using available time series data on bond supply). Thus, w_t is effectively the share of investment as CBDC (and thus the share of investment into bonds is represented as $(1 - w_t)$). Therefore, using this w_t specification, there is an equation for the weighted interest rate for the entire portfolio holdings of the domestic economy, denoted as r_t^P .

$$r_t^P = w_t r_t^{DC} + (1 - w_t) r_t \quad (7)$$

Equation (7) assigns weights to interest rates based on differing combinations of holdings, ultimately affecting the overall interest rate provided on domestic securities. This equation is functional because the model can now compare r_t^* to r_t^P to derive a single net arbitrage equation, as seen below.

$$r_t^* - r_t^P = r_t^* - [w_t r_t^{DC} + (1 - w_t) r_t] = E_t ner_{t+1} - ner_t \quad (8)$$

Equation (8) depicts the overall arbitrage equation of the foreign and domestic economy. This is valid since the exchange rate portion of the UIP mirrors the interest rate differential and is intuitive since the exchange rate deviations also depend on the weighting, *i.e.*, the combinations of the securities held. Thus, the final, aggregated UIP arbitrage equation was derived and is seen in Equation (9).

$$r_t^* - [w_t r_t^{DC} + (1 - w_t) r_t] = E_t ner_{t+1} - ner_t \quad (9)$$

The inclusion of the portfolio share as the mechanism to augment the Uncovered Interest Parity (UIP) condition is structurally supported by literature focused on asset imperfect substitutability and active portfolio management, as shown by Faia, Salomao, and Veghazy (2022), in their work on granular investors. Their portfolio optimization models show that optimal portfolio shares are derived based on the total asset supply and the equilibrium "moments of the excess return (UIP deviation)". This demonstrates that the asset composition, defined by the w_t term in Equation (9), is a necessary variable to account for the premium or deviation in the exchange rate equation.

2.4. CBDC Demand

At this point, the model has not yet considered the most integral part: the liquidity benefits of CBDCs, which lead us to define a function for total CBDC demand. Since CBDC demand is taken as being endogenous, to quantify the demand/holdings of CBDC, the model can look to Equation (10) according to Ferrari, Mehl, and Stracca (2020), which effectively correlates the demand for CBDC to (i) the interest rate on CBDC, (ii) the interest rate on bonds,

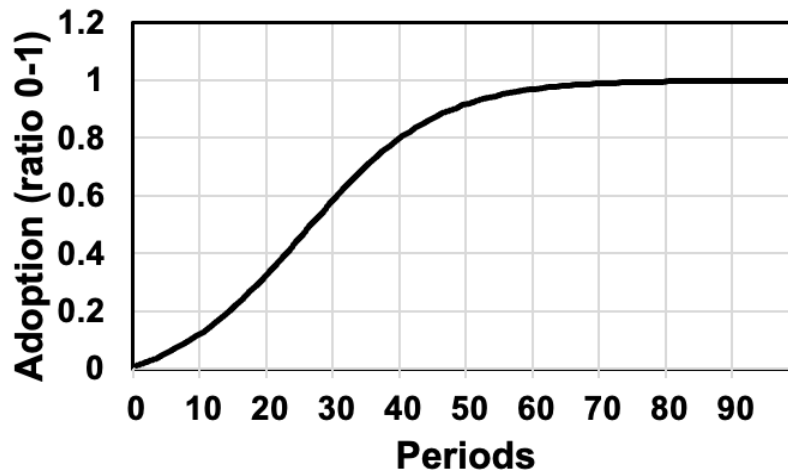
and (iii) the liquidity benefit of CBDCs. This is economically intuitive, as it mimics the trade-off investors must make: liquidity versus remuneration.

$$dc_t = \left[1 - \frac{r_t^{DC}}{r_t} \right]^{-1/\sigma_{dc}} \left[\frac{\mu_{dc}}{\lambda_t} \right]^{1/\sigma_{DC}} \tag{10}$$

In Equation (10), r_t^{DC} is the interest rate on CBDCs that is modeled in the three counterfactual scenarios, while R_t is the interest rate on domestic bonds. Furthermore, σ_{DC} is the curvature parameter governing how sensitive foreign CBDC demand is to returns and liquidity. Furthermore, μ_{DC} represents the liquidity benefit of CBDC while λ_t is the marginal utility of consumption (that is normalized to 1, akin to Ferrari, Mehl, and Stracca (2020)). Thus, the equation quantifies the demand for CBDC as a function of its remuneration, the opportunity cost of holding it (r_t), and its liquidity benefit. Note that this paper intentionally omits the Ferrari, Mehl, and Stracca (2020) equation for CBDC demand in the foreign economy. Since the paper assumes that only domestic investors access CBDCs, the domestic tradeoff is between domestic bonds and CBDCs.

One key addition this paper makes to the demand equation is the implementation of an S-curve for CBDC adoption. Equation (10) assumes 100% adoption in the economy as soon as CBDCs are released, but, in reality, adoption is a longer process. To model this, a Bass diffusion model (Bass 1969) is used, which creates an S-curve as seen below.

Figure 1: Adoption of CBDC over time in the domestic economy



Equation (11) defines the adoption level, α_t .

$$\alpha_t = \alpha_{t-1} + (p + q \alpha_{t-1})(1 - \alpha_{t-1}) \tag{11}$$

The term α_0 (adoption in time period 0) is taken as 0.01. Sultan, Farley, and Lehmann (1990) produce a mean of the annual calibrations for p and q , which are 0.03 and 0.38, respectively. When converted to quarterly calibrations, p and q are calibrated to 0.075 and 0.0906, respectively. This adoption variable is added to the demand equation as seen below.

$$dc_t = \left[1 - \frac{R_t^{DC}}{R_t} \right]^{-1/\sigma_{dc}} \left[\frac{\alpha_t \mu_{dc}}{\lambda_t} \right]^{1/\sigma_{DC}} \tag{12}$$

Notice that α_t is only multiplied in the liquidity wedge of the equation. This is because the liquidity benefit is affected by adoption rates, while remuneration spreads remain constant regardless of adoption levels. For example, holders of CBDC have a higher liquidity benefit from CBDC if many merchants accept it as a form of payment. Also note that dc_t is expressed relative to consumption in the economy, and so to convert dc_t to dollar values, it is multiplied by consumption.

This equation generates time-series data on CBDC holdings, which is then used to estimate w_t , the percentage of CBDC holdings (as a percentage of total assets) over time. This then provides us with the portfolio allocation between CBDCs and bonds in the whole economy. Thus, the CBDC UIP condition is established, accounting for the substitution of bonds by CBDC. The CBDC ON exchange rate path (using the CBDC UIP) can

then be directly compared to the CBDC OFF exchange rate path (using the Control UIP) to determine its effect on exchange rates over time. The table below summarizes the calibrations for each parameter in the model.

Table 1. Parameter Calibrations and Sources

Parameter	Value	Source
<i>Markdown Rule</i>		
$R_{markdown}^{DC}$	0.005	Bindseil (2022)
<i>Taylor Rule</i>		
ρ^r	0.15	(Chow, Lim, and McNelis 2014)
ρ^π	1.025	(Chow, Lim, and McNelis 2014)
ρ^y	0.425	(Chow, Lim, and McNelis 2014)
<i>Bass Diffusion</i>		
p	0.075	Sultan, Farley, and Lehmann (1990)
q	0.0906	Sultan, Farley, and Lehmann (1990)
<i>Liquidity and Frictions</i>		
σ_{DC}	9.558	Ferrari, Mehl, and Stracca (2020)
μ_{DC}	0.55	Ferrari, Mehl, and Stracca (2020)
λ_{DC}	1	Ferrari, Mehl, and Stracca (2020)

Source: All sources for parameter calibration are listed in the "Source" column of the table.

2.5. Instruments

Excel was used to store data and perform calculations using the equations above. The data visualisations are also made and then edited in Excel.

3. Research Results

3.1. Overview of Results

Using the exchange rate values in a time series, this section compares the properties of the counterfactual exchange rates with the original exchange rates in the same period (2000 Q1: 2024 Q4). The results focus on the path fidelity (extent of deviation from the original), volatility, persistence, and volatility during shock to analyze the ideal remuneration regime when compared to the other regimes and the original exchange rate time-series. According to the data collected, the Markdown Rule is found to be the ideal regime as its path is closest to the Control exchange rate (without CBDC) and also has the lowest volatility among the CBDC regimes. Furthermore, the change in volatility between the Markdown Rule and the Control exchange rate is found to be statistically insignificant, and thus does not reflect a notable difference for policymakers. There is a large appreciation of SGD across the counterfactuals, with this appreciation ranging from 35.8% to 80.4%. The counterfactual and original exchange rate time-series data are graphed below and show the general trend of the counterfactuals in relation to the control. Note that all numbers are in log points and quarterly unless explicitly stated otherwise.

Figure 2: USD/SGD Exchange Rate over time (Control vs Baseline)

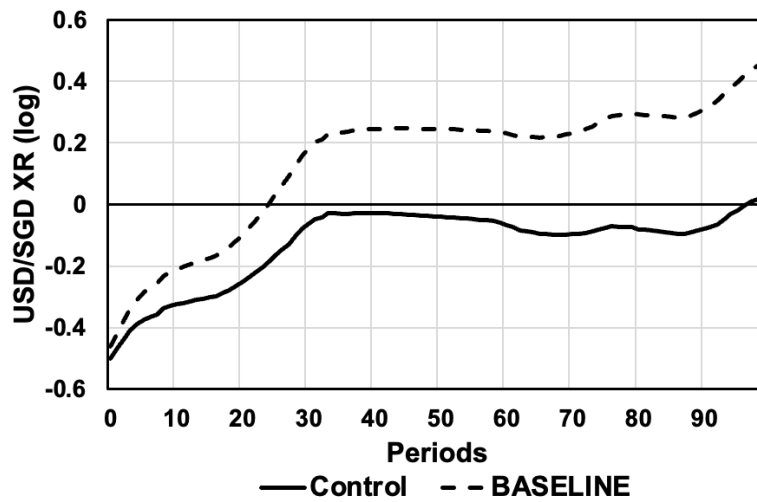


Figure 3: USD/SGD Exchange Rate (Control vs Markdown)

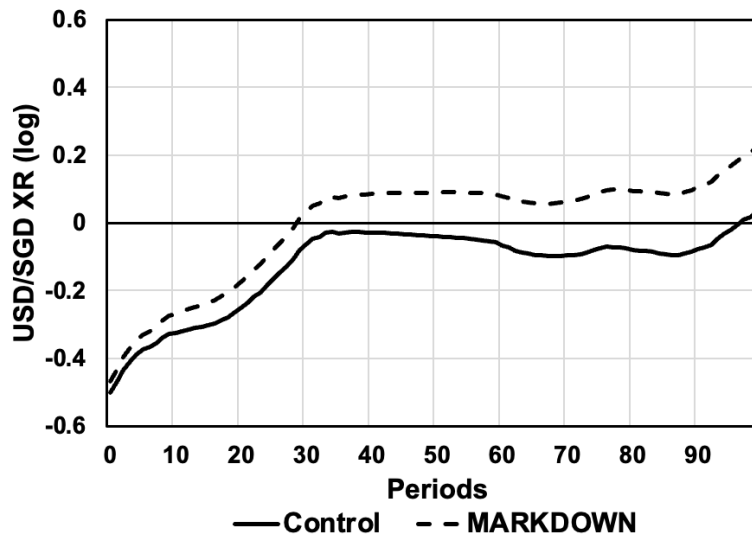
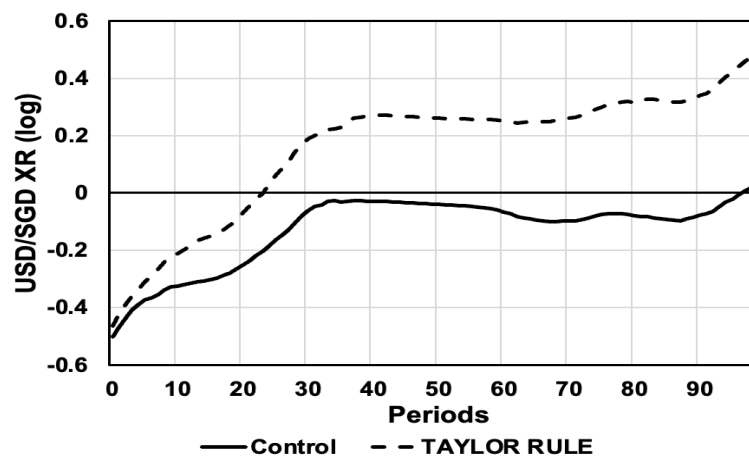


Figure 4. USD/SGD Exchange rate (Control vs Taylor Rule)



3.2. Path Fidelity

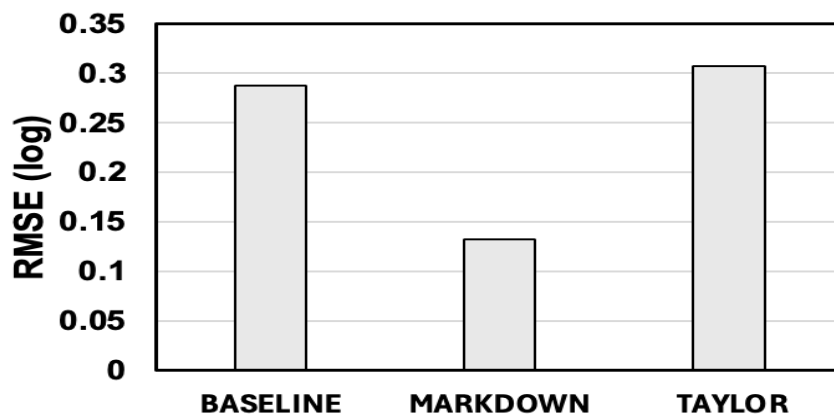
Path fidelity is evaluated using (i) RMSE/MAE of the log deviation δ_t and ii) persistence via an AR(1) with 95% confidence intervals and the implied long-run mean misalignment. Across these metrics, the results show that the Markdown rule attains lower RMSE, MAE, big move frequency, and long-run mean misalignment than the other remuneration regimes, *i.e.*, it is closest to the original exchange rate path. The summary of the results can be seen in the table below.

Table 2. Path Fidelity Statistics

Parameter	Baseline	Markdown	Taylor
RMSE	0.287	0.132	0.307
MAE	0.268	0.123	0.286
AR(1) Slope	0.987	0.991	0.986
Stationary Mean	0.586	0.306	0.590
Big Move Frequency	0.690	0.000	0.720

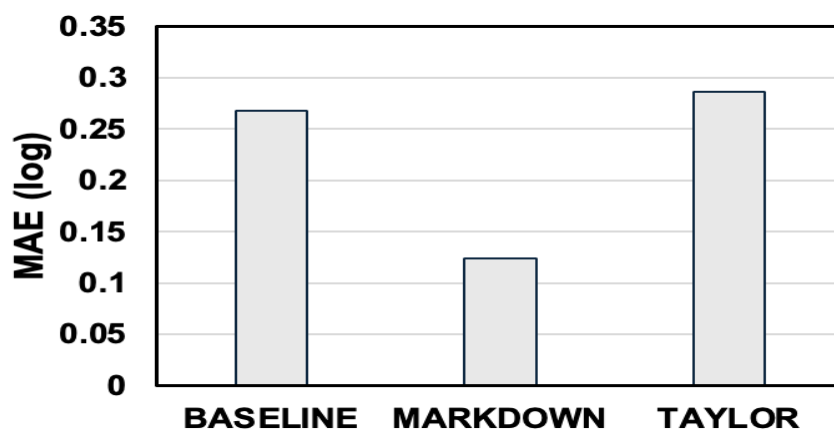
Firstly, root-mean-squared error (RMSE) is lowest under the Markdown rule (0.132), with Baseline (0.287) and Taylor Rule (0.307) larger and very similar. Note that this reflects how far the respective counterfactual path is from the original path.

Figure 5: Root Mean Squared Error across regimes



Secondly, the Mean Absolute Error (MAE) measures the average magnitude of errors between the original exchange rate path and the counterfactual path. It gives a similar result, with the Markdown rule having the lowest (0.123), and Baseline (0.268) and Taylor Rule (0.286) having similar MAEs.

Figure 6. Mean Absolute Error across regimes



Furthermore, persistence is high across regimes as seen by the AR(1) process for deviation, δ_t , by Equation (13).

$$\delta_t = \mu + \phi\delta_{t-1} + \varepsilon_t \quad (13)$$

In Equation (13), μ is the intercept, ϕ is the slope, and ε_t is the error term. AR(1) estimates of deviations yield slopes (ϕ) near 0.98-0.99 (Baseline = 0.987, Markdown = 0.991, Taylor = 0.986). These values are below but close to 1, implying that deviations are sticky. This effectively means that about 98-99% of any deviation carries over to the next quarter, and only 1-2% of the deviation closes.

With the estimates for μ and ϕ , the stationary mean for the deviation time series can be found using the formula $\mu / (1 - \phi)$ (Hamilton 1994). In the context of the paper, deviations are the log differences between the original and counterfactual paths; thus, a non-zero stationary mean indicates a systemic negative or positive bias in the counterfactual. This is an important metric because it isolates the systematic level shifts to which the counterfactual exchange rates gravitate, whereas the RMSE/MAE metric also includes noise. Measuring this systematic shift is essential because, as noted before, the high persistence (near 0.99 across regimes) causes exchange rate gaps between the original and the counterfactual to close extremely slowly.

The stationary mean is closest to zero for Markdown (0.306) and is larger in magnitude for Baseline (0.586) and Taylor Rule (0.590). These values clearly indicate that the exchange rates across regimes sit materially higher (systemically biased upward) than the original exchange rate and suggest that the Markdown rule is closer to the original path than the Baseline or Taylor Rule. Though the Markdown rule provides the lowest systemic gap, it still does not replicate the original exchange rate. Thus, none of the CBDC interest rate regimes hit the target if preserving original exchange rate levels is paramount to policymakers.

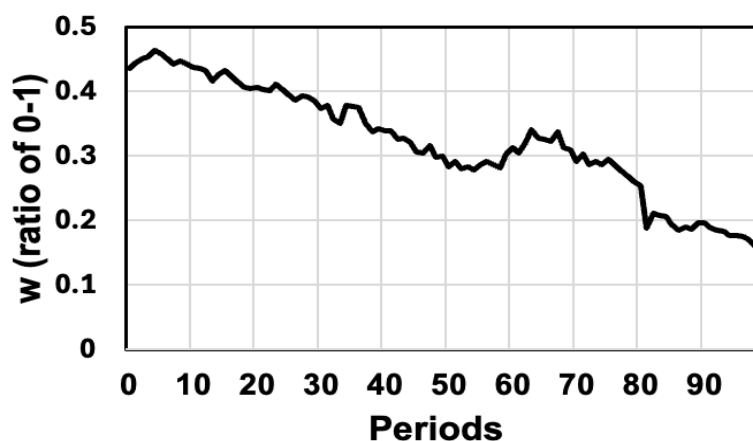
Overall, deviations are large and persistent under all regimes. A commonality in all the CBDC counterfactuals is that the exchange rate series sits materially higher than the Control exchange rate (as characterized by the positive long run mean misalignment measured for all CBDC counterfactuals). The Control UIP and the CBDC counterfactuals also consistently appreciate throughout the time period.

There are three main forces that cause the general appreciation of the exchange rate in the CBDC counterfactuals.

Firstly, Singaporean bonds generally have very low interest rates. In this analysis, 1-year Singapore bonds are used, and they have a mean gross return of 1.014, *i.e.*, an interest rate of 1.41%. Simultaneously, the mean gross return on US 1-year bonds was 1.02, *i.e.*, a 2% interest rate. Thus, in the Control UIP and the CBDC counterfactuals, there is an appreciation of the Singapore exchange rate as Singaporean bonds offer lower remuneration.

However, this appreciation is more pronounced in the CBDC counterfactuals because of the second force: the liquidity benefits of CBDCs. Due to the low-interest-rate environment that domestic investors are subject to, the liquidity benefits of CBDCs cause investors to reallocate to CBDCs as the liquidity provides high utility relative to low remuneration on bonds. Thus, this causes the value of w (the percentage of investment in CBDC) to remain relatively high even when CBDCs have very low or even negative rates. Take the example of the Markdown regime, which has the lowest deviation from the original.

Figure 7. Value of w over time in the Markdown Rule



In the Markdown Rule, the average gross return on CBDCs is 1.0091, *i.e.*, an interest rate of 0.91% (while the average Singapore bond rate is 1.41% and the average US bond is 2%), and, in some periods, provides negative interest rates. Despite this, the value for w remains relatively high, at a mean of 0.322 (meaning 32.2% of domestic investment in the economy is into CBDCs). In the weighted UIP, this causes the weighted domestic interest rate (which is weighted to the percentage holdings of bonds and CBDCs) to decrease compared to the non-CBDC status quo. Thus, this causes the Singapore exchange rate to appreciate significantly.

The final force is that foreign investors cannot invest in the CBDC because it is only open for Singapore locals. Thus, due to the lower rate on CBDC, the weighted interest rate in Singapore is lowered while the foreign interest rates remain the same as foreign investors do not reallocate their investments into CBDCs, causing domestic exchange rates to appreciate under the UIP condition.

Additionally, another finding that is economically intuitive is that the Markdown Rule provides the lowest deviation from the status quo. This is intuitive because the Markdown Rule consistently sets the interest rate on CBDCs to 0.5% below the rate on bonds. Thus, when bond interest rates are below 0.5%, the Markdown Rule can also freely place a negative interest rate on CBDCs. The Baseline Rule cannot do this: it remains fixed and cannot shift its rates dynamically to bond rates. Similarly, the Taylor Rule has the most significant deviation, which may seem counterintuitive. However, interest rates in Singapore are set using exchange rate targeting, and thus the Taylor Rule, though accommodating for inflation and the output gap, does not change in relation to bonds either. Therefore, these results depict that treating the CBDC as having a constant lower remuneration to bonds (0.5% lower) provides the lowest discrepancy in rates and mimics the substitution effect between bonds and CBDCs.

There are, thus, two findings in this section: (i) CBDC implementation causes an appreciation in the exchange rate across the board, and (ii) the Markdown Rule regime has the least deviation from the Control (non-CBDC). It is important to note, however, that though the Markdown Rule reduces both typical distance and systemic gaps, deviations are statistically significant and thus should be considered by policymakers.

3.3. Volatility

The previous section focused on the proximity of the counterfactual exchange rate paths to the original path. This section compares the volatility of the CBDC counterfactuals and the control exchange rate path to determine which regime yields the most stable exchange rates, *i.e.*, the least fluctuations. Volatility can be defined as either the average of absolute exchange rate movements or the standard deviation of percentage changes. For this paper, the latter is taken. Across the entire time period, the Control exchange rate has the lowest volatility, while the Markdown Rule (marginally higher than the Control) has the lowest volatility among the CBDC regimes. However, during periods of shock, the Markdown Rule and the Baseline Rule exhibit the lowest volatility, even lower than the Control exchange rate. The summary table of volatility results is below.

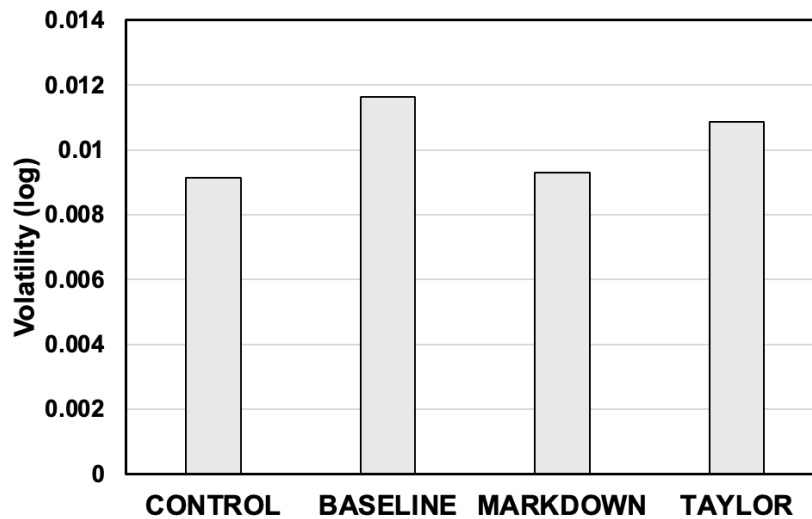
Table 3. Volatility Statistics

Parameter	Control	Baseline	Markdown	Taylor
Periods (0-100)				
Volatility	0.00914	0.0116	0.00930	0.0109
p value of F test	N/A	0.0169	0.865	0.0864
VaR 95%	0.0224	0.0317	0.0244	0.0284
CVaR 95%	0.0283	0.0380	0.0303	0.0341
$\Omega > 0.02$ Frequency	0.0606	0.202	0.101	0.212
Shock Periods				
Volatility (2008 Crisis)	0.0076	0.0078	0.0076	0.0077
Volatility (COVID-19)	0.0038	0.00276	0.00357	0.00805

To measure volatility, the return series of exchange rates is used. This is the difference between the log of exchange rates in consecutive quarters for each series. The return is defined as ρ and is determined by the equation below, where E_t is the exchange rate in levels.

First, the volatility of exchange rates over the entire period (2000 Q1-2024 Q4) is examined. Volatility is defined by the sample standard deviation of log returns (Ω) in the exchange rate. The results show that the Control exchange rate has the lowest volatility, at 0.0091, while all the CBDC counterfactuals exhibit marginally higher volatilities (Baseline Rule=0.012, Markdown Rule=0.0093, Taylor Rule=0.0109). Among the CBDC regimes, the Markdown Rule had the lowest volatility.

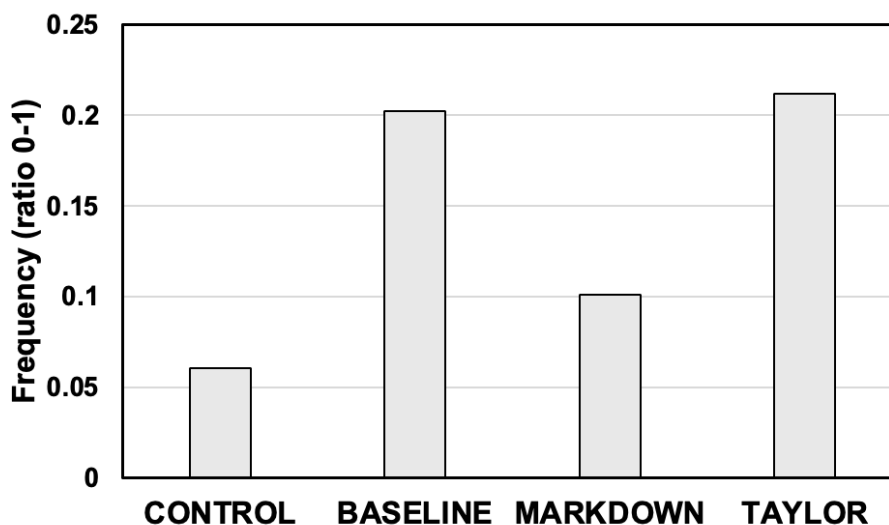
Figure 8: Volatility of Exchange Rates in Control and across CBDC regimes



However, it is also found that the change in volatility for the Markdown Rule (compared to the Control) is statistically insignificant at a significance level of 0.10 (p value of F test = 0.865), while the other two regimes remain statistically significant ($p < 0.10$).

To complement the standard deviation measure, the frequency with which exchange rate returns (Ω in absolute values) exceed 0.02 log points is also calculated (Figure 9). Similar results are observed, with the Control (0.061) demonstrating a much lower frequency than the CBDC regimes (Baseline Rule=0.202, Markdown Rule=0.101, Taylor Rule 0.212). Among the CBDC counterfactuals, the Markdown Rule had the lowest frequency for significant moves between quarters.

Figure 9. Frequency of moves greater than 0.02 log points

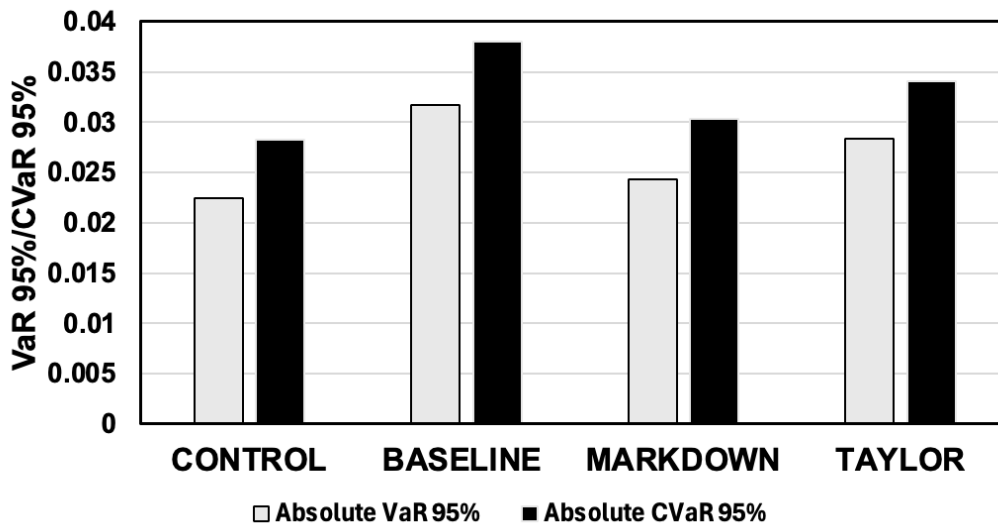


Furthermore, the Absolute VaR 95% (Value-at-Risk 95%) and the Absolute CVaR 95% (Conditional Value-at-Risk 95%) are calculated for each exchange rate return series. Effectively, VaR 95% provides the absolute value

of return that lies at the 95th percentile of all returns in that series, *i.e.*, it marks the threshold at which the “worst” 5% of absolute value returns begin. The higher the absolute returns, the more volatile the exchange rate series, and thus a lower Absolute VaR 95% is better. The Absolute CVaR at 95% provides insight into the average absolute return for the worst 5% of quarters (*i.e.*, higher absolute returns).

Similar results are found here also. Relative to the Control (VaR95 = 0.022, CVaR95 = 0.028), all the counterfactuals have higher values. Markdown (VaR95 = 0.024, CVaR95 = 0.030) again had the lowest when compared to the Baseline Rule (VaR95 = 0.032 and CVaR95 = 0.038) and Taylor Rule (VaR95 = 0.028 and CVaR95 = 0.034).

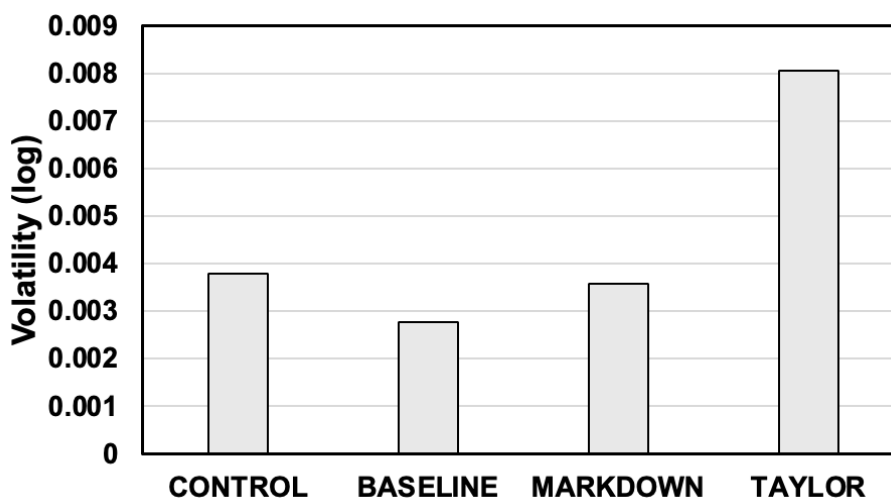
Figure 10. Absolute VaR 95% and Absolute CVaR 95% for Control and across CBDC regimes



The volatility test is also conducted during periods of shock present in the dataset, specifically, COVID-19 and the 2008 crisis. For COVID-19, the period from 2019 Q4 to 2020 Q2 (end of quarter) is picked. For the 2008 crisis, the period from 2008 Q2 to 2009 Q1 is used. An interesting finding here is that volatility during these shock periods is lower for the CBDC regimes.

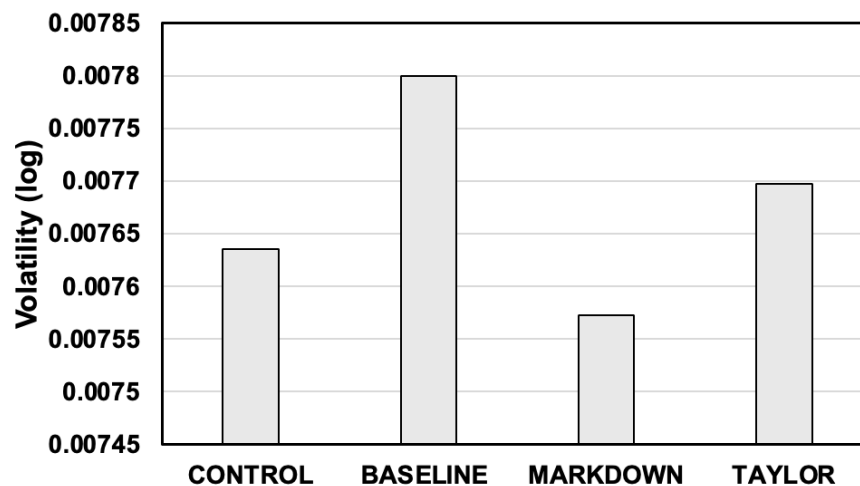
In the case of COVID-19, the Baseline Rule (0.0028) and the Markdown Rule (0.0036) have lower volatility than the Control (0.0038), while the Taylor Rule (0.0081) has the highest volatility.

Figure 11. Volatility of Exchange Rates in Control and across CBDC regimes during COVID-19



The 2008 shock also shows a similar trend. In this case, however, the Control exchange rate and the Markdown Rule volatilities hover almost exactly at 0.0076 (Markdown Rule thinly lower). At the same time, the Taylor Rule (0.0077) and Baseline Rule (0.0078) are slightly higher during the period. Note that VaR 95% and CVaR 95% values are not found because of the low number of time periods assessed during the shock.

Figure 12. Volatility of Exchange Rates during the 2008 financial crisis



Overall, there are three main findings on volatility. Firstly, over the entire time period, the Control exchange rate and the Markdown Rule had the lowest volatility among all the exchange rate paths assessed, with the difference in volatility between the two being statistically insignificant. Secondly, over the time period, the Markdown Rule exhibits the lowest volatility among the CBDC regimes. Lastly, it is worth noting that the CBDC regimes, specifically the Baseline Rule and the Markdown Rule, exhibited a marginal decrease in volatility during periods of shock, namely the COVID-19 pandemic and the 2008 crisis. However, the differences here are very slight, and are not indicative of a superiority of CBDCs during shock periods.

The results on volatility are economically intuitive. Under the Markdown rule, the CBDC pays a fixed discount to government bonds and is available only to residents. This creates a stable, liquid asset that people hold for convenience rather than yield, so the CBDC share changes little when interest rates move. The steadier CBDC share dampens movements in the portfolio-weighted domestic return that feeds the UIP condition, and most rebalancing occurs between domestic assets rather than through cross-border flows. By contrast, the Taylor rule moves the policy rate whenever inflation or output shifts, producing larger and more frequent changes in the interest differential and, therefore, higher exchange-rate volatility. The Baseline rule lacks the fixed markdown anchor, so small rate changes trigger more switching between CBDC and bonds. As a result, the Markdown rule delivers lower volatility than both the Taylor and Baseline rules.

4. Discussions

A closed-border CBDC implementation in Singapore is shown to have significant effects on the exchange rate, which can directly impact Singapore's exchange rate-targeting monetary policy. Some of the results shown are open to interpretation and depend directly on the Monetary Authority of Singapore's goals and priorities.

The paper addresses two questions: (i) which CBDC interest rate regime is ideal for Singapore if CBDCs are implemented, and (ii) the general impacts of CBDCs on Singapore's exchange rate. The paper focuses on two determinants of exchange rate changes: path fidelity and volatility.

To answer the first question, the results show that among CBDC interest rate regimes, the Markdown regime is the ideal, as its exchange rate path is closest to the original path (path fidelity) and exhibits the lowest volatility over the time period assessed. These findings can inform policy, as the Markdown regime is the ideal implementation of CBDCs from a purely exchange-rate perspective.

The second finding compares the CBDC implementation counterfactual to the status quo. Regarding volatility, over the entire time period assessed (and thus on average), changes in volatility between the Control exchange rate and the Markdown Rule are statistically insignificant.

The results on path fidelity are up to interpretation. In all the counterfactuals, the exchange rate steeply appreciated relative to the Control. Even under the Markdown regime, the SGD level sits materially higher than the Control: the long-run mean misalignment is 0.306 log points, which corresponds to the exchange rate being about 35.8% stronger on average, an essential concern for the MAS to assess. It is also worth noting that in other counterfactuals, specifically the Taylor Rule, this appreciation can reach 80.4%.

The methodology and results fit well into the literature. The first point of focus is the methodology. Relative to Ferrari, Mehl, and Stracca (2020), who embed CBDC in a two-country DSGE and show that design choices

shape international spillovers, this paper uses a reduced-form UIP framework to quantify how specific remuneration rules would alter Singapore's exchange-rate path and volatility under a closed-border retail CBDC. Furthermore, the counterfactual approach taken in this paper echoes the approach taken by Kumhof and Noone (2021), while adapting their approach for an open economy that targets the exchange rate. Lastly, as mentioned earlier, the portfolio weighting variable in the modified UIP is a novel usage of the granularity of investors shown in Faia, Salomao, and Veghazy (2022).

The next point of focus is the results of the paper. Relative to the existing literature, the exchange rate implications of this paper line up with, but also narrow and sharpen, several strands of prior work. Ferrari, Mehl, and Stracca (2020) show in a two-country DSGE setting that introducing a cross-border CBDC reshapes the arbitrage conditions between currencies and tends to amplify exchange-rate responses to monetary and financial shocks. George, Xie, and Alba (2020) find in a small-open-economy model that an interest-bearing retail CBDC can be configured to dampen exchange-rate fluctuations by giving policymakers an additional lever to influence risk premia and expected depreciation. Fan, Walker, and Wright (2025) also report that CBDC design affects the exchange rate mainly through its impact on portfolio choices and external financing conditions, though in their calibration the resulting exchange-rate movements are relatively modest for small open economies. In comparison, this paper's exchange-rate findings complement these contributions by focusing specifically on how alternative retail CBDC architectures can systematically tilt the exchange rate's average path and volatility specifically in a Singaporean context.

Beyond the specific policy implications for the MAS, the results carry broader methodological significance. Firstly, the method of the portfolio-weighted uncovered interest parity to accommodate a closed-border CBDC instead of a separate UIP equation is novel and clearly demonstrates that even a domestically restricted digital currency can generate persistent deviation in the exchange rate level by reshaping the effective domestic interest rate. Second, the superiority of the Markdown Rule over both the Taylor Rule and the zero-rate baseline is a novel finding that is highly specific to the exchange rate targeting economy of Singapore, and thus challenges existing CBDC literature. The result is consistent with the view that, in an economy like Singapore's (that already operates its monetary policy using the exchange rate), adding a second "active" instrument like the Taylor Rule creates additional volatility rather than an additional monetary policy lever (as described in George, Xie, and Alba (2020)). Lastly, the consideration of adoption dynamics, especially since a CBDC is a completely new asset class for investors, plays a meaningful role in influencing the portfolio weights (and thus the exchange rate paths), suggesting that future CBDC modelling efforts should also treat adoption as an endogenous variable.

Conclusions and Further Research

This paper highlights two policy implications: (i) the Markdown Rule provides the lowest exchange rate deviation and maintains the original volatility of exchange rates, and (ii) there is an appreciation of the SGD by 35.8% (Markdown) to 80.4% (Taylor Rule). These findings have wider implications for Singapore's economy.

On the one hand, a higher exchange rate can enable Singapore to import goods at a lower price due to the increased value of the currency. This can increase the purchasing power of Singaporeans. However, the price of exports from Singapore will also increase due to higher domestic production costs. It is important to note, however, that 43.8% of Singapore's exports rely directly on imported inputs, such as value-added components, suggesting that an appreciation could mitigate the export competitiveness harms (OECD 2023). This paper does not aim to assess or comment on whether a stronger SGD is a boon or a disadvantage to Singaporean trade as a host of literature tackles this very topic. However, this paper empirically exposes the underlying mechanisms that can cause changes in the exchange rate path and volatility, which can help inform decisions on CBDC implementation for the MAS and other small, open-economy central banks worldwide.

Further research can go in a few directions. Firstly, future research on CBDC implementation effects should focus on including a variety of asset classes such as equities, real estate, cash, etc in the portfolio allocation model to simulate the diversity of investment options. Secondly, future research can also look to model alternative CBDC regimes that have more innovative structures in the Singaporean economy such as tiered remuneration structures and quantity rules. Thirdly, as actual CBDC implementations accumulate empirical data (for example from the Bahamas' Sand Dollar or the Eastern Caribbean DCash), future work could test the calibration of the adoption and demand parameters used in this model against observed outcomes.

Declarations

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Credit Authorship Contribution Statement:

Arnav Agrawal: Conceptualization, Investigation, Methodology, Software, Data Analysis, Writing, Review and Editing, Formatting, Project administration

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