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 from an exchange rate perspective. 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 exchange rate volatility. 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.

1. Introduction

Playing a massive role in the future of monetary policy considerations, CBDCs are digital currencies issued by a country's central bank (Seth, 2024). The central bank controls the supply of CBDCs, which are equivalent to the country's fiat currency (Seth, 2024). 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 (RBA, 2015). On the other hand, a retail CBDC (used in this paper) is available to the general public, similar to cash (in a digital form).

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 a CBDC on exchange rate volatility and path and (ii) ideal CBDC implementation from an exchange rate perspective. This paper focuses on exchange rates because they are a significant factor driving Singaporean monetary policy, with the Monetary Authority of Singapore following an exchange rate targeting regime (Monetary Authority of Singapore, n.d.), and is also a substantial research gap, especially in the Singapore context.

Consequently, analyzing the effect of a possible CBDC implementation on exchange rates is a significant objective that can help understand its impact on Singapore's monetary policy.

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 et al. (2020), and is similar to the assumption made in George et al. (2021). The Bank of International Settlements n.d also agrees 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).

2. Related Literature

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.

Financial Sector. In the literature on CBDC and its impacts on portfolio allocation, there has been a heavy focus on modeling bank disintermediation, bank runs, and other financial sector concerns in the domestic economy, such as Agur et al. (2019), Brunnermeier and Niepelt (2019), Andolfatto (2018), Chiu et al. (2019), and Niepelt (2020).

The implications of bank disintermediation and CBDC design preferences show a range of interpretations. Agur et al. (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 Neipelt (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 (2018) believes disintermediation isn't guaranteed, as banks could raise deposit rates to compete with interest-bearing CBDCs. Chiu et al. (2019) 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. Fernandez-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.

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%.

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 Dreschler et al. (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.

Lastly, 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 et al. (2024) 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. Auer et al. (2021) explain that a currency's digital nature alone is unlikely to replace the dollar. 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, ECB (2021) explains that dollarisation is plausible in less developed economies with unstable currencies. While this may help currencies like the US dollar retain reserve status, as shown by Sandback (2024), it undermines the strengthening of monetary policy in developing economies.

Open economy. Three papers develop open economy models of CBDCs (to the reviewer's knowledge). George et al. (2021) 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 et al. (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 et al. (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.

3. Method

3.1 CBDC Interest Rates Time Series Counterfactual

This paper generate three separate counterfactual time series for CBDC interest rates under distinct remuneration regimes, à la Kumhof et al. (2023). However, the CBDC rules that are assessed follow Ferrari et al. (2020).

In the baseline scenario, the model assumes that CBDCs are not remunerated, i.e., $r_t^{DC} = 0$. Thus, CBDCs act 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 is 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; thus, it is an appropriate extension of the model. A Taylor Rule with its calibrated parameters (calibrated to Singapore) is seen below (Chow et al., 2014).

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

The Taylor Rule defines the interest rate in period t (R_t) as being affected by R_{t-1} (the interest rate in the previous period), the difference between target inflation and current inflation

($\frac{\prod t}{\prod c}$) and the output gap ($\frac{Yt}{Yflex}$). The parameters are also calibrated to Singaporean data in the same paper. The Taylor Rule is used to generate a time series of CBDC interest rate data using interest rates, inflation differences, and output gaps from previous years. To find the long term GDP trend for the output gap, the Hodrick-Prescott filter is used (Hodrick & 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 paper uses the estimates from Chiu et al. (2019). In their calibration, Chiu et al (2019) find 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 is taken, as seen in Ferrari et al. (2020). Essentially, the interest rate on CBDCs will always be a constant percentage below the policy rate (and thus less attractive). This penalty on returns can be interpreted as a trade-off for the liquidity benefit of the CBDC.

$$R_t^{DC} = R_t - R_{\text{spread}}^{DC}$$

Here, R^{DC}_{spread} is a constant that is calibrated to 0.005, as per Panetta and Bindseil (2020). This means that the interest rate on CBDC (R^{DC}) is always 0.5% less than the policy rate (R). 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.

3.2. Standard Uncovered Interest Parity (Non-CBDC)

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 below.

$$r_t^* - r_t \;=\; E_t\, ner_{t+1} \;-\; ner_t$$

Here, $r_t = \ln(1+R_t)$ is the log gross return on the home risk-free asset, $r_t^* = \ln(1+R_t^*)$ 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). $E_t(ner_{t+1})$ 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. This time period is taken because of data availability reasons, and because it captures periods of shock, namely COVID-19 and the 2008 financial crisis. 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.

3.3. Modified Uncovered Interest Parity (CBDC)

The Control UIP is then modified to fit CBDC implementation in Singapore. The 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. Below 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.**

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

The below is the second arbitrage equation which is in 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.

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

Next, the weightage variable, w_t , is defined.

$$w_t = \frac{dc_t}{dc_t + b_t}$$

Here, 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)). 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.

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

The above equation 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* to r^P_t to derive a single net arbitrage equation, as seen below.

$$r_t^* - r_t^P = r_t^* - \left[w_t r_t^{DC} + (1 - w_t) r_t \right] = E_t[\Delta e_{t+1}]$$

The above equation depicts the overall arbitrage equation of the foreign and domestic economy. Note that the RHS shows $E_t [\Delta e_{t+1}]$, which stands for the total exchange rate deviation (defined by the interest rate differential between foreign and domestic assets).

The above 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, it ends with the final UIP arbitrage equation seen below. Note that the previous representation of the RHS is equivalent to the one below.

$$r_t^* - \left[w_t \, r_t^{DC} + (1 - w_t) \, r_t \right] \; = \; E_t \, ner_{t+1} - ner_t$$

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 the above UIP equation, is a necessary variable to account for the premium or deviation in the exchange rate equation.

3.4. 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 the equation by Ferrari, Mehl, and Stracca (2020) (below), 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.

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

In this equation, 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, $\boldsymbol{\sigma_{DC}}$ 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. The above equation 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.

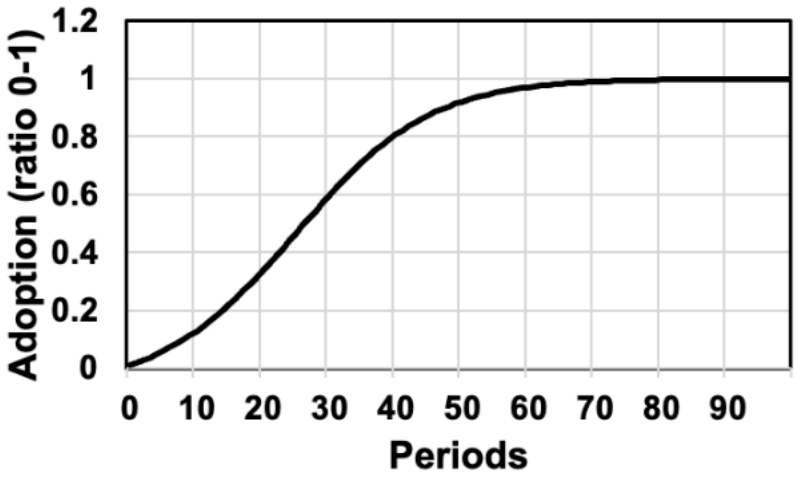


Figure 1: Adoption of CBDC over time in the domestic economy

The equation below defines the adoption level, α_t.

$$\alpha_t = \alpha_{t-1} + \left(p + q\,\alpha_{t-1}\right)\left(1 - \alpha_{t-1}\right)$$

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.

$$dc_t = \left(1 - \frac{R_t^{DC}}{R_t}\right)^{-\frac{1}{\sigma_{DC}}} \left(\frac{\alpha_t \mu_{DC}}{\lambda_t}\right)^{\frac{1}{\sigma_{DC}}}$$

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 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. Calibrations

PARAMETER	***VALUE***	***SOURCE***
	Markdown Rule	
R^{DC}_{spread}	0.005	Panetta and Bindseil (2020)
	Taylor Rule	
ρ^{r}	0.15	Chow et al., 2014
ρ^{π}	1.025	Chow et al., 2014
ρ^{y}	0.425	Chow et al., 2014
	Bass Diffusion	
p	0.075	Sultan et al. (1990)
q	0.0906	Sultan et al. (1990)
	Liquidity and Frictions	
σ_{DC}	9.558	Ferrari et al. (2020)
μ_{DC}	0.55	Ferrari et al. (2020)
λ_{DC}	1	Ferrari et al. (2020)

4. 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 original), volatility,

persistence, and volatility during shock to analyse 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.

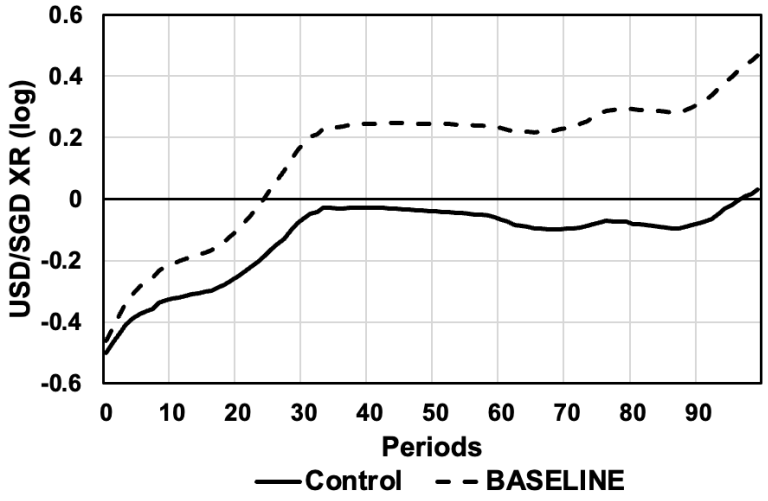


Figure 2: USD/SGD Exchange Rate over time (Control vs Baseline)

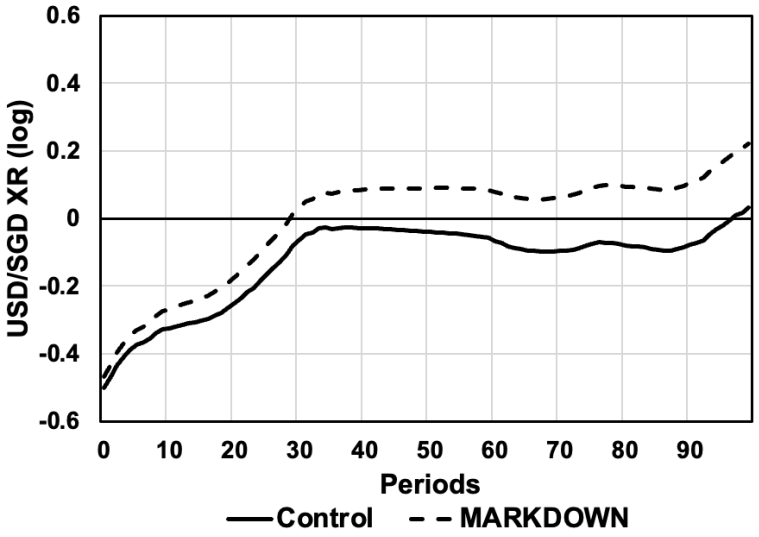


Figure 3: USD/SGD Exchange Rate (Control vs Markdown)

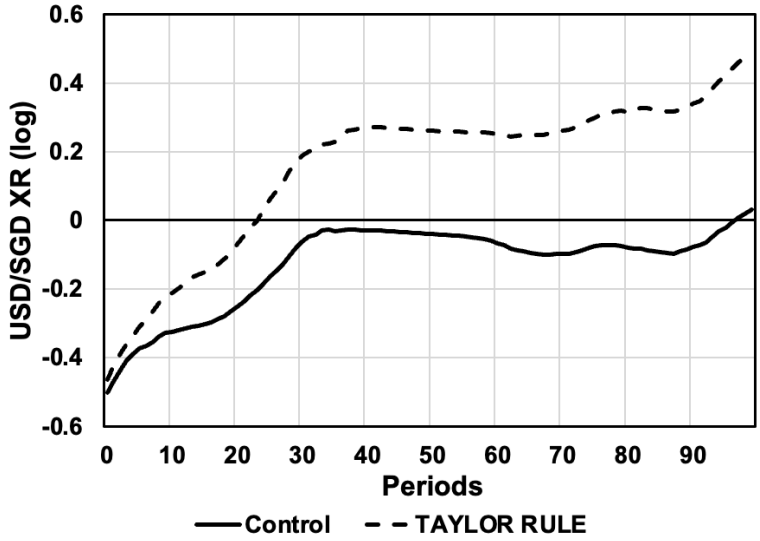


Figure 4: USD/SGD Exchange rate (Control vs Taylor Rule)

4.1 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, $\frac{\mu}{(1-\phi)}$ (where μ is the intercept and ϕ is the slope). Across these metrics, the results show that the Markdown rule attains lower RMSE, MAE, band stress share, 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

	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

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.

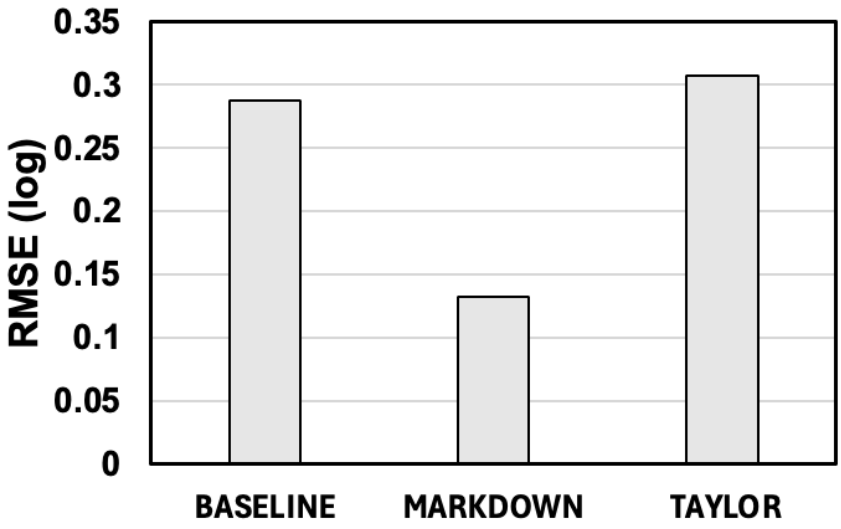


Figure 5: Root Mean Squared Error across regimes

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.

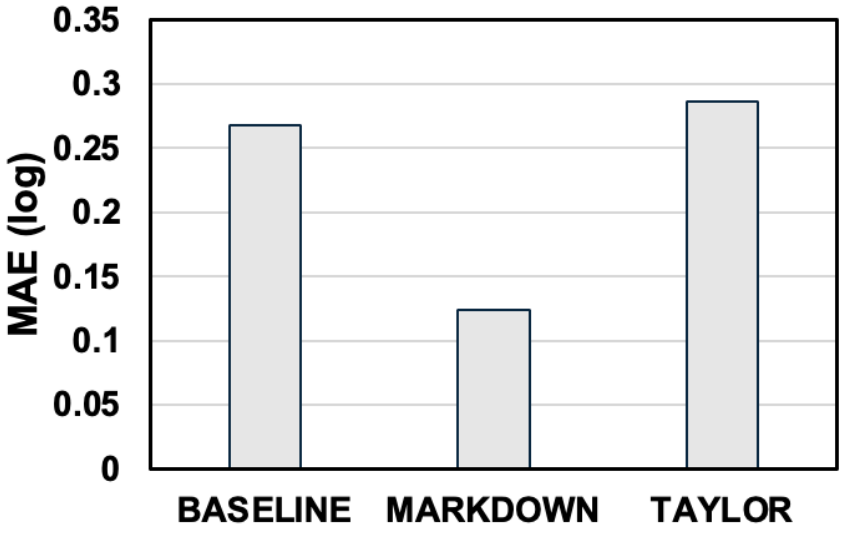


Figure 6: Mean Absolute Error across regimes

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

$$\delta_t = \mu + \phi\delta_{t-1} + \varepsilon_t$$

Here, 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; i.e., about 98% of any deviation carries over to the next quarter, and only 3% 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 $\frac{\mu}{(1-\phi)}$ (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 0.97 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 (0.586) and is larger in magnitude for Baseline (0.306) 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 characterised 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. These results are economically intuitive due to three main forces.

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.

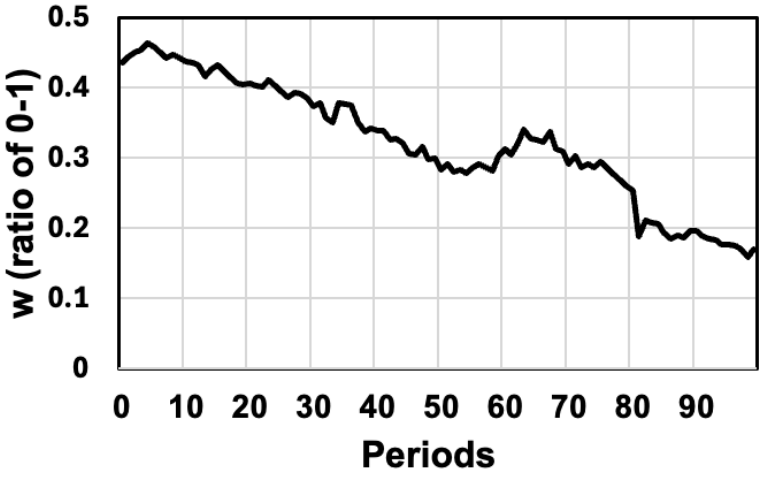


Figure 7: Value of w over time in the Markdown Rule

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 often provided 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 (and thus it sits below the original rate).

The final force is that foreign investors cannot invest in the CBDC because it is only open for Singapore locals. Thus, due to 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 with 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, it does not replicate the exchange rate path in the control series.

4.2 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 (Boulton et al., 2021). 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

	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 Q1-2000 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.

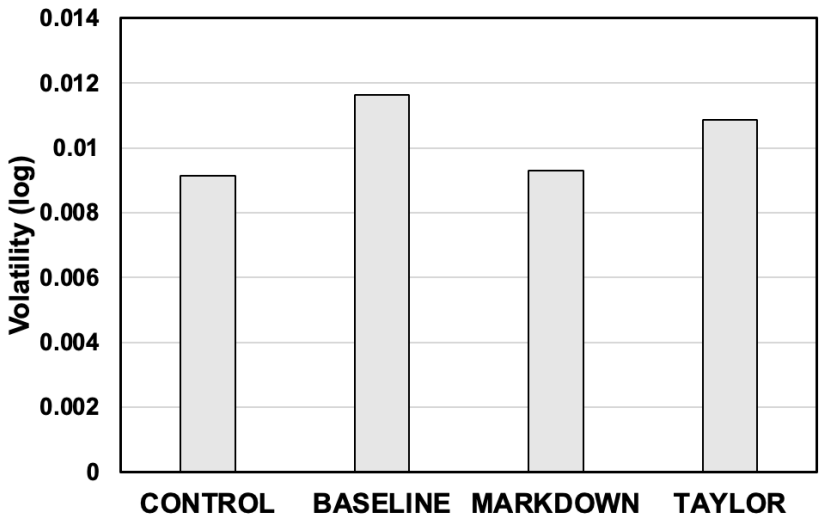


Figure 8: Volatility of Exchange Rates in Control and across CBDC regimes

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. 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.

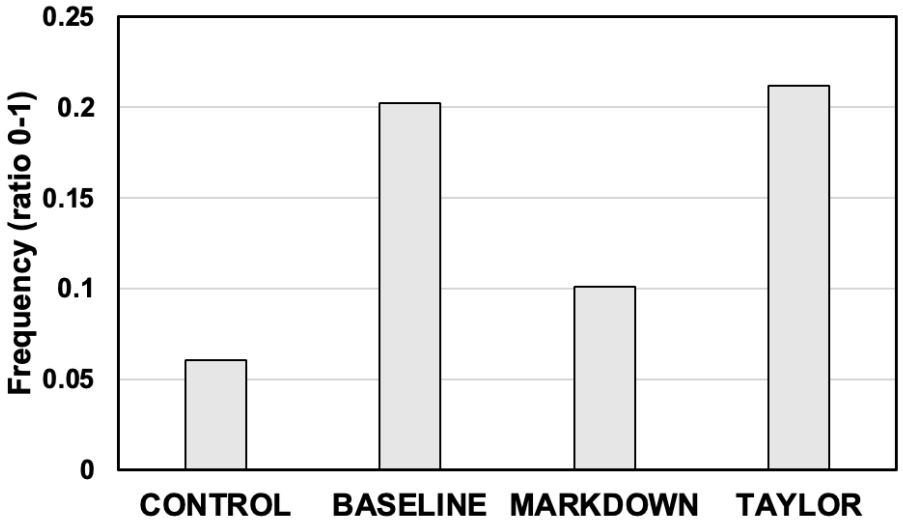


Figure 9: Frequency of moves greater than 0.02 log points (ρ)

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 ($|\Omega|$) 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).

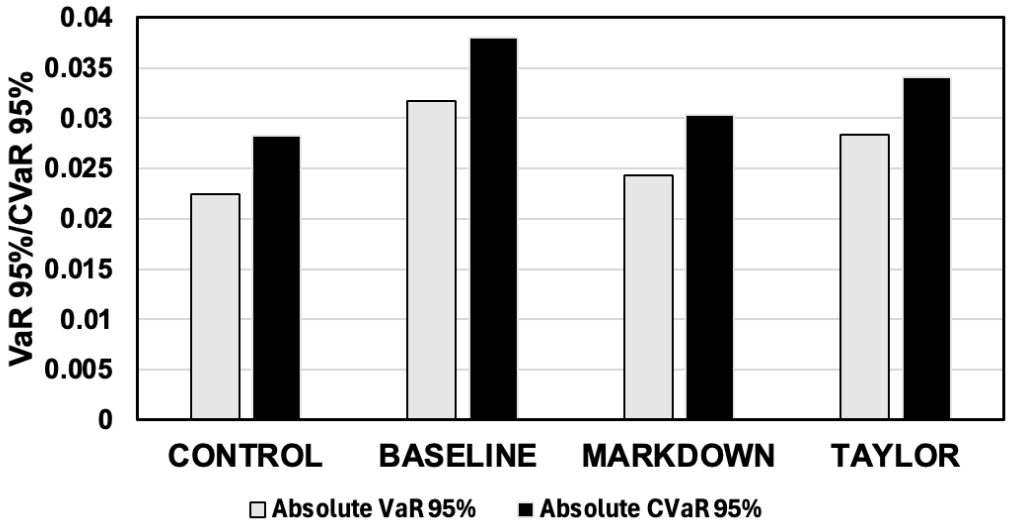


Figure 10: Absolute VaR 95% and Absolute CVaR 95% for Control and across CBDC regimes

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 because the WHO declared a pandemic in March 2020 (Cucinotta & Vanelli, 2020), and the IMF's April 2020 GFSR (IMF, n.d.) documented an abrupt tightening of global financial conditions as the pandemic hit. 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.

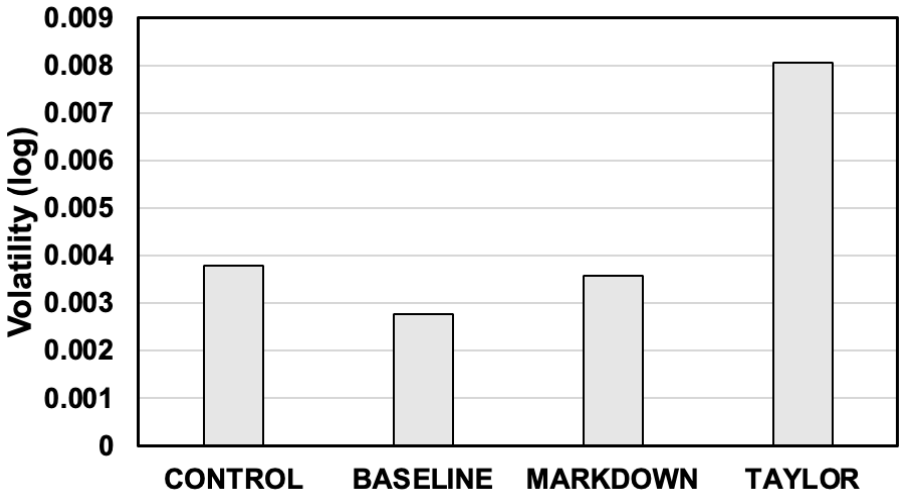


Figure 11: Volatility of Exchange Rates in Control and across CBDC regimes during COVID-19

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.

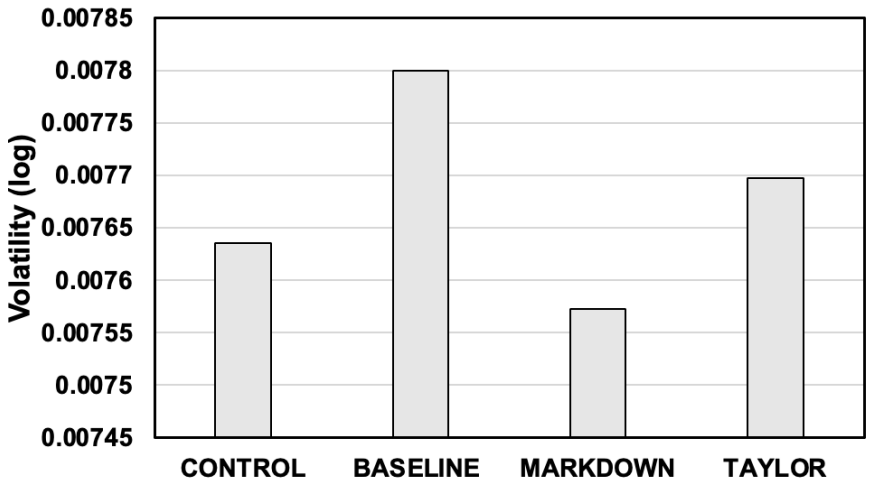


Figure 12: Volatility of Exchange Rates during the 2008 financial crisis

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.

4.3 Robustness

The calibrations in the scenario assessed are seen in Table 1. A significant driving factor when it comes to CBDC demand is the liquidity benefit of holding them, as quantified in μ_{dc} as the liquidity benefit parameter. Thus, the change in RMSE (primary indicator of path fidelity) and volatility (across the time period) for each CBDC regime are shown in Table 4.

Table 4. Sensitivity table to % changes in μ_{dc}

			Baseline Rule		
	-50%	-25%	Original	25%	50%
RMSE	0.275	0.282	0.287	0.291	0.294
Volatility	0.0115	0.0116	0.0116	0.0117	0.0117
			Markdown Rule		
	-50%	-25%	Original	25%	50%
RMSE	0.1270	0.130	0.132	0.133	0.135
Volatility	0.00930	0.00930	0.00930	0.00930	0.00930
			Taylor Rule		
	-50%	-25%	Original	25%	50%
RMSE	0.295	0.302	0.307	0.312	0.315
Volatility	0.0108	0.0108	0.0109	0.0109	0.0109

Table 4 shows that even when the CBDC liquidity benefit (μ_{dc}) is halved or doubled, the Markdown rule continues to produce the lowest root-mean-square error and the lowest annual exchange-rate volatility, confirming the robustness of the main findings.

5. Conclusion

The implications outlined here result from an open-economy model that uses the uncovered interest parity equation (weighted by portfolio composition) to link the interest rate differential to exchange rate changes in the context of a hypothetical CBDC implementation. To simulate this scenario, the paper outlines three plausible CBDC implementations (Baseline, Markdown Rule, and Taylor Rule) to generate counterfactual data on CBDC interest rates and compares it to a non-CBDC counterfactual of exchange rates. All parameters and data are calibrated to Singapore due to its unique exchange-rate-based monetary policy.

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 (MAS) 's goals and priorities.

The paper aims to describe two things: (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 changes in the exchange rate: 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. Thus, to answer the second question on the general impacts of CBDCs, only the Markdown Rule is compared to the Control (status quo), as it has been identified as the ideal form of implementation.

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. During shocks, however, the Markdown Rule had lowered exchange rate volatility by 0.82% (2008 crisis) to 5.98% (COVID-19). However, there isn't a clear economic link as to why volatility decreases during crises in the Markdown Rule, and thus the differences in volatility are likely due to sampling noise due to the short time period assessed in the shock.

The results on path fidelity are up to interpretation. In all the counterfactuals, the Singapore dollar steeply appreciated relative to the Control exchange rate. 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. This depreciation can have advantages and disadvantages.

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, on the other hand, the price of exports from Singapore will also increase due to the price of producing goods and services increasing domestically. 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, 2020). This paper does not aim to assess whether a stronger SGD is a boon or a disadvantage to Singaporean trade. Still, it empirically shows 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.

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