Australian National University

Crawford School of Public Policy

CAMA

Centre for Applied Macroeconomic Analysis

Central bank digital currency: A review and some macro-financial implications

CAMA Working Paper 12/2022
February 2022

Hongyi Chen
Hong Kong Institute for Monetary and Financial Research

Pierre Siklos
Wilfrid Laurier University
Balsillie School of International Affairs
Centre for Applied Macroeconomic Analysis, ANU

Abstract

Central Bank Digital Currency (CBDC) has attracted considerable interest and its deployment on a global scale is imminent. However, digital currencies face several challenges. They include: legal, technological, and political considerations. We summarize those challenges and add a few more that have not received much attention in the literature. We then consider two forms of CBDC: a narrow version that only replaces notes and coins and a broader form with a deposit feature. The narrow CBDC is the most likely one to be first introduced. Next, relying on evidence of past episodes of financial innovation, and using cross-country data, we explore the hypothetical impact of CBDC on inflation and financial stability, based on the historical behaviour of the velocity of circulation and incorporating a CBDC's impact in McCallum's policy rule which defines the stance of monetary policy based on money growth. Our simulations suggest that CBDC need not produce higher inflation, but financial stability remains at risk. We provide some policy implications.

Keywords

Central Bank Digital Currency, Velocity, Money Demand, Monetary Policy, McCallum Rule

JEL Classification

O31, O33, E41, E42, E51, E52, E54

Address for correspondence:

(E) cama.admin@anu.edu.au

ISSN 2206-0332

CENTRAL BANK DIGITAL CURRENCY: A REVIEW AND SOME MACRO-FINANCIAL IMPLICATIONS

HONGYI CHEN
HONG KONG INSTITUTE FOR MONETARY AND FINANCIAL RESEARCH

and

PIERRE L. SIKLOS
WILFRID LAURIER UNIVERSITY,
BALSILLIE SCHOOL OF INTERNATIONAL AFFAIRS, and
CENTRE FOR APPLIED MACROECONOMIC ANALYSIS (CAMA)

This Draft: December 2021

* The second author is grateful to the Hong Kong Institute for Monetary and Financial Research for a Fellowship under their Thematic Research Programme. Opinions in this paper are those of the authors and not the Hong Kong Institute for Monetary and Financial Research or the Hong Kong Monetary Authority. The authors are grateful to Michael Bordo, the Editor, and to three anonymous referees for comments on earlier drafts.

Hongyi Chen, Hong Kong Monetary Authority, hchen@hkma.gov.hk
Pierre Siklos, Wilfrid Laurier University, psiklos@wlu.ca

ABSTRACT

Central Bank Digital Currency (CBDC) has attracted considerable interest and its deployment on a global scale is imminent. However, digital currencies face several challenges. They include: legal, technological, and political considerations. We summarize those challenges and add a few more that have not received much attention in the literature. We then consider two forms of CBDC: a narrow version that only replaces notes and coins and a broader form with a deposit feature. The narrow CBDC is the most likely one to be first introduced. Next, relying on evidence of past episodes of financial innovation, and using cross-country data, we explore the hypothetical impact of CBDC on inflation and financial stability, based on the historical behaviour of the velocity of circulation and incorporating a CBDC's impact in McCallum's policy rule which defines the stance of monetary policy based on money growth. Our simulations suggest that CBDC need not produce higher inflation, but financial stability remains at risk. We provide some policy implications.

Keywords: Central Bank Digital Currency, Velocity, Money Demand, Monetary Policy, McCallum Rule

JEL Classification codes: O31, O33, E41, E42, E51, E52, E54

"You can see the computer age everywhere but in the productivity statistics." (Solow 1987) [1]

1. Introduction

The last decade will be remembered as disruptive because of a series of crises, two financial in nature and one health related, in a time of rapid growth in computing technology. While Solow's aphorism may well be correct his view does not detract from an emerging bout of 'creative destruction' in the monetary sphere. This is exemplified by the proliferation and growing sophistication of various forms of electronic payments. These developments have now turned to the impact from the potential introduction of a central bank digital currency or currencies (CBDC). The present paper is concerned with the potential inflationary impact of two potential forms of CBDC that would be used by the general public.[2] They are: a digital equivalent to existing notes and coins in circulation and a version that can also be deposited either in a central bank or in the banking system. The former would impact a narrow money supply aggregate (e.g., M0 or M1) while the second form of CBDC would also impact a broader monetary aggregate (e.g., M2 or M3).[3] BIS (2021, Graph III.4 and III.5) provide visualizations of the main forms of CBDC being contemplated. One can refer to the first form of digital money as a narrow CBDC; the second form would be called a broad CBDC. Notes and coins represent a central bank liability while broader monetary aggregates include various types of commercial bank deposits which are private sector liabilities.

Digitalization also offers the possibility for the central bank to issue CBDC in the form of a deposit, held either at the central bank or with an intermediary. Digitalization also implies that CBDC deposits can earn interest (positive or negative). Hence, a CBDC deposited with a central

[1] Solow's quip originates from a book review (Solow 1987) in which he also writes: "…what everyone feels is a technical revolution, …has been accompanied everywhere… by a slowdown in productivity growth, not by a step up." The term is associated, of course, with the work of Schumpeter and, succinctly, refers to "…process of industrial mutation that continuously revolutionizes the economic structure from within, incessantly destroying the old one, incessantly creating a new one…".

[2] This is distinct from w-CBDC, that is, digital money used to settle large or wholesale transactions. The Swiss National Bank, among other central banks, is already experimenting with this form of payment (see SNB 2020). Both alternatives have attracted considerable attention from policy makers because ther eis scope to avoid using central bank issued money. It also raises the potential to shift business away from the banking sector to non-bank institutions. See Waller (2021), and President's Working Group (2021).

[3] We do not consider the case of cryptocurrencies. Moreover, at times, there is sometimes confusion between CBDC and stablecoins. The latter are created by the private sector and may be backed by physical assets (e.g., gold), or financial assets (e.g., dollars), existing cryptocurrencies, or can be unbacked. See BIS (2019) and Barontini and Holden (2019) for additional details.

bank poses the risk that the monetary authority performs some of the functions of commercial banks (also see n. 3). Not surprisingly then, central banks have underscored their intention for CBDC, first and foremost, to complement existing notes and coin (e.g., Barrdear and Kumhof, 2016; Auer and Böhme 2021).

If the impending arrival of CBDC is treated as another type of financial innovation then economic history, subject to the limitations we point out below, may offer lessons for what might happen to inflation and financial stability. Since CBDC can potentially impact the money supply, we resort to two devices to explore the potential link between the introduction of a CBDC, inflation and financial stability. First, we examine the link between velocity (i.e., money demand) and inflation, an old concept in economics and largely downplayed or ignored in a world where the monetary policy transmission mechanism was viewed as being adequately described by considering interest rate movements only. We then incorporate the implications of our findings into an instrument rule (i.e., reaction function) proposed by McCallum (1988). The rule, proposed before Taylor's (1993) policy rule became the norm in monetary policy analysis, is defined in terms of money supply growth and velocity. We argue that it is well-suited to explore the hypothetical inflationary and financial stability impact of CBDC. McCallum's rule also has the advantage of being compatible with any definition of the money supply.

Why the surge of interest in CBDC? Initial indications, in part based on surveys of central banks, is that monetary policy and financial stability considerations top the list of motivating factors (e.g., see Boar et. al. 2020).[4] A contentious area of debate about the impact of CBDC is its potential impact on the conduct of monetary policy. Given that central banks have frequently intervened in financial markets in the form of unconventional monetary policy (UMP; e.g., see Lombardi et. al. (2019) for a survey), CBDC creates the prospect of central banks becoming more deeply involved in the realm of fiscal policy and credit allocation. After all, a CBDC offers the option for a central bank to digitally transfer funds to individuals.[5] Consequently, the digital

[4] Other explanations include as a vehicle for raising financial inclusion, improving the efficiency of payments systems, reducing the costs and facilitating cross-border payments, and mitigating illegal financial activities.
[5] The pandemic may have allayed these fears somewhat as governments were able to quickly, and digitally, transfer funds directly into individual households' bank accounts.

equivalent of a "helicopter money" drop becomes feasible. For example, testifying before a committee, Bank of England Governor Andrew Bailey stated recently that: "…helicopter money are not, for me, the reason that lie behind …." CBDC to which the committee Chair responded: "But it could be." (House of Lords, 2021) As a result, some private sector observers have sounded the alarm that CBDC may herald an era of higher inflation (e.g., Campbell 2020; Dantes 2021).

Another implication of CBDC is that it represents a vehicle to overcome the zero lower bound of interest rates (ZLB; e.g., Rogoff 2017b, Bordo and Levin 2018; Haldane 2021).[6] Moreover, if CBDC include deposit-like features it is likely that commercial banks will claim interference in their role as intermediaries though, as noted above, the threat of disintermediation also looms large due to non-financial firms' abilities to essentially replicate traditional commercial bank deposits (Waller, 2021). The potential blurring of fiscal and monetary policies means that central bank autonomy is also potentially under threat. In this paper we do not consider these implications any further.[7]

Many papers deal with the practical, technical, and legal issues surrounding the introduction of CBDC. There are also theoretical studies that examine the hypothetical financial and macroeconomic impact of CBDC. We briefly review the literature in the next section. Ours, however, is the first to rely on historical data to consider the range of hypothetical inflationary effects from the introduction of CBDC. We restrict our attention to the two versions of CBDC defined above.[8]

In motivating our findings, we turn to the literature on the velocity of circulation, that is, the ratio of GDP to the money supply, as a reminder that periods of rapid financial change are not new

---

[6] Assuming that notes and coins are largely replaced a central bank can, in principle, charge a penalty rate (i.e., a negative interest rate) on digital money holdings to spur spending. If the experience with negative interest rates so far provides any indications (e.g., see IMF, 2017) such a policy may have beneficial short-run macroeconomic effects.

[7] The threat of UMP to central bank independence is well-known (e.g., see de Haan and Eijffinger, 2017) while it has been argued that the autonomy of the monetary authority is also a function of the extent to which the financial sector opposes inflation (Posen, 1995).

[8] There is a proliferation of money supply definitions depending on the type of asset included in the definition. Nevertheless, the CBDC considered in this paper would be part of either M0 or M1 (currency and demand deposits) or broader variants, such as M2 or M3, which include bank deposits that are interest earning and highly liquid.

and that an historical understanding of institutional factors may be helpful to determine whether inflation control can be retained once CBDC are introduced. Velocity and, therefore, money demand, has a long history of being used as an indicator of the frequency of transactions taking place for consumptions purposes and, hence, can signal inflationary pressures (e.g., Laidler, 1993). That said, we also point out some of the potential limitations of our empirical results.

Because CBDC may impact the money supply it is less convenient to rely on instrument rules of the Taylor (1993) rule variety. In principle, a monetary aggregate becomes the instrument of interest. McCallum (1988) developed just such a money growth rule. McCallum's rule is, perhaps just as important, unencumbered by the ZLB and it also has the virtue, together with UMP, of shifting focus to the central bank's balance sheet. McCallum's rule is used to simulate scenarios of different monetary policy stances in an environment where financial innovations take place. We rely on over a century of data to explore past episodes of rapid technological developments in transactions technologies noting the potential pitfalls in doing so, to determine hypothetical future inflation paths and consequences for money supply growth. We also consider a shorter sample covering more recent decades and consisting of both advanced and emerging market economies to provide additional support for the main contentions of this paper. Finally, since it is claimed that CBDC can also aid in preserving financial stability, we also empirically consider whether CBDC can reduce its incidence.

The rest of the paper is organized as follows. Section 2 considers the main issues arising from the prospect of introducing CBDC. The discussion focuses on the issues of greatest relevance to this paper, namely some of the monetary policy implications of CBDC. Section 3 then considers the institutional and historical evidence that might be informative about the consequences of introducing CBDC. This strategy is adopted because it offers some clues about the consequences of the latest trends in payments innovations and how this can affect the velocity of circulation. Our simulations suggest that CBDC need not impair inflation control. However, financial stability concerns are not necessarily overcome by the introduction of a CBDC. Indeed, the regulatory and institutional environments will dictate the eventual inflation and macroeconomic effects of CBDC. Section 4 concludes by summarizing our findings and some questions left for future research.

2. Framing the Issues: Literature Survey

Several authors have highlighted the confusion surrounding the definition of CBDC (e.g., Meaning et. al. 2018). In the present paper, we are interested in a digital currency issued by the central bank that complements its traditional role as supplier of notes and coins in circulation. The possibility that some features associated with digital technology, to be described below, can also be added is also entertained. At a minimum, CBDC are intended as a perfect substitute for circulating notes and coins. In practice, however, the digitalization of money provides an avenue for CBDC to potentially overlap with some of the services provided by commercial banks, as we shall see.

Rogoff (2017a), Bordo and Levin (2018), Davoodalhosseini and Rivardeneyra (2018), Brunnermeier et. al. (2019b), and BIS (2021), are just a few of the many studies that have taken a 'big picture' approach to explain the economic and financial stability implications of CBDC. Theoretical guidance about the impact of CBDC on monetary policy and monetary transmission mechanisms is, to date, limited. Niepelt (2020) concludes that theory is unsatisfactory in informing policy makers about the consequences of introducing CBDC. He notes: "…the discussion about digital central bank money could benefit from well-articulated, coherent, formal models that clarify equivalence relations…" (op.cit., p. 233).[9] Turning to empirical evidence, we suffer from a lack of data. Instead, the existing literature has resorted to surveys and other indicators to assess the acceptability and public concerns surrounding the introduction of CBDC and central banks' role in the process (e.g., see BIS, 2021; Auer and Böhme, 2021; Haldane, 2021).

The existing literature is heterogeneous, often highly stylized, and is not always clear about how CBDC fits in with existing traditional definitions of money since the precise form CBDC in

[9] A classic example of an irrelevance or equivalence proposition is the Modigliani-Miller theorem which states that, in an efficient market with no transaction costs, taxes, or agency costs, the value of a firm is not affected by whether it is financed by selling debt or equity. Reality, of course, contradicts these assumptions. Another example is the concept of Ricardian equivalence which defines conditions under which debt-financed spending today will fail to stimulate economic activity because it is treated by individuals as a deferred tax. The theory is viewed as being implausible in explaining the long-run impact of government borrowing.

question plays a critical role. Narrow money typically consists of notes and currency that circulate outside the banking system and reserves held at the central bank inside the banking system.[10] Similarly, the sheer number and variety of financial assets make it difficult to come up with a comparable definition for a broad monetary aggregate across countries. Traditionally, however, broad money consists of narrow money and a set of highly liquid financial assets booked in the regulated (i.e., typically commercial) financial system.[11]

In what follows, a narrow version of CBDC is assumed to be a digital version and perfect substitute for notes and coins, with no additional features. Hence, it is a perfect substitute for circulating notes and coins only. However, CBDC also offers the potential for the payment of interest. It also conceivably allows citizens to directly access the central bank or for commercial banks to create new types of digital accounts to accommodate CBDC holdings.[12]

Several authors have also raised a potential externality from CBDC for the commercial banking sector (see, inter alia, Rogoff 2017a; Bordo and Levin 2018; and Brunnermeier and Niepelt 2019; Fernández-Villarverde et. al. 2020; BIS 2021; Haldane 2021). Because of the potential interest earning component of CBDC, it may blur the distinction between central banks and commercial banks and, hence, impact the conduct of monetary policy by pitting the monetary

---

[10] This is also called base money. Regulatory and other changes in financial structure in several countries have done away with required reserves. Although the International Monetary Fund continues to publish base to (broad) money ratios and base growth series in *international Financial Statistics* only the currency component is, strictly speaking, comparable across countries. There are differences in definitions for the remaining components of the monetary base though the IMF strives to ensure international comparability. See IMF (2016, pp. 197-200). CBDC has the potential to further reduce the relevance of traditional forms of reserves, depending on whether or not it is intended only as a perfect substitute for cash.

[11] Monetary aggregates are typically obtained by summing various financial assets with differing degrees of moneyness. Attempts at weighting various components of existing monetary aggregates proved popular for a time in the form of divisia monetary aggregates (Barnett 1980, inspired by Diewert 1976) subsequently re-branded as monetary services indices. While some are still published most have been discontinued in part because of the perceived decline in the predictive role of monetary aggregates even if they retain some of their power to do so (e.g., see Siklos and Barton 2001, and references therein).

[12] The relevant literature often does not make clear that commercial banks offer a wide variety of services. Central banks have no desire to emulate all the complementary services offered by banks. For example, by 2003, that is, well before the GFC, U.S. banks generated almost half of their income from non-interest sources (De Young and Rice 2004). Interestingly, this ratio has declined and Haubrich and Young (2019) conclude this reflects a reaction to the falling out of favour of securitization. Brunnermeier et. al. (2019b) find that non-interest income and systemic risk co-vary for U.S. banks. The foregoing trends provide another avenue for CBDC to potentially impact financial stability risks.

authority and banks against each other in attracting depositors.[13] Central banks, of course, are aware of the pitfalls and, hence, generally favor a form of CBDC that is restricted to functioning as an alternative only to notes and coins in circulation (e.g., as in Auer and Böhme 2021).

Two theoretical strands have emerged to tackle the potential role and significance of CBDC (see also Carapello and Flemming 2021). The 'new monetarist' theory (e.g., see Lagos et. al. 2017) is grounded in the micro-foundations of money and asks what motivates transactions using an asset with the functions ascribed to money in the presence of costly frictions (e.g., search). One of the monetary policy implications of this theoretical approach is the conclusion that some inflation is desirable, although money is not interpreted as providing separate utility to individuals in this modeling strategy. Another approach draws from Diamond and Dybvig's (1983) seminal bank run model which is useful to understand the implications of CBDC in a world where markets are subject to disruption due to financial innovations. The focus here is on the liquidity of monetary assets and the role of trust and confidence in banking institutions to ensure that transactions are settled. This is particularly relevant when considering the risk characteristics of various assets. According to this theory individuals may not view digital equivalents to conventional notes and coins as risk-free.[14]

Other theoretical approaches incorporating CBDC include cash-in-advance models, where money is essential to buy goods and services and must therefore be held by individuals, or models where two different assets with monetary characteristics circulate side-by-side (Kiyotaki and Wright 1989), as well as overlapping generations models (Kim and Kwon 2019). The former is relevant to the CBDC debate because of the potential for narrow money to possess some of the characteristics of inside money. The latter is useful if, for example, CBDC are adopted by some groups but not by others who prefer to hold conventional notes and coins.

[13] This is clearly the case if individuals are permitted to choose between holding CBDC balances at the central bank or in a commercial bank. If this is not the case, then the services provided by CBDC and interest on digital currency holdings can conceivably compete with debit and credit type transactions.

[14] It is common to assume, for example, that U.S. Treasuries are essentially risk-free assets. However, as is now well-known, this normally highly liquid market experienced considerable stress in early March 2020 as the pandemic's economic and financial consequences rapidly magnified. See, for example, Cheng et. al. (2020). The crisis was addressed only when the Federal Reserve intervened heavily in U.S. Treasuries. The bottom line, however, is that classes of financial assets once deemed risk-free may contain more risk than previously thought.

Much has been made about how CBDC can improve the efficiency and safety of payments systems (e.g., BIS 2020a, 2020b; 2021). This provides a link between the introduction of CBDC and the desire to maintain financial system stability. For example, the Bank of Japan and the ECB have underscored the payments dimension of the digitization of the economy.[15] Globally, there exist a large number of networks, not all equal in terms of their readiness for real-time settlement. Readiness is a desirable objective given that settlement in cash is final.[16] This is on top of retail payment systems where delays in settlement imply some residual risk, at least relative to cash. Whether these risks are small enough to be ignored is an issue we do not consider nor whether cyber risks, and the capacity of the authorities to counteract them, also imply risks to the introduction of CBDC not be present with holding conventional notes and coins.

It is sometimes under-appreciated that CBDC would be introduced an environment where a proliferation of other forms of electronic and digital payments have become commonplace (e.g., credit and debit cards). Moreover, commercial banks, and their non-bank competitors, have also adapted to technology in the current environment through the spread of automatic teller machines (ATM) which have, over time, gone beyond simply dispensing cash.[17] Nevertheless, as BIS (2021) reveals, the public underestimates how costly common alternatives, such as debit and credit cards, are relative to a CBDC.

One curious omission in the debate over the introduction of CBDC (see G30 (2020), Arner et. al. (2020), Kiff et. al. (2020), and Allen et. al. (2020), Bank of England 2020), with potential financial stability implications, is the problem of data storage. Digital forms of payment require that balances in CBDC be stored. The idea of centralizing such storage raises all sorts of risks,

[15] See ECB (2020), And Kihara and Wada (2020).

[16] The authorities are aware of the need for "interoperability" and, at least in 2016, domestic interoperability between retail and wholesale systems is common in advanced economies while cross-border interoperability is still a work in progress (see Tompkins an Olivares 2016). Also, see Auer et. al. (2020) for an overview of the technical architecture of CBDC.

[17] Data from the World Bank (not shown but see *Appendix*) suggest stability or modest increases only in the number of ATMs in the advanced economies. Many of the largest EMEs have seen sharp increases in ATMs. Sweden is somewhat of an exception as the number of ATMs has seen a steady drop since 2011. Similarly, based on BIS data, the number of cards (cash, debit, and credit) issued has remained steady in AE while rising quickly in most EME. Also see Auer et. al. (2020).

from privacy to security, but even if storage is decentralized[18] the sheer size of storage required, not to mention its durability, are details that have not been adequately addressed to date.[19]

The political-economy implications from the introduction of CBDC also cannot be ignored. These include improvements in financial inclusion, a goal normally outside that of conventional central banking,[20] the risks to monetary sovereignty or in the status of global reserve currencies, as well as the independence of central banks not only from governments but from the commercial banking sector and the loss of anonymity that cash transactions provide.[21] Indeed, in a first report published by a consortium of central banks, complete anonymity for CBDC is deemed "not plausible" (Bank of Canada et. al. 2020).

The GFC, and now spurred by the ongoing pandemic, has enhanced the potential for CBDC to generate monetary policy effects since it is seen as an additional instrument that helps overcome the reduction in the effectiveness of conventional monetary policy at the zero or effective lower bounds (ELB).[22] In particular, CBDC opens up the possibility of QE for all because liquidity in a digital form can be made available to all citizens. Similarly, a CBDC with an interest rate component could also be used to discourage money holdings via negative interest rates. The digital element, combined with the eventual withdrawal of conventional notes and coins, would then mitigate the impact of the ELB. CBDC can therefore be viewed as another safe asset that can overcome shortages during crisis conditions (e.g., as with USD during the GFC). Of course, in these situations, CBDC are no longer perfect substitutes for existing notes and coins. Haldane

---

[18] If this is done across borders, then potentially sovereignty related questions will also emerge.
[19] The question of storage and durability is inspired by challenges faced in other fields as in physics, notably the storage of data generated by CERN (Central organization for Nuclear Research), and the life expectancy of current technology which is far less than that of conventional paper or polymer notes.
[20] Data from the World Bank Development Indicators (see the *Appendix*) reveal a tendency for the income share of the bottom 20% of the distribution to have fallen in advanced economies while the opposite trend is more apparent among EME. Furthermore, bank account ownership among the poorest 40% of the population has tended to rise in EME remaining stable in AE. Also see Sahay et. al. (2020).
[21] The loss of anonymity has frequently been raised as a critical issue. To be sure, many individuals and business will always prefer cash. Yet, the proliferation of online and card use, not to mention smartphones, also suggests that some of these concerns are overblown (e.g., see Warzel and Thompson 2019). Indeed, cards and smartphones underscore the role that 'loyalty' plays in transactions technology (e.g., see Amamiya 2019). Central banks are keenly aware of the issues, but the bottom line is that no technology is able yet to provide full-proof anonymity with digital transactions. Darbha and Arora (2020) clearly outline the technical challenges, but also see Bindseil (2020) and Shirai (2019).
[22] Not everyone shares this opinion. Lombardi et. al. (2018, 2019), and references therein, consider both sides of the debate.

(2015, 2021), Rogoff (2017a), and Meaning et. al. (2018) are a few of the authors who have discussed these issues.

It is reasonable to ask whether introducing a financial asset, whose share is modest in the universe of liquid and safe assets, can make such a difference. The simple answer is that we do not yet know. However, by way of an analogy, central banks intervene in foreign exchange rate markets and, while the amounts are dwarfed by the size of the market, there is little doubt that exchange rate levels and volatility can be impacted, even if only temporarily.[23] More importantly, CBDC has the potential to blur fiscal and monetary policies. A concern is whether it is appropriate for the central bank to become involved in credit allocation if CBDC are used as a QE vehicle for all. Many see a further expansion role of the central bank as potentially problematic.[24]

Turning to the empirical dimension, the arrival of CBDC may well lead to a resurgence of interest of putting 'money' back into monetary policy. Some of the debate has also revolved around questions noted earlier such as how to define monetary aggregates. Notably absent, however, from much of the discussion is the role of the velocity of circulation. The so-called institutionalist hypothesis of velocity (Bordo and Jonung 1981, 1987) is a theory that explains how technological changes in payments systems, improved communications, and changes in the services offered by banks, impact velocity. Modern time series analysis later highlighted how financial innovations could create stability in the long-run behavior of velocity where traditional specifications, mirrored in conventional money demand functions, could not (Siklos 1993). It is but a short theoretical step to link the behavior of velocity to inflation (also see Laidler 1993). We rely on this approach to consider the potential impact of CBDC.

Beyond the traditional monetary policy functions of money, the introduction of CBDC provides a means to mitigate financial stability risks. For example, if CBDC have deposit and interest rate characteristics, the central bank can use these to ensure that there is sufficient liquidity when

[23] See Fratzscher et. al. (2019) for a recent survey and international evidence.
[24] The view that central banks ought to have a well-defined and a remit narrowly focused on price stability was impacted by the GFC. CBDC is yet another challenge society faces in deciding how many responsibilities central banks should have. See, for example, Hartmann et. al. (2018).

crisis conditions would otherwise lead to a flight to quality. CBDC, even in its narrow money form, can also be viewed as a broadening of the central bank's traditional role as a lender of last resort but in a new guise (e.g., see Henckel et. al. 1999, Armelius et. al. 2020). Moreover, CBDC provide additional underpinnings to ensure the smooth and secure functioning of the payments system. That said, given the existence of a large number and variety of systems the technical elements required to improve the quality of payments systems appears daunting. Perhaps this is one reason why central banks have emphasized the public-private partnership potential for CBDC (e.g., see Bank of Canada et. al. 2020, FSB 2020).[25]

3. Empirical Analysis

3.1 Institutional Change and Velocity Redux

CBDC may be viewed as the latest in a long line of financial innovations with institutional implications. Bordo (2021) also underscores how monetary history can inform the debate about the potential importance and consequences of the imminent introduction of CBDC. As Laidler (1993) points out economists have: (1) historically stressed the transactions velocity of circulation, namely the ratio of GDP to a money supply measure, and their longer-run connection to inflation; and, (2) theory has focused on the "nature of the institutional arrangements surrounding the transactions-making process." (Laidler 1993, p. 48).

Theoretically, velocity and money demand are determined by income and an opportunity cost of money (or other assets with money-like features). The institutionalist hypothesis (see Bordo and Jonung 1981, 1987) points out, however, that the traditional model of velocity omits two critical ingredients. First, increased monetization and, subsequently, the growing sophistication of financial markets also impact velocity over time. Below we describe how these developments are empirically proxied.

[25] Since CBDC has sparked interest among many central banks (see Boar et. al. 2020) this also highlights the need for international cooperation or coordination for the same reason that the GFC, and financial crises before that, led to the creation and raised the profile of the Financial Stability Board (FSB). The FSB was created in the wake of the GFC to enhance regulation and supervision of the financial sector at the international level. See https://www.fsb.org/history-of-the-fsb/.

Equation (1) describes a traditional model of velocity. The institutionalist hypothesis posits that the traditional model suffers from an omitted variables bias and, therefore, adds a second vector of variables to capture the role of financial innovations over time. The resulting specification is written as equation (2) below.

$$v_t = \delta_0 + \boldsymbol{\delta}_\mathbf{j}\boldsymbol{\Phi}_t + \varepsilon_{0t} \quad (1)$$

$$v_t = \beta_0 + \boldsymbol{\beta}_\mathbf{j}\boldsymbol{\Phi}_t + \boldsymbol{\beta}_\mathbf{k}\boldsymbol{\Omega}_t + \varepsilon_{1t} \quad (2)$$

where $\boldsymbol{\Phi}_t = \left[y_t^{pc}, i_t \right]'$, and $\boldsymbol{\Omega}_t = \left[CM_t, TNBFA_t, \pi_t^e \right]'$ are the vectors of determinants that drive velocity. The traditional model (1) requires only income and an interest rate (y,i), while the institutionalist approach (equation (2)) adds the currency-money ratio (CM), considered a proxy for financial innovation (total non-bank financial assets to GDP or TNBFA), and expected inflation (π^e).[26] To economize on notation, equations (1) and (2) are understood to apply to each economy considered or to a cross-section of countries (i.e., panel). Money is either proxied by a narrow measure (e.g., monetary base, M0, M1) or a broad measure (e.g., M2, M3).

Income is theoretically expected to be negatively related to velocity while interest rates positively influence velocity (e.g., see Laidler 1993; Bordo and Jonung 1981).[27] Empirical evidence suggests that relationships such as (1) can break down for a variety of reasons, ranging from changing definitions of the money supply to a shift in emphasis at central banks to using an interest rate instrument to conduct monetary policy. Nevertheless, there has been a small revival of interest and recent empirical evidence is suggestive that expressions like equation (1) may be stable if proper account is taken in the definition of monetary aggregates to capture the impact of financial innovations (e.g., Lucas and Nicoloni 2015) or if the long-run equilibrium condition, namely that money demand and supply are equated to each other, is explicitly accounted for

[26] The vast literature that links financial innovation to economic growth (e.g., see Laeven et. al. (2015) and references therein) also always uses some indicator of private credit to GDP. Leaven et. al. (2015) also investigate using an indicator based on when private credit bureaus were created but this does not detract from the conventional credit to GDP proxy. Other data, such as that contained in the BIS's Red Book which collects information about the number and type of payments cards, ATMs, electronic payments, and the like, (https://stats.bis.org/statx/toc/CPMI.html) are available only for relatively short samples (e.g., starting in 2010 in many cases). Similar data can be found in the World Bank's World Development indicators (https://databank.worldbank.org/source/world-development-indicators). We have used some of these data (see the appendix).

[27] Since velocity is the inverse of money demand the positive influence of interest rates on velocity becomes negative when money demand is considered. The sign is similarly reversed for income.

(e.g., see Benati et. al. 2018).[28] In other words, this amounts to an acknowledgment that financial innovations play a critical role in explaining economic activity, including inflation (e.g., also see Levine, 2005a, 2005b).

Figure 1a reproduces, using more up to date definitions of income and the money supply, the long-run pattern of velocity described above, at least until 1986, for five advanced economies that formed the basis of the empirical evidence for the institutionalist hypothesis (Bordo and Jonung, 1981). Conveniently, discussions are far-advanced about the potential introduction of CBDC in at least three of the countries shown (Canada, Sweden, and the UK) but CBDC is also a topic increasingly debated in the US and Norway. The velocity series from Siklos (1993) have been updated as have the other series, including the monetary aggregates.[29] Figure 1b updates the data until 2016, using the same definition as in the top portion of the same figure. We now observe a broad decline in velocity. However, it is worth noting that the definitions of money aggregates, the denominator in the definition of velocity, include a wider array of liquid interest earning assets. It is natural, of course, to ask whether the descriptions above generalize to other economies. The plots shown in Figure 2, for 19 economies, suggests that developments in velocity observed in the bottom portion of Figure 1 is a global phenomenon and not restricted only to advanced economies.[30]

Figure 3 displays a measure of velocity based on a narrow monetary aggregate, consisting of notes, coins, and checkable deposits. Rising velocity is now especially visible for Sweden and Norway beginning in the early 1990s. In the remaining three countries shown, velocity stalls

[28] Another important element in the debate concerns whether the semi-logarithmic form of (1) is adequate as opposed to the log-log form (e.g., see Ireland 2008, Nakashima and Saito 2012, Benati et. al, 2018). We retain the semi-logarithmic form, as did the earlier literature on velocity cited above, though all our conclusions are unchanged even when the log-log specification is used.

[29] There are long-run time series for a few other countries, though not all, in Jordà-Schularick-Taylor (http://www.macrohistory.net/data/). However, below we add information from a wider array of countries for the most recent history of velocity. The *appendix* contains a plot using the original data from Siklos (1993). There have been some changes in the definition of some of the monetary aggregates (M2 in Siklos, 1993) though they are still referred to as broad measures of the money supply. We were also able to add Australia, Japan, and Switzerland to the data set (not shown). All conclusions below were repeated for a panel that included these three additional countries with no impact on the main conclusions to follow (results not shown).

[30] Interestingly, Uruguay is one exception to this phenomenon. It is also one of the few to have briefly experimented with a digital currency. See, for example, Licandro (2018). Similarly, the decline in interest rates, albeit to levels that are relatively higher in emerging markets, is also observed in all the economies besides the ones examined in Figure 1. We relegate the relevant data to the *appendix*.

from the middle to the end of the 1980s and then declines. Hence, the data reveal the impact of the shift away in some, but not all, advanced economies considered in their holdings of notes and coins. Velocity is comparatively stable in Canada, and in the U.S. at least until the GFC. The gentle decline in velocity in the U.K. dates approximately from the early 1990s, that is, around the time inflation targeting is introduced (1992) and following a noticeable acceleration in the aftermath of the financial 'big bang' (1986).[31]

Figure 4a plots real per capita income on a normalized scale since the late 1980s while Figure 3b shows central bank policy rates. Other things equal, the rise in income would have contributed to reducing velocity (i.e., increase money demand) as would have the broad decline in interest rates shown in Figure 4b. These developments might explain some of the changes in velocity based on a narrow money aggregate as in Figure 2, at least for Sweden and, possibly, Norway.

Figures 5 and 6 display two institutional determinants of velocity since 1871. They are: in Figure 5, the currency-money ratio (CM), that is, notes and coins in circulation over the broad money measures used to calculate velocity (see Figure 1), and, in Figure 6, total loans to the private non-bank financial sector (TNBFA) as a percent of GDP. As explained above, both have been widely used as proxies for financial innovation. In three of the five countries the drop in CM shown in Figure 5 is consistent with the decline in velocity. For the U.S. there is relative stability but a sudden change beginning with the GFC that only begins to be reversed in the last few years of the sample. Canada is the only exception though the pattern reflects a return of sorts to late 1970s levels. Figure 6 shows the share of total loans to the non-bank private sector as a percent of GDP. To be sure, such a measure also captures the rising financialization of the economy, especially in the post-World War II era. However, to the extent that the rise in the series exhibited in all five economies shown also reflects the rise in the number of assets with money-like characteristics, then this would also presage a decline in velocity. Stated differently, the rise in loans would be reflected in the broad monetary aggregates used to calculate velocity.

[31] There was also a sharp increase in the assets at financial institutions, as a percent of GDP, in the early 1990s owing to reforms to deposit insurance and the introduction of real time gross settlement. See Bowen et. al. (1999).

Equations (1) and (2) are two alternative ways of expressing equilibrium relationships. In statistical terms, this translates into two versions of cointegrating relationships. In particular, if cointegration is not obtained in (1), but is found using (2) then an equilibrium relationship that describes velocity's behaviour requires the inclusion of institutional factors including ones that can be traced to financial innovations.[32] Hence, the equilibrium relationship defined in theory requires that we account for the impact of financial innovations. This renders equation (2) as the relevant relation to consider hypotheses about the potential impact of either a narrow or a broad form of CBDC.

The potential for cointegration implies that these equations must be expressed in error correction form:

$$\Delta v_t = \delta_0^{'} + \boldsymbol{\delta}_{\mathbf{j}}^{'} \Delta \boldsymbol{\Phi}_t + \boldsymbol{\delta}_{\mathbf{2}}^{'} \boldsymbol{\Sigma}_{t-1} + \varepsilon_{0t}^{'} \qquad (1)'$$

$$\Delta v_t = \beta_0^{'} + \boldsymbol{\beta}_{\mathbf{j}}^{'} \Delta \boldsymbol{\Phi}_t + \boldsymbol{\beta}_{\mathbf{k}}^{'} \Delta \boldsymbol{\Omega}_t + \boldsymbol{\beta}_{\mathbf{1}}^{'} \boldsymbol{\Sigma}_{t-1}^{'} + \varepsilon_{1t}^{'} \qquad (2)'$$

where Δ is the differencing operator, $\boldsymbol{\Sigma}$ are the error correction terms,[33] and all other terms have already been defined. Since the variables in (1) and (2) are endogenous it is natural to express the equations in vector autoregressive (VAR) form. The addition of error correction terms in (1)' and (2)' means that the models are written in vector error correction model (VECM) form.

To test for cointegration we perform two sets of tests using the long-run data set shown in Figure 1. Table 1 presents several test results. Part A of the Table shows test results for the conventional velocity equation (1) for the panel of five countries as well as each cross-section; part B of the Table repeats the same exercise for the extended velocity model (equation (2)).[34] The top portion

[32] Cointegration may be sensitive to the possibility of large shocks (i.e., breaks) or the fact that the behaviour of velocity has common features across several countries. Bordo et. al. (1996) provide evidence suggestive of a 'North Atlantic' velocity function.
[33] If there is only one cointegrating vector, then the error correction term becomes a scalar; otherwise, it becomes a vector.
[34] The tests results discussed below represent a mix of country-specific and panel estimates. In the case of panels cross-section and time fixed effects are considered when statistical tests conclude they are required. Cross-section fixed effects are retained in the final specifications. A referee correctly pointed out that there exist other panel cointegration tests. We did consider other residuals-based type test (e.g., Pedroni 2004; Westerlund 2007) but these corroborate the results shown in Table 1.

of part A of Table 1 suggests that there is evidence of common features in velocity which confirms and updates the evidence in Bordo et. al. (1996). When we turn to the individual cross-sections there is, at conventional significance levels, mixed evidence about the cointegration property for velocity model (1). In three of five countries shown the null of no cointegration cannot be rejected.[35] Turning to the extended model (part B of Table 1) the evidence is more convincing in favour of a finding of one or, at most, two cointegrating relationships whether the panel or the individual cross-sections are considered, with the possible exception of Sweden. Hence, cointegration again requires adding additional variables to proxy changes in financial sophistication or institutional change.[36]

Figure 7 plots the fitted values from the estimated cointegrating relationships for all five countries since 1870, focusing on the case where there is a single cointegrating relationship. The left hand-side column shows estimates based on equation (1) while the right hand-side column plots the case for equation (2). In theory, the residuals (left hand-side scale) from the estimated cointegrating relationship should be stationary (i.e., I(0)).[37] A visual comparison of the two sets of series illustrates that, to obtain the necessary condition of stationarity, the traditional velocity model (left hand-side) fails while the model augmented with proxies for financial innovations (right hand-side) generates the desired results.

We also examine a broader set of economies, namely the ones shown in Figure 2, for a more recent but shorter sample. When estimated in a panel setting, we find some evidence that the variables in a conventional velocity model are not cointegrated. However, when additional proxies for institutional change are added (e.g., income share of the poorest 20% of the population, number of mobile subscribers, number of secure internet servers) does yield a long-run or cointegrating relationship with velocity.[38] This suggests that accounting for financial

[35] Indeed, application of Hansen's alternative test for cointegration (the null is cointegration) is suggestive of the fragility of cointegration based on the traditional velocity model for all five countries.
[36] The results in part B include expected inflation but the conclusions are unchanged when this variable is excluded. Indeed, estimates of the cointegrating vectors and the resulting estimates of the income and interest rate elasticities (not shown but see the *appendix*) suggest that inflation expectations are highly insignificant for all countries with the possible exception of Sweden.
[37] The residuals from equations (1) or (2), lagged one period, represent the error correction terms.
[38] Owing to a relatively small number of observations (18 cross-sections for annual data for the 1998-2018 sample or 378 total observations) the residual ADF-test is, for example, -1.48 (p-value 0.16) for equation (1) and 1.35 (.09) for equation (2) when ATMs and the fraction of the poorest 20% are the institutional change proxies. Other variants

innovation is essential to generate the cointegration property and , hence, establishes the statistical equivalent of an equilibrium relationship. Another implication of the results is that the long-run forces that explain velocity in the advanced economies considered above appear to be global in nature.

Having examined the statistical properties of velocity over time and across countries, we can now turn to asking: what are the potential inflationary effects of CBDC? Since digital money represents a financial innovation, it can potentially impact velocity and, hence, inflation and economic activity according to the institutionalist hypothesis. Since, there are no data for CBDC in circulation we resort to simulations to ascertain how inflation might be affected by the introduction of CBDC.

3.2 Monetary Policy Under CBDC: Using McCallum's Monetary Policy Rule

An implication of the foregoing discussion is that CBDC have the potential to be actively used to influence monetary policy conditions even if policy makers have tended to downplay this possibility as noted in the introduction.[39]

Therefore, at this stage, we can only speculate how a central bank's balance sheet might evolve once a CBDC is introduced. A plausible starting argument is that CBDC's impact can be likened to developments following previous eras of financial innovation. Resort to outside money (i.e., issued outside the private sector such as a central bank), as well as the convenience and return from inside money (i.e., private sector issued financial assets; e.g., see Lagos, 2008), was influenced beginning in the 1970s and 1980s, at least in advanced economies and then globally, by the introduction of automatic teller machines (ATMs), the introduction of credit, debit, and cash cards, and eventually the emergence of online banking and shopping. In addition, in some

(no shown) yield similar results. When an estimate of credit to GDP is used instead we obtain similar conclusions (not shown).

[39] It is also worth noting that, as far as money supply injections are concerned, the unit costs to financial institutions will differ according to whether a narrow or a broader form of CBDC is introduced. This is outside the scope of the paper. Perhaps surprisingly, unit costs of financial services in a few advanced economies appear not to have declined over time perhaps in part because of the phenomenon noted by Solow in the opening quote. Philippon (2019) finds that unit costs have varied considerably over time in the US but are no lower in the 2000s than in many earlier decades. Bazot (2018) generally concurs for data since the 1950s from the US, Germany, France, and the UK.

countries, the spread of money market funds was given impetus by changes to post-Depression era financial regulations in the United States that were eventually changed (i.e., regulation Q). The combined impact of developments referred to above would show up at least in part in a shift away from some types of deposits (e.g., the non-interest-bearing variety) in banking institutions towards others that offer better returns. Indeed, if we estimate the non-cyclical variation in deposits over time based on an M3 definition of the money supply (not shown), it appears that the decades from the 1970s to the 1990s faithfully reflects the impact of technological developments in the financial industry.[40] Therefore, in constructing a simulation of monetary policy under a CBDC regime, this period will serve as a benchmark.

The shift in emphasis toward changes in the level and composition of the balance sheet of the central bank represents a challenge to the standard approach that sees monetary policy conducted solely via changes in a central bank policy rate.[41] As a consequence, standard New Keynesian models, even ones that incorporate financial frictions, continue to be built on the eponymous Taylor rule. However, in a world with CBDC, a more appropriate instrument rule is McCallum's policy rule (McCallum 1988, 1993, 2003) wherein changes in the stance of monetary policy are driven by money supply growth. It also has the virtue of explicitly incorporating a role for velocity while also being determined, like the Taylor rule, by a response to real economic developments. More precisely, instead of relating inflation and economic slack to a central bank policy rate as in a Taylor type rule, McCallum's rule defines the stance of monetary policy in terms of money supply growth as opposed to a policy rate. Additionally, the rule can accommodate either narrow or broader definitions of the money supply potentially impacted by the introduction of CBDC. McCallum's rule also has the virtue of being compatible with a policy regime that keeps inflation stable (e.g., see Kozicki and Tinsley, 2009). It should be stressed that policy prescriptions based on McCallum's money growth rule need not contradict the Taylor rule (e.g., see Bordo and Siklos 2016, pp. 77-78). Furthermore, as Piazzesi et. al. (2019) demonstrate,

[40] The precise dates will, of course, vary but for the countries where we have long-term data the following periods (years in parenthesis) appear to capture the impact of the innovations mentioned previously. Australia (1974-1992); Canada (1974-1994), Switzerland (1962-1998), United Kingdom (1973-2011), Japan (1972-2002), Norway (1977-1996), Sweden (1979-1993), and United States (1974-1993).

[41] There are also other challenges including the 'short-rate disconnect' wherein the rest of the term structure is also relevant for intertemporal decisions so that links between short-term and long-term financial assets requires that an allowance be made for the fact that financial assets are not all equally safe.

without explicitly referring to McCallum's rule, a suitably modified New Keynesian model can accommodate CBDC to react to money growth and changes in velocity instead of the output gap. Hence, in McCallum's own words, the rule is "…designed to be insensitive to regulatory changes and technical innovations in the payments and financial industries." (McCallum (1988), p. 173) McCallum's prescription is then an especially useful vehicle to address the inflationary implications of digital money. Moreover, as shown below, it is linked to the discussion above about the behavior and determinants of velocity.

More formally, a calibrated version of McCallum's rule is defined by the following set of equations.

$$\Delta m_t = \Delta x^* - \Delta \tilde{v}_t + \theta(\Delta x^* - \Delta x_{t-1}), \theta = 0.5 \quad (3)$$
$$\Delta m_t = \beta_0 + \beta_1(\Delta x^* - \Delta x_{t-1}) + \boldsymbol{\beta_2 \Omega}_t + u_t \quad (4)$$
$$\Delta m_t = \beta_0 + \gamma \Delta \tilde{v}_t + \beta_1(\Delta x^* - \Delta x_{t-1}) + \boldsymbol{\beta_2 \Omega}_t + u_t \quad (5)$$
$$\bar{\pi}_t = \Delta \bar{m}_t - \Delta \bar{y}_t + \Delta \bar{v}_t \quad (6)$$
$$\Delta x_t = \Delta \pi_{t+1} + \lambda \Delta y_{t+1} \quad (7)$$

The rule itself is defined by equation (3) where money growth is determined by nominal GDP growth (x) and velocity (v). More precisely, $\Delta m_t, \Delta x^*, \Delta x_t, \Delta \tilde{v}_t$, respectively, are the observed growth rate of base money or a broad monetary aggregate (e.g., M0 or M3; Δm), the notional nominal GDP growth objective (Δx^*), observed nominal GDP growth (Δx), and the average rate of change in the equilibrium level of velocity ($\Delta \bar{v}$; also see Burdekin and Siklos 2008). To estimate the money growth instrument we turn to equations (4) and (5)). Equations (4) and (5) are regression equivalent versions of (3). In both equations $\boldsymbol{\Omega_t}$ is a vector of institutional determinants of the policy rule discussed earlier. The difference between equations (4) and (5) is that, in equation (4), the assumption is that $\beta_0 = \Delta x^* - \Delta v_t$ while in equation (5) Δx^* is treated as a constant. This is akin to asking whether the intercept term in the Taylor rule (the equilibrium or natural real interest rate) is constant or not. Equations (6) shows how McCallum's rule generates stable inflation while equation (7) closes the model by adding Okun's law (e.g., Ball et. al.,

2013) linking nominal GDP growth, which partially drives McCallum's rule (e.g., see equation (3)), to real GDP growth.

How is Δx^* estimated? One can take a 'long-run' average of observed nominal GDP growth, or estimate the average low frequency variation in nominal GDP growth. McCallum found that simple long-run averages work best. After some experimentation we set $\Delta x^* = 4\%$.[42] For example, if inflation is 2% then real GDP growth is also 2%. Neither value is very far from the historical experience of the past few decades in advanced economies. Clearly, it is straightforward to consider other estimates for Δx^*.

Although the remaining variables in McCallum's rule are observed some choices need to be made when implementing equations (3) though (5). For money growth we rely on the narrow and a broad money aggregates from the Jordà-Schularik-Taylor database. We label the narrow monetary aggregate M0 while the broad money supply measure is referred to as M3. In the case of the average rate of change in the equilibrium level of velocity we can readily obtain estimates from the estimated cointegrating relationships above.[43] To conserve space, we focus on the results for M0, the narrow definition of money as CBDC is likely, at least at first, to have its greatest impact on holdings of currency and demand deposits. It is also the form of CBDC most likely to be introduced at first. Results for M3 closely mirror ones discussed below. Figures 8 through 10 and Table 2 display the results. Figure 8 shows observed and simulated M0 growth. We focus on the post 1950 period since this is the era of rising financial sophistication (also see Bordo et. al., 1996). Recall that changes in equilibrium (log) levels of velocity are assumed to mimic their behaviour when, based on the historical evidence, financial innovations had their greatest impact.

Figure 8 reveals that, even with financial innovations, the gap between observed and simulated money growth explains inflation movements quite well. Recall that equation (3) best describes

[42] We relegate to the *appendix* a plot that illustrates the range of estimates contemplated for the nominal GDP growth objective. The 4% value chosen seems to work well with the economies considered previously for which we have long-run data.
[43] These are obtained from Figure 7. To facilitate interpretation, the values used in equations (3) through (5) are smoothed via application of the Christiano-Fitzgerald symmetric filter (3 lags, the smoothed portion represent cycles longer than 8 years). Conclusions are unaffected when the raw data shown in Figure 7 are used.

the long-run behavior of velocity. Hence, the gaps shown in Figure 8 represent departures from equilibrium that are eventually restored thanks to the estimated cointegrating relationship. Attah-Mensah et. al. (1996) use an equilibrium relationship similar to equation (1) to explore the connection between money growth and inflation.

In terms of money growth movements, the gaps translates into signals about inflation performance. When the gap rises so does inflation, when the gap falls inflation declines. This is especially noticeable during the high inflation rates of the 1970s. When the gap shrinks, beginning sometime in the 1990s until the end of the sample as it does in all the countries shown, inflation declines. Since Figure 8 is based on McCallum's original rule one might ask whether other factors ought to be controlled for and, indeed, whether the responsiveness of money growth to deviations of notional nominal GDP growth from lagged GDP growth is 0.5 (in absolute value). Table 2 provides some estimates based on equation (5) in regression form. θ is not statistically different from 0.5 for Australia, Canada, the U.K., Japan, and Norway and is considerably smaller in Sweden and the USA but much larger in Japan. Moreover, we can reject the unit impact of a change in velocity on money growth in all eight countries. However, in the cases of Switzerland, the U.K., and Norway, velocity is not statistically significant. Nevertheless, equation (5) is preferred over equation (4) to model money growth. Interest rate spreads, periods of deflation (i.e., when CPI inflation is negative), and a dummy for World Wars I and II, are also frequently statistically significant.

Next, we compare observed M0 growth, the narrow monetary aggregate, against a range of simulated estimates based on varieties of estimates based on McCallum's rule. In most cases the range of simulated estimates a version of McCallum's rule encompasses observed money growth. Only in the case of the U.K. is observed M0 growth comparable to the lowest simulated growth estimates. Moreover, the rule provides, partly by construction, less volatile money growth than what has actually been observed.

Finally, a concern in deploying CBDC is the potential impact on financial stability, as pointed out in section 2(b) above. Accordingly, we consider estimates in Table 2 and ask whether there is evidence of GARCH like effects in estimates based on McCallum's rule. This would represent evidence of conditional volatility in the portion of the monetary policy rule that is not controlled by the central bank. GARCH-type models are designed to convey insights relying on the concept of conditional volatility which tends to swing between periods of calm and episodes when the risks to financial stability rise.

We estimated EGARCH versions of equation (5) because it is arguably the most popular model of its kind when volatility is thought to move in an asymmetric manner over time.[44] If the introduction of CBDC threatens financial stability it is likely because of asymmetric type of shocks. Figure 10 plots the estimated conditional variances for the US.[45] It is interesting to note that the spikes in conditional volatility occur at important moments in US history. They are: the founding of the Fed (1913), the deflationary and boom periods of 1919 and 1922, the recession of 1938, the tech bubble of 2000, and, by far the largest spike occurs during the GFC of 2009. Hence, even if inflation control in the presence of financial innovations does not appear especially problematic via McCallum's rule, this need not prevent episodes associated with periods of financial stress or crisis from emerging even if CBDC are introduced.[46] Hence, additional controls, perhaps of the macroprudential variety, are necessary to reign in episodes of excess volatility.

4. Conclusions

Interest in the eventual introduction of a central bank digital currency has mushroomed recently. The ongoing pandemic has further incentivized central bankers and policy makers to consider digital alternatives to cash. Publicity over possible disruptions to the conduct of monetary policy, including from the proliferation of varieties of cryptocurrencies, has also contributed to sparking more discussion.

---

[44] Write the residual u_t in equations (4) or (5) as $u_t = \sigma_t z_t$ where z_t has the typical Gaussian properties of regression residuals while u_t is now conditionally heteroskedastic. Nelson (1991), who proposed the model as an extension to Engle's (1982) original ARCH model extended by Bollerslev (1986) to the GARCH model , specifies conditional heteroskedasticity as follows: $ln\sigma_t = \omega + \alpha(|z_{t-1}| - E[|z_{t-1}|) + \gamma z_{t-1} + \beta \ln(\sigma_{t-1})$.

[45] Detailed model estimates for the US and the other countries in the data set are provided in the appendix.

[46] However, the proposal by Coronado and Potter (2020) to create a form of digital payment fully backed by reserves at the central bank may provide a means to prevent the estimated spikes shown in Figure 10.

Several challenges await central banks as they consider introducing CBDC. There are legal, technical, and political economy related issues that need to be addressed. In addition, economic theory has yet to catch up to the potential micro and macroeconomic impact of CBDC. Instead, we suggest that economic history can be informative for estimating the possible impact of CBDC on inflation since, in principle, its introduction will raise the speed and frequency of cash like transactions. To be sure, whether central banks allow households to directly access their balance sheet also represents an important consideration, but this is a separate question from the implications of complementing paper money with a digital equivalent.

Periods of rapid financial innovations and growing sophistication are nothing new (e.g., Bordo, 2021). CBDC merely represents the latest vintage in a long line of improvements in financial technology. As with the unconventional monetary policies of the past decade and a half, CBDC requires a focus on the liabilities of central banks. Hence, it is appropriate to revisit how the velocity of circulation may be potentially impacted by technological changes in payments systems and potentially affect inflationary developments. We first show that an empirically stable velocity exists but requires explicit recognition of institutional change in the financial sector and payments systems especially. Next, drawing on a period of changes in financial technology during the 1970s to the 1990s, which may offer clues about the potential impact of introducing CBDC, we revive McCallum's monetary policy rule which is designed for a central bank that sets the stance of policy according to some indicator of money growth. The rule was pushed aside by the Taylor rule which was better suited in a world where central banks conduct policy via interest rate changes. Another advantage of McCallum's rule is that it is unencumbered by constraints in easing monetary policy when faced with an effective lower bound for interest rates since it is not an interest rate rule.

We use McCallum's rule to illustrate that growing financial sophistication, of which CBDC is the latest manifestation, need not lead to a loss of inflation control. In addition, our findings are largely insensitive to how 'money' is defined in our estimates. While this result may well change if other definitions for monetary aggregates are used, they suggest that a suitable design for CBDC that eliminate large denominations from circulation will not hamper inflation control. We are not, however, able to take a stand on the implications of eliminating notes and coins altogether. Overall, our evidence draws from a long historical time series from eight countries although we also present some evidence using a larger data set that also includes several emerging market economies for the more recent period.

That said, our analysis does have its limitations. While the prospect that many economies will remain at the zero lower bound is reasonable, given current economic conditions, a return to more 'normal' interest rates will impact the usage of CBDC in a manner perhaps not adequately captured by looking at history alone. There are other potential caveats to this study. Obviously, the past does not always repeat itself exactly. After all, CBDC can potentially impact inflation in a fashion that past history cannot anticipate by providing governments and central banks with new tools to intervene in markets (e.g., see Prasad, 2021). Finally, CBDC can impact not only the relationship between governments and central banks but also the relationship between the central bank and the financial sector and this may well threaten the autonomy of central banks.

What are some policy implications? First, whether central banks allow households direct access to its balance sheet will be critical. Indeed, if it is true that the unit costs of financial services have not declined over time (BIS 2021), then pressure from the direct involvement of central banks via CBDC might lead to future reductions. However, the technical and political economy related issues that must be overcome make this option highly unlikely at present. Second, history suggests that even if inflation control is not impaired by the introduction of CBDC, digital equivalents to money likely cannot deal with all sources of financial instability according to our simulations. Real world events may well produce different outcomes. Third, though this aspect is downplayed in our analysis, it is also likely that CBDC will play a role in the relative holdings of major currencies, notably the US dollar. One reason to be cautious is because of the formidable coordination problems (again technical and political economy in nature) that stem from using CBDC as a means not only to facilitate cross-border payments but to encourage the creation of a wider portfolio of assets denominated in different currencies. Nevertheless, this element of the potential economic impact of CBDC may well prompt policy makers to revive a question that has been largely ignored for over two decades, namely the significance of currency substitution (e.g., see ECB 2020). We are currently pursuing this extension.

Finally, even the narrow form of CBDC (i.e., an alternative to circulating notes and coins) risks increasing the institutional and policy challenges for central banks. Arguably, central banks have yet to fully digest how far they can go in fulfilling a role in managing financial system stability (e.g., see Lombardi and Siklos 2016). CBDC can mitigate future bouts of instability but cannot overcome all forms of financial stress. Moreover, if CBDC continue to blur the distinction between fiscal and monetary policies, the additional responsibilities placed on central banks may not be welcomed. Therefore, the potential remains for CBDC to be the proverbial ‘wolf in sheep’s clothing’.

References

Alderman, L. (2018), "Sweden's Push to Get Rid of Cash Has Some Saying, 'Not So Fast'", *New York Times*, 21 November.

Allen, S., S. Capkun, I. Eyal, G. Fanti, B. Ford, J. Grimmelmann, A. Juels, K. Kostiainen, S. Meiklejohn, A. Miller, E. Prasad, K. Wüst, and F. Zhang (2020), "Design Choices for Central bank Digital Currency: Policy and Technical Considerations", NBER working paper 27634, August.

Amamiya, M. (2019), "Should the Bank of Japan Issue a Digital Currency?", speech given at a Reuters Newsmakers event in Tokyo, 5 July, Bank of Japan.

Anderton, R., V. Jarvis, V. Labhard, J. Morgan and L. Vivian (2020), "Virtually Everywhere? Digitalisation and the Euro Area and European Union Economies, Occasional paper 244, European Central Bank, June.

Armelius, H., C. Claussen, and S. Hendry (2020), "Is Central bank Currency Fundamental to the Monetary System?", Bank of Canada Staff Discussion paper 2020-2, May.

Arner, D., R. Buckley, D. Zetzsche, and A. Didenko (2020), "After Libra, Digital Yuan, and COVID-19: Central bank Digital Currencies and the New World of Money and Payments Systems", European Banking Institute working paper 65, June.

Ashworth, J., and C. Goodhart (2020), "The Surprising Recovery of Currency Usage", *International Journal of Central Banking* (June): 239-277.

Attah-Mensah, J., W. Engert, S. Hendry, and J. Armour (1996), "A Distant-Early-Warning Model of Inflation Based on M1 Disequilibia", Bank of Canada Staff Working Paper 1996-5, April, available from https://www.bankofcanada.ca/1996/04/working-paper-1996-5/.

Auer, R., and R. Böhme (2020), "The Technology of Retail Central Bank Digital Currency", BIS *Quarterly Review*, march: 85-100.

Auer, R., G. Cornelli, and J. Frost (2020), "Rise of the Central Bank Digital Currencies: Driver, Approaches, and Technologies", BIS working paper 880, August.

Ball, L,. D. Leigh, and P. Loungani (2013), "Okun's Law: Fit at Fifty?", NBER working paper 18688, January.

Bank of Canada, European Central Bank, Bank of Japan, Sveriges Riksbank, Swiss National Bank, Bank of England, Board of Governors of the Federal Reserve System, Bank for International Settlements (2020), "Report No. 1, Central Bank Digital Currency: Foundational Principles and Core Functions", Bank for International Settlements, Basel.

Bank of England (2020), “Central Digital Currency”, central bank digital currencies team, discussion paper, March.

Bank for International Settlements (2021), “CDBCs: An Opportunity for the Monetary System”, Chapter III, BIS Annual Report 2021, June (Basel: Bank for International Settlements), pg. 65-95.

Bank for International Settlements (2020a), “The Digital Economy and Financial Innovation”, BIS paper no. 109, February.

Bank for International Settlements (2020b), *Annual Economic Report 2020* (Basel: Bank for International Settlements, chapter III.

Bank for International Settlements (2019), “Investigating the Impact of Global Stablecoins”, G7 working group on Stablecoins, October.

Barontini, C., and M. Holden (2019), “Proceeding With Caution: A Survey on Central Bank Digital Currency”, BIS papers no. 101, January.

Barrdear, J., and M. Kumhof (2016), “The Macroeconomics of Central Bank Issued Digital Currencies”, Bank of England working paper 605, July.

Barnett, W. (1980), “Economic Monetary Aggregates: An Application of Aggregation and Index Number Activity”, *Journal of Econometrics* 14: 11-48.

Bazot, G. (2018), “Financial Consumption and the Cost of Finance: Measuring Financial Efficiency in Europe (1950-2007)”, *Journal of the European Economic Association* 16 (February): 123-160.

Benati, L., R. Lucas, and J.-.P. Nicolini, and W. Weber (2018), “Long-Run Money Demand Redux”, University of Bern, working paper wp 18-04, January.

Bindseil, U. (2020), “Tiered CBDC and the Financial System”, European Central Bank working paper 2351, January.

Boar, C., H. Holden, and A. Wadsworth (2020), “Impending Arrival – A Sequel to the Survey on Central Bank Digital Currency”, BIS working paper 107, January.

Bollerslev, T. (1986), “Generalized Autoregressive Conditional Heteroskedasticity”, *Journal of Econometrics* 31(April): 307-327.

Bordo, M. (2021), “Central Bank Digital Currency in Historical Perspective: Another Crossroad in Monetary History”, prepared for the Bank of England Centre for Banking Studies, July.

Bordo, M., and L. Jounung (1981), *The Long-run Behaviour of the Velocity of Circulation* (Cambridge: Cambridge University Press).

Bordo, M., and L. Jonung (1987), "Some Qualms About the Institutionalist Hypothesis of te Long-run Behaviour of Velocity: A Reply", *Economic Inquiry* 26 (July): 546-50.

Bordo, M., L. Jonung, and P. Siklos (1996), "Institutional Change and the Velocity of Money: A Century of Evidence", *Economic Inquiry* 35 (October): 710-724.

Bordo, M.D., and P.L. Siklos (2016), "Central Bank Credibility: An Historical and Quantitative Exploration", in Central Banks At A Crossroads, edited by M.D. Bordo, Ø. Eitrheim, M. Flandreau, and J. Qvigstad (Cambridge, Mass: Cambridge University Press), pp. 62-144.

Bordo, M.D., and A. Levin (2018), "Central Bank Digital Currency and the Future of Monetary Policy", in M.D. Bordo, J. Cochrane and A. Seru (Eds.), *The Structural Foundations of Monetary Policy* (Stanford, CA: Hoover Institution Press), pp. 143-78.

Brainard, L. (2020a), "The Future of Retail Payments in the United States", remarks at the FedNow service webinar, 6 August.

Brainard, L. (2020b), "An Update on Digital Currencies", at the Federal Reserve Board and Federal Reserve Bank of San Francisco's innovation office hours, 13 August.

Bowen, A., G. Hoggarth, D. Pain (1999), "The Recent Evolution of the UK Banking Industry and Some Implications for Financial Stability", BIS Conference Papers No. 7, pp. 251-294.

Brunnermeier, M., and D. Niepelt (2019), "On the Equivalence of Private and Public Money", *Journal of Monetary Economics* 106 (October): 27-41.

Brunnermeier, M., H. James, and J.-P. Landau (2019a), "The Digitalization of Money", NBER working paper 26300, September.

Brunnermeier, M., G. Dong, and D. Palia (2019b), "Banks' Non-Interest Income and Systemic Risk", working paper, Princeton University, January.

Burdekin, R., and P. Siklos (2009), "What has Driven Chinese Monetary Policy Since 1990? Investigating the People's Bank's Policy Rule", *Journal of International Money and Finance* 27: 847-859.

Campbell, B. (2020), "The Pandora's Box of Central Bank Digital Currencies", DoubleLine Capital, October, www.doubleline.com.

Carapella, F., and J. Flemming (2021), "Central Bank Digital Currency: A Literature Review", FEDS Notes, 9 November.

Chen, H., W. Engert, K. Huynh, G. Nicholls, M. Nicholson, and J. Zhu (2020), "Cash and COVID-19: The Impact of the Pandemic pm Demand for and Use of Cash", Staff Discussion paper 2020-6, Bank of Canada, July.

Cheng, J., D. Wessel, and J. Younger (2020), "How Did COVID-19 Disrupt the Market for U.S. Treasury Debt", 1 May, https://www.brookings.edu/blog/up-front/2020/05/01/how-did-covid-19-disrupt-the-market-for-u-s-treasury-debt/.

Coronado, J., and S. Potter (2020), "Securing Macroeconomic Monetary Stability with a Federal Reserve Banked Currency", policy brief 20-4, Peterson Institute for International Economics, March.

Dantes, D. (2021), "Central Bank 'Money Drops' With Digital Currencies Could Fuel Inflation: Bank of America", Coindesk, 2 April, available from https://ca.news.yahoo.com/central-bank-money-drops-digital-122542314.html.

Darbha, S., and R. Arora (2020), "Privacy in CBDC Technology", Staff Analytical Note 2020-9, Bank of Canada, June.

Davvodalhosseini, M., and F. Rivadeneyra (2018), "A Policy Framework for E-Money: A Report on Bank of Canad Research", staff discussion paper DP2018-5, April.

de Haan, J., and S. Eijffinger (2017), "Central Bank Independence Under Threat?", CEPR Policy Insights No. 87, January, available from https://cepr.org/sites/default/files/policy_insights/PolicyInsight87.pdf.

DeYoung, R., and T. Rice (2004), "How Do Banks make Money? The Fallacies of Fee Income", *Economic Perspectives*, Federal Reserve Bank of Chicago, 4Q: 34-51.

Diamond, D., and P. Dybvig (1983), "Bank Runs, Deposit Insurance, and Liquidity", *Journal of Political Economy* 91 (June): 401-419.

Diewert, E. (1976), "Exact and Superlative Index Numbers". *Journal of Econometrics* 4 (1976), 115-146.

Eichengreen, B. (2019), "From Commodity to Fiat and Now Crypto: What Does History Tell Us?", NBER working paper 25426, January.

Engert, W., and B. Fung (2017), "Central bank Digital Currency: Motivations and Implications", Staff Discussion Paper 2017-16, November.

Engle, R. F. (1982), "Autoregressive Conditional Heteroskedasticity with Estimates of the Variance of UK Inflation", *Econometrica* 50 (July): 987-1008

European Central Bank (2020), "Report on a Digital Euro", October.

Fernández-Villaverde, J., D. Sanches, L. Schilling, and H. Uhlig (2020), "Central Bank Digital Currency: Central Banking for All?", CEPR discussion paper 14337, January.

Financial Stability Board (2020), "Enhancing Cross-Border Payments: Stage 3 Roadmap", 13 October.

Flannigan, G., and S. Parsons (2018), "High Denomination Banknotes in Circulation: A Cross-Country Analysis", Reserve Bank of Australia *Bulletin*, march: 1-19.

Garcia, A., B. Lands, X. Liu, and J. Slive (2020), "The Potential Effect of a Central Bank Digital Currency on Deposit Funding in Canada", Staff Discussion Analytical Note 2020-15, July.

Fratzscher, M., (2019), "When is Foreign Exchange Intervention Effective? Evidence from 33 Countries", *American Economic Journal: Macroeconomics* 11 (January): 132-156.

Fung, B., S. Hendry, and W. Weber (2018), "Swedish Riksbank Notes and Enskilda Notes: Lessons for Digital Currencies", Staff working paper 2018-27, June

G30 (2020), "Digital Currencies and Stable Coins: Risks, Opportunities, and Challenges Ahead", July.

Godbole, O. (2020), "Debate Rages on Whether a Digital Dollar Will Unleash Inflation", *Coindesk*, 9 November.

Goodhart, C. (1988), *The Evolution of Central Banks* (Cambridge: Cambridge University Press).

Gurley, J.G., and E.S. Shaw (1960), *Money in Theory and Finance* (Washington, D.C.: Brookings).

Ha, J., M.A. Kose, and F. Ohnsorge (2019), "Global Inflation Synchronisation", CEPR discussion paper 13600.

Haldane, A. (2021), "Thirty Years of Hurt, Never Stopped Me Dreaming", speech given at the Institute for Government, Bank of England, 30 June 2021.

Haldane, A. (2020), "Seizing the Opportunities from Digital Finance", TheCityUK 10th Anniversary conference, 18 November.

Haldane, A. (2015). "How Low Can You Go?", Speech at Portadown Chamber of Commerce, Northern Ireland.

Hartmann, P., H. Huang, D. Schoenmaker, Editors (2018), *The Changing Fortunes of Central Banking* (Cambridge: Cambridge University Press).

Haubrich, J., and T. Young (2019), "Trends in the Noninterest Income of Banks", *Economic Commentary*, Federal Reserve Bank of Cleveland, 2019-14, 24 September.

Henckel, T., A. Ize, and A Kovanen (1999), "Central Banking Without Central Bank Money", International Monetary Fund working paper 99/92, July.
House of Lords (2021), "Economic Affairs Committee: Corrected Oral Evidence: CBDC", 23 November, available from committees.parliament.uk/oralevidence/3062/html.

Huynh, K., G. Nicholls, and M. Nicholson (2020), "2019 Cash Alternative Survey Results", Bank of Canada Staff Discussion Paper 2020-08, August.

International Monetary Fund (2017). "Negative Interest Rate Policies—Initial Experiences and Assessments". IMF Policy Paper. https://www.imf.org/en/Publications/Policy-Papers/Issues/2017/08/03/pp080317-negative-interest-rate-policies-initial-experiences-and-assessments.

International Monetary Fund (2016), *Monetary and Financial Statistics Manual and Compilation Guide* (Washington, D.C.: International Monetary Fund).

Ireland, P. (2009), "On the Welfare Loss of Inflation the Recent Behavior of Money Demand", *American Economic Review* 99: 1040-52.

Kiff, J., J. Alwazir, S. Davidovic, A. Farias, A. Khan, T. Khiaonarong, M. Malaika, H. Monroe, N. Sugimoto, H. Tourpe, and P. Zhou (2020), "A Survey of Research on Retails Central Bank Digital Currency, IMF working paper 20/104, June.

Kihara, L., and T. Wada (2020), "Bank of Canada Official Downplays Fears Over China's Digital Currency", Reuters, October 15.

Kim, Y., and O. Kwon (2019), "Central Bank Digital Currency and Financial stability", Bank of Korea working paper 2019-6.

King, M. (1999), "Challenges for Monetary Policy: New and Old", in *New Challenges for Monetary* Policy, Symposium sponsored by the Federal Reserve Bank of Kansas City, pp. 11-57.

Kiyotaki, N., and R. Wright (1989), "On Money as a Medium of Exchange", *Journal of Political Economy* 97 (August): 927-954.

Kozicki, S., and P.A. Tinsley (2009), "Perhaps the 1970s FOMC Did What it Said it Did", *Journal of Monetary Economics* 56: 842-855.

Lagos, R. (2008), "Inside and Outside Money", in S. Durlauf, A. Blume (Eds.), *Monetary Economics*, The New Palgrave Economics Collection (New York: Springer Link), pp. 132-6.

Lagos, R., G. Rocheteau, and R. Wright (2017), "Liquidity: A New Monetarist Perspective", *Journal of Economic Literature* 55 (2): 371-440.

Laeven, L., R. Levine, and S. Michalopoulos (2015), “Financial Innovation and Endogenous Growth”, *Journal of Financial Intermediation* 24: 1-24.

Laidler, D. (1993), *The Demand for Money, 4th Edition* (New York: Harper & Row).

Levine, Ross (2005a)., Finance and growth: theory and evidence. In: Philippe, Aghion, Durlauf, Steven N. (Eds.), Handbook of Economic Growth. Elsevier North-Holland. Publishers, pp. 866–934.

Levine, Ross (2005b), Law, endowments, and property rights. Journal of Economic Perspectives 19, 61–88.

Lombardi, D., and P. Siklos (2016), “Benchmarking Macroprudential Policies: An Initial Assessment”, *Journal of Financial Stability* 27 (December): 35-49.

Lombardi, D., P. Siklos, and S. St. Amand (2018), “A Survey of the International Evidence and Lessons About Unconvnetional Monetary Policies: Is A ‘New Normal’ in Our Future?”, *Journal of Economic Surveys* 32 (December): 1229-1256.

Lhuissier, S., B. Mojon, and J. Rubio Ramirez (2020), “Does the Liquidity Trap Exist?”, BIS working paper 855, April.

Licandro, G. (2018), “Uruguayan e-Peso on the Context of Financial Inclusion”, Banco Central Del Uruguay, November.

Lucas, R E, Jr, and J-P. Nicolini (2015) “On the stability of money demand”, *Journal of Monetary Economics*, 73(July): 48–65.

McCallum, B. (1988), “Robustness Properties of a Rule for Monetary Policy”, *Carnegie-Rochester Conference Series on Public Policy*, vol. 29: 173-203.

McCallum, B.T. (1993), “Specification and Analysis of a Monetary Policy Rule for Japan”, Bank of Japan Monetary and Economic Studies 11 (2), 1–45.

McCallum, B.T. (2003), “Japanese Monetary Policy, 1991–2001”, Federal Reserve Bank of Richmond Economic Quarterly 89 (1), 1–31.

Meaning, J., B. Dyson, J. Barker, E. Clayton (2018), “Broadening Narrow Money: Monetary Policy with Central Bank Digital Currency”, Bank of England working paper 724, May.

Nakashima, K., and M. Saito (2012), "On the comparison of alternative specifications for money demand: The case of extremely low interest rate regimes in Japan," *Journal of the Japanese and International Economies*, 26(3): 454-471.

Nelson, D. B. (1991), “Conditional Heteroskedasticity in Asset Returns: A New Approach”, *Econometrica* 59 (March): 347-370.

Niepelt, D. (2020), “Reserves for All? Central bank Digital Currency and their Non-Equivalence”, *International Journal of Central Banking* (June): 211-238.

Nuno, G. (2018), “Monetary Policy Implications of Central Bank-Issued Digital Currency”, Banco de Espana Economic Bulletin 3/2018, July.

Otani, A., T. Suzuki (2008), “Background to the High Level of Banknote in Circulation and Demand Deposits”, *Bank of Japan Review*, September, 2008-E-05.

Philippon, T. (2019), “On Fintech and Financial Inclusion”, BIS working paper 841, February.

Piazessi, M., C. Rogers, and M. Schneider (2019), “Money and Banking in a New Keynesian Model”, working paper, Stanford University, March.

Posen, A. (1995), Declarations are Not Enough: Financial Sector Sources of Central Bank Independence”, in B. Bernanke and J. Rotemberg (Editors), *NBER Macroeconomics Annual 1995* (Cambridge: Cambridge University Press), pp. 253-274.

Prasad, E. (2021), *The Future of Money* (Cambridge, Mass.: Harvard University Press).

Rogoff, K. (2017a) *The Curse of Cash: How Large-denomination Bills Aid Crime and Tax Evasion and Constrain Monetary Policy* (Princeton: Princeton University Press).

Rogoff, K. (2017b), “Dealing with Monetary Policy paralysis at the Zero Lower Bound”, *Journal of Economic Perspectives* 31 (Summer): 47-66.

Sahay, R., U. von Allmen, A. Lahreche, P. Khera, S. Ogawa, M. Bazarbash, and K. Beaton (2020), “The Promise of Fintech: Financial Inclusion in the Post COVID-19 Era”, Money and Capital Markets Departmental Paper Series 20/09.

Shirai, S. (2019), “Money and Central bank Digital Currency”, ADBI working paper 122, February.

Siklos, P.L. (1993), “Income Velocity and Institutional Change: Some New Time Series Evidence, 1870-1986”, *Journal of Money, Credit and Banking* 25 (August, Part I): 377-92.

Siklos, P.L., and A. G. Barton (2001), “Monetary Aggregates as Indicators of Economic Activity in Canada: Empirical Evidence”, *Canadian Journal of Economics* 34 (1): 1-17.

Solow, R. (1987), “We’d Better Watch Out”, *New York Times Book Review* 12 July, p. 36.

Swiss National Bank (2020), “Project Helvetia: Settling Tokenized Assets in Central Bank Money”, December.

Taylor, J. (1993), "Discretion Versus Policy Rules in Practice", *Carnegie-Rochester Conference Series on Public Policy* 39:195-214.

Tompkins, M., and A. Olivares (2016), "Clearing and Settlement Systems from Around the World: A Qualitative Analysis", Staff Discussion Paper 2016-14, Bank of Canada.

Waller, C. (2021), "Reflections on Stablecoins and Payments Innovations", speech at the 'Planning for Surprises, Learning from Crises', 2021 Financial Stability Conference, co-hosted by the Cleveland Federal Reserve Bank and the Office of Financial Research, 17 November.

Warzel, C, and S. A. Thompson (2019), "How Your Phone Betrays Democracy", *New York Times* 21 December, available from https://www.nytimes.com/interactive/2019/12/21/opinion/location-data-democracy-protests.html?action=click&module=Opinion&pgtype=Homepage.

Westerlund, J. (2007) "Testing for Error Correction in Panel Data", *Oxford Bulletin of Economics and Statistics*, vol. 69 (6): 709-748.

Table 1 Panel and Individual Cross-Section Cointegration Tests: 1870-2016

A. Conventional Velocity Function (equation (1))		
Panel: CAN, NOR, SWE, GBR, USA		
No. cointegrating vectors	Trace (p-value)	Maximal eigenvalue
r=0	*25.51 (.01)*	*33.74 (.002)*
r=1	3.52 (.97)	3.51 (.97)
r=2	7.51 (.68)	7.51 (.67)
Individual Cross-Sections		
r=0		
CAN	*33.16 (.02)*	*24.02 (.02)*
NOR	22.83 (.25)	16.66 (.19)
SWE	20.97 (.36)	17.39 (.15)
GBR	23.42 (.23)	19.17 (.09)
USA	*36.60 (.01)*	*32.28 (.00)*
r=1		
CAN	9.14 (.35)	8.89 (.30)
NOR	6.17 (.68)	4.12 (.85)
SWE	3.58 (.93)	3.58 (.90)
GBR	4.25 (.88)	4.02 (.86)
USA	4.32 (.88)	3.63 (.90)
r=2		
CAN	0.25 (.62)	0.25 (.62)
NOR	2.05 (.15)	2.05 (.15)
SWE	0.001 (.97)	0.001 (.97)
GBR	0.23 (.63)	0.23 (.63)
USA	0.69 (.41)	0.69 (.41)

Note: based on the VAR (Johansen – Fisher) test with 2 lags. Number of observations per cross-section=147. No breaks or exogenous variables added. Rejections of the null of *r* cointegrating vectors (less than or equal to *r* for the trace test; maximum of *r* vectors for the maximal eigenvalue test) are in italics, using a 5% threshold. Same notes apply to part B of the table shown below. Panel estimates include cross-section fixed effects.

B. Extended Velocity Function (equation (2))		
Panel: CAN, NOR, SWE, GBR, USA		
No. cointegrating vectors	Trace (p-value)	Maximal eigenvalue
r=0	*129.60 (.00)*	*103.90 (.00)*
r=1	*53.81 (.00)*	*47.55 (.00)*
r=2	*18.15 (.05)*	15.19 (.13)
r=3	8.01 (.63)	5.10 (.88)
r=4	8.56 (.57)	6.28 (.79)
r=5	14.06 (.17)	14.06 (.17)
Individual Cross-Sections		
r=0		
CAN	*125.84 (.00)*	*66.43 (.00)*
NOR	*113.24 (.002)*	*38.03 (.08)*
SWE	*217.92 (.00)*	*91.50 (.00)*
GBR	*134.34 (.00)*	*71.76 (.00)*
USA	*124.20 (.00)*	*58.29 (.00)*
r=1		
CAN	59.40 (.25)	22.16 (.60)
NOR	*75.22 (.02)*	30.25 (.13)
SWE	*126.42 (.00)*	*70.95 (.00)*
GBR	62.58 (.16)	30.74 (.11)
USA	65.91 (.10)	*36.29 (.03)*
r=2		
CAN	37.25 (.34)	18.50 (.45)
NOR	44.98 (.09)	21.38 (.25)
SWE	*55.47 (.01)*	*32.38 (.01)*
GBR	31.83 (.62)	16.84 (.59)
USA	29.63 (.74)	16.08 (.66)
r=3		
CAN	18.74 (.51)	12.25 (.52)
NOR	23.60 (.22)	9.90 (.75)
SWE	23.09 (.24)	15.39 (.26)
GBR	14.99 (.78)	9.50 (.79)
USA	13.54 (.87)	7.00 (.95)
r=4		
CAN	6.50 (.64)	5.54 (.67)
NOR	13.71 (.09)	8.97 (.29)
SWE	7.70 (.50)	7.46 (.44)
GBR	5.49 (.95)	5.21 (.71)
USA	6.25 (.63)	5.19 (.72)
r=5		
CAN	0.95 (.33)	0.95 (.33)
NOR	*4.73 (.03)*	*4.73 (.03)*
SWE	0.24 (.62)	0.24 (.62)
GBR	0.28 (.60)	0.28 (.60)
USA	1.36 (.24)	1.36 (0.24)

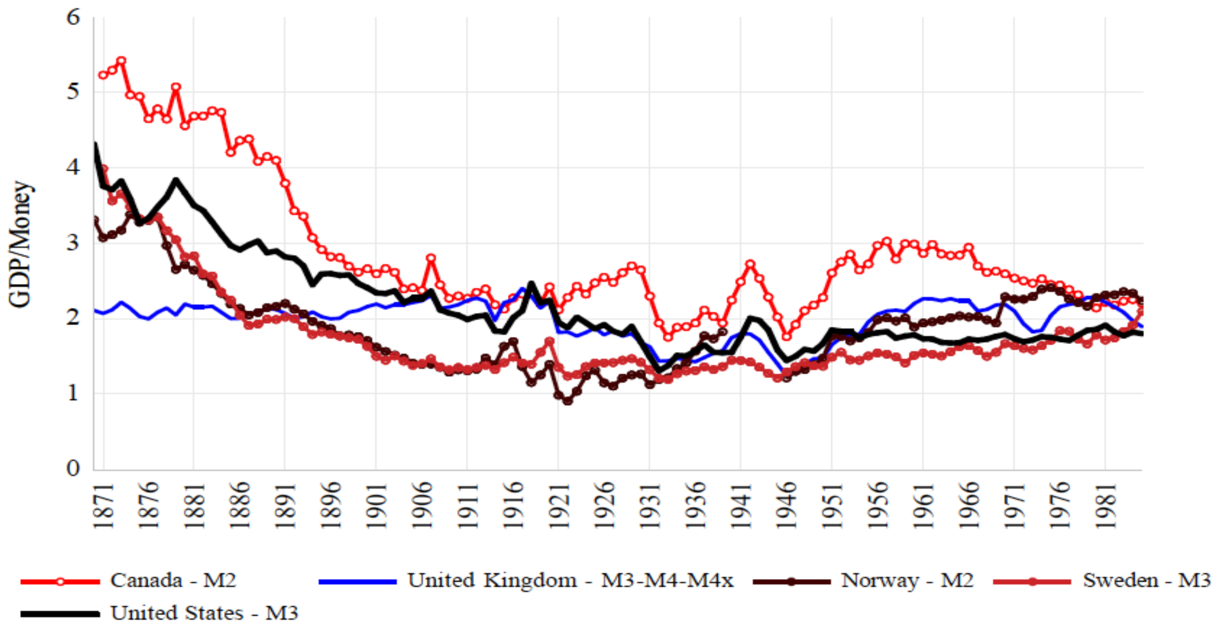
Table 2 McCallum Rule Estimates for Years of Financial Innovation to Mimic CBDC Effect: M0 Growth

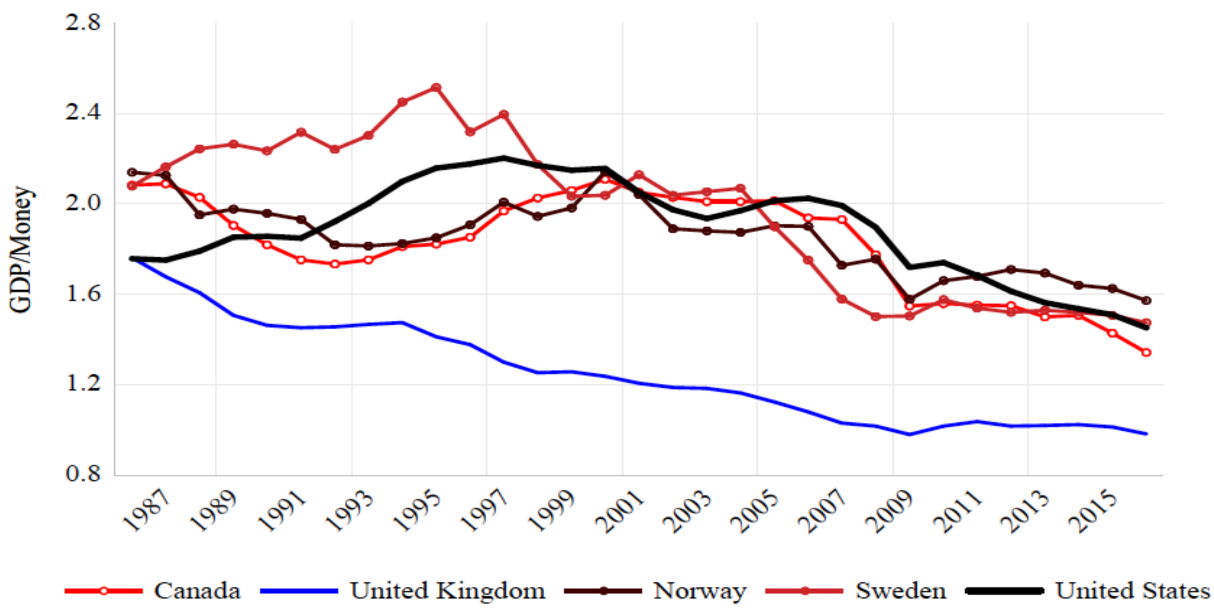
Variable	AUS	CAN	CHE	GBR	JPN	NOR	SWE	USA
Constant	5.21* (0.92)	5.06* (1.23)	3.88 (1.12)	3.31* (0.43)	7.18* (1.55)	4.05* (1.16)	4.67* (0.69)	4.92* (0.86)
$\widetilde{\Delta \mathrm{v}}_t$	-0.60* (0.18)	-0.47@ (0.20)	-1.01 (0.15)	-0.07 (0.09)	-0.52@ (0.24)	-0.26 (0.18)	-0.38* (0.15)	-0.63* (0.15)
$\Delta x^* - \Delta x_{t-1}$	-0.32* (0.12)	-0.43* (0.15)	-1.01 (0.15)	-0.40* (0.06)	-0.56* (0.07)	-0.34* (0.12)	-0.10 (0.09)	-0.26@ (0.11)
$r_{Lt} - r_{St}$	0.15 (0.63)	0.84 (0.57)	-0.28* (0.14)	0.38+ (0.20)	0.71+ (0.42)	0.61 (0.84)	0.97@ (0.43)	0.54 (0.51)
Deflation	-1.96 (2.07)	-8.06+ (4.10)	0.45 (0.39)	-2.18@ (0.93)	1.78 (2.39)	-2.87 (2.45)	-4.10* (1.37)	-1.45 (2.36)
World Wars	6.83* (2.43)	7.20* (2.46)	-3.19 (1.95)	10.40* (1.22)	16.33* (3.76)	17.64* (3.57)	13.23* (1.90)	6.93* (2.49)
Years of Innovation	1974-1992	1974-1996	1962-1998	1973-2011	1972-2002	1977-1996	1979-1993	1974-1993
Adj. R^2	0.23	0.30	0.31	0.68	0.58	0.34	0.56	0.22
F	8.23*	7.62*	12.00*	51.05*	25.55*	15.44*	21.16*	8.24*
Observations	145	83	137	145	145	145	145	145

Note: Estimates of equation (5). Standard errors in parenthesis. * means significant at the 1% level; @ at the 5% level; + at the 10% level. Estimated via least squares. Countries: AUS (Australia); CAN (Canada); CHE (Switzerland); GBR (United Kingdom); JPN (Japan); NOR (Norway); SWE (Sweden); USA (United States). For the cases with 145 observations the sample is 1872-2016 (after transformations), 1880-2016 (137 observations), and 1934-2016 (83 observations).

Figure 1 Velocity of Circulation in Five Countries: 1870-2016

(a) Velocity: 1870-1986

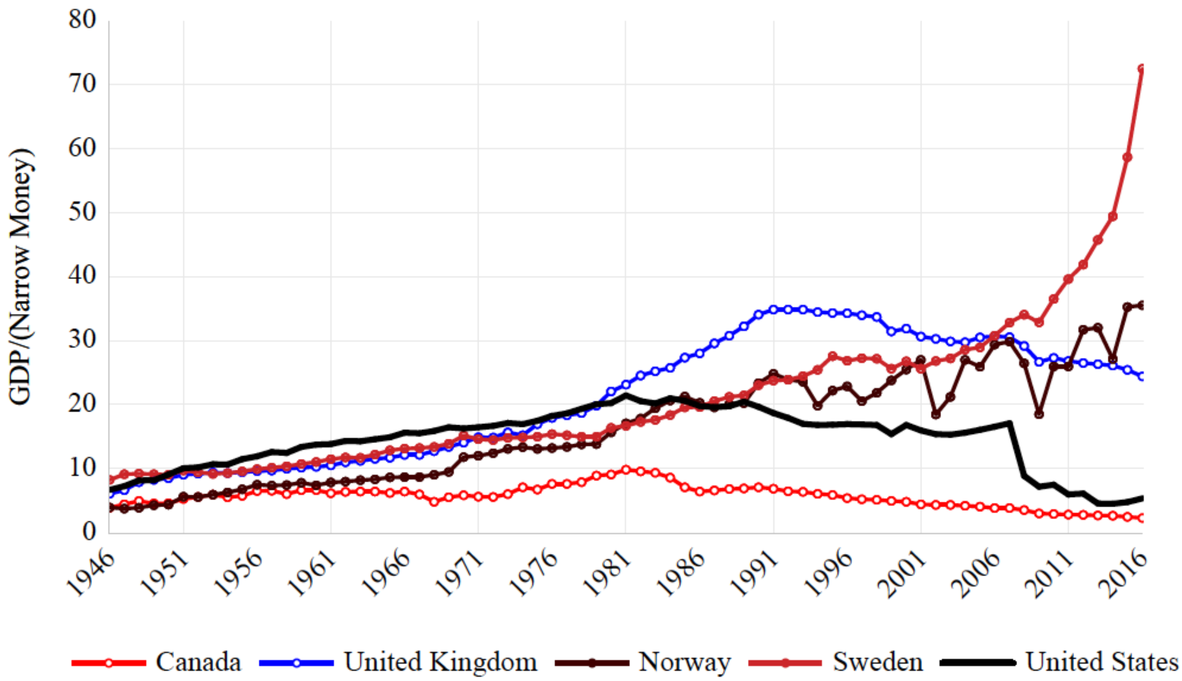




(b) Velocity 1987-2016

Note: Velocity is GDP divided by the money supply aggregates shown in the legend of the top figure. Calculated from the Jordà-Schularik-Taylor database (http://www.macrohistory.net/data/). The bottom figure is the same data but for a sample beginning in 1987. Data are annual.

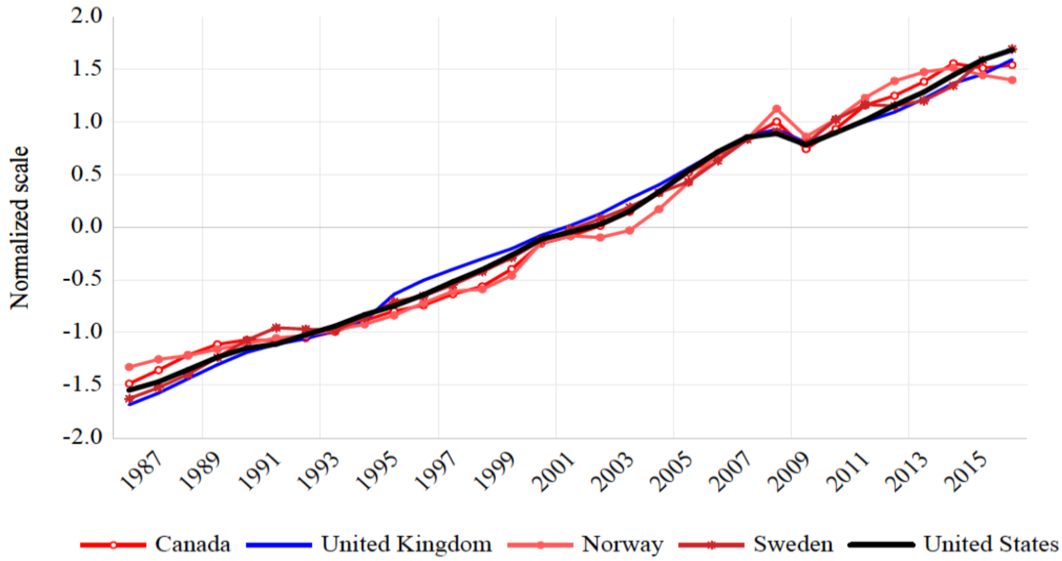
Figure 2 Velocity of Circulation Since the late 1980s in Five Countries



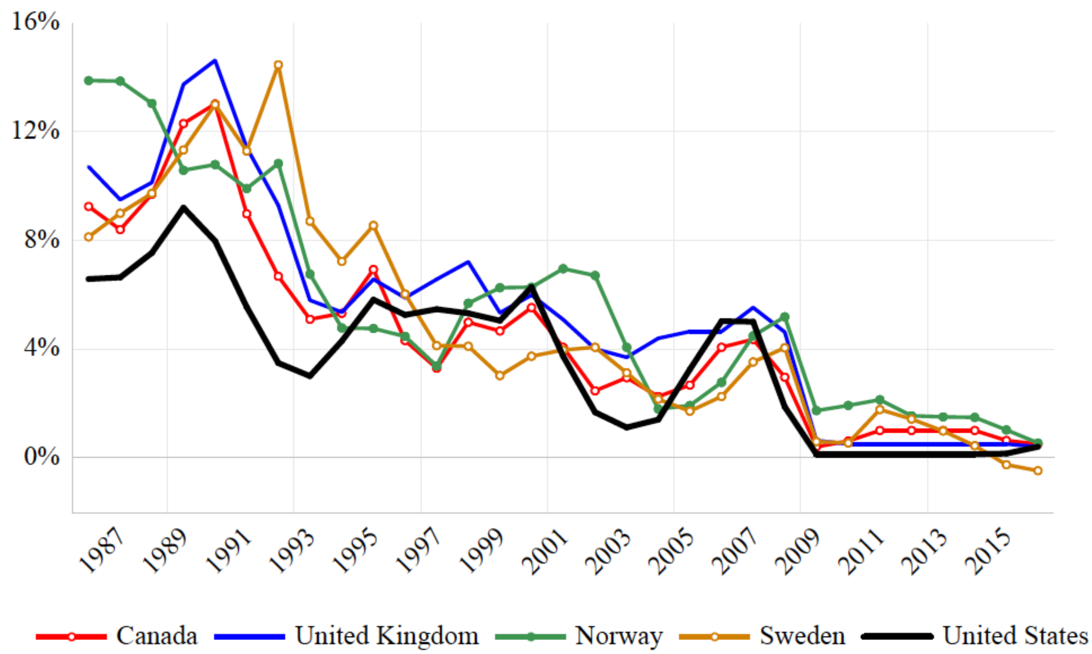
Note: Source and definition of velocity are that same as in Figure 1. Narrow money is the money supply definition and consists of notes and coins in circulation plus demand deposits. Data are annual.

Figure 3 Real Per Capita GDP and Policy Rates in Five Countries: 1987-2016

(a) Real per capita GDP

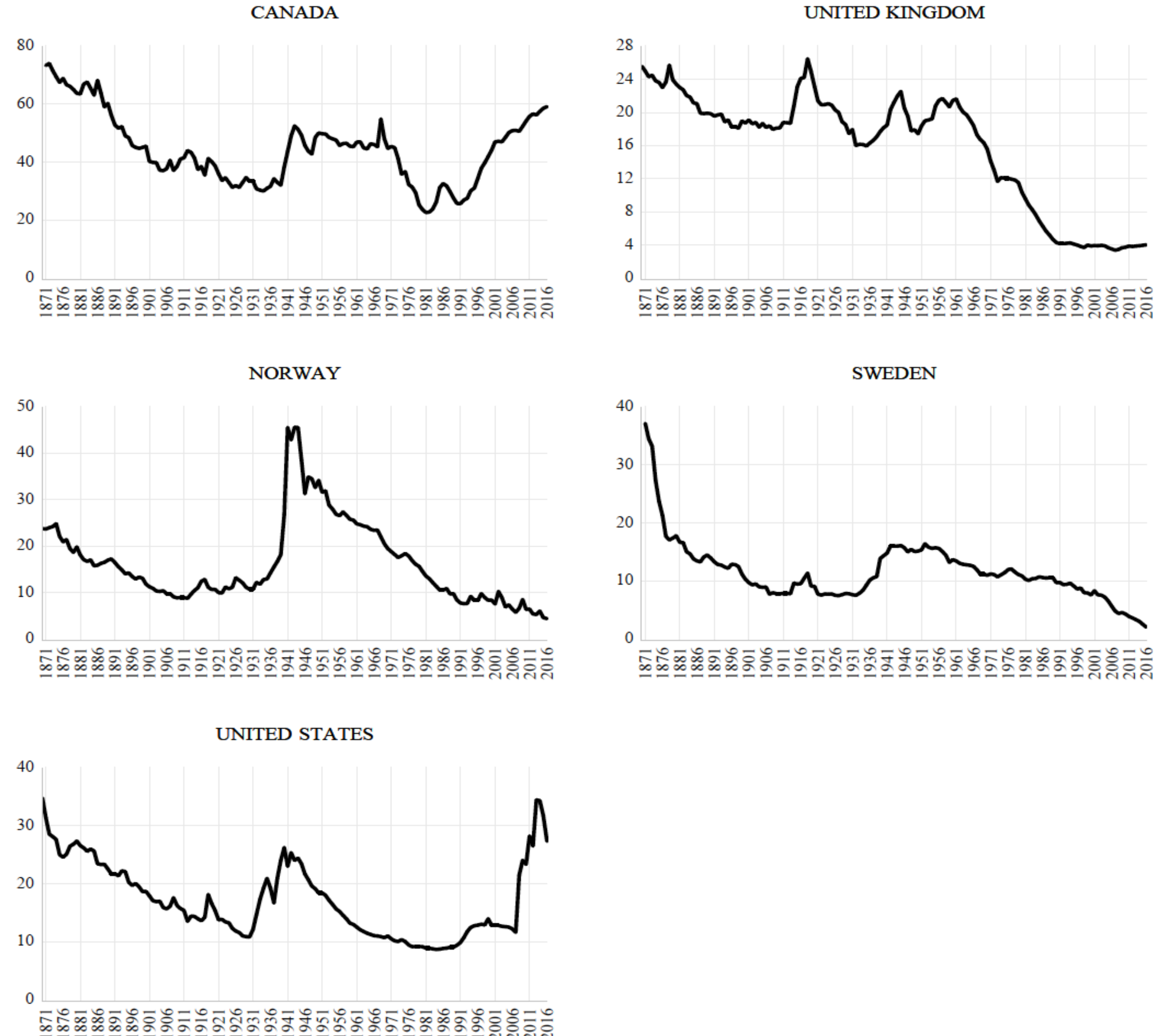


(b) Policy interest rates



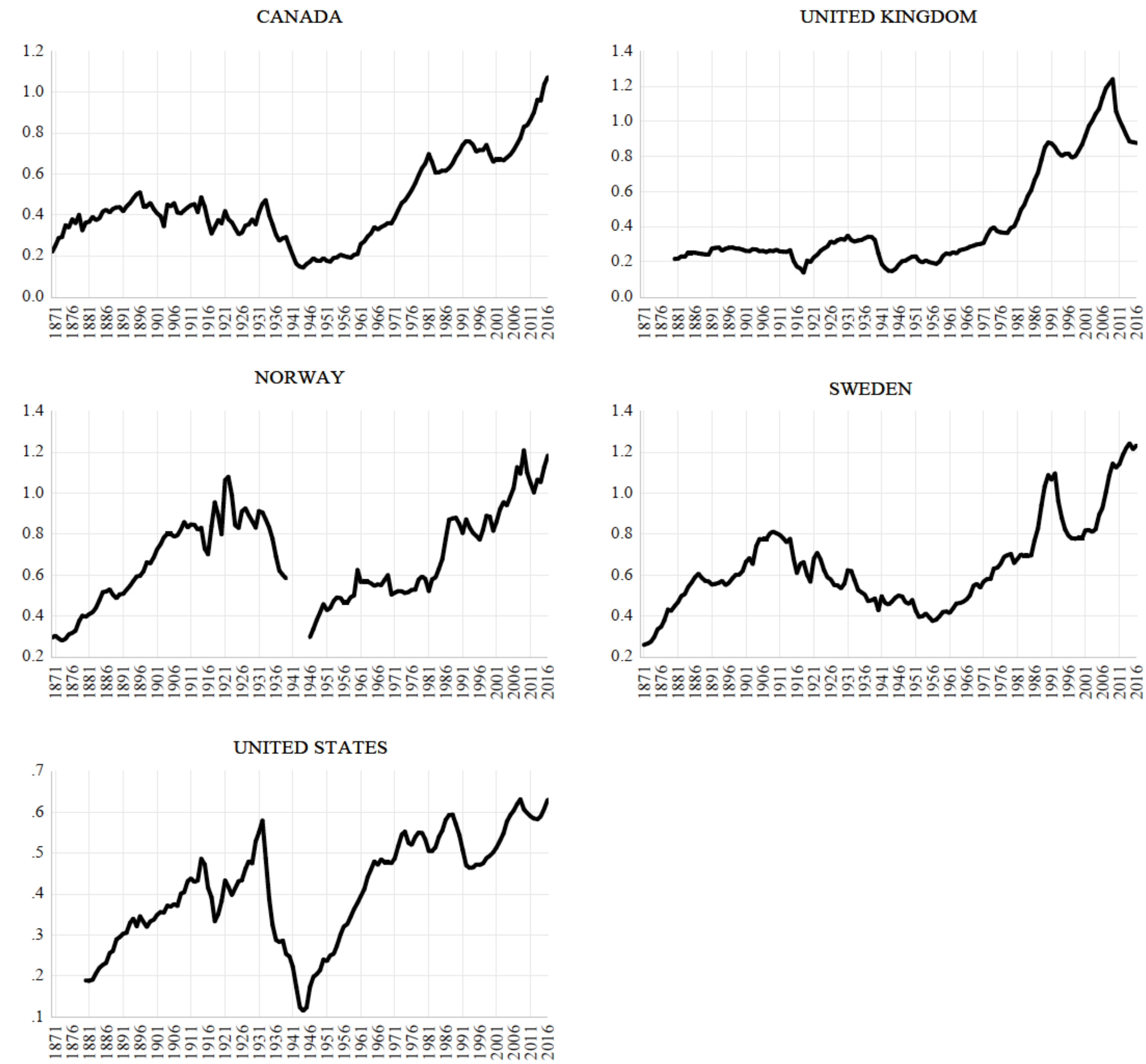
Note: Data for the top figure obtained from the same source as in Figure 1. Data used as provided. Other than the normalization no other calculations made. Bottom figure is from BIS Statistics (https://www.bis.org/statistics/cbpol.htm?m=6%7C382%7C679). Data are annual. BIS data originally monthly but simple arithmetic average used to create annual data.

Figure 4 Currency to Money Ratio in Five Countries: 1870-2016



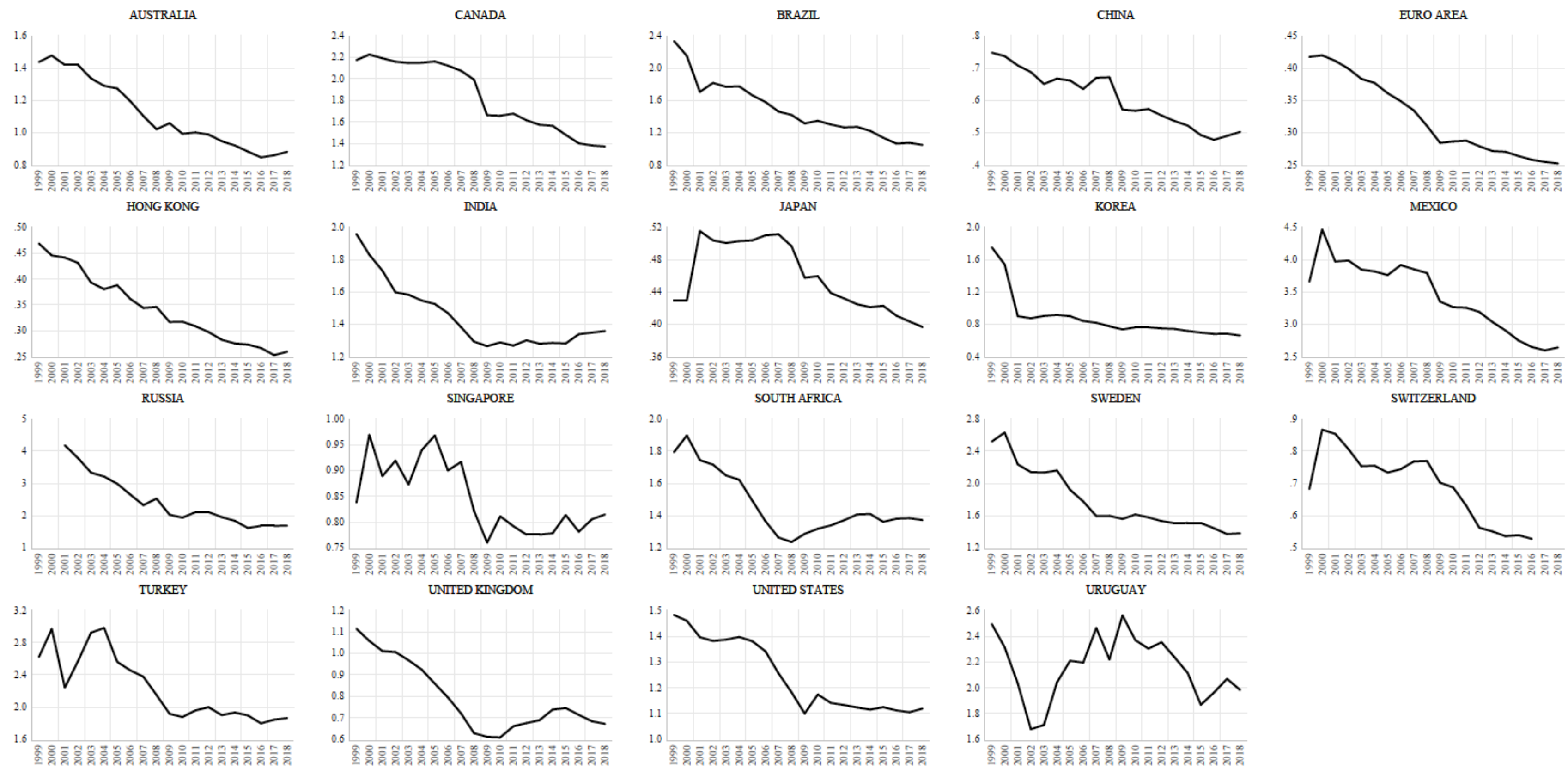
Note: in percent. Data from the same source as in Figure 1. "Currency" is narrow money (see Figures 2), "money" is broad money (see Figure 1). Data are annual.

Figure 5 A Proxy for Financial Innovation in Five Countries: 1870-2016



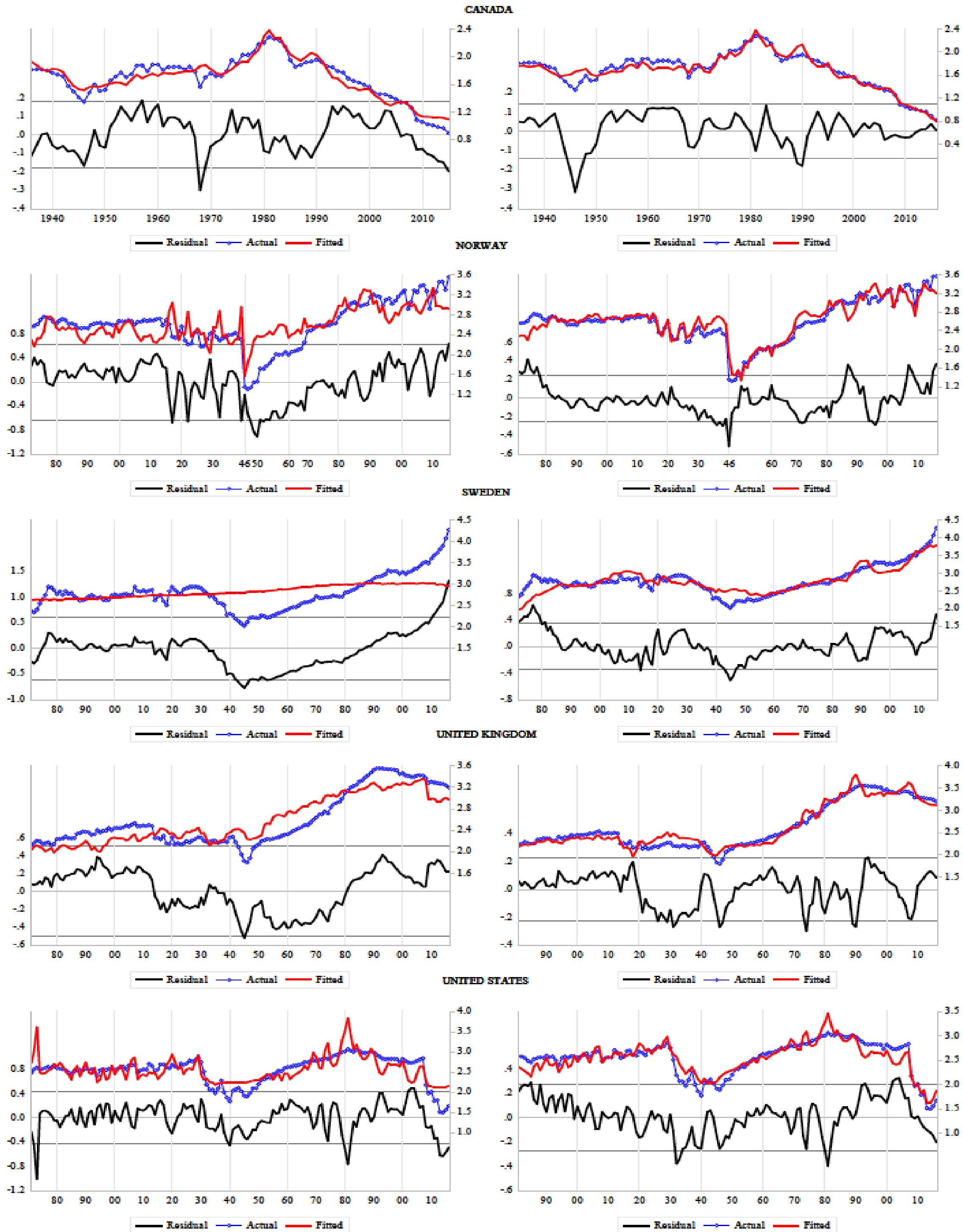
Note: Data from the same source as in Figure 1. Gap for Norway due to World War II is filled via interpolation (Catmull-Roll Spline) in the estimated specifications. The ratio shown is Total Loans to non-bank private sector over GDP. Data are annual.

Figure 6 Velocity of Circulation in 19 Economies: 1999-2018



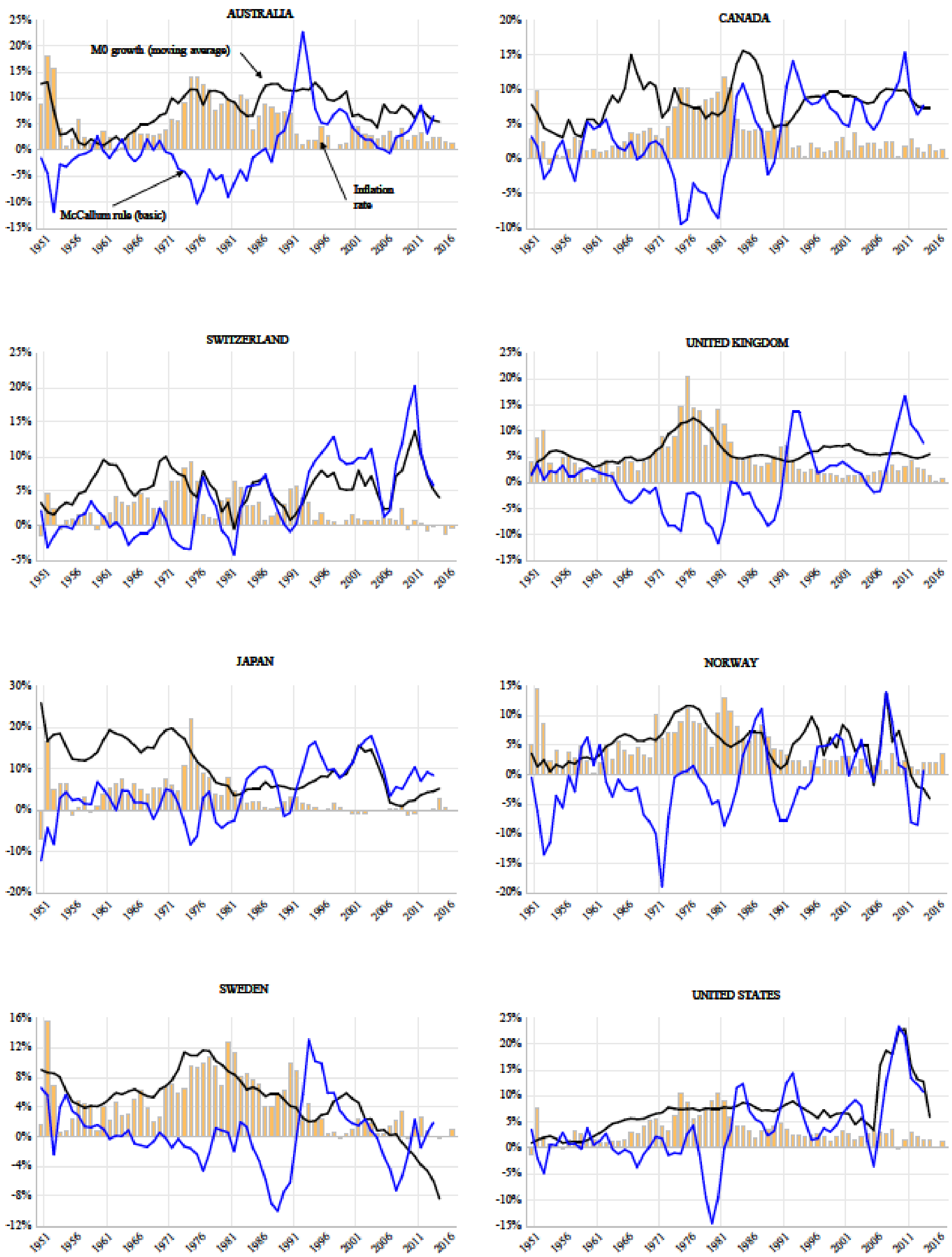
Note: Velocity is GDP divided by estimate of broad money (IMF definition) obtained from World Bank Development Indicators (https://databank.worldbank.org/source/world-development-indicators). Data are annual.

Figure 7 Cointegrating Equations, Error Correction, and Velocity of Circulation in Five Countries: 1870-2016



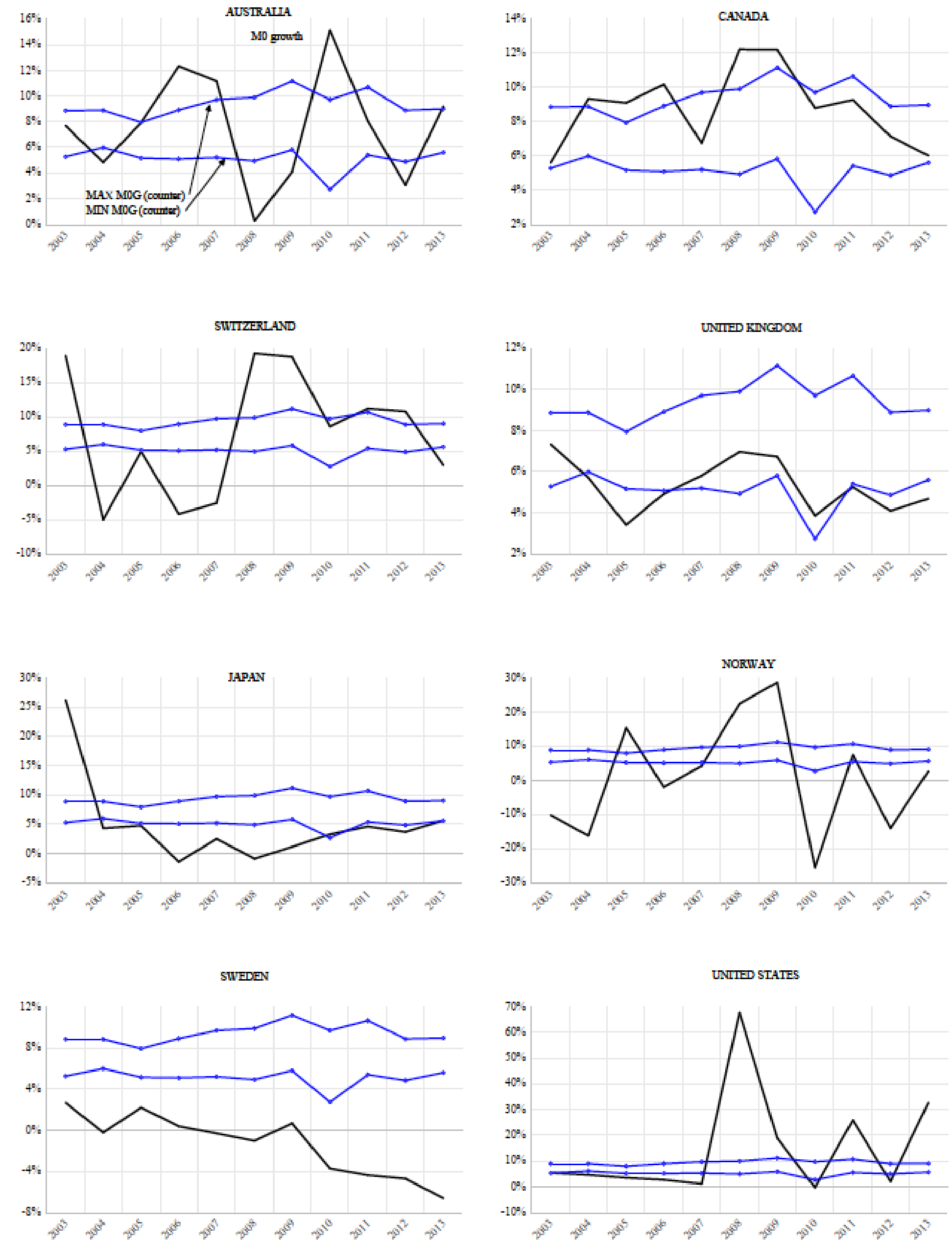
Note: All cointegrating equations estimated via fully modified OLS. The fitted values are estimates of the cointegrating relationships for the conventional (equation (1), left hand-side column) and extended velocity models (equation (2), right hand-side column).

Figure 8 McCallum Rule for M0 Growth, Observed M0 Growth and Inflation



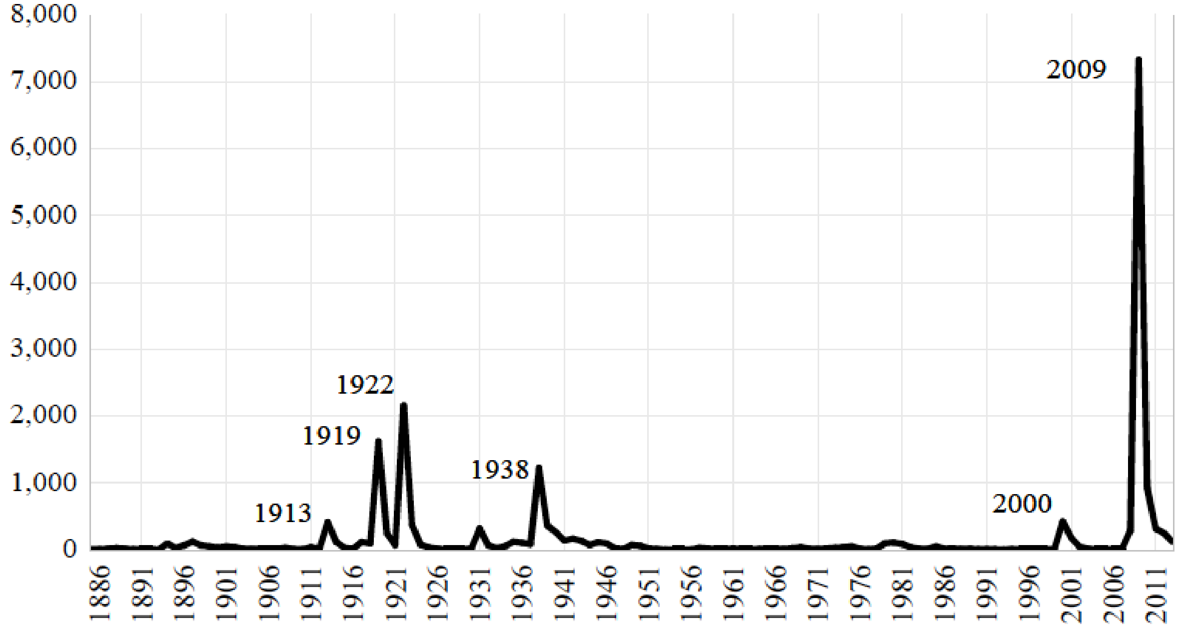
Note: McCallum rule equation (3). Inflation is CPI inflation. M0 Growth (5 year centred moving average) and CPI from same source as Figure 1. See the text for additional estimation details including some smoothing of certain series via application of the Symmetric Christiano-Fitzgerald filter.

Figure 9 Hypothetical (Counterfactual) M0 Growth Under a CBDC Regime



Note: Varieties of McCallum rules (equations (3) through (5)) estimated and maximum (MAX M0G) and minimum estimates (MIN M0G) obtained are plotted to provide a range of hypothetical values for narrow money growth under a CBDC regime. See text for estimate details. M0 is a narrow monetary aggregate definition (i.e., currency and demand deposits).

Figure 10 Conditional Variance: McCallum Rule for USA M0 Growth



Note: Conditional variance estimates from EGARCH fitted to equation (4). M0 is defined in Figure 9.