Title
Three Essays in International Finance

Author
Yin, Licheng

Publication Date
2020

Peer reviewed|Thesis/dissertation

UNIVERSITY OF CALIFORNIA
SANTA CRUZ

THREE ESSAYS IN INTERNATIONAL FINANCE

A dissertation submitted in partial satisfaction of the
requirements for the degree of

DOCTOR OF PHILOSOPHY

in

ECONOMICS

by

Licheng Yin

September 2020

The Dissertation of Licheng Yin
is approved:

Professor Michael M. Hutchison, Chair

Professor Kenneth M. Kletzer

Professor Chenyue Hu

Quentin Williams
Interim Vice Provost and Dean of Graduate Studies

Table of Contents

List of Figures

List of Tables

Abstract

THREE ESSAYS IN INTERNATIONAL FINANCE

by

Licheng Yin

This dissertation consists of three chapters, which discuss three topics of international finance such as the effect of exchange rate volatility on economic growth, evidence of law of one price, and regulation effect on price differential. Each topic is studied by one of three chapters.

The first chapter empirically tests the effect of country's domestic and international credit access on effect of exchange rate volatility on growth. In this chapter, I uses annual panel data from 2003 to 2015 for 115 countries. System GMM estimation with two step standard error is used for regression analysis. Country's financial development level is used to measure country's domestic credit access, and country's foreign bank presence level is used to measure country's international credit access. The empirical finding of this chapter show that countries with higher level of financial development are less likely to be adversely affected by exchange rate volatility, and higher level of foreign bank presence can ameliorate the adverse growth effect of exchange rate volatility. Results of this chapter implies that countries with high levels of credit access can use more flexible exchange rate regime since countries' high credit access helps to insulate the economy from the adverse effect of exchange rate volatility. For countries with low credit access, exchange rate stability is important for economic growth so that it is preferable to use the fixed exchange rate regime.

The second chapter studies the speed of convergence of Bitcoin across markets globally to find supportive evidence for LOOP. The data used in this chapter includes Bitcoin trading data of 20 exchanges under 14 currencies, which is the most

comprehensive Bitcoin dataset used in the literature. Cointegration analysis and Vector Error Correction Model are performed to investigate long run relationship and short run dynamics in Bitcoin markets. Empirical results of this chapter confirm the existence long run equilibrium in Bitcoin market. Half-lives of Bitcoin trading pairs are estimated using VEC model and range from 0.133 days to 6.93 days, which are significantly fast than half lives (range from months to several years) of other assets studied in previous literature. The fast speed of converge in Bitcoin markets implies efficient arbitraging activities, which provide strong evidence to support LOOP. Using estimated half-lives as data, I also identifies border effect in Bitcoin markets.

The third chapter empirically examines the effect of regulation changes on Bitcoin cross country premium using my self-collected daily panel data for 22 Bitcoin exchanges under 11 currencies. To measure Bitcoin regulation changes, I constructs an original country level Bitcoin regulation news index. Web crawler is used to collect Bitcoin regulation related reporting from news websites like CNBC, Reuters and Coindesk etc. Results of this chapter suggest that tighter relative regulation increase level of market segmentation, which induce higher premium. By investigating the effect of each type of news individually, warning news and formal news are found to be main drivers of the result, and formal news have higher estimated effect on premium. In this chapter, I also identify the spillover effect from regulation change in other countries. Country's Bitcoin premium increases as other countries tighten their Bitcoin regulations.

Acknowledgments

I want to express my sincere gratitude to all people who helped me to complete this dissertation in pursuit of my Ph.D. in Economics.

First and foremost, I want to thank my advisor Professor Michael Hutchison for his guidance and mentoring throughout my Ph.D. study. He taught me how to do research and provided invaluable feedback on my research. He gave me tremendous amount of freedom and supports so that I can have the courage to explore research topics that are niche but intriguing. I would like to thank the other two members on my dissertation committee, Professor Kenneth Kletzer and Professor Chenyue Hu, for their continuous and generous support. It has been a great privilege to have such prominent economists as my advisors and mentors.

Furthermore, I would like to thank Professor Carl Walsh and Dr. Fernanda Nechio for their support and feedback through my Ph.D. Qualifying Exam. I would also like to thank all the participants at the macro and international finance workshops and job market practices for their invaluable suggestions.

I want to thank the UCSC economics department for the physical and financial support for my study and research. I want to thank Professor Jonathon Robinson and Professor Natalia Lazzati for their leadership of the Ph.D. program. I would also like to thank our program coordinator Sandra Reebie for her continuous assistant.

In addition, I want to thank all my friends and fellows for their advice, supports and communications not only on my academic study but also personal life through this entire process. Special thanks to my UCSC friends and fellows: Penghao Cheng, Qing Ge, Dahyeon Jeong, Alan Ledesma, Baizhu Chen, Wei Xu, and Jijian Fan.

Last but not least, I would like to thank my family for all their love and encouragement. I am extremely grateful to my parents Qi and Hongbing for their dedication and sacrifice to support my life and study. None of these would be possible without them. Thank you!

Chapter 1

Exchange Rate Volatility and Economic Growth: Importance of Access to Credit

1.1 Introduction

Choosing whether to maintain exchange rate stability or embrace flexible exchange rate is often a concern for policy makers. When empirical studies often present ambiguous results on relationship between exchange rate volatility and economic growth, which exchange rate regime the country should embrace given the country's current economic background is not an easy question to answer. However, it is also common in the literature to find that exchange rate volatility has significant negative impact on economic growth for emerging economies while it is not the case for developed countries. Therefore, it is natural to ask what kinds of characteristics of emerging economies make them more vulnerable to exchange rate volatility.

The phenomenon of "fear of floating" is often discovered in emerging economies, and it is not surprising since the literature found that emerging economies are more negatively influenced by exchange rate volatility. Therefore, by understanding the reason behind the phenomenon of "fear of floating", we can gain some ideas about the characteristics that make emerging economies more vulnerable to exchange rate fluctuation. Reinhart and Calvo [2002] suggests four reasons that could attribute to policy makers' dislike of exchange rate volatility in emerging economies. First, monetary authorities in developing countries lack credibility so that monetary authority has no authority. Lack of credibility will lead to the problem of volatile interest rate and sovereign rating, liability dollarization as well as central banks' failure to be last resort lender, which all feed the "fear of floating". Second, exchange rate volatility hurts the trade in emerging markets more severely since trades are predominately invoiced in dollars, and the share of trade to GDP is bigger in developing countries. Third, emerging markets have a higher pass through of exchange rates to price so that monetary authorities don't like exchange rate swings if they care about inflation. Last but not least, currency instability adversely affect countries' credit market access so that countries with low credit market access, especially for most of emerging economies, are reluctant to have exchange rate swings.

Based on above reasons, it is not difficult to conjecture that countries that lack credibility, heavily depend on trade, are deeply concerned on inflation and have low access to credit market will be more vulnerable to exchange rate volatility. While it is interesting to explore all these four factors, this research is going to focus on the last point to study the role that credit access plays in exchange rate volatility and economic growth. More specifically, this research is going to test whether the economic growth of countries with high credit access would be less negatively influenced by exchange rate volatility than low credit access countries.

The rest of the paper is structured as follows. Section II reviews the related literature. Section III explains the data and empirical model specification used. Section IV will discuss the results of regression. Section V goes over the issue of endogeneity and section V concludes.

1.2 Literature Reviews

1.2.1 Studies on Exchange Rate Volatility and Economic Growth

Given that the aim of this research is to study how different levels of credit access influence the effect of exchange rate volatility on countries' economic growth, it is important to know how past literature describes the relationship between exchange rate volatility and economic growth first. However, the fact is that neither theories nor empirical evidences present a definitive relationship between exchange rate volatility and economic growth.

Theoretical Evidences

Theoretically, the study of the effect of exchange rate volatility on growth can be seen as the cost benefit analysis of exchange rate stabilization. The transmission channels of exchange rate volatility to growth can be summarized as asymmetric shocks, international trade and capital market. For the channel of asymmetric shocks, Meade [1951] has argued that a flexible exchange rate system is an important source to absorb asymmetric (real) shocks. The idea behinds it is that due to price and wage rigidities, the real adjustments process under the fixed exchange rate regime is very costly as it has to be associated with relative price and productivity changes. The result is lower growth. On the contrary, McKinnon [1963] finds exchange rate volatility could impede economic growth in face of nominal shocks. The idea is that for a small open economy with high ratio of tradable to non-tradable goods, exchange rate volatility would lead to domestic price fluctuation since a class of tradable goods is a more representative bundle of domestic consumption. Therefore, domestic nationals have a tendency to accumulate foreign bank balance (result in capital outflow even in the case when marginal efficiency of investment is higher domestically), which impedes growth. In other words, exchange rate stability ensures domestic price stability, which creates a more desirable environment for investment and growth. Later work of Mundell [1973] also supports the above idea that exchange rate volatility creates uncertainty for small open economies, and growth can be stimulated by smoothing exchange rate volatility.

For the channel of international trade, it is common to think that exchange rate volatility would increase the uncertainty and foreign exchange rate risk, which in turn induce higher transaction cost. This high transaction cost would negatively influence the competitiveness of exporting and import-competing firms and thereby lower the growth. Consistent with above idea, McKinnon and Ohno [1997] shows that exchange rate volatility strongly affected the growth of Japan after the Yen became flexible to US dollars in 1970s. However, in contrast with common belief, some literature also discuss the potential benefit of the flexible exchange rate regime from the perspective of the trade channel. Clark [1973] constructs a model of exporting firms that are risk-averse, and he finds that the fixed exchange rate regime is not necessarily associated with higher welfare. He argues that the fixed exchange rate provides a subsidy to international transactions by reducing uncertainty so that the economies are having too much trade, and the flexible exchange rate allow international trades shift toward the optimum point. Moreover, De Grauwe [1988] finds that the modern theory under risk does not provide a clear cut conclusion that exchange rate volatility reduces trade, and whether exchange rate volatility negatively affects trade depends largely on how risk-averse individuals are. Under exchange rate fluctuation, the model suggests that very risk-averse individuals worry more about the drastic declines of the revenue in the worst possible outcome so that they will export more to avoid it (income effect), while the less risk-averse individuals would just export less given higher risk (substitution effect) as they concern less about extreme outcomes. Therefore, if the income effect dominates the substitution effect, exchange rate volatility would actually induce more export.

For the last channel of capital market, the common intuition is what McKinnon [2010] suggests: the fixed exchange rate regime would reduce the exchange rate risk and reduce the transaction cost for capital flow, which would foster economic growth by having a more efficient international allocation of capital. This would be especially true in emerging economies whose foreign debts tend to be denominated in foreign currency so that a sharp depreciation of domestic currency might lead to crisis by inflating the liabilities in terms of domestic currency. On the contrary, another popular theory of moral hazard hypothesis points out the drawback of exchange rate stability. As suggested by Burnside et al. [2001], the fixed exchange rate regime is an implicit source of moral hazard because it is same as offering the private sector insurance against exchange rate risk. The presence of this government guarantee eliminates the banks' incentive to hedge exchange rate risk, which becomes the source of the moral hazard problem. Banks will take excessive risk and magnify their foreign exchange exposure, and a large amount of unhedged foreign denominated liabilities will then become time bombs for domestic financial system. Therefore, the moral hazard theory suggests more flexible exchange rates would buttress the financial stability and promote stable economic growth.

Some theories about the capital market channel provide some insights into this study. Eichengreen and Hausmann [1999] points out origin sin hypothesis which emphasize the importance of incompleteness of financial markets. This theory argues that economies with incomplete financial markets (origin sin) are unable to borrow aboard or borrow long-term domestically using domestic currency. This incompleteness will result in either currency mismatch[1] or maturity mismatch[2] for domestic investments. With this origin sin, both fixed and flexible exchange rate regime would be problematic. Under the flexible exchange rate regime, currency mismatch would cause bankruptcies if there is a sharp depreciation. Under the fixed exchange rate regime, maturity mismatch will cause defaults on short-term loans if domestic interest rates hike as the result of selling reserves to defend peg. This theory sheds light on this study because the origin sin hypothesis also suggests that countries with developed financial markets are less fragile and crisis prone because they are able to borrow long-term papers denominated

[1]Projects that generate domestic currency will be financed by foreign currency

[2]Long-term project will be financed by multiple short-term loans.

in domestic currency from both international and domestic financial markets. In other words, economies with more developed financial markets (economies with abundant credit access both domestically and internationally) can handle flexible exchange rate (exchange rate volatility) much better than economies with incomplete financial markets. This is also what this study is going to test empirically.

Empirical Evidences

Consistent with the finding of theoretical studies, the empirical literature of exchange rate volatility and economic growth also provides mixed results. Many researchers find either no or weak evidence of the exchange rate regimes influencing economic growth (Baxter and Stockman [1989]; van Wincoop and Bacchetta [2000]; Ghosh et al. [2003]; Tenreyro [2007]; Diallo [2015]). At the same time, some empirical studies also find that some degree of exchange rate volatility can promote economic growth (Edwards and Levy Yeyati [2005]; Eichengreen and Leblang [2003];Katusiime et al. [2016]).

By contrast with the mixed results discussed above, for emerging economies, existing literature generally finds that exchange rate volatility (exchange rate stability) negatively (positively) influences economic growth. Grauwe and Schnabl [2008]'s research on Southeastern and Central Europe finds a positive correlation between exchange rate stability and economic growth. Arize et al. [2008] reveals that exchange rate volatility has a significant negative impact on both short-run and long-run exports in their study of eight Latin American countries. Moreover, Schnabl [2009] performs GLS panel estimations for 17 countries in Emerging Europe and 9 East Asian countries, and the results suggest a robust negative relationship between exchange rate volatility and economic growth. For more recent studies, Chit et al. [2010]'s study on emerging east Asian economies and Alagidede and Ibrahim [2016]'s study on Ghana both find negative linkage between exchange rate volatility and economic growth.

This research will complement the existing literature by studying the reasons why emerging economies are more likely to be negatively affected by exchange rate volatility than advanced economies.

1.2.2 Studies on Access to Credit

A substantial literature documents that emerging economies tend to be more vulnerable to exchange rate volatility than developed economies. Grossmann et al. [2014] employs a Panel VAR model for 29 economies and finds that the feedback effects from exchange rate volatility to macro fundamentals are much stronger for developing countries relative to developed economies. Diallo [2015] shows that the negative effect of exchange rate volatility on productivity growth is very large for developing countries, while the negative effect is not very high for developed countries.

To explain this discrepancy in growth effects between developed and developing countries, most of literature points to different development levels of financial markets. For instance, Prasad et al. [2005] suggests that exchange rate volatility has a detrimental effect on economic growth especially on emerging economies with underdeveloped capital markets and unstable economic policies. Husain et al. [2005] argues that exchange rate stability might be more important for countries with fragile financial and political institutions. However, except some informal discussion, neither of them provide any direct evidence to the theory that fragile financial system amplify the negative effect of exchange rate volatility on growth. In fact, few researchers empirically examine the reason why emerging economies and advanced economies react so differently on exchange rate volatility, and this study is going to contribute to this literature by doing empirical tests as well as building a theoretical model.

The reason why financial sectors is important for growth is that, as pointed out by Levine et al. [2000], better-functioning financial systems ease external financing constraints, and economic growth increases by allowing financially constrained firms to expand. Other literature also posits that higher credit access (less credit access) promotes (impedes) firm's growth, which in turn promotes (impedes) economic growth. (Broadman et al. [2004]; Rizov [2004]; Beck et al. [2006]) The intuition behind this is that if a firm is credit constrained, the firm needs to choose between investments and inputs depending on the level of credit it received, instead of choosing input optimally as a credit-unconstrained firm would. Therefore, the firm's production and profits are going to be negatively affected. Moreover, when facing crisis and opportunities, the firm is less likely to have an optimal response to crisis due to the credit constraint. In developing economies with less developed credit markets, this problem of limited credit access is more likely to be amplified.

Aghion et al. [2009] link the domestic credit access (measured by financial development level), exchange rate volatility and economic growth together. They find that real exchange rate volatility reduces economic growth for countries with low levels of financial development, but for countries with high levels of financial development, real exchange rate volatility does not have significant impact on their economic growth. The logic is that less financially developed countries have tighter domestic credit constraints so that the financial market shocks are amplified. Therefore, firm's accessibility to credit market explains the reason why emerging markets are more negatively influenced by exchange rate volatility. Héricourt and Poncet [2015] supports the view of Aghion et al. [2009] using micro data of 100000 Chinese exporting firms and finds that the negative effect of exchange rate volatility on firms' exporting decision is magnified for financial vulnerable firms and financial development can dampen this negative impact.

It is important to notice that Aghion et al. [2009] only discuss the importance of domestic credit access. However, as suggested by Demir [2013], the micro evidence of 500 private manufacturing firms in Turkey shows that access to both foreign and domestic equity markets can reduce the negative effect on firm growth caused by exchange rate volatility. Therefore, it is important to consider both domestic and international credit access in order to fully understand the linkage between exchange rate volatility and economic growth, and one of the contribution of this study is to complement the discussion of Aghion et al. [2009] by incorporating international credit access.

1.2.3 Studies on foreign bank presence

As mentioned earlier, this research is going to explore the channels of both domestic and international credit access to explain the different effects of exchange rate volatility on economic growth of different economies (developing and developed). While this research is using the financial development level to measure domestic credit access similar to other literature, in addition the foreign bank presence level is used to measure counties' access to international credit market.

Foreign bank presence is used here because foreign bank entry enhance countries' access to international credit. (Levine et al. [2003]; Clarke et al. [2006]) More importantly, high foreign bank presence means domestic borrowers can borrow loans that are denominated in domestic currency from international credit market. As suggested by the theoretical discussion in the first part of literature review, this would imply less fragile financial system and could buttress economy in the event of exchange rate fluctuation.

The literature of foreign bank presence and economic growth often reflects mixed results. On the one hand, some literature suggests that foreign bank entry promotes economic growth. This is because foreign bank entry causes bank competition, which leads to a more efficient allocation of resources and better quality of financial services. (Bhattacharaya [1993]; Levine [2001]; Li [2011]). Moreover, the existence of foreign banks gives credibility to the home country, and this would enhance home country's access to international credit market and stabilize country's total credit supply (de Haas and van Lelyveld [2006]). On the other hand, there are also studies highlighting the negative impacts of foreign bank presence. One main argument against foreign bank entry is that foreign banks have handicaps using soft information[3] in their lending practices. As a result, domestic small businesses will be insufficiently funded[4], and the economic growth of countries with more small businesses will be impeded (Mian [2003]; Clarke et al. [2003]; Giannetti and Ongena [2009];Owen and Temesvary [2014]).

[3]As opposed to hard information, which includes verifiable data and knowledge, soft information includes unquantifiable factors like feelings, opinions, perceptions and values.

[4]Small businesses have more soft information available than hard information.

Therefore, the existing literature provides no definitive result on the growth effect of foreign bank presence. Indeed, given the interest of this study, it would be more useful to review literature that incorporates foreign bank presence, exchange rate volatility and economic growth all together. However, there is a literature gap in this area, and this study will fill this literature gap by finding the linkage among the foreign bank presence, exchange rate volatility and economic growth. To be more precise, this research will test whether different levels of foreign bank presence (international credit access) would influence the effect of exchange rate volatility on economic growth.

1.3 Empirical Model & Data

1.3.1 Data

This study constructs annual panel data from 2003 to 2015 for 115 countries. Data used for this research are compiled and calculated from *World Bank's World Development Indicators (WDI)* and *Worldwide Governance Indicators (WGI)*, *IMF's International Financial Statistics (IFS)* and *Claessens and Van Horen [2014]*. The summary of variables and the list of 115 countries included in the data can be found in tables A1 and A2 in Appendix.

1.3.2 Model Specification

The benchmark specification follows Aghion et al. [2009], which posits that countries with lower levels of financial development tend to suffer more from exchange rate volatility on long run growth. System GMM estimation with two step standard error is used here for the regression analysis. Since this study of research focuses on short-run growth, the annual growth of GDP per employed is used as the dependent variable instead of five year average growth of GDP per employed as in Aghion et al. [2009]. Starting from the benchmark, this study examines the growth effect of exchange rate volatility by including the interaction terms of exchange rate volatility with financial development and foreign bank penetration. More specifically, the following equation is estimated:

$$\begin{aligned} y_{i,t} - y_{i,t-1} =& (\alpha - 1)y_{i,t-1} + \gamma_1 RER_{i,t} + \gamma_2 FD_{i,t} + \gamma_3 FBNUMBER_{i,t} \\ &+ \gamma_4 RER_{i,t} * FD_{i,t} + \gamma_5 RER_{i,t} * FBNUMBER_{i,t} + \beta' Z_{i,t} \\ &+ \mu_t + \eta_i + \epsilon_{i,t} \end{aligned} \tag{1.1}$$

where $y_{i,t}$ is the logarithm of GDP per worker; $RER_{i,t}$ is the real exchange rate volatility measured by the annual standard deviation of the log difference of daily real exchange rate; $FD_{i,t}$ is the financial development level measured by domestic credit to private sector by banks as percentage of GDP; $FBNUMBER_{i,t}$ is the number share of foreign bank as a measure for foreign bank penetration level; $Z_{i,t}$ is a set of macroeconomic control variables including trade openness (OPENNESS), lack of price stability (LPS), government size (GSIZE) and human capital (HUM); and μ_t, η_i and $\epsilon_{i,t}$ are time specific effect, country specific effect and error term, respectively. The detailed definitions and construction of the variables used in the regression can be found in table A1 in Appendix. The summary of statistics and sample correlation can be found in Table 3.1 and Table 3.2, respectively.

Table 1.1: Sample Summary Statistics

Variable	Obs.	Mean	Std. Dev	Min	Max
GDP Per Employed (Y)	917	10.18	1.116	7.287	12.33
GDP Per Employed Growth (G)	917	0.0201	0.0351	-0.137	0.273
Private Credit/GDP (FD)	917	58.88	47.86	2.933	312.2
Foreign Bank's Number Share (FBNUMBER)	917	42.68	28.36	0	100
Real Exchange Rate Volatility (RER)	917	0.00636	0.00557	0.000530	0.121
Government Expenditure/GDP (GSIZE)	917	15.99	4.852	3.460	31.57
Inflation Rate (CPI)	917	5.579	5.350	-4.480	51.46
Trade Openness (OPENNESS)	917	89.86	54.65	22.11	455.3
Secondary Schooling (HUM)	917	80.62	27.66	9.011	163.10

Table 1.2: Sample Correlation

	Y	G	FD	FBNUMBER	RER	GSIZE	OPENNESS	CPI
Y	1							
G	-0.130	1						
FD	0.607	-0.133	1					
FBNUMBER	-0.246	0.0267	-0.219	1				
RER	-0.0372	-0.156	-0.00620	0.0868	1			
GSIZE	0.356	-0.145	0.376	-0.0689	0.0752	1		
OPENNESS	0.343	0.0420	0.321	0.322	-0.0850	0.0566	1	
CPI	-0.322	0.0273	-0.348	-0.0530	0.279	-0.289	-0.168	1
HUM	0.843	-0.0582	0.571	-0.205	-0.0250	0.413	0.244	-0.285

As suggested in the equation above, the estimated effect of exchange rate volatility is:

$$\frac{\partial(y_{i,t} - y_{i,t-1})}{\partial RER_{i,t}} = \gamma_1 + \gamma_4 FD_{i,t} + \gamma_5 FBNUMBER_{i,t} \tag{1.2}$$

Therefore, the estimated combined effect of exchange rate volatility depends on both financial development level and foreign bank penetration level as both of them influence countries' access to credit. The main hypothesis of this paper is $\gamma_1 < 0$, $\gamma_4 > 0$ and $\gamma_5 > 0$ so that the negative growth effect of exchange rate volatility is more severe if a country has low levels of both financial development and foreign bank presence. However, if a country has high levels of both financial development and foreign bank presence or one of the factors is high enough, it is possible for this country to benefit from exchange rate volatility. In other words, both the financial development level and foreign bank penetration level ameliorate the adverse effect of exchange rate volatility. If the hypothesis can't be rejected, our study helps explain the past literature's ambiguous result of the growth effect of exchange rate volatility, especially in developed countries.

The expected effect of financial development on growth is positive. The positive relationship between financial development level and growth is almost a consensus. Demirguc-Kunt and Levine [2008] suggest that financial development reduces market friction and promotes economic growth in five aspects: 1. Produce information and allocate capital; 2. Monitor investments and exert corporate governance; 3. Facilitate the trading, diversification, and management of risk; 4.

Mobilize and pool savings; 5. Ease the exchange of goods and services. The empirical works also widely support the view of positive correlation between financial development and growth (McKinnon [2010]; Levine et al. [2000]; Christopoulos and Tsionas [2004]. Although the causality between financial development and growth is still in debate, it is not the main discussion of this paper and the system GMM estimator used in this study helps to deal with the potential endogeneity problem.

As discussed in the last part of literature review, the expected economic effect of foreign bank penetration on growth is ambiguous. What's more, it is also important to notice that with the involvement of interaction term in the regression, the interpretation of the economic effect of financial development and foreign bank number should include the coefficient before the interaction (γ_4 and γ_5) as well instead of only looking at γ_3 and γ_4.

1.4 Empirical Analysis

1.4.1 Regression Results

Table 3.3 presents results using two-step system GMM with small-sample adjustments, and orthogonal deviations for estimation with Windmeijer-corrected standard errors. Orthogonal deviation is used to maximize sample size due to the existence of gaps in panel data used in this study. Windmeijer-corrected standard errors are used because, as suggested by Windmeijer [2005], standard errors of two-step GMM estimation can be severely downward biased without correction. Regression [3.1] is similar to the result of Aghion et al. [2009], which suggests higher levels of financial development can ameliorate the adverse effect of real exchange rate volatility on short run economic growth. Countries with higher levels of financial development are less likely to be adversely affected by exchange rate volatility. Regression [3.2] considers the effect of foreign bank penetration, and the result suggests that higher levels of foreign bank presence can reduce the adverse effect of exchange rate as well. Regression [3.3] includes the interaction term of both financial development and foreign bank presence with exchange rate volatility, and the result gives the desired direction for γ_1, γ_4 and γ_5, and all three coefficient are statistically significant. This result shows that countries with high levels of financial development or high levels of foreign bank presence or both are less likely to be adversely affected by exchange rate volatility. In other word, high levels of credit access, either from domestic or international credit market, can help countries reduce the negative economic shock from real exchange rate volatility. In order to have a better understanding of the result, graphs of marginal effect of real exchange rate volatility on growth with different levels of financial development and foreign bank presence is presented as below in Figure 1.1. The shaded area in the graphs is the 95% confidence interval, which is calculated using delta method.

Figure 1.1 suggest countries are adversely affected by real exchange rate volatility when both financial development and foreign bank presence level are low. However, countries with high credit access (high level of foreign bank presence and financial development) are no longer affected by real exchange rate volatility.

Table 1.3: Two-Steps System GMM with Windmeijer (2005) Correction

Dependent Variable: Growth of GDP per Empoyed

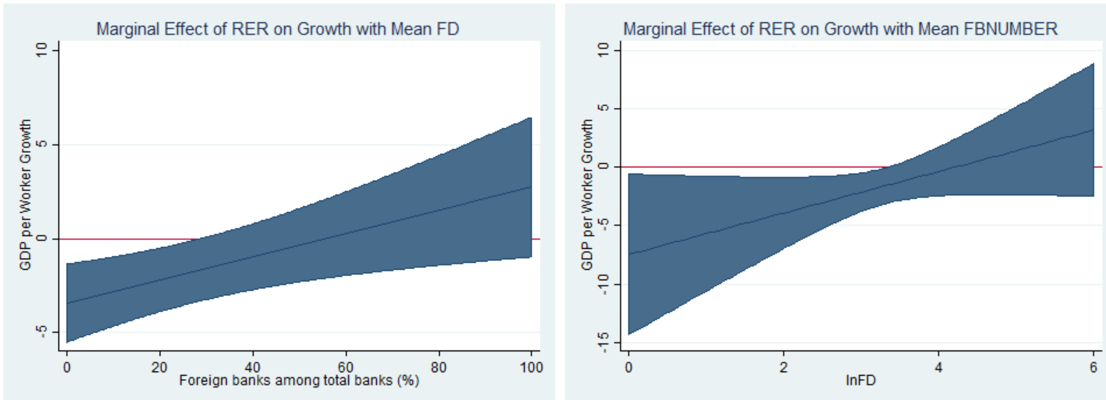
VARIABLES	(3.1)	(3.2)	(3.3)
Real Exchange Rate Volatility (RER)	-5.154**	-4.306***	-10.10**
	(2.235)	(1.411)	(3.870)
Financial Development (FD)[a]	-0.00803	-0.00915	-0.0176**
	(0.00612)	(0.00654)	(0.00768)
Foreign Bank Number Share (FBNUMBER)		-0.000506***	-0.000574***
		(0.000177)	(0.000196)
RER*FD	1.126*		1.776*
	(0.575)		(1.036)
RER*FBNUMBER		0.0643**	0.0616***
		(0.0265)	(0.0234)
Lack of Price Stability (LPS)	-0.00422	0.0792	0.0713
	(0.0441)	(0.0524)	(0.0475)
Trade Openness (OPENNESS)[a]	0.00403	0.00642	0.00967*
	(0.00340)	(0.00513)	(0.00545)
Government Size (GSIZE)[a]	-0.00743	0.00737	0.00509
	(0.00740)	(0.00700)	(0.00700)
Human Capital (HUM)[a]	0.00990	0.0196***	0.0178**
	(0.00669)	(0.00694)	(0.00737)
Inintial GDP per Employed[a]	-0.0326**	-0.0443***	-0.0407***
	(0.0133)	(0.0110)	(0.00912)
No. Countries/No. Observations	137/1,102	115/917	115/917
SPECIFICATION TEST (p-values)			
Arellano-Bond test for AR(1)	0.001	0.000	0.019
Arellano-Bond test for AR(2)	0.405	0.603	0.491
Hansen test of over-identification	0.214	0.223	0.597

Notes: The estimation method is two-step system GMM with Windmeijer-corrected standard errors, small-sample adjustments, and orthogonal deviations. Time and fixed effects are included in all specifications.

Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

[a] In the regression, this variable is included as log (variable)

Figure 1.1: Marginal effect of Real exchange rate volatility (RER)



1.4.2 Impact of Credit Access on Developed and Developing Countries

In order to examine the nonlinearity effect, regression analysis on subsamples of developed and developing countries is also presented in table 3.4. The same set of controls are used in the regression but the result from developed and developing countries differs dramatically. As we can see from table A3, the major difference between developed countries' subsample and developing countries' subsample is that developed countries have much higher financial development levels. (Average financial development for developed countries here is around 98% as opposed to around 35% for developing countries, while foreign bank presence and real exchange rate volatility are similar for two subsample.) Regression [4.1] presents results for 41 developed nations, and coefficients that were significant in regression [3.3] are no longer significant, which means exchange rate volatility has no significant impact when domestic credit access is high. Moreover, the sign of coefficient for real exchange rate volatility reverses from negative to positive, which suggest that real exchange rate volatility might be able to promote economic growth when financial development is high, and this result is consistent with Aghion et al. [2009]'s finding.

Regression [4.2] presents results for 74 developing countries, and the results are similar to regression [3.2]. γ_1, γ_4 and γ_5 are in the desired direction and are statistically significant. Therefore, the comparison between regression [4.1] and [4.2] suggests that exchange rate volatility can have more adverse effects on countries with low credit access, and high credit access helps countries to insulate the potential adverse effects of exchange rate volatility.

1.5 Endogeneity issues

Like all other empirical studies, it is important to know whether the standard question of endogeneity is a severe issue in the context of this research. Both tests within GMM method and existing empirical evidences of exchange rate volatility will be examined to determine whether endogeneity is a big factor.

Bond et al. [2001] presents that system GMM is capable to control for potential endogeneity issue. This technique is a system of relevant regressions expressed in first-differences and in levels. Instruments for differenced equations are obtained from levels of at least twice lagged explanatory variables, and instruments for levels equation are lagged differences of the variable. These instruments are considered to be appropriate under the assumption that the correlation between explanatory variables does not exist when those variables are in differences despite of possible correlation in levels. Therefore, it is important to make sure that the estimation does not violate the key assumption of weak exogeneity of explanatory variables. Following Blundell and Bond [1998], the Hansen test and Arellano-Bond test are implemented after estimation, and the results are presented at the bottom of the

Table 1.4: Subsample Comparison of Developed and Developing Countries

Dependent Variable: Growth of GDP per Empoyed

VARIABLES	(4.1) Developed Countries	(4.2) Developing Countries
Real Exchange Rate Volatility (RER)	17.2	-13.35***
	(26.34)	(4.174)
Financial Development (FD)[a]	-0.0451	-0.00967
	(0.0345)	(0.0103)
Foreign Bank Number Share (FBNUMBER)	0.00114	-0.000944***
	(0.000956)	(0.000289)
RER*FD	-4.856	2.374*
	(4.942)	(1.271)
RER*FBNUMBER	-0.0360	0.116***
	(0.0675)	(0.0358)
Lack of Price Stability (LPS)	-0.644	0.0830
	(0.386)	(0.0825)
Trade Openness (OPENNESS)[a]	0.0264	0.00953
	(0.0229)	(0.00871)
Government Size (GSIZE)[a]	-0.00885	0.00424
	(0.0375)	(0.0104)
Human Capital (HUM)[a]	0.0568	0.0143*
	(0.0833)	(0.00853)
Inintial GDP per Employed[a]	0.0141	-0.0245**
	(0.0381)	(0.0101)
No. Countries/No. Observations	41/343	74/574
SPECIFICATION TEST (p-values)		
Arellano-Bond test for AR(1)	0.444	0.000
Arellano-Bond test for AR(2)	0.177	0.653
Hansen test of over-identification	0.333	0.936

Notes: The estimation method is two-step system GMM with Windmeijer-corrected standard errors, small-sample adjustments, and orthogonal deviations. Time and fixed effects are included in all specifications.

Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

[a] In the regression, this variable is included as log (variable)

table 3.

Arellano-Bond test for AR (2) is used to test the second order serial correlation in this study. It is important to make sure the error term of differenced equation is not serially correlated in second order. We can see from the bottom of Table 3 that regression [3.1], [3.2] and [3.3] all pass the Arellano-Bond test. The Hansen test is used to test the validity of the instruments with the null hypothesis that all instruments as a group are exogenous. Roodman [2009] points out that too many instrument can overfit the model, generating a perfect p-value of 1.00 for the Hansen test. Therefore, the ideal p-value for the Hansen test should not be too high or too low. The Hansen test results for regression [[3.1], [3.2] and [3.3] all suggest the validity of instrument should not be rejected.

Furthermore, as pointed out by Aghion et al. [2009], endogeneity issue is less of the issue with interaction term than with single variable as this research focuses on exchange rate volatility's growth effect with different level of financial development and foreign bank presence. The idea is that if a variable is correlated to both exchange rate volatility and growth, although it would bias the result for linear regression immediately, it would bias the coefficient of interaction term only if the correlation between this variable and exchange rate varies significantly with levels of financial development and foreign bank presence.

To examine whether endogeneity is a serious issue, it is also important to know what existing literature says regarding the possibility of reverse causality. Hausmann et al. [2006] finds that GDP growth has a positive and statistically significant effect on determining real exchange rate volatility. Based on the result of Hausmann et al. [2006], even if the reverse causality link from GDP growth to exchange rate volatility happens, it would only reinforce the result of this research as this research is focusing on the potential adverse effect of real exchange rate volatility on growth.

Therefore, in the context of this research, endogeneity is not a major factor behind the result.

1.6 Conclusion

From the aspect of the domestic credit market, our empirical results find countries with higher level of financial development are less likely to be adversely affected by exchange rate volatility. As for the aspect of the international credit market, our results suggest that a higher level of foreign bank presence can ameliorate the adverse growth effect of exchange rate volatility. Therefore, for countries with high levels of credit access, either from domestic or international credit market or both, real exchange rate volatility would have little or no negative effect on countries' growth. In contrast, growth of countries with low level of credit access on both domestic and international credit markets would be more adversely affected by real exchange rate volatility.

The potential policy implication that can be drawn from this study is at two-pronged. First, for countries with high levels of credit access (high levels of financial development or foreign bank presence or both), more flexible exchange rate regime can be used as countries' high credit access helps to insulate the economy from the adverse effect of exchange rate volatility. Second, for countries with low credit access, exchange rate stability is important for economic growth so that the fixed exchange rate regime is preferred.

Table 1.A1: Summary of variables

Variable	Description	Formula used	Source
Y	Real GDP per capita	GDP per person employed is gross domestic product (GDP) divided by total employment in the economy. Purchasing power parity (PPP) GDP is GDP converted to 2011 constant international dollars using PPP rates.	Author's calculation using data from World Bank's WDI
G	Growth rate of real GDP per capita	Log difference of GDP per capita	Author's calculation using data from World Bank's WDI
RER	Real Exchange Rate Volatility	Annual standard deviation of daily log differences real exchange rate. Real exchange rate is calculated from nominal exchange rate by adjusting price.	Author's calculation using data from IMF's IFS.
FBNUMBER	Foreign banks' number share	Percentage of the number of foreign owned banks to the number of the total banks in an Economy. A foreign bank is a bank where 50 percent or more of its shares are owned by foreigners.	Claessens and Van Horen [2014]
FD	Financial Development	Domestic credit to private sector by banks (% of GDP)	IMF's IFS
GSIZE	Government Size	General government final consumption expenditure (% of GDP)	World Bank's WDI
LPS	Lack of Price Stability	log (100+inflation rate). Inflation is annual percentage change of CPI	Author's calculation using data from IMF's IFS.
OPENNESS	Trade Openness	Ratio of sum of export and import to GDP	World Bank's WDI
HUM	Human Capital	Ratio of total secondary enrollment, regardless of age, to the population of the age group that officially corresponds to that level of education.	World Bank's WDI
GOVEFFECT	Government effectiveness	Government effectiveness indicator	World Bank's WGI

Table 1.A2: List of 115 Countries

Developed Countries:	United Kingdom	Madagascar
Austria	Uruguay	Malawi
Barbados		Malaysia
Belgium		Mali
Canada	**Developing Countries:**	Mauritania
Chile	Albania	Mauritius
Croatia	Algeria	Mexico
Cyprus	Armenia	Moldova
Czech Republic	Bangladesh	Mongolia
Denmark	Benin	Morocco
Estonia	Bolivia	Mozambique
Finland	Botswana	Namibia
France	Brazil	Nepal
Germany	Bulgaria	Nicaragua
Greece	Burkina Faso	Niger
Hong Kong SAR, China	Burundi	Nigeria
Hungary	Cambodia	Pakistan
Iceland	Cameroon	Panama
Ireland	China	Paraguay
Israel	Colombia	Peru
Italy	Congo, Rep.	Philippines
Japan	Costa Rica	Romania
Korea, Rep.	Dominican Republic	Russian Federation
Kuwait	Ecuador	Rwanda
Latvia	El Salvador	Senegal
Lithuania	Georgia	Serbia
Luxembourg	Ghana	South Africa
Netherlands	Guatemala	Sri Lanka
Norway	Honduras	Sudan
Oman	India	Swaziland
Poland	Indonesia	Tanzania
Portugal	Iran, Islamic Rep.	Thailand
Qatar	Jamaica	Togo
Saudi Arabia	Jordan	Tunisia
Slovak Republic	Kazakhstan	Turkey
Slovenia	Kenya	Uganda
Spain	Kyrgyz Republic	Ukraine
Sweden	Lebanon	Venezuela, RB
Switzerland	Libya	Yemen, Rep.
Trinidad and Tobago	Macedonia, FYR	

Table 1.A3: Summary Statistics for developed and developing countries

1.A3.1: Subsample Summary Statistics for developed countries

Variable	Obs.	Mean	Std. Dev	Min	Max
GDP Per Employed (Y)	343	11.20	0.398	10.20	12.33
GDP Per Employed Growth (G)	343	0.0132	0.0293	-0.135	0.105
Private Credit/GDP (FD)	343	98.93	51.09	20.48	312.2
Foreign Bank's Number Share (FBNUMBER)	343	38.07	31.29	0	100
Real Exchange Rate Volatility (RER)	343	0.00654	0.00677	0.000647	0.121
Government Size (GSIZE)	343	19.09	3.972	8.418	28.06
Inflation Rate (CPI)	343	2.800	2.328	-4.480	15.43
Trade Openness (OPENNESS)	343	110.9	73.24	24.46	455.3
Secondary Schooling (HUM)	343	103.2	10.07	78.99	163.1

1.A3.1: Subsample Summary Statistics for developing countries

Variable	Obs.	Mean	Std. Dev	Min	Max
GDP Per Employed (Y)	574	9.571	0.953	7.287	11.42
GDP Per Employed Growth (G)	574	0.0242	0.0375	-0.137	0.273
Private Credit/GDP (FD)	574	34.94	23.86	2.933	135.4
Foreign Bank's Number Share (FBNUMBER)	574	45.44	26.10	0	100
Real Exchange Rate Volatility (RER)	574	0.00625	0.00471	0.000530	0.0443
Government Size (GSIZE)	574	14.14	4.366	3.460	31.57
Inflation Rate (CPI)	574	7.240	5.928	-3.100	51.46
Trade Openness (OPENNESS)	574	77.28	33.90	22.11	210.4
Secondary Schooling (HUM)	574	67.15	26.00	9.011	114.6

References

Philippe Aghion, Philippe Bacchetta, Romain Rancière, and Kenneth Rogoff. Exchange rate volatility and productivity growth: The role of financial development. *Journal of Monetary Economics*, 56(4):494–513, May 2009.

Paul Alagidede and Muazu Ibrahim. On the causes and effects of exchange rate volatility on economic growth: evidence from ghana. *Journal of African Business*, pages 1–25, 2016.

Augustine C. Arize, Thomas Osang, and Daniel J. Slottje. Exchange-rate volatility in Latin America and its impact on foreign trade. *International Review of Economics & Finance*, 17(1):33–44, 2008.

Marianne Baxter and Alan C. Stockman. Business cycles and the exchange-rate regime : Some international evidence. *Journal of Monetary Economics*, 23(3): 377–400, May 1989.

T.H.L. Beck, A. Demirgüc-Kunt, L. Laeven, and V. Maksimovic. The determinants of financing obstacles. Technical report, 2006.

Joydeep Bhattacharaya. The role of foreign banks in developing countries: A survey of evidence. *Unpublished manuscript, Cornell University*, 1993.

Richard Blundell and Stephen Bond. Initial conditions and moment restrictions in dynamic panel data models. *Journal of Econometrics*, 87(1):115–143, August 1998.

Stephen Roy Bond, Anke Hoeffler, and Jonathan Temple. GMM Estimation of Empirical Growth Models. CEPR Discussion Papers 3048, C.E.P.R. Discussion Papers, November 2001.

Harry G. Broadman, James Anderson, Constantijn A. Claessens, Randi Ryterman, Stefka Slavova, Maria Vagliasindi, and Gallina A. Vincelette. *Buildings Market Institutions in South Eastern Europe : Comparative Prospects for Investment and Private Sector Development*. Number 14947 in World Bank Publications. The World Bank, 2004. ISBN ARRAY(0x5274b978).

Craig Burnside, Martin Eichenbaum, and Sergio Rebelo. Hedging and financial fragility in fixed exchange rate regimes. *European Economic Review*, 45(7): 1151–1193, 2001.

Myint Moe Chit, Marian Rizov, and Dirk Willenbockel. Exchange rate volatility and exports: new empirical evidence from the emerging east asian economies. *The World Economy*, 33(2):239–263, 2010.

Dimitris K. Christopoulos and Efthymios G. Tsionas. Financial development and economic growth: evidence from panel unit root and cointegration tests. *Journal of Development Economics*, 73(1):55–74, February 2004.

Stijn Claessens and Neeltje Van Horen. Foreign banks: Trends and impact. *Journal of Money, Credit and Banking*, 46(s1):295–326, 2014.

Peter B. Clark. Uncertainty, Exchange Risk, And The Level Of International Trade. *Economic Inquiry*, 11(3):302–313, 09 1973.

George Clarke, Robert Cull, Maria Soledad Martinez Peria, and Susana M Sanchez. Foreign bank entry: Experience, implications for developing economies, and agenda for further research. *The World Bank Research Observer*, 18(1):25–59, 2003.

George R.G. Clarke, Robert Cull, and Maria Soledad Martinez Peria. Foreign bank participation and access to credit across firms in developing countries. *Journal of Comparative Economics*, 34(4):774–795, December 2006.

Paul De Grauwe. Exchange rate variability and the slowdown in growth of international trade. *Staff Papers*, 35(1):63–84, 1988.

Ralph de Haas and Iman van Lelyveld. Foreign banks and credit stability in Central and Eastern Europe. A panel data analysis. *Journal of Banking & Finance*, 30(7):1927–1952, July 2006.

Firat Demir. Growth under exchange rate volatility: Does access to foreign or domestic equity markets matter? *Journal of Development Economics*, 100(1): 74–88, 2013.

Asli Demirguc-Kunt and Ross Levine. Finance, financial sector policies, and long-run growth. Policy Research Working Paper Series 4469, The World Bank, January 2008.

Ibrahima Amadou Diallo. The Effects of Real Exchange Rate Volatility on Productivity Growth. *Eastern European Business and Economics Journal*, 1(2): 66–84, 2015.

Sebastian Edwards and Eduardo Levy Yeyati. Flexible exchange rates as shock absorbers. *European Economic Review*, 49(8):2079–2105, November 2005.

Barry Eichengreen and Ricardo Hausmann. Exchange rates and financial fragility. *Proceedings - Economic Policy Symposium - Jackson Hole*, pages 329–368, 1999.

Barry Eichengreen and David Leblang. Exchange Rates and Cohesion: Historical Perspectives and Political-Economy Considerations. *Journal of Common Market Studies*, 41(5):797–822, December 2003.

Atish R. Ghosh, Anne-Marie Gulde, and Holger C. Wolf. *Exchange Rate Regimes: Choices and Consequences*, volume 1 of *MIT Press Books*. The MIT Press, 2003. ISBN ARRAY(0x6b7b9d40).

Mariassunta Giannetti and Steven Ongena. Financial Integration and Firm Performance: Evidence from Foreign Bank Entry in Emerging Markets. *Review of Finance*, 13(2):181–223, 2009.

Paul De Grauwe and Gunther Schnabl. Exchange Rate Stability, Inflation, and Growth in (South) Eastern and Central Europe. *Review of Development Economics*, 12(3):530–549, 08 2008.

Axel Grossmann, Inessa Love, and Alexei G Orlov. The dynamics of exchange rate volatility: A panel var approach. *Journal of International Financial Markets, Institutions and Money*, 33:1–27, 2014.

Ricardo Hausmann, Ugo Panizza, and Roberto Rigobon. The long-run volatility puzzle of the real exchange rate. *Journal of International Money and Finance*, 25(1):93–124, February 2006.

Jérôme Héricourt and Sandra Poncet. Exchange Rate Volatility, Financial Constraints, and Trade: Empirical Evidence from Chinese Firms. *World Bank Economic Review*, 29(3):550–578, 2015.

Aasim M. Husain, Ashoka Mody, and Kenneth S. Rogoff. Exchange rate regime durability and performance in developing versus advanced economies. *Journal of Monetary Economics*, 52(1):35–64, January 2005.

Lorna Katusiime, Frank W. Agbola, and Abul Shamsuddin. Exchange rate volatility–economic growth nexus in Uganda. *Applied Economics*, 48(26):2428–2442, June 2016. doi: 10.1080/00036846.2015.112.

Ross Levine. International Financial Liberalization and Economic Growth. *Review of International Economics*, 9(4):688–702, November 2001.

Ross Levine, Norman Loayza, and Thorsten Beck. Financial intermediation and growth: Causality and causes. *Journal of monetary Economics*, 46(1):31–77, 2000.

Ross Levine et al. More on finance and growth: more finance, more growth? *Review-Federal Reserve Bank Of Saint Louis*, 85(4):31–46, 2003.

Wei Li. Effects of foreign banks entry on efficiency of chinese commercial banks. *Research Institute of Statistical Sciences, National Bureau of Statistics of China*, 2011.

Ronald I McKinnon. Optimum currency areas. *The American Economic Review*, 53(4):717–725, 1963.

Ronald I McKinnon. *Money and capital in economic development*. Brookings Institution Press, 2010.

Ronald I. McKinnon and Kenichi Ohno. *Dollar and Yen: Resolving Economic Conflict between the United States and Japan*, volume 1 of *MIT Press Books*. The MIT Press, 1997. ISBN ARRAY(0x6b69bca0).

James Edward Meade. *The theory of international economic policy*, volume 1. Oxford University Press, 1951.

Atif Mian. Foreign, private domestic, and government banks: New evidence from emerging markets. *Journal of Banking and Finance*, 27(7):1219–1410, 2003.

Robert A Mundell. Uncommon arguments for common currencies. *The economics of common currencies*, pages 114–132, 1973.

Ann L. Owen and Judit Temesvary. Heterogeneity in the growth and finance relationship: How does the impact of bank finance vary by country and type of lending? *International Review of Economics & Finance*, 31(C):275–288, 2014. doi: 10.1016/j.iref.2014.02.00.

Eswar Prasad, Kenneth Rogoff, Shang-Jin Wei, and M Ayhan Kose. Effects of financial globalization on developing countries: some empirical evidence. In *India's and China's Recent Experience with Reform and Growth*, pages 201–228. Springer, 2005.

Carmen Reinhart and Guillermo Calvo. Fear of floating. MPRA Paper 14000, University Library of Munich, Germany, May 2002.

Marian Rizov. Credit Constraints and Profitability : Evidence from a Transition Economy. *Emerging Markets Finance and Trade*, 40(4):63–83, July 2004.

David Roodman. How to do xtabond2: An introduction to difference and system GMM in Stata. *Stata Journal*, 9(1):86–136, March 2009.

Gunther Schnabl. Exchange Rate Volatility and Growth in Emerging Europe and East Asia. *Open Economies Review*, 20(4):565–587, September 2009. doi: 10.1007/s11079-008-9084-6.

Silvana Tenreyro. On the trade impact of nominal exchange rate volatility. *Journal of Development Economics*, 82(2):485–508, March 2007.

Eric van Wincoop and Philippe Bacchetta. Does Exchange-Rate Stability Increase Trade and Welfare? *American Economic Review*, 90(5):1093–1109, December 2000.

Frank Windmeijer. A finite sample correction for the variance of linear efficient two-step GMM estimators. *Journal of Econometrics*, 126(1):25–51, May 2005.

Chapter 2

Price Convergence of Bitcoin: a VECM Study

2.1 Introduction

Law of One Price (LOOP) suggests that the price of identical goods should be sold at the same price in different locations after adjusting for exchange rate in absence of trade frictions. However, traditional literature often find evidences of same good with different prices at different locations, and price adjustment process usually takes a very long time. Researchers often attribute this slow price adjustment process to high transaction cost and transportation time of moving commodities. It makes people wonder: does LOOP hold for a commodity with minimal transaction cost and transportation time? This question can be answered by studying Bitcoin.

Introduced by Satoshi Nakamoto in 2009, Bitcoin is the first crytocurrency to serve as peer-to-peer payment system. Bitcoin does not have physical presence and can be stored in digital wallet virtually. All Bitcoins are identical, and can be traded 24/7 through Bitcoin exchanges. Bitcoin can be sent from one digital address to another address very quickly by paying very small transaction fee even if owners of addresses are in different countries. As of April 22nd, 2020, average transaction fee is 0.91 US dollar per transaction, and median confirmation time for Bitcoin to be recorded in a block is 13 minutes, according to data from *blockchain.com*.

Low transaction time and cost make Bitcoin a great studying object to test Law of One Price. This paper is trying to answer three question mainly. First, does Law of One Price hold for Bitcoins traded in different markets under different currency? Second, does Bitcoin have faster speed of price convergence that other commodities and assets studied in the LOOP literature? Third, does border effect exist in Bitcoin market? Using Bitcoin trading data from 20 Bitcoin Exchanges under 14 currencies, Johansen cointegration test is used to test whether Bitcoins traded in different markets are cointegrated and have same long run equilibrium. Vector Error Correction Model (VECM) is used to estimate speeds of adjustment for each trading pair of Bitcoins. Using dataset constructed by estimated Bitcoin half lives in VECM, the existence of border effect is tested to see if price adjustment process of Bitcoin is affected by borders.

Results of this paper find all Bitcoin trading pairs have a cointergration relationship, which present evidences of Law of One Price in the long run. This study also find that price adjustment process in Bitcoin markets are significantly faster than other markets including gold and other financial products. Moreover, empirical results suggest that price adjustment speed in Bitcoin markets is significantly lower if different currencies are involved in Bitcoin trading pair, which indicates the existence of border effect and market segmentation.

The rest of paper is organized as follows: Section II gives a brief review of Bitcoin. Section III reviews related literature and discusses contribution of this study. Section IV provides information on sources of data and methodology used for analysis. Section V presents empirical results that support Law of One Price. Section VI tests border effect in Bitcoin markets and interprets regression results. Section VII concludes.

2.2 Brief Review of Bitcoin

2.2.1 Introduction of Bitcoin

Bitcoin is a decentralized digital currency and a peer to peer payment method introduced by Satoshi Nakomoto[1] in 2009. By design, Bitcoin network can work without intermediaries and central authorities. Ownership of Bitcoins is implemented through the "blockchain", a public ledger that records Bitcoin transactions. Bitcoin "addresses", managed by client software "wallet", are used by Bitcoin owners to store Bitcoins. Number of Bitcoins owned by each address is recorded on blockchain, which will be updated when new transactions occur.

For any decentralized payment system, a common concern is double spending problem, which refers to the issue that single digital token can be spent more than once. To address this issue, Bitcoin network includes a process called "mining"

[1]The true identity of Satoshi Nakomoto is remained unknown

conducted by "miners" to verify previous spent Bitcoin are not involved in newly added transactions. As an economic incentive, miners are eligible to be rewarded with fixed number of Bitcoins by verifying 1 megabyte worth of previous transactions. In order to obtain rewards, miners need to compete to solve an encrypted numeric problem. Bitcoins will be rewarded to first miner who solves the problem and a new "block" will be added to existing blockchain. Other than fixed Bitcoin reward from Bitcoin network, miners can also obtain transaction fee [2] paid by Bitcoin users when new transactions are initiated. To complete a Bitcoin transaction, three to six blocks are required to be added, which takes around 30 minutes to an hour.

As suggested by Ali et al. [2014], few actual transactions are denominated in Bitcoin, and for transactions that use Bitcoin as payment, quote prices from retailers frequent adjust to maintain a relatively stable price when expressed in fiat currencies. Therefore, users of Bitcoin have needs to converts Bitcoin into fiat currency, and online exchanges, known as "cryptocurrency exchanges", facilitate such transactions. Bitcoin can be traded on cryptocurrency exchanges 24 hours a day, 7 days a week. Through crytocurrency exchanges, Bitcoin users can convert their Bitcoin into fiat currencies or stable coins like USDT[3] and USDC[4] that peg their value to some fiat currencies or commodities like gold. Maker[5]-taker[6] fee model is often used in crypto-exchanges for trading fee, and the mount of fee

[2] The transaction fee is around 0.91 US dollar per transaction as of April 22nd, 2020

[3] USDT (Tether) is a type of stablecoin issued by Tether Limited. The value of one USDT is approximately one US dollar

[4] USDC (USD Coin) is a type of stablecoin issued by Coinbase, which has a one to one exchange rate with US dollar promised by Coinbase.

[5] You are considered as a maker if your order is not immediately matched and get filled by a matching order from another investor later.

[6] You are considered as a taker if your order is placed at the market price and get filled immediately.

charged varies by account's trading volume. Using Coinbase Pro (a US based cryptocurrency exchange) as an example, taker and maker fee are both 0.5% of trading value for account with less than 10,000 USD trading volume in past 30 days. Trading fee will decrease as trading volume increases. In Coinbase, for account with 30 day trading volume exceeding 1 billion USD, taker fee can be reduced to 0.04%, and maker fee can be reduced to 0%.[7] Therefore, high trading volume traders face very small trading fee.

To convert Bitcoin into fiat currency, traders need valid bank accounts in home country of corresponding fiat currency. While it is possible to have a crypto-exchange offering Bitcoin trading denominated in multiple fiat currencies, traders are not allowed to trade in multiple currencies unless they have corresponding bank accounts. For instance, both US dollar and Euro tradings are supported by Coinbase pro, but US bank account owners can trade Bitcoins only in US dollars and EU bank account owners can only trade in Euros. Therefore, trading Bitcoin in different fiat currencies is equivalent with trading in different countries even when these tradings are hosted by same crypto-exchange.

2.2.2 Bitcoin Arbitrage Activities

Occasionally, Bitcoin price on one market can be different from Bitcoin price on another market, which provides arbitrage opportunity. For example, when Bitcoins are traded at premium in Korea, traders can purchase Bitcoin in US using dollars, transfer Bitcoins to North Korea and sell in korean won. After completing sales in North Korea, traders can convert korean won back to US dollars and wire the money back to US and repeat the process.

[7] Detailed trading fee schedule can be found following this link:
https://support.pro.coinbase.com/customer/en/portal/articles/2945310-fees

Bitcoin arbitragers face three transaction costs in above process, trading cost when they buy and sell Bitcoins, transaction cost when they send Bitcoin from one address to another and service cost charged by banks when they convert and wire money back to home country. For large volume trader, as explained earlier, both trading cost and transaction cost are very low, and banks' service fee will be low for big clients as well.

Arbitrage process is even easier between Bitcoin markets using same fiat currency since traders no longer need to do currency conversion and international wire. Therefore, arbitrage activities in Bitcoin markets are not costly and complicated to do, which provides grounds for Law of One Price.

2.2.3 Why using Bitcoin to Study Law of One Price?

Three difficulties are often faced by traditional LOOP literature. First, transaction costs are very high and cannot be ignored for most commodities, which is especially the case when transferring goods across borders. Second, transaction process takes a long time to complete, and prices of commodities and asset are likely to fluctuate a lot during transaction. Third, as pointed out by Pippenger [2016], arbitrage process for many commodities are simply not possible. For instance, Asplund and Friberg [2001] finds identical goods dominated in different currencies have different prices on the same Scandinavian ferry, which challenges LOOP. Pippenger [2016] suggests Asplund and Friberg [2001]'s study is problematic because arbitrage activities are not possible on these ferries.

By studying Bitcoin, all three difficulties can be addressed. As discussed earlier, transactions of Bitcoin between markets (even across borders) are fast and inexpensive. Traders can send Bitcoins from one address to another within an hour with very minimal transaction cost. Moreover, Bitcoin arbitrage activities are relatively simple to execute. These features of Bitcoin make it an ideal object for Law of One Price literature.

2.3 Literature Reviews

2.3.1 Past Literature

The Law of One price (LOOP) states in absence of trade friction, identical goods sold in different location should have same price when expressed in term of same currency. Under the assumption of effective arbitrage, price deviations from LOOP can be eliminated by arbitragers very quickly. Therefore, ideally, we should be able to observe relatively fast speed of price converge. However, past empirical literature on LOOP often find very slow speed of convergence on commodities and financial products.

Half life is the amount of time for half of the price deviation to die out, and it is used as a standard measure of the speed of price convergence in the literature. The consensus is that prices may converge to a long equilibrium but the speed of convergence is very slow (Lothian and Taylor [1997] and Taylor [2003]). As pointed out by Rogoff [1996], the general consensus for past LOOP literature on estimated half lives ranging from 3 to 5 years, which are extremely long. Rogoff [1996] suggests that persistent price difference in international good market is caused by large trading frictions, which include transportation, tariff policy, information cost and lack of labor mobility. Goldberg and Verboven [2005]'s study on European car market estimates half-lives to be 1.3 to 1.6 years, which are substantially shorter than estimations in earlier works but still very high.

Espinoza et al. [2011] investigates cross listed stocks for member countries of the Gulf Cooperation Council (GCC) and finds half lives to be 3.5 to 5.5 months. Comparing with past literature, Espinoza et al. [2011]'s estimation of half live is significantly lower, and it is possibly due to lower transaction cost and time in the financial market. In this study, we can discover what will happen to half life if transaction time and cost are very minimal by looking into Bitcoin market

Kroeger and Sarkar [2017] studies price differences of Bitcoin trading on 6 exchanges and has estimated half-lives from 1.4 to 6.6 days for converging trading pairs, which are significantly lower than half-lives estimated from other markets. However, data used by Kroeger and Sarkar [2017] only contains 6 Bitcoin exchanges, and trading currency is limited to US dollars. Their data contains a very small fraction of total Bitcoin trading so that their results are not enough to provide inference to overall Bitcoin market. 20 Bitcoin exchanges with 14 different trading currencies included in the data of this research constitutes 1035 trading pairs (15 trading pairs are formed in Kroeger and Sarkar [2017]'s study) and represent more than 72% of total Bitcoin trading volumes. With this comprehensive dataset, results are more convincing, and can be generalized to entire Bitcoin market.

2.3.2 Contribution of this study

The paper contributes to the existing literature in following ways. First, this paper provides evidence for LOOP by demonstrating the speed of price convergence of Bitcoin, a commodity with very low transaction cost and time, are significantly faster than other assets with high transaction time and long transportation time.

Second, Bitcoin trading data used in this paper is the most comprehensive data that I am aware of in relevant literature. Results of this paper can be generalized to entire Bitcoin market.

Finally, this study demonstrates border effect in Bitcoin market by presenting significantly longer estimated half-lives in Bitcoin trading pairs involving different currencies, which contribute to Bitcoin price difference literature.

2.4 Data and Methodology

2.4.1 Data

This study uses daily data with 20 Bitcoin exchanges and 14 different currencies from 01/27/2018 to 04/02/2020. Exchange rate data are pulled from *openexchangerate.org*. Sources of Bitcoin activity data are *blockchain.com* and *bitcoinity.org*. Bitcoin price and trading data are self-collected by author from Bitcoin exchanges' API using scripts written by python. This data includes 9 out of 10 largest cryptocurrency exchanges by volume and estimated revenue listed by

Bloomberg[8] in 2018, which consist about 72% of the total trading volume in the world according to *bitcoinity.org*. Hence, data used in this study is representative. The detailed list of Bitcoin exchanges and currencies included in the data can be found in Table A1 and A2 in the Appendix at end of paper.

2.4.2 Methodology

Economic theories behind Law of One Price suggest economic forces will restore prices in markets back to equilibrium if these prices move away from the equilibrium for a while. Therefore, if Law of One Price hold in Bitcoin markets, prices in these markets should be linked by a long run equilibrium relation. Johansen conitegration test will be used to test for the existence of long run equilibrium in all Bitcoin trading pairs.

Before performing Johansen conintegration test, it is necessary to check stationary property of prices in each Bitcoin market. In order to have a cointegration relation, Bitcoin prices in markets need to be non-stationary at level but stationary at first difference so that Bitcoin price series need to be integrated of order one, or I(1). Augmented Dickey-Fuller (ADF) test will be used to test stationary property of Bitcoin prices.

Other than testing for the existence of a long run equilibrium between Bitcoin markets, this paper also wants to estimate the efficiency of arbitrage activities in Bitcoin markets, which can be indicated by the amount of time for Bitcoin prices to revert back to long run equilibrium after a deviation. Half-lives, amount of

[8] Reports by Russo, Camila (5 March 2018).https://www.bloomberg.com/news/articles/2018-03-05/crypto-exchanges-raking-in-billions-emerge-as-kings-of-coins

time for half of the price deviation to die out, are used to capture the efficiency of arbitrage activities in Bitcoin markets.

Following Vector Error Correction Model (VECM) is used to estimate half-lives in Bitcoin markets.

$$\Delta \boldsymbol{y}_t = \boldsymbol{\alpha}(\boldsymbol{\beta}' \boldsymbol{y}_{t-1} + \boldsymbol{\mu} + \boldsymbol{\rho} t) + \sum_{i=1}^{p-1} \boldsymbol{\Gamma}_i \Delta \boldsymbol{y}_{t-i} + \boldsymbol{\theta} \boldsymbol{X}_t + \boldsymbol{\gamma} + \boldsymbol{\tau} t + \epsilon_t \tag{4.1}$$

where $\boldsymbol{y}_t = \begin{bmatrix} ln(Price_t^1) \\ ln(Price_t^2) \end{bmatrix}$ and $Price_t^i$ is Bitcoin price of market (exchange currency pair) i, and price is converted to equivalent US dollars if the trading currency is different from USD. $\boldsymbol{X}_t$ is a vector of exogenous control variables include Bitcoin transaction fee, transaction time, trading volume and 30 days price volatility. The number of lag p is determined by lag exclusion Wald test. $\boldsymbol{\alpha} = \begin{bmatrix} \alpha_1 \\ \alpha_2 \end{bmatrix}$, and α_1 measures how fast price of Bitcoin market 1 adjust toward Bitcoin market 2 in response to a Bitcoin price deviation. The speed of price convergence is estimated by half-life, which is calculated as $ln(0.5)/\alpha_1$ if α_1 is negative and statistically significant. If α_1 is not statistically significant, it means Bitcoin price of market 1 is unresponsive to price deviation, and half life can not be estimated. If α_1 is found to be positive, it means Bitcoin price of exchange currency pair 1 diverge from equilibrium in the short run, and half life can not be estimated in this case either.

2.5 Empirical Result

2.5.1 Stationarity test of Bitcoin prices

As discussed earlier, stationarity test for Bitcoin prices is the premise of cointegration test and the model. Augmented Dicky Fuller (ADF) test is used to test the stationarity of Bitcoin price in each Bitcoin market (exchange currency pair) in both level and first differences. ADF test results for all 45 Bitcoin markets are presented in Table 3.1 and Table 3.2. Lag length for each test is based on Akaike Information Criterion (AIC)

ADF tests results shows that Bitcoin price in all Bitcoin markets are not stationary in level since p values of all level series are greater than 0.1, but as presented in the last column of Table 3.1 and Table 3.2, sequences are all stationary at 1% level of significance when they are first differenced. Therefore, we can conclude that Bitcoin price series for all Bitcoin markets are integrated of order 1, I(1).

2.5.2 Cointegration test and analysis

Bivariate Johansen Cointegration Test is used to test the existence of long run equilibrium for each trading pair. Data used in this paper include 45 markets (exchange currency pairs), and 1035 trading pairs are formed. Two null Hypotheses are tested for each trading pair, $r=0$ and $r\leq1$. $r=0$ means zero cointegrating vectors, and $r\leq1$ means number of coingegrating vectors is less than or equal to one. Both trace statistics and maximum eigenvalue statistic are used to determine the result of Johansen cointegration test. Results of Johansen Cointegration Test are presented in Table 3.3. To save space, Table 3.3 only shows Johansen

Table 2.1: ADF Unit Root Test of Bitcoin Prices

Exchange	Currency	Level Series		1st Differenced Series	
		ADF Statistic	P-value	ADF Statistic	P-value
Bitfinex	EURO	-1.6684	0.4474	-18.7934	0.0000
Bitflyer	EURO	-1.6939	0.4343	-19.3218	0.0000
Bitstamp	EURO	-1.7170	0.4224	-18.7828	0.0000
Cexio	EURO	-1.7318	0.4148	-12.3126	0.0000
Coinbase-pro	EURO	-1.7193	0.4212	-18.7534	0.0000
Kraken	EURO	-1.7079	0.4271	-12.5496	0.0000
Quoine	EURO	-1.7071	0.4275	-12.5441	0.0000
Bitfinex	JPY	-1.6852	0.4388	-12.4784	0.0000
Bitflyer	JPY	-1.7054	0.4283	-18.6716	0.0000
Kraken	JPY	-1.8221	0.3695	-12.8803	0.0000
Quoine	JPY	-1.6500	0.4570	-18.6157	0.0000
Bithumb	KRW	-1.6960	0.4332	-11.7468	0.0000
Coinone	KRW	-1.7005	0.4308	-11.7289	0.0000
Kraken	CAD	-1.7360	0.4126	-12.3357	0.0000
Cexio	GBP	-1.7367	0.4123	-11.4369	0.0000
Coinbase-pro	GBP	-1.7186	0.4216	-12.4933	0.0000
Kraken	GBP	-1.7215	0.4201	-31.9418	0.0000
Quoine	AUD	-1.5819	0.4927	-29.7506	0.0000
Luno	ZAR	-1.6836	0.4396	-12.0231	0.0000
Quoine	HKD	-1.6574	0.4532	-26.0560	0.0000
Quoine	SGD	-1.6979	0.4322	-12.5778	0.0000
Luno	IDR	-1.7174	0.4222	-11.6988	0.0000
Cexio	RUB	-2.5936	0.4943	-26.3000	0.0000

Note: Augmented Dickey Fuller (ADF) Unit Root Test for level and first-differenced natural log of Bitcoin prices of each exchange-currency pair. Lag length for each test is based on Akaike Information Criterion (AIC).

Table 2.2: ADF Unit Root Test of Bitcoin Prices (Continued)

Exchange	Currency	Level Series		1st Differenced Series	
		ADF Statistic	P-value	ADF Statistic	P-value
Bitfinex	USD	-1.6617	0.4509	-18.8657	0.0000
Bitflyer	USD	-1.7143	0.4237	-12.5202	0.0000
Bitstamp	USD	-1.6581	0.4528	-18.7929	0.0000
Bittrex	USD	-1.5017	0.5327	-17.7030	0.0000
Cexio	USD	-1.7364	0.4125	-12.2101	0.0000
Coinbase-pro	USD	-1.6587	0.4525	-18.7613	0.0000
Gemini	USD	-1.6579	0.4529	-18.8192	0.0000
Kraken	USD	-1.6611	0.4513	-18.7488	0.0000
Okcoin	USD	-1.7260	0.4178	-12.5646	0.0000
Quoine	USD	-1.6430	0.4607	-18.8165	0.0000
Binance	USDT	-1.7259	0.4178	-18.7134	0.0000
Bittrex	USDT	-1.6636	0.4500	-18.7061	0.0000
Bitz	USDT	-2.1108	0.2402	-9.4588	0.0000
Gateio	USDT	-2.8645	0.4496	-8.8686	0.0000
Hitbtc	USDT	-1.6776	0.4427	-18.6370	0.0000
Huobi	USDT	-1.5477	0.5098	-11.4728	0.0000
Okex	USDT	-1.7678	0.3965	-18.4105	0.0000
Poloniex	USDT	-1.7280	0.4167	-18.7577	0.0000
Binance	USDC	-1.9970	0.2879	-25.6043	0.0000
Coinbase-pro	USDC	-1.3280	0.6163	-10.3269	0.0000
Hitbtc	USDC	-2.2416	0.1915	-9.3060	0.0000
Poloniex	USDC	-1.3413	0.6101	-16.2601	0.0000
Luno	NGN	-1.6445	0.4599	-27.9353	0.0000

Note: Augmented Dickey Fuller (ADF) Unit Root Test for level and first-differenced natural log of Bitcoin prices of each exchange-currency pair. Lag length for each test is based on Akaike Information Criterion (AIC).

cointegration test results for 8 out of 1035 trading pairs. Readers of this paper can request full table from Author if interested.

As shown in Table 3.3, all trading pairs have trace statistic and maximum eigenvalue statistics greater than their corresponding critical value (5% significance level) for null hypothesis of r=0, and tests statistics are less than critical value for second null hypothesis, r≤1. Hence, we can reject the null hypothesis of zero cointegration vectors but fail to reject the null hypothesis of at most one cointegration vector at 5% level of significance. Hypothesis testing results are identical for all trading pairs includes pairs that are not included in the table.

Results of Johansen cointegration test suggest the existence of a long run equilibrium for any trading pair in Bitcoin markets, which can be viewed as evidence of Law of One Price in general Bitcoin markets in the long run.

Table 2.3: Johansen Cointegration Test for Bitcoin Trading Pairs

Trading Pair	Null Hypothesis	Test Statistics		0.05 Critical Value	
		Trace Stats	Max Eigen Stats	Trace Critical	Max Eigen Critical
Bitfinex(EURO) and Bitflyer(EURO)	r=0*	95.05	92.26	15.49	14.26
	r≤1	2.79	2.79	3.84	3.84
Bitfinex(EURO) and Coinbase-pro(EURO)	r=0*	37.36	34.65	15.49	14.26
	r≤1	2.71	2.71	3.84	3.84
Bitfinex(EURO) and Kraken(JPY)	r=0*	23.89	20.82	15.49	14.26
	r≤1	3.07	3.07	3.84	3.84
Bitfinex(EURO) and Quoine(JPY)	r=0*	35.74	33.02	15.49	14.26
	r≤1	2.71	2.71	3.84	3.84
Bitfinex(EURO) and Bithumb(KRW)	r=0*	54.87	51.90	15.49	14.26
	r≤1	2.97	2.97	3.84	3.84
Bitfinex(EURO) and Coinone(KRW)	r=0*	53.08	50.09	15.49	14.26
	r≤1	2.99	2.99	3.84	3.84
Bitfinex(EURO) and Kraken(CAD)	r=0*	43.55	40.76	15.49	14.26
	r≤1	2.78	2.78	3.84	3.84
Bitfinex(EURO) and Coinbase-pro(GBP)	r=0*	50.93	48.13	15.49	14.26
	r≤1	2.80	2.80	3.84	3.84

Note: Given data used in this paper, total 1035 can be formed. This table includes Johansen Cointegration Test Result for 8 trading pairs for demonstration purpose. All trading pairs present similar Johansen Cointergration Test result. 0.05 Critical Values are used for both trace test and maximum eigenvalue test.

* means null hypothesis is rejected based on result of Johansen Cointegration Test

2.5.3 VECM Result and Estimated Half Lives

Results of Johansen Cointegration Test from last section provides evidences of Law of One Price for Bitcoin market in the long run. This section of paper is going to focus on the short run reactions in Bitcoin markets. More specifically, this section is going to use Vector Error Correction Model (VECM) to estimate half lives, the speed of price convergence between two Bitcoin markets in the short run if they converge.

The specification of VECM used is described earlier as equation 4.1. Results of VECM and estimated half lives are presented in table 3.4. P-value presented in the table is for α_1, and as discussed earlier, if α_1 is not statistically significant (p-value is greater than 0.1), it means Market 1 will not converge to equilibrium in the short run so that half life cannot be estimated. "Median Differential" in table 3.4 is the median of absolute value of Bitcoin price differential for each trading pair. The absolute value of Bitcoin price differential for each trading pair is defined as $\mid ln(Price_t^{market1}) - ln(Price_t^{market2}) \mid$. Trading pairs with higher "Median Differential" values have larger price deviation between markets. To conserve space, Table 3.4 only presents VECM results of 15 out 1035 trading pairs. Full table can be requested from author if interested.

241 half lives in Bitcoin markets are estimated, and the summary statistics of estimated half lives are presented in Table 3.5. The average half life in Bitcoin markets is 1.71 days with the maximum of 6.93 days and minimum of 0.133 days. Comparing to estimated half lives (past literature estimate half lives to be years and months) of previous LOOP literature on other commodities, half lives for Bitcoin markets are significantly shorter. This result suggests that price devia-

tions between markets disappear very quickly in Bitcoin markets, a market with minimal transaction time and cost. It provides evidence that relatively efficient arbitrage activities are taken in place in Bitcoin markets, which is consistent with LOOP.

Out of total 1035 trading pair in sample, 794 trading pairs have statistically insignificant α_1, which means prices are not converging in these trading pairs, and therefore half lives cannot be estimated. This is mainly due to small size of price deviation in these trading pairs. Bitcoin exchanges charge buying and selling fee up to around 0.5% of transaction, which means if the magnitude of price differential is too small between two Bitcoin markets, prices will not converge since arbitrage is not profitable between these markets. The median value of "Median Differential" (measures the size of price deviation between markets) is 0.003 for trading pairs without half lives, which is significant smaller than the median value of 0.008 for trading pairs with estimated half lives.

2.6 Border Effect in Bitcoin Markets

2.6.1 Model Specification

McCallum [1995] and Helliwell [1997] find that national borders reduce trade volumes. Therefore, border effect can slow down the price adjustment process for commodities traded internationally. This section of the paper is going to test the existence of border effect in Bitcoin market. More precisely, this section is going to test if borders have effect on the size of half lives in Bitcoin markets. This paper is the first paper in literature to test for border effect in Bitcoin market.

Table 2.4: VECM Results and Estimated Half Lives of Bitcoin Markets

Market1	Market2	α_1	p value	Half Life	Differential Median
Bitfinex(EURO)	Bitstamp(EURO)	-0.2502	0.1655	NA	0.002996
Bitfinex(EURO)	Bitstamp(USD)	-0.2293	0.2066	NA	0.002908
Bitfinex(USD)	Cexio(USD)	-0.1286	0.5112	NA	0.003670
Kraken(USD)	Quoine(USD)	-0.6210	0.3966	NA	0.001225
Bitstamp(USD)	Gemini(USD)	-2.3268	0.4055	NA	0.000602
Coinbase-pro(USD)	Quoine(USD)	-0.6539	0.4077	NA	0.001204
Kraken(JPY)	Coinbase-pro(USD)	-0.5696	0.0002	1.2168 days	0.006520
Kraken(JPY)	Poloniex(USDT)	-0.4414	0.0027	1.5703 days	0.007617
Luno(IDR)	Coinbase-pro(USD)	-0.3028	0.0133	2.2890 days	0.01354
Bitflyer(EURO)	Luno(ZAR)	-0.2513	0.0496	2.7583 days	0.04808
Kraken(CAD)	Luno(NGN)	-0.1000	0.0558	6.9310 days	0.01461
Poloniex(USDT)	Luno(NGN)	-0.1193	0.0604	5.8118 days	0.01455
Coinone(KRW)	Quoine(AUD)	-0.3400	0.0610	2.0386 days	0.01310
Kraken(GBP)	Okex(USDT)	-0.5242	0.0000	1.3221 days	0.01222
Kraken(GBP)	Binance(USDC)	-0.7897	0.0000	0.8776 days	0.01228

Note: This table provide VECM results and Estiamted half lives of selected trading pairs of Bitcoin Markets. P value presented in the table is the p value of α_1. Half life is caculated as $ln(0.5)/\alpha_1$. Half life is NA if α_1 is not statistically significant(p value is greater than 0.1). Differential Median is the median of absolute value of price differential between Market1 and Market.

Table 2.5: Summary Statistics of Estimated Half Lives

No. of Obs	Mean	Media	SD	Min	Max
241	1.71	1.42	1.43	0.133	6.93

Data used in this section are results of VECM estimation presented in section 5.3. Specification of empirical model used in this section is presented as follows.

$$HalfLife = \beta_0 + \beta_1 Border + \beta_2 DifferetialSize + \beta_3 VolumeMin \qquad (6.1)$$

where "HalfLife" include all estimated half lives from previous section, "Border " is a dummy variable and is equal to one if two markets in the trading pair have different currencies[9], "DifferetialSize" is the Median Differential defined in section 5.3 to measure trading pairs' size of price differential, and "VolumeMin" is the average trading volume of the smaller market in each trading pair.

The expected sign for β_1 is positive because if border effect exists, it creates market segmentation and reduces arbitrage activities, which slow down price convergence between markets and increase half life. The expected sign for β_2 is positive. For trading pairs with large size of price differential on average, half lives are expected to be smaller than trading pairs with small size of price differential since more arbitrage activities are required to eliminate price gap, which takes more time. Expected sign for β_3 is ambiguous. While it is possible that market with very small trading volume could slow down price adjustment process, most of exchanges included in the data are exchanges with healthy depth so that the effect of small trading volume on half life may not be captured since there are not enough small volume exchanges in the data.

[9]Since USDC and USDT are stable coin that have approximately one to one exchange rate with USD, trading pairs that trade among USDC, USDT and USD are not deemed to have border in this research.

2.6.2 Results and Interpretation

Table 3.6 presents regression results of equation 6.1, and robust standard errors are used. As expected, coefficient of Border is positively significant cross specifications. Results suggest if a trading pair evolves two markets that trade Bitcoins in different currencies, half life of this trading pair is on average 0.412 days higher than trading pairs that trade in same currency. This result provides evidence for the existence of border effect in Bitcoin markets.

β_2 is consistently positively significant as well, which is in align with expectation. It means higher size of price differential in trading pair increases the amount of time needed for price deviation to die out because more arbitrage activities are required. β_3, coefficient of VolumeMin is positively significant, but the magnitude is very small.

The key take away from this section is that borders do have effect on Bitcoin markets. Borders create market segmentation and reduce trading activities, which decrease the speed of price convergence between Bitcoin markets.

Table 2.6: Regression Result of Border's Effect on Half Lives

	(6.1)	(6.2)	(6.3)
Dependent Variable	Half Life	Half Life	Half Life
Border	1.037***	0.403***	0.412***
	(0.159)	(0.132)	(0.157)
DifferetialSize		85.14***	88.86***
		(12.14)	(12.44)
VolumeMin			0.000395***
			(4.30e-05)
Constant	0.731***	0.474***	0.346***
	(0.127)	(0.0922)	(0.128)
Observations	241	241	241
R-squared	0.029	0.254	0.321

Note: Dependent variable half life is the estimated half life from section 5.3. Border is a dummy variable, which equal to one if two markets in trading pair use different currencies. DifferentialSize is the median of absolute value of price differential for each trading pair. VolumeMin is the average trading volumes of the market with less trading activities in each trading pairs.
Robust standard errors are reported in the parentheses.
** p<0.01, ** p<0.05, * p<0.1

2.7 Conclusion

In this paper, I study the speed of price convergence in Bitcoin markets on 20 Bitcoin exchanges trading in 14 different currencies. My data constitutes roughly 72% of the total Bitcoin trading volume, and the Bitcoin market data used in this paper is the most comprehensive data used in the literature. Unlike commodities and assets previously studied in LOOP literature, Bitcoin has characteristics of low transaction fee and time, which make Bitcoin a great studying object to test LOOP. Past LOOP studies often attribute long half lives of commodities and assets to high transaction cost and transportation time. By looking at Bitcoin, we are able to see if LOOP still hold without having transaction cost and fee as excuses.

1035 Trading pairs are constituted by 45 Bitcoin markets (exchange-currency pairs) in my data. I performed Johansen cointegration test and confirmed the existence of a long run equilibrium in all trading pairs. Using VEC model, I estimated half lives of each trading pair. My estimated half lives range from 0.133 days to 6.93 days, which are significantly lower than estimated half lives (months and even years) from previous literature on other commodities and asset. My results not only confirm LOOP hold in Bitcoin market, but also provide strong evidence to support LOOP. My results shows that without high transaction cost and long transportation time, price adjustment process between markets can be a lot faster than past literature's estimates.

Using half lives estimated as data, I further examined the existence of border effect in Bitcoin market. This paper is the first paper in the literature to look at the border effect on half-lives that I am aware of. I find that borders increase half lives (slow down price convergence progress). This result implies borders create market segmentation in Bitcoin markets and reduce or slow down arbitrage activities so that price convergence between markets takes more time. The reason behind border effect and market segmentation in Bitcoin markets is beyond the scope of this paper, but it is going to be discussed further in the next chapter of my dissertation.

Table 2.A1: List of Bitcoin Exchanges and Trading Currencies

Exchange	Trading Currency	Exchange	Trading Currency
Binance	USDT[2] USDC[1]	Bitfinex	EUR JPY USD
Bitflyer	EUR JPY USD	Bithumb	KRW
Bitstamp	EUR USD	Bittrex	USDT[2] USD
Bitz	USDT[2]	Cexio	EUR GBP RUB USD
Coinbase Pro	EUR GBP USD USDC	Coinone	KRW
Gateio	USDT[2]	Gemini	USD
Hitbtc	USDC[1] USDT[2]	Huobi	USDT[2]
Kraken	JPY EUR GBP CAD USD	Luno	ZAR IDR NGN
Okcoin	USD	OKEX	USDT[2]
Poloniex	USDT[2] USDC[1]	Quoine	AUD EUR HKD JPY SGD USD

Table 2.A2: Currency List

Currency Symbol	Currency Name
AUD	Australia Dollar
CAD	Canadian Dollar
EUR	Euro
GBP	British Pound
HKD	Hongkong Dollar
IDR	Indonesian Rupiah
JPY	Japanese Yen
KRW	Korean Won
RUB	Russian Ruble
SGD	Singapore Dollar
USD	US Dollar
USDC[1]	USD Coin
USDT[2]	Tether
ZAR	South African Rand

[1]USDC (USD Coin) is a type of stablecoin issued by Coinbase, which always has a one to one exchange rate with US dollar

[2]USDT (Tether) is a type of stablecoin issued by Tether Limited. The value of one USDT is approximately one US dollar

References

Robleh Ali, John Barrdear, Roger Clews, and James Southgate. The economics of digital currencies. *Bank of England Quarterly Bulletin*, Q3, 2014.

Marcus Asplund and Richard Friberg. The law of one price in scandinavian duty-free stores. *American Economic Review*, 91(4):1072–1083, 2001.

Raphael Espinoza, Ananthakrishnan Prasad, and Oral Williams. Regional financial integration in the gcc. *Emerging Markets Review*, 12(4):354–370, 2011.

Pinelopi K Goldberg and Frank Verboven. Market integration and convergence to the law of one price: evidence from the european car market. *Journal of international Economics*, 65(1):49–73, 2005.

ohn F Helliwell. National borders, trade and migration. *Pacific Economic Review*, 2(3):165–185, 1997.

Alexander Kroeger and Asani Sarkar. Law of one bitcoin price? *Federal Reserve Bank of Philadelphia*, 2017.

James R Lothian and Mark P Taylor. Real exchange rate behavior. *Journal of international money and finance*, 16(6):945–954, 1997.

John McCallum. National borders matter: Canada-us regional trade patterns. *The American Economic Review*, 85(3):615–623, 1995.

John Pippenger. Commodity Arbitrage and the Law of One Price: Setting the Record Straightt. *Theoretical Economics Letters*, (6):1017–1033, 2016.

Kenneth Rogoff. The purchasing power parity puzzle. *Journal of Economic literature*, 34(2):647–668, 1996.

Mark P Taylor. Purchasing power parity. *Review of International Economics*, 11 (3):436–452, 2003.

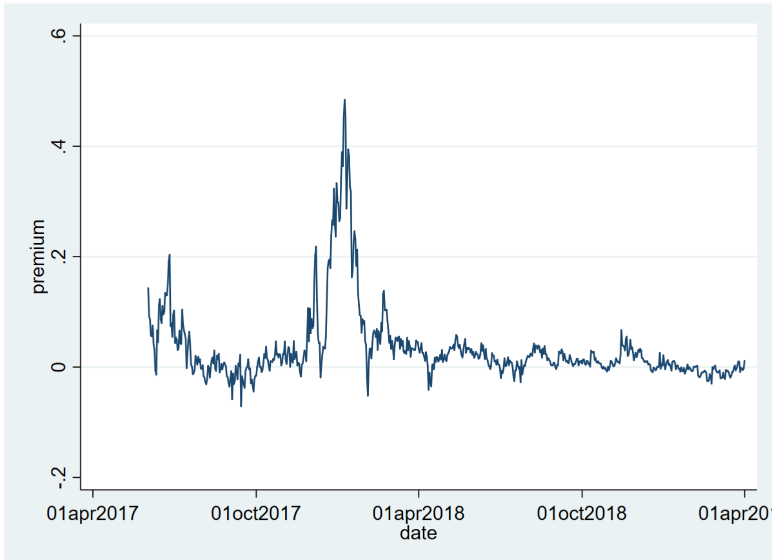
Chapter 3

Bitcoin Cross Country Premium: The Effect of Regulation Changes

3.1 Introduction

The concept of Law of One Price (LOOP) is no longer new. It states that the price of identical goods should be sold at same price in different locations after adjusting for exchange rate in absence of trade frictions. Bitcoin is the first crytocurrency created with no physical or virtual presence. By holding Bitcoin, the only thing that holder has is a digital address with a consensus of number of Bitcoins owned by this address from Bitcoin network. As a result, Bitcoins traded all over the world are exactly the same. That is, by law of one price, prices of Bitcoin in different locations should be the same when prices are expressed in common currency. However, prices of Bitcoin in different countries are often different, and sometime these differences can be quite significant. For instance, Bitcoin price in South Korea is often higher than Bitcoin price in other countries, and this Bitcoin price differential between South Korea and rest of the world is commonly referred

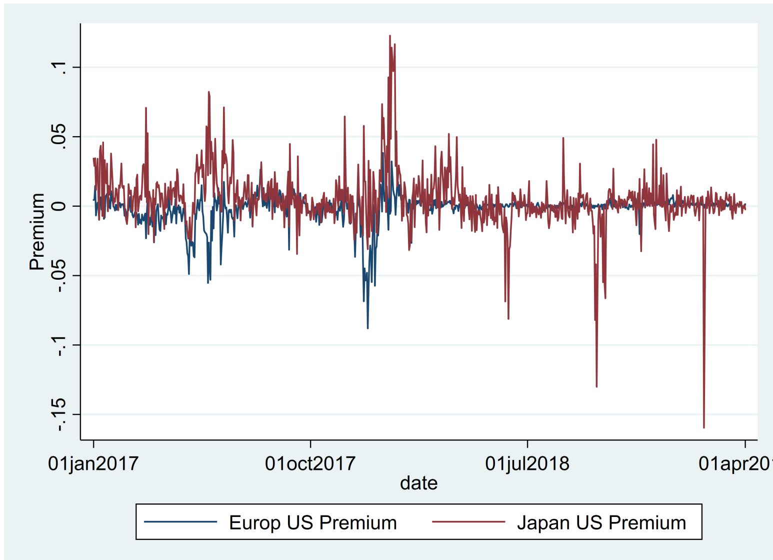
Figure 3.1: Bitcoin Price Differential between Korean and US



as Kimchi Premium. In Dec 2017, the price of Bitcoin in South Korea was almost 50% higher than prices in United States, and the gap was quite persistent as shown in Figure 3.1. What's more, as Figure 3.1 presented, price differential between South Korea and US is not an one time event, and as suggested by Figure 3.2, Bitcoin price differential exists in both Europe and Japan as well.

As discussed earlier, Bitcoins are identical around the world, and this kind of price abnormality should not exist based on law of one price unless there are some sort of frictions or market segmentation. This paper uses relative changes of regulation between Bitcoin markets to explain Bitcoin price differential. Regulation change for each country is measured by the change of Bitcoin regulation news index created in this paper. Results of this paper suggest country's tightening Bitcoin regulation relative to US increases its Bitcoin price differential relative to US, and this result is driven mainly by warning and formal news. This paper also finds the effect of regulation change on Bitcoin price differential spills over across

Figure 3.2: Bitcoin Price Differential, US, Japan and Europe



borders. Country's Bitcoin price differential increases when another country implements tightening regulation on Bitcoin.

The rest of the paper is structured as follows: Section II gives a brief review of Bitcoin. Section III reviews related literature and discusses contributions of this study. Section IV describes the data and specification of empirical model. Section V discusses results of estimated regressions, and Section VI is the conclusion.

3.2 Brief Review of Bitcoin

3.2.1 Introduction of Bitcoin

Bitcoin is a decentralized digital currency that can be transacted on peer to peer Bitcoin network without the need for any intermediaries invented by Satoshi

Nakomoto[1] in 2008 and started in 2009. The ownership of Bitcoin is implemented through blockchain technology which is a public ledger that records all Bitcoin transactions. Blockchain records the number of Bitcoin owned in each address and will be updated when new transactions occur.

Recorders of blockchain are known as "miners". Miners are eligible to get Bitcoin rewards by verifying 1 megabyte worth of previous transactions that are not recorded on blockchain yet. Eligible miners around the world will compete to solve an encrypted numeric problem. First miner who solves the problem will be rewarded with Bitcoins, and a block with newly verified transactions will be added to the existing blockchain. Users of Bitcoin are required to pay miner a small transaction fee[2] whenever they want to initiate a transaction. Normally, three to six blocks are required to be added before completion of a transaction, which takes around 30 minutes to an hour.

Bitcoin can be purchased and sold through online trading websites known as "cryptocurrency exchanges" (crypto-exchanges). Unlike traditional stock exchanges, Bitcoin can be traded on cryptocurrency exchanges 24 hours a day, 7 days a week. Most of major crytocurrecny exchanges support Bitcoin trading in one or multiple fiat currencies. Stablecoins like USDT[3] and USDC[4] that attempt to peg their value to fiat currencies or commodities like gold are also commonly used for trading in cryto-exchanges. Trading fees charged by crypto-exchanges of-

[1]The true identity of Satoshi Nakomoto is remained unknown

[2]The transaction fee is around 1.2 us dollar per transaction as of July 19th,2019

[3]USDT (Tether) is a type of stablecoin issued by Tether Limited. The value of one USDT is approximately one US dollar

[4]USDC (USD Coin) is a type of stablecoin issued by Coinbase, which has a one to one exchange rate with US dollar promised by Coinbase.

ten use a maker[5]-taker[6] fee model and vary by account's trading volume. Taking Coinbase Pro (a US based cryptocurrency exchange) as an example, both taker and maker fee are 0.5% of the total trading value when account's 30 day trading volume is below 10,000 USD. As 30-day USD trading volume increases, trading fee decreases. Maker fee can be reduced to 0% when account's 30 day trading volume exceeds 50 million USD, and taker fee can be reduced to 0.04% for accounts with over 1 billion USD 30 day trading volume.[7] It is very common for crypto-exchanges to adopt similar fee structure. As a result, traders with high trading volume will have very minimal trading fee.

In order to trade Bitcoin in fiat currency, traders are required to have a bank account in the home country of that currency. Therefore, if a trader wants to trade Bitcoin in US dollars, a valid US bank account is required. Some exchanges offer Bitcoin trading in multiple fiat currencies but it does not mean traders can convert Bitcoin into different fiat currencies freely inside exchanges, corresponding bank accounts are still needed for multiple currency trading. For example, Coinbase Pro offer Bitcoin trading in both Euros and US dollars, but euro bank account is required to trade Bitcoins in euros and trading Bitcoins in US dollars requires US bank account. Therefore, trading Bitcoins in different fiat currencies are essentially trading in different countries even though tradings are facilitated by the same crypto-exchange.

[5]You are considered as a maker if your order is not immediately matched and get filled by a matching order from another investor later.

[6]You are considered as a taker if your order is placed at the market price and get filled immediately.

[7]Detailed trading fee schedule can be found following this link:
https://support.pro.coinbase.com/customer/en/portal/articles/2945310-fees

3.2.2 Bitcoin Arbitrage Process

It is a simple process to take advantage of Bitcoin cross country premium. Using US and Korea as an example, in order to exploit profit from previously referred "Kimchi Premium", traders first need to purchase Bitcoins using US dollars from an exchange that supports US dollar trading. Then, Bitcoins purchased can be sent to a North Korean Exchange[8] and sell in Korean Won. This step will take around 30 minutes to a hour. Last, traders will convert Korean Won back to US dollar, wire the money back their US accounts and repeat the process.

Three types of transaction cost are involved in this arbitrage process. First type is trading fee from buying and selling Bitcoins on exchanges. As mentioned earlier, for traders with large trading volume, trading fees are close to zero. The second type of transaction cost is fee charged by miners in the process of sending Bitcoin from US exchange to Korean exchange. This type of transaction cost changes daily depending on demand for Bitcoin transactions. When the demand for Bitcoin transactions is high, miners will charge higher transaction fee and vice versa. This is a fixed per transaction fee, which is irrelevant to the number of Bitcoins involved in the transaction. So, if the volume of Bitcoin involved is high, this fee is almost nothing when fee is measured in percentage of total transaction value. The last type of transaction cost is service fee charged by bank in the process of currency conversion and international wiring. Again, this type of cost is small for large volume traders.

Since the entire arbitrage process can be completed within a few hours[9], ex-

[8]There is not any crypto-exchange outside Korea that supports Korean Won trading to the awareness of author.

[9]Transaction time for international wiring is not included since this part does not contain any risk.

Figure 3.3: 1 Hour Candlestick Chart of Bitcoin to USD trading

change rate risk can be mostly avoided. The biggest risk in the process is the fluctuation of Bitcoin price since traders still need to wait for about an hour to transfer Bitcoins. As Figure 3.3 shown, on June 26th, 2019 at 13:00 PDT, the price of Bitcoin went from $13,850 to $11,650 at the lowest in the next hour, which is a 15.9% decrease. Therefore, Bitcoin arbitrage activities can be risky at the time when Bitcoin price is unstable.

3.2.3 Why is Bitcoin an Interesting Object to Study?

Traditional literature on law of one price often have three difficulties. First, the transaction cost of the commodity is very high, which cannot be ignored, and the data for transaction fee is usually hard to obtain. It is especially the case if goods are transferring across borders. Second, the transportation time for commodities are high, and price fluctuates during transportation. So, data of futures for that given commodity is needed to study LOOP, and future market for some commodities simply does not exist. Third, Pippenger [2016] suggests that some past literature on LOOP for commodity was problematic because arbitrage was not possible on those commodities. For example, Asplund and Friberg [2001] finds prices of identical goods are different as long as they are dominated in different currencies on the same Scandinavian ferry, which suggests the failure of LOOP. However, Pippenger [2016] points out this study is problematic because it is impossible to arbitrage on these ferries.

All three difficulties discussed above can be addressed when study Bitcoin. First, the transaction cost of moving Bitcoins is low. Bitcoins can be sent from one country to another with low transaction cost especially for large volume trader. Second, Bitcoin takes short amount time to transact. Transferring Bitcoins between countries will only take around an hour, and price of Bitcoin won't fluctuate much at stable time period[10]. Last, Bitcoins are traded on exchanges 24/7 globally so that traders can engage in arbitrage activities whenever opportunity presents. Therefore, these characteristics of Bitcoin make it an ideal object to study Law of One Price (LOOP).

3.3 Literature Reviews

3.3.1 Past Studies on Price Differential

Law of One price (LOOP) suggests in absence of trade friction, identical goods sold in different location should have same price when expressed in term of same currency. The assumption of effective arbitrage plays a key role in deriving LOOP since arbitragers will eliminate the price deviation from equilibrium very quickly. However, past literature often find evidences that are inconsistent with LOOP.

[10]It is not hard for experienced traders to predict the time of day when Bitcoin price stagnates.

Asplund and Friberg [2001] finds LOOP does not hold even for identical good sold at the same location as long as the good are denominated in different currencies on Scandiavian ferries. The amount of time for half of the price deviation to disappear is called half life, which should be a very small time period if LOOP holds. However, Rogoff [1996] points out that the general consensus for half life estimated in literature ranges from 3 to 5 years, which implies a very slow rate of price adjustment process. Rogoff [1996] suggests persistent price differentials in international good market are due to large trading friction, which include transportation, tariff policy, information cost and lack of labor mobility. Goldberg and Verboven [2005]'s study on European car market estimates half-lives to be 1.3 to 1.6 years, which are substantially lower than half lives estimated in earlier works. They suggest the integration of European market reduce the degree of market segmentation, which they believe to be the main source of price dispersion.

As for financial market, Espinoza et al. [2011] investigates cross listed stocks for member countries of the Gulf Cooperation Council (GCC) and finds the price convergence speed is faster within-GCC countries than between GCC country and Europe. They suggest relatively open capital accounts within GCC help explaining this difference. Akram et al. [2009]'s study on inter-market price differentials for borrowing and lending service discovers that LOOP holds on average, but they also identify numerous significant violations of law of one price.

Pointed out by Pippenger [2016], persistent price differentials discovered in past literature are often associated with institutional differences, high transaction cost and slow transportation. Since Bitcoin transactions are cheap and quick, this study of Bitcoin cross country premium will be mainly focus on institutional difference across countries.

3.3.2 Past studies on Bitcoin Premium

As previously discussed, Bitcoin sometimes presents unusually high price differential across countries, which has drawn attention from not only arbitragers but also researchers. Various reasons are proposed to explain Bitcoin price differential.

Yim et al. [2018] examines the legal framework of Korea in Bitcoin markets and points out that North Korea's persistent cryptocurrency price premiums are caused by Korean Foreign exchange restrictions under the Foreign Exchange Transaction Act (FETA). Most of North Korean crypto investors are restricted to purchase cryptocurrency in foreign exchanges as they are restricted to send fiat currency overseas for purchases of cryptocurrencies. Choi et al. [2018] finds Kimchi Premium is positively related to transaction costs, average confirmation time, and Bitcoin price volatility. They also find number of Bitcoin news in North Korea is negatively related to premium.

Kroeger and Sarkar [2017]'s study on BTC-E, an exchange allows anonymous trading, discovers that price premium in BTC-E can be explained by the motive of avoiding regulation. Makarov and Schoar [2019]'s empirical work suggests that countries' Bitcoin price deviations co-move and open up in times of large appreciation of Bitcoin. They discover that Bitcoin arbitrage spread are higher for countries with stricter regulation. Auer and Claessens [2018] also confirms that Bitcoin valuation and volume are related regulatory action.

Past literature have recognized the importance of institutional difference and regulation on Bitcoin price differential. However, none of the studies empirically test the effect of country's regulation change on Bitcoin price differential, and this study will empirically investigate this effect.

3.3.3 Contribution of this study

The contribution of this study is three folds. First, the data used for this research are mainly original. All the Bitcoin price data are self-collected by author directly from each Bitcoin exchange's API. In order to measure Bitcoin regulation changes for each country, this study creates an original daily country-level news index for Bitcoin regulation using Bitcoin regulation news collected by authors from news websites. While past literature often ignore directions and stages of news, news' direction and stage are both taken into consideration in the process of news index construction. Therefore, this new measure of Bitcoin regulation index itself is a great add-on to the existing literature.

Second, this study provides an empirical analysis of the effect of regulation change on Bitcoin price differential, while past studies of regulation effect on Bitcoin premium are mainly qualitative. In order to have further understanding of the effect, this study also empirically examines effects of different stages of Bitcoin news and potential spillover effect from other countries' regulation change.

Third, the contribution of this paper does not limit to Bitcoin markets but has broader meaning as well. This study contribute to the existing Law of One Price literature by empirically examining the effect of institutional change on price difference of a truly homogeneous good. By studying Bitcoin market responses to regulation changes, this paper also provide implications for other newly developed assets.

3.4 Empirical Model & Data

3.4.1 Data

This study uses daily panel data for 22 Bitcoin exchanges under 11 different currencies dated from 01/01/2017 to 03/31/2019. 46 unique trading pairs are formed in this dataset. Exchange rate data are pulled from *openexchangerate.org*. Sources of Bitcoin activity data are *blockchain.com* and *bitcoinity.org*. US macro data are obtained from *FRED Economic Data*. Countries' stock data comes from *Yahoo! finance*. Bitcoin price and trading data are self-collected by author from Bitcoin esxchanges' API using scripts written in python. This data includes 9 out of 10 largest cryptocurrency exchanges by volume and estimated revenue listed by Bloomberg[11] in 2018, which consist about 72% of the total trading volume in the world according to *bitcoinity.org*. Hence, data used in this study is very representative.

3.4.2 Bitcoin Regulation News Index

Since many previous literature mention that Bitcoin price differential can be affected by regulation difference, this study constructs a Bitcoin regulation news index to measure Bitcoin regulation level in each country so that countries' regula-

[11] Reports by Russo, Camila (5 March 2018).https://www.bloomberg.com/news/articles/2018-03-05/crypto-exchanges-raking-in-billions-emerge-as-kings-of-coins

tion changes and differences can be calculated. Bitcoin news used in the index are obtained from reports published in various websites (BBC,CNN, CNBC, Reuters, Coindesk and Bitcoin News etc.). News are self-collected by author using web crawler. More than fifteen thousands Bitcoin related news are collected, and 334 news that reflect countries' Bitcoin regulation changes are identified by author during the time period of study. If there are multiple reports regarding same issue, only the one with earliest publish date is kept. Table 3.A4 presents an example of the raw data for Bitcoin regulation news collected.

News are classified into three categories based on their stages: warning (report of interview and statement from government or central banks), pre-act (bill proposal and regulation draft) and formal (passed bill, formal law or ban). Positive sign is assigned to news that tighten Bitcoin regulation, and negative sign is assigned to news that loose country's Bitcoin regulation. Daily data on Bitcoin regulation news index is constructed by aggregating all three types of news index with equal weight for each country on daily basis. Country's current regulation level is the sum of country's weighted sum of all three types of news in currency period and previous period's regulation level. Therefore, if country's Bitcoin news index increases, we know that tighter Bitcoin regulation is implemented in that country.

3.4.3 Model Specification

The empirical model I used for this study is presented as follows.

$$\begin{aligned} Premium_{it} =& \alpha + \delta_i + \beta_1 dregulationdiff_{it} + \beta_2 ln(Fee)_t \\ & \beta_3 ln(Time)_t + \beta_4 ln(Volume)_{it} + \beta_5 Volatility_t + \beta_6 GoldReturn_t \\ & + \beta_7 Return_{it} + \beta_8 EFFR_t + \epsilon_{it} \end{aligned} \tag{4.31}$$

The dependent variable $premium_{it}$ refers to the price's deviation of each trading pair i at time t. In this study, a trading pair is defined as pair formed by one Bitcoin exchange in a specific currency (call this market 1) and a major US based Bitcoin exchange, Coinbase Pro, in US dollar (call this market 1). For Bitcoin exchanges supporting multiple currencies, multiple trading pairs will be created. Each trading pair i has its corresponding country based on the home country of its trading pair currency[12]. For instance, for trading pair formed by Bithumb (exchange name) trading in Korean Wons and Coinbase-Pro trading in US dollars, trading pair country is North Korea, and market 1 in this trading pair is Bithumb trading in Korean Wons. Prices of Bitcoin denominated in currencies other than US dollars are converted into US dollar prices using corresponding exchange rate on that day. Therefore, higher $premium_{it}$ means higher adjusted USD price of Bitcoin for market 1 in trading pair i relative to Coinbase Pro's USD price at time t. The listed of Bitcoin Exchanges used in this study along with their trading currency are presented in the Table 3.A2. Table 3.A3 shows the list currencies included in the sample. The detailed description of variables used in regression can be found in the table 3.A1. Summary statistics of variables and correlation

[12]Trading pair currency is the counterpart of Coinbase Pro USD price in the trading pair

Table 3.1: Sample Summary Statistics

	No. of Obs	Mean	SD	Min	Max
Premium	25,282	0.00578	0.0291	-0.513	0.484
Return	25,159	0.00188	0.0460	-0.406	0.444
dregulationdiff	29,010	0.00872	0.196	-2	2
dregulationdiff1	25,129	0.0169	0.362	-6	3
dregulationdiff2	29,010	0.0185	0.453	-5	6
dwarningdiff	29,010	0.00238	0.115	-1	2
dpreactdiff	29,010	0.00507	0.136	-1	1
dformaldiff	29,010	0.00128	0.0736	-2	1
Volatility	29,056	3.995	1.681	1.131	9.024
ln(Fee)	29,056	3.555	0.819	1.656	5.086
ln(Volume)	25,400	6.090	3.169	-8.153	16.91
Return	25,159	0.00188	0.0460	-0.406	0.444
ln(Time)	29,056	2.266	0.116	1.986	2.932
EFFR	19,953	1.584	0.559	0.560	2.430
Gold Return	15,821	2.02e-05	0.00587	-0.0164	0.0192
Number of Trading Pair	46	46	46	46	46

Table 3.2: Sample Correlation

	Premium	dregulationdiff	ln(Fee)	ln(Time)	ln(Volume)	Volatility	Gold Return	Return
Premium	1							
dregulationdiff	0.0116	1						
ln(Fee)	0.00760	0.0304	1					
ln(Time)	0.0450	-0.0403	-0.137	1				
ln(Volume)	0.0297	-0.0165	-0.0546	-0.00830	1			
Volatility	0.0337	0.0320	0.316	-0.168	0.0605	1		
Gold Return	0.0347	-0.0127	-0.0753	0.0441	-0.000400	0.0376	1	
Return	0.0472	0.00570	-0.0155	-0.0334	-0.00700	0.0360	-0.0394	1
EFFR	0.0802	-0.00510	0.345	0.213	-0.0901	-0.342	-0.0298	-0.101

table are presented in Table 3.1 and Table 3.2, respectively.

In order to empirically examine the effect of regulation change on Bitcoin price differential, variable “dregulationdiff” is used to measure the change of country’s Bitcoin regulation relative to US. Using country’s regulation index constructed in section 3.4.2, variable “dregulationdiff” is calculated as follows.

$$dregulationdiff_{it} = (regulation_{i,t} - regulation_{US,t}) - (regulationn_{i,t-1} - regulation_{US,t-1} \quad (4.32)$$

Therefore, an increase in "dregulationdiff" means country’s Bitcoin regulation is tightening relative to US. The expected effect of “dregulationdiff” is positive, because as regulation difference increases, it creates market segmentation between Bitcoin markets in two countries. Market segmentation creates market frictions that impede effective arbitrage activities, which cause price differences.

As suggested by Choi et al. [2018], transaction fee (Fee), transaction time (Time) and price volatility (Volatility) matters in determining price differential and they are added as control variables in the regression. Higher transaction fee reduce the profit of arbitrage so that it reduces arbitrage activities and allows higher price differential. Higher transaction time and price volatility increase the risk of holding Bitcoins while transferring Bitcoin from one address to another, which reduce arbitrage activities and induce higher price differential as well. Bitcoin transaction time is measured by time between blocks in this research, which is the daily average time for one Bitcoin block to be created. To complete a Bitcoin transaction, 3-6 confirmations are usually required, which means 3-6 blocks needs to be created. So, more time required Bitcoin block creation means longer transaction time. Some regression specifications also include stock return (Stock Return), which is the daily Stock index return for corresponding country of each trading pair. Stock return is used to control for macroeconomic conditions in each country.

Bitcoin daily return (Return) is included in the regression because Makarov and Schoar [2019] finds that Bitcoin price deviation increases in the time of large appreciation of Bitcoin. So, Bitcoin return is expected to have a positive effect on Bitcoin price differential. The daily return of gold (Gold Return) is used as a control for general economic condition since gold price usually increase during the economic downturn. Effective federal fund rate (EFFR) is also controlled due to its influence on US exchange rate, which could affect Bitcoin price differential.

3.5 Empirical Analysis

3.5.1 Result of Proposed Regression Equation

Panel Fixed Effect Model is used to estimate equation (4.31), and results are presented at Table 3.3. Standard errors are clustered at trading pair level for columns from (3.1) to (3.4) and are clustered at currency level for column (3.5). From results in Table 3.3, the estimated coefficient for "dregulationdiff" is positively statistically significant across specifications as expected, which indicates country's Bitcoin price differential increases with tightening regulation on Bitcoin relative to US.

Aside from effect of regulation change, results also suggest transaction time (Time), daily return of Bitcoin (Return) and gold (Gold Return) are important factors in explaining Bitcoin price differential. Results finds higher transaction time leads to higher Bitcoin price differential, which is in consistent with expectation. Bitcoin daily return is found to have positive effect on price differential, which is in alignment with previous finding of Makarov and Schoar [2019]. The daily return of gold is found to have positive effect on Bitcoin price differential as well. My interpretation of this result is that when economic situation is not optimistic, more investments flow into alternative assets like gold and Bitcoin, which affect the price and price differential.

Table 3.3: Panel Fixed Effect Model with Equal Weight News Index

	(3.1)	(3.2)	(3.3)	(3.4)	(3.5)
	Dependent Variable: Premium				
dregulationdiff	0.00310**	0.00302**	0.00321**	0.00272**	0.00272*
	(0.00140)	(0.00138)	(0.00135)	(0.00133)	(0.00122)
ln(Fee)	-0.00146	-0.00120	-0.00135	-0.00296	-0.00296
	(0.00121)	(0.00120)	(0.00123)	(0.00201)	(0.00196)
ln(Time)	0.0118***	0.0119***	0.0114**	0.00502***	0.00502***
	(0.00396)	(0.00409)	(0.00457)	(0.00164)	(0.00105)
ln(Volume)	0.000325	0.000464	0.000755	0.000955	0.000955
	(0.000883)	(0.000968)	(0.00102)	(0.00118)	(0.00127)
Volatility	0.000803	0.000752	0.000526	0.00160**	0.00160**
	(0.00108)	(0.00110)	(0.00120)	(0.000695)	(0.000620)
Gold Return	0.151***	0.168***	0.168***	0.166***	0.166***
	(0.0339)	(0.0352)	(0.0427)	(0.0318)	(0.0425)
Return		0.0319**	0.0332**	0.0360**	0.0360**
		(0.0135)	(0.0139)	(0.0146)	(0.0128)
Stock Return			-3.86e-05		
			(0.0301)		
EFFR				0.00693*	0.00693
				(0.00391)	(0.00412)
Fixed Effect	Yes	Yes	Yes	Yes	Yes
Cluster	Trading Pair	Trading Pair	Trading Pair	Trading Pair	Currency
Observations	13,790	13,651	11,657	13,527	13,527
No. of Trading Pair	46	46	46	46	46

Note: Standard errors in parentheses. Standard Errors Clustered by Each Trading Pair for Column 1-4. Standard Errors Clustered by Currency for Column 5
"dregulationdiff" is daily change of country's Bitcoin regulation difference with USA with equal weight on each type of news. "Fee" measures the transaction fee of transferring Bitcoin, and "Time" measures the transaction time. "Volume" is the daily trading volume for each trading pair. "Volatitility" is the 30 day historical return volatility of Bitcoin. "Gold Return" is daily gold return, and "Stock Return" is daily return of Stock index for each corresponding country. "Return" is daily Bitcoin return for each trading pair. "EFFR" is US effective federal fund rate.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

3.5.2 Regression using Intensity Adjusted Regulation News Index

As discussed in section 3.4.2, Bitcoin Regulation News Index "regulation" is the aggregate of warning, pre-act and formal news by applying equal weight to each type of news. This part of study is a robustness check to see if results are sensitive to the choice of weight in constructing regulation index. Therefore, two more regulation indexes are created. "regulation1" is created by assigning most weight to formal news and least weight to warning news. "regulation2" is the opposite so that warning news have the highest weight and formal news have the lowest. Variables "dregulationdiff1" and "dregulationdiff2" are created in a same way with "dregulationdiff" but using "regulation1" and "regulation2", respective. Regression results using two intensity adjusted regulation indexes are presented in Table 3.4. Standard errors are clustered at trading pair level for column (4.1) and (4.3). Column (4.2) and (4.4) have standard errors clustered at currency level.

Results from Table 3.4 are consistent with previous findings from Table 3.3. Therefore, estimated results are not sensitive to the choice of weight used in constructing Bitcoin News Regulation Index. Significant coefficients for both "dregulationdiff1" and "dregulationdiff2" also have implication that both formal news and warning news have significant effect on country's Bitcoin price differential. What's more, estimated coefficient for "dregulationdiff1" (variable that use regulation index that put more weight on formal news) is munch larger that estimated coefficient of ""dregulationdiff2", which suggests formal news might have larger impact on Bitcoin price differential.

Table 3.4: Panel Fixed Effect Model with Intensity Adjusted News Index

	(4.1)	(4.2)	(4.3)	(4.4)
	Dependent Variable: Premium			
dregulationdiff1	0.00189**	0.00189*		
	(0.000822)	(0.000876)		
dregulationdiff2			0.000913*	0.000913**
			(0.000468)	(0.000394)
ln(Fee)	-0.00295	-0.00295	-0.00297	-0.00297
	(0.00201)	(0.00196)	(0.00201)	(0.00196)
ln(Time)	0.00508***	0.00508***	0.00493***	0.00493***
	(0.00164)	(0.00107)	(0.00166)	(0.00106)
ln(Volume)	0.000955	0.000955	0.000955	0.000955
	(0.00118)	(0.00127)	(0.00118)	(0.00127)
Volatility	0.00159**	0.00159**	0.00160**	0.00160**
	(0.000694)	(0.000619)	(0.000696)	(0.000620)
Gold Return	0.167***	0.167***	0.165***	0.165***
	(0.0322)	(0.0431)	(0.0316)	(0.0422)
Return	0.0361**	0.0361**	0.0359**	0.0359**
	(0.0146)	(0.0129)	(0.0146)	(0.0128)
EFFR	0.00692*	0.00692	0.00694*	0.00694
	(0.00391)	(0.00412)	(0.00391)	(0.00412)
Fixed Effect	Yes	Yes	Yes	Yes
Cluster	Trading Pair	Currency	Trading Pair	Currency
Observations	13,527	13,527	13,527	13,527
No. of Trading Pair	46	46	46	46

Note: Standard errors in parentheses. Standard Errors Clustered by Each Trading Pair for Column 1 and 3. Standard Errors Clustered by Currency for Column 2 and 4 "dregulationdiff1" is daily change of country's Bitcoin regulation difference with USA with high weight on formal news, and "dregulationdiff2" has high weight on warning news. "Fee" measures the transaction fee of transferring Bitcoin, and "Time" measures the transaction time. "Volume" is the daily trading volume for each trading pair. "Volatitility" is the 30 day historical return volatility of Bitcoin. "Gold Return" is daily gold return, and "Stock Return" is daily return of Stock index for each corresponding country. "Return" is daily Bitcoin return for each trading pair. "EFFR" is US effective federal fund rate.

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

3.5.3 Effects of Different Types of News on Bitcoin Price Differential

The discovery from last section suggests that different types of news could have different effects on Bitcoin price differential. In order to examine this issue further, estimated effect of each type of news on Bitcoin price differential will be empirically tested separately to see which types of news are the driving factors of results discovered in Table 3.3. Variables "warning", "pre-act" and "formal" are Bitcoin regulation index with news only in warning, pre-act and formal category, respectively. Variables "dwarningdiff", "dpreactdiff" and "dformaldiff" are generated following the same procedure with equation 4.32. Following three regressions are estimated to study the effect of each type of news.

$$\begin{aligned} Premium_{it} =& \alpha + \delta_i + \beta_1 dwarningdiff_{it} + \beta_2 ln(Fee)_t \\ & \beta_3 ln(Time)_t + \beta_4 ln(Volume)_{it} + \beta_5 Volatility_t + \beta_6 GoldReturn_t \\ & + \beta_7 Return_{it} + \beta_8 EFFR_t + \epsilon_{it} \end{aligned} \tag{4.41}$$

$$
\begin{aligned}
Premium_{it} =& \alpha + \delta_i + \beta_1 dpreactdiff_{it} + \beta_2 ln(Fee)_t \\
& \beta_3 ln(Time)_t + \beta_4 ln(Volume)_{it} + \beta_5 Volatility_t + \beta_6 GoldReturn_t \\
& + \beta_7 Return_{it} + \beta_8 EFFR_t + \epsilon_{it} \qquad (4.42)
\end{aligned}
$$

$$
\begin{aligned}
Premium_{it} =& \alpha + \delta_i + \beta_1 dformaldiff_{it} + \beta_2 ln(Fee)_t \\
& \beta_3 ln(Time)_t + \beta_4 ln(Volume)_{it} + \beta_5 Volatility_t + \beta_6 GoldReturn_t \\
& + \beta_7 Return_{it} + \beta_8 EFFR_t + \epsilon_{it} \qquad (4.43)
\end{aligned}
$$

Results of regressions are presented in Table 3.5. Coefficients of both "dwarningdiff" and "dformaldiff" are positive and statistically significant while the coefficient of "dpreactdiff" have opposite sign and not statistically significant. It can also be noticed that the size of estimated effect is larger for "dformaldiff". Findings from Table 3.5 are consistent with observations from section 3.5.2. Results suggest warning and formal news are driving factors of aggregate results estimated in Table 3.3, while pre-act news do not seem to affect Bitcoin price differential. Formal news is also found to have larger impact on Bitcoin price differential, which is in consistent with the finding in Table 3.4.

Here are my interpretations of these results. Tightening warning regulation news increase Bitcoin price differential because they signal the market about countries awareness of Bitcoin and potential intention wit further regulations on Bitcoin, which increase people's expectation on market segmentation and lead to higher price differential. At the stage of warning news, market segmentation is not formally created yet except expectation. When Bitcoin regulations are being formally introduced at the stage of formal news, market segmentation is formally created so that the change of formal regulation news has much higher effect on

Bitcoin cross country price differential comparing to warning news. My interpretation of why pre-act news do not affect Bitcoin price differential is that market has already adjusted its expectation on market segmentation at the stage warning news, which leaves pre-act news having insignificant effect on Bitcoin premium.

3.5.4 Spillover Effect from Regulation Change in Other Countries

Auer and Claessens [2018] suggests country's regulatory measure can spill over across borders. Therefore, it is possible that country's Bitcoin price differential can be affected by Bitcoin regulation change in other country. For example, China announced its plan to strict regulation of Bitcoin at the end of Jan. 2017. As a result, Bitcoin tradings which was originally dominated in Chinese Yuan quickly shifted to other Asian currencies like Japanese Yen and Korean Won. Bitcoin price and price differential of Japan and Korea are greatly affected by this change. Spillover effect of other country's regulation changes will be tested in this section and the following regression equation will be estimated.

$$\begin{aligned} Premium_{it} =& \alpha + \delta_i + \beta_1 dregulationdiff_{it} + \beta_2 dspillover_{it} \\ & + \beta ln(Fee) + \beta_4 ln(Time)_t + \beta_5 ln(Volume)_{it} + \beta_6 Volatility_t \\ & + \beta_7 GoldReturn_t + \beta_8 Return_{it} + \beta_9 EFFR_t + \epsilon_{it} \end{aligned} \tag{4.41}$$

"dspillover" measures the regulation change from all countries except the home country of its trading pair currency (assume equal weight for all types of news). If

Table 3.5: Panel Fixed Effect Model with Each Type of News

	(5.1)	(5.2)	(5.3)	(5.4)	(5.5)	(5.6)
	Dependent Variable: Premium					
dformaldiff	0.0131**			0.0132*		
	(0.00496)			(0.00673)		
dpreactdiff		-0.000770			-0.000780	
		(0.00104)			(0.00109)	
dwarningdiff			0.00398***			0.00398***
			(0.00125)			(0.00114)
ln(Fee)	-0.00290	-0.00296	-0.00297	-0.00286	-0.00292	-0.00293
	(0.00201)	(0.00201)	(0.00201)	(0.00199)	(0.00199)	(0.00199)
ln(Time)	0.00477***	0.00462***	0.00480***	0.00490***	0.00475***	0.00492***
	(0.00170)	(0.00167)	(0.00170)	(0.00115)	(0.00110)	(0.00113)
ln(Volume)	0.000940	0.000956	0.000950	0.000790	0.000810	0.000803
	(0.00117)	(0.00118)	(0.00118)	(0.00111)	(0.00112)	(0.00112)
Volatility	0.00160**	0.00161**	0.00161**	0.00161***	0.00163***	0.00163***
	(0.000692)	(0.000698)	(0.000696)	(0.000594)	(0.000599)	(0.000596)
Gold Return	0.176***	0.165***	0.165***	0.176***	0.165***	0.165***
	(0.0338)	(0.0315)	(0.0316)	(0.0464)	(0.0424)	(0.0423)
EFFR	0.00695*	0.00697*	0.00697*	0.00678*	0.00681*	0.00680*
	(0.00391)	(0.00391)	(0.00391)	(0.00394)	(0.00394)	(0.00394)
Return	0.0371**	0.0361**	0.0360**	0.0369***	0.0359***	0.0357***
	(0.0146)	(0.0145)	(0.0146)	(0.0130)	(0.0128)	(0.0128)
Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes
Cluster	Trading Pair	Trading Pair	Trading Pair	Currency	Currency	Currency
Observations	13,527	13,527	13,527	13,527	13,527	13,527
No. of Trading Pair	46	46	46	46	46	46

Note: Standard errors in parentheses. Standard Errors Clustered by Each Trading Pair for Column 1 and 2. Standard Errors Clustered by Currency for Column 3 and 4 "dformaldiff", "dpreactdiff" and "dwarningdiff" are daily change of country's Bitcoin regulation difference with USA with only formal news, warning new and pre-act news, respectively. "Fee" measures the transaction fee of transferring Bitcoin, and "Time" measures the transaction time. "Volume" is the daily trading volume for each trading pair. "Volatitility" is the 30 day historical return volatility of Bitcoin. "Gold Return" is daily gold return, and "Stock Return" is daily return of Stock index for each corresponding country. "Return" is daily Bitcoin return for each trading pair. "EFFR" is US effective federal fund rate.

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Table 3.6: Panel Fixed Effect Model with Spillover effect

	(6.1)	(6.2)	(6.3)	(6.4)
	Dependent Variable: Premium			
dregulationdiff	0.00305**	0.00325**	0.00276**	0.00276**
	(0.00137)	(0.00134)	(0.00132)	(0.00121)
dspillover	0.000694**	0.000737**	0.000735**	0.000735**
	(0.000313)	(0.000339)	(0.000312)	(0.000314)
ln(Fee)	-0.00118	-0.00133	-0.00294	-0.00294
	(0.00120)	(0.00122)	(0.00201)	(0.00196)
ln(Time)	0.0120***	0.0115**	0.00512***	0.00512***
	(0.00409)	(0.00459)	(0.00164)	(0.00107)
ln(Volume)	0.000452	0.000743	0.000943	0.000943
	(0.000969)	(0.00102)	(0.00118)	(0.00127)
Volatility	0.000714	0.000487	0.00156**	0.00156**
	(0.00110)	(0.00120)	(0.000696)	(0.000625)
Gold Return	0.169***	0.167***	0.167***	0.167***
	(0.0354)	(0.0428)	(0.0321)	(0.0429)
Return	0.0317**	0.0330**	0.0357**	0.0357**
	(0.0135)	(0.0139)	(0.0146)	(0.0128)
Stock Return		-0.000633		
		(0.0302)		
EFFR			0.00694*	0.00694
			(0.00391)	(0.00412)
Fixed Effect	Yes	Yes	Yes	Yes
Cluster	Trading Pair	Currency	Trading Pair	Currency
Observations	13,651	11,657	13,527	13,527
No. of Trading Pair	46	46	46	46

Note: Standard errors in parentheses. Standard Errors Clustered by Each Trading Pair for Column 1-3. Standard Errors Clustered by Currency for Column 4.
"dregulationdiff" is daily change of country's Bitcoin regulation difference with USA. "dspillover" is the daily change of Bitcoin regulation for other countries. "Fee" measures the transaction fee of transferring Bitcoin, and "Time" measures the transaction time. "Volume" is the daily trading volume for each trading pair. "Volatitility" is the 30 day historical return volatility of Bitcoin. "Gold Return" is daily gold return, and "Stock Return" is daily return of Stock index for each corresponding country. "Return" is daily Bitcoin return for each trading pair. "EFFR" is US effective federal fund rate.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

the coefficient of "dspillover" is not zero, it presents evidence of spillover effect that country's price differential can be affected by other countries' regulation changes. Results of equation (4.41) are presented in Table 3.6. Main results from in Section 3.5.1 are not altered. The coefficient of "dspillover" is positive and statistically significant but the magnitude is small. This finding suggests that country's Bitcoin regulation change has spillover effect on other countries so that tightening Bitcoin regulation in one country can increase Bitcoin price differentials of other countries. However, since country's Bitcoin regulation changes do not actually alter other countries' regulations, the size of spillover effect is found to be small. My interpretation is that regulation change in one country can have influence on the expectation of market segmentation in other countries, but the size of impact is expected to be small because this change do not actually create market segmentation in other countries. Besides, it is also important to note that investors of Bitcoin do not trade Bitcoins only in one currency. For example, one investor can invest Bitcoin in both Japanese Yen and Korean Won. Therefore, regulation change in one country (North Korea in the example) can have effect on investor's Bitcoin investment decision in other countries (Japan in the example) as well. This is another potential explanation for spillover effect.

3.6 Conclusion

This paper sets out to empirically investigate the effect of regulation change on Bitcoin cross country price differential. A representative daily country level data is used for regression analysis. An original daily country-level Bitcoin regulation news index is created to measure country's Bitcoin regulation changes.

Results of this paper suggest that tightening Bitcoin regulation in a country creates market segmentation and trade frictions, which impedes effective arbitrage activities and results in higher Bitcoin price differential for this country. By investigating the effect of each type of news individually, warning news and formal news are found to be main drivers of this result, while the estimated effect of formal new has larger magnitude. Pre-act news are found to have insignificant impact on Bitcoin price differential. These findings suggest stages of news are important. Market forms its expectation on market segmentation at the stage of warning news, and the expectation is realized at the stage of formal news. Thus, warning news and formal news are more important than pre-act news in determining Bitcoin cross country price differential. Moreover, this study finds that the effect of countries' regulation change spills over across borders. More specifically, tightening regulation in one country positively affects other country's price differential, which could result from multi-asset class investors or expectation change.

At the end of this study, I would like to reemphasize that the contribution of this study does not limit to only Bitcoin or cryptocurrency market. As mentioned earlier, Bitcoins are truly homogeneous across markets by construction with fast and cheap transaction. Therefore, this study contributes to the existed Law of One Price literature by studying how price differential can be affected by regulation changes for homogeneous good. Moreover, Bitcoin is a new asset trading in markets where regulations are arriving. This study provides findings of how markets will behave in response to new regulations for new asset, which can provide implications and help determine trading and investment strategies for other new assets that will emerge in the future as well.

Table 3.A1: Summary of variables

Variable	Description	Source
Premium	Exchange's adjusted USD price deviation from a US based exchange Coinbase Pro $Premium_{i,t} = (price_{i,t}/price_{coinbasepro,t}) - 1)$	Author's calculation
regulation	Bitcoin Regulation News Index in each trading pair's country, home country of its trading currency. Different types of news are aggregated using equal weight here. The construction of this new index is discussed in section 4.2	Author's calculation
dregulationdiff	Daily change of crypto regulation index difference between each country and U.S. $dregulationdiff_{it} = (regulation_{i,t} - regulation_{US,t}) - (regulationn_{i,t-1} - regulation_{US,t-1})$	Author's calculation
dspillover	Daily regulation change from all countries except home country of the trading pair currency and US (assume equal weight for all types of news)	Author's calculation
regulation1	Bitcoin Regulation News Index in each trading pair's country. Formal news is given highest weight and warning news has lowest weight in the process of aggregation	Author's calculation
regulation2	Bitcoin Regulation News Index in each trading pair's country. Warning news is given highest weight and formal news has lowest weight in the process of aggregation	Author's calculation
ln(Fee)	natural log of average bitcoin transaction fee per transaction	www.blockchain.com
ln(Volume)	natural log of the daily bitcoin trading volume in each exchange for each trading pair	Exchanges' API
ln(Time)	natural log of time between block	www.bitcoinity.org
Volatility	30 day historical Bitcoin return volatility	Author's Calculation
Return	Daily Bitcoin return $Return = (price_{i,t}/price_{i,t-1}) - 1$	Exchanges' API
Gold Return	Daily return of Gold. Price of gold used is Gold Fixing Price 10:30 A.M. (London time) in London Bullion Market, based in U.S. Dollar $GoldReturn_t = (price_{Gold,t}/price_{Gold,t-1}) - 1$	FRED Database
EFFR	Effective Federal Funds Rate	FRED Database
Stock Return	Daily Stock Index return for each country. SP500 Index, Nikkei Index, KOSPI Index, STI Index, JKSE Index, HSI Index, FTSE Index EURO STOCKXX 50 Index and S&P/TSX are used for USA, Japan, South Korea, Singapore, Indonesia, Hong Kong, United Kingdom, Europe and Canada, respectively.	Yahoo! finance

Table 3.A2: List of Bitcoin Exchanges and Trading Currencies

Exchange Name	Trading Currency	Exchange Name	Trading Currency
Bitflyer	EUR JPY USD	Bitfinex	EUR JPY USD
Coinone	KRW	Bithumb	KRW
Bitstamp	EUR USD	Bitsquare	EUR USD
Bittrex	USDT[2] USD	Cexio	EUR GBP USD
Coinbase Pro	EUR GBP USD USDC [1]	Gemini	USD
Kraken	JPY EUR GBP CAD USD	Okcoin	USD
Poloniex	USDT[2] USDC[1]	Quadriga	CAD USD
Liquid	JPY HKD SGD IDR EUR USD	Luno	IDR
Hitbtc	USDC[1] USDT[2]	Huobi	USDT[2]
Okex	USDT[2]	Bitz	USDT[2]
Gateio	USDT[2]	Binance	USDT[2] USDC[1]

Table 3.A3: Currency List

Currency Symbol	Currency Name
KRW	Korean Won
JPY	Japanese Yen
HKD	Hongkong Dollar
SGD	Singapore Dollar
IDR	Indonesian Rupiah
EUR	Euro
GBP	British Pound
USD	US Dollar
CAD	Canadian Dollar
USDC[1]	USD Coin
USDT[2]	Tether

[1]USDC (USD Coin) is a type of stablecoin issued by Coinbase, which always has a one to one exchange rate with US dollar

[2]USDT (Tether) is a type of stablecoin issued by Tether Limited. The value of one USDT is approximately one US dollar

Table 3.A4: Example of News Index Dataset

Date	Title	Source	Types	Country	T/L
11/30/2017	Fed's Quarles warns that digital currencies like bitcoin pose 'serious financial stability issues' as they grow	CNBC	Warning	USA	Tightening
12/01/2017	Invest in Bitcoin 'At Your Own Risk,' Warns French Central Bank	Coindesk	Warning	EU	Tightening
12/01/2017	Bitcoin Not Legal Tender in India, Finance Minister Says	Coindesk	Warning	India	Tightening
12/05/2017	Mexican Senate passes fintech law	Reuters	Pre-act	Mexico	Tightening
12/06/2017	South Korean Financial Regulators Ban Bitcoin Futures Trading	Bitcoin News	Ban	Korea	Tightening

References

Q Farooq Akram, Dagfinn Rime, and Lucio Sarno. Does the law of one price hold in international financial markets? evidence from tick data. *Journal of Banking & Finance*, 33(10):1741–1754, 2009.

Marcus Asplund and Richard Friberg. The law of one price in scandinavian duty-free stores. *American Economic Review*, 91(4):1072–1083, 2001.

Raphael Auer and Stijn Claessens. Regulating cryptocurrencies: assessing market reactions. *BIS Quarterly Review September*, 2018.

Kyoung Jin Choi, Alfred Lehar, and Ryan Stauffer. Bitcoin microstructure and the kimchi premium. *Available at SSRN 3189051*, 2018.

Raphael Espinoza, Ananthakrishnan Prasad, and Oral Williams. Regional financial integration in the gcc. *Emerging Markets Review*, 12(4):354–370, 2011.

Pinelopi K Goldberg and Frank Verboven. Market integration and convergence to the law of one price: evidence from the european car market. *Journal of international Economics*, 65(1):49–73, 2005.

Alexander Kroeger and Asani Sarkar. Law of one bitcoin price? *Federal Reserve Bank of Philadelphia*, 2017.

Igor Makarov and Antoinette Schoar. Trading and arbitrage in cryptocurrency markets. *Journal of Financial Economics*, 2019.

John Pippenger. Commodity Arbitrage and the Law of One Price: Setting the Record Straightt. *Theoretical Economics Letters*, (6):1017–1033, 2016.

Kenneth Rogoff. The purchasing power parity puzzle. *Journal of Economic literature*, 34(2):647–668, 1996.

Samuel Yim, Gye-Jeong Kim, and Mooni Kim. The korean premium: Cryptocurrency—arbitrage phenomenon in korea. *Includes Chapter News*, 31(1):30, 2018.