One Coin, Many Markets - How Market Frictions Affect Arbitrageurs *

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Abstract

This paper investigates how different levels of financial integration affects price differences and trading activity. I use the global bitcoin market, as cryptocurrency exchanges have different levels of financial integration and transactions between exchanges are recorded on the blockchain. I therefore identify how arbitrageurs adapt to different market frictions. The results show that when arbitrageurs have to use fiat currencies as quote currencies or comply with capital control regulation, the price differences increase, and arbitrage activity decrease compared to a pure blockchain arbitrage process. The results have implications for international financial integration and the discussion of central bank digital currencies.

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1 Introduction

Arbitrage is one of the central conditions of markets efficiency. In theory, pure arbitrage should be without capital requirements and without risk. In practice, however, arbitrage is both risky and costly due to the frictions on trading venues, bank transfers, and settlement (Shleifer and Vishny, 1997; Liu and Longstaff, 2004; Gromb and Vayanos, 2010). Quantifying the cross border frictions that limit the activities of arbitrageurs is the focus of several papers studying cross listed stocks, American Depository Receipts (ADR) (Gagnon and Karolyi, 2010; Alsayed and McGroarty, 2012), and Dual Listed Companies (DLC) (Rosenthal and Young, 1990; De Jong et al., 2009). However, ADRs and DLCs are not fully fungible, which makes it difficult to isolate the effect of the market frictions (currency conversions, international transfers, opening hours) from the asset frictions (conversion fees, handling and processing). For the few fully fungible assets, such as some cross listed stocks, arbitrage opportunities rarely occur as institutions are able to circumvent the frictions of international transfers and currency conversions (Lok and Kalev, 2006; Kryzanowski and Zhang, 2002). The frictions however remain for retail investors.

Recent literature use the global market for bitcoin to study arbitrage and price formation as bitcoin is fully fungible. Makarov and Schoar (2020) show that the price of bitcoin varies when traded in different fiat currencies and estimate daily unexploited arbitrage profits of more than $75 million in 2017. The authors are however puzzled by the magnitude of the price differences between regions and within countries. To explain the price differences this paper takes a different approach by segmenting the heterogeneous exchanges into three categories based on the frictions they impose on the arbitrageurs rather than the geographical location of the exchange. This approach allows me to show that institutions cannot circumvent cross border frictions as all market participants have to deposit and withdraw fiat currencies to and from cryptocurrency exchanges using bank transfers. Additionally, I isolate how different cross border frictions (currency conversions, international bank transfers, and capital controls) limit the ability of arbitrageurs to exploit the price differences compared to a pure blockchain arbitrage strategy. The market for bitcoin is a useful laboratory as the global 24 hour bitcoin to fiat currency market is substantial, with over $3.5 billion being traded daily on the 21 largest global exchanges (Lu, 2020). Daily dollar volume increases to $18 billion when including all cryptocurrency and derivatives trading in bitcoin.

Moreover, as transactions between exchanges are recorded on the blockchain, I can identify how arbitrageurs adapt to different market frictions.

Using the clustering algorithm introduced by Ron and Shamir (2013) to identify the cryptocurrency exchanges and the transactions between them, I can shed light on the mechanisms of arbitrage by showing how quickly arbitrageurs react, how much volume is transferred when prices deviate from parity, the cost of transferring bitcoin between exchanges (which indicates their sense of urgency), and the delay in transaction processing. This level of insight into arbitrage activity is rarely possible for equities or other assets, as the transactions between venues are neither linked nor publicly available.

Using minute closing prices from Cryptocompare.com and blockchain data between 14 highly liquid exchanges from 22 July 2016 to 8 September 2019 I find that in categories where investors face greater frictions such as different fiat currencies, money transfers via banks, or capital control regulation, the arbitrage opportunities are larger and take longer to resolve as arbitrage volume is lower and less frequent. This result does not change as the market for bitcoin matures and institutional participation increases, which indicates that the entry of institutions does not eliminate the price differences.

The results suggest that regulatory changes may be needed to reduce the cross country frictions by increasing the speed of transfers, as price differences are not eliminated by increased market participation. While money transfer companies such as TransferWise and MoneyGram are competing on reducing the processing times, domestic bank transfers can take one to two working days and international bank transfers can take between one and five working days to clear. This implication is especially pertinent as central banks develop central bank digital currencies (CBDC).[1] Integrating central bank digital currencies with stock exchanges that already trade digital shares could therefore reduce price differences for assets that are listed in multiple countries and reduce the cost of transacting for market participants who cannot circumvent the frictions. This implication is especially clear when analyzing the price difference duration which increases with the frictions. The results show that arbitrage opportunities persist as arbitrageurs are not able to transfer fiat currencies between exchanges several times within a day.

The remainder of the paper is structured as follows. Section 2 discusses the arbitrage strategies on the bitcoin blockchain, how exchanges work, how exchanges interact with the blockchain, and introduces the three categories of financial integration. Section 3 presents the results of the price differences, transaction activity and price difference duration as frictions increase.

[1] A recent survey by the Bank for International Settlements show that 80% of central banks are engaged in CBDC projects and that one in ten central banks find it likely that they will offer CBDC within the next three years (Boar et al., 2020).

Section 4 introduces the different types of transactions, identifies arbitrage transactions, and discusses how the composition of transaction types changes as frictions increase. Section 5 analyzes the differences between arbitrage and non arbitrage transactions and Section 6 concludes.

2 The arbitrage process in bitcoin

Arbitrage strategies and the process of carrying out the strategies vary depending on the assets and markets involved. The simplest empirical example of arbitrage is trading the same stock on two exchanges in the same country. The arbitrage process involves buying on one exchange and simultaneously selling on another exchange. The primary risk arbitrageurs face is implementation risk, as they compete down to the microsecond to exploit the price difference first (Aquilina et al., 2020; Shkilko and Sokolov, 2020; Budish et al., 2015). As short selling is generally not available on cryptocurrency exchanges, the arbitrage process in bitcoin is circular in nature and takes longer than microseconds.

Generally arbitrageurs have two strategies to carry out arbitrage in cryptocurrencies. The first strategy is to simply buy bitcoin on the cheap exchange, send the bitcoin to an expensive exchange, sell the bitcoin and return whichever quote currency was used to the originating exchange. This strategy can be risky, as it takes time to move bitcoin from one exchange to the other, during which time the price can move. An alternative strategy is to hold bitcoin on the exchange which most frequently has higher prices. The arbitrageur can then immediately buy bitcoin on the cheap exchange, sell the bitcoin she has in inventory at the expensive exchange and then re-balance without the risk of adverse price movements. This strategy is particularly useful between exchanges where the price difference is primarily one directional. For example, during the sample period, the bitcoin price on Yobit is rarely lower than the price on Kraken. An arbitrageur who employs this alternative strategy will however have inventory costs, which can be very high given the volatility of the bitcoin price.

The arbitrage process in bitcoin is different from traditional cross border arbitrage in three ways. First, the bitcoin arbitrage process involves trading the same asset on multiple exchanges. This is in contrast to arbitrage in Dual Listed Companies (DLC), where the underlying stocks are not the same but the price should move in lockstep. An arbitrageur of DLC stocks therefore has to keep two open positions until the prices converge rather than buying and selling at the same time (Rosenthal and Young, 1990; Froot and Dabora, 1999; De Jong et al., 2009). Second, bitcoin is fully fungible. The process is therefore different from arbitrage in American Depository Receipts (ADR) where an arbitrageur has the extra step and cost of converting the ADRs (Gagnon and Karolyi, 2010). Third, cryptocurrency exchanges are open 24 hours a day. An arbitrageur can therefore take advantage of a price difference at any time. This is in contrast to arbitrageurs of cross-listed stocks and ADRs where opening hours of stock exchanges may not overlap (Gagnon and Karolyi, 2010)[2].

2.1 Levels of market frictions

Whichever strategy the arbitrageur uses she will have to move bitcoin and a quote currency between venues. One of the major costs and risks she faces is therefore how quickly she can complete a round-trip and restart. The duration of the round-trip will be influenced by the level of integration between the exchanges as well as the integration between banks to facilitate cross border payments. To analyze how the round-trip duration affects the price deviations and the arbitrage transaction activity I have categorized each exchange pair (transactions between two exchanges) into one of three categories. The categories, as highlighted in Figure 1, are: (1) between stablecoin exchanges, (2) between fiat currency exchanges and (3) between fiat currency exchanges and exchanges in countries with capital control.

2.1.1 Stablecoin exchanges

The first category, which has the fewest frictions, is arbitrage between stablecoin exchanges. Stablecoins are token versions of fiat currencies such as USD Tether (USDT) or the euro-backed stablecoin (EURS). The exchanges do not trade in fiat currencies, they only exchange cryptocurrencies and stablecoins. The exchanges are global and traders from most of the world can open an account and trade. In the sample these exchanges include Bittrex, HITBTC, Huobi,[3] and Poloniex. The exchanges trade a wide variety of cryptocurrencies (287 on Bittrex, 380 on HITBTC, 226 on Huobi, and 97 on

[2] There are many other examples of arbitrage which are different from arbitrage in bitcoin. For example: informational arbitrage (Ljungqvist and Qian, 2016), performance based arbitrage (Shleifer and Vishny, 1997), equity carve-outs (Lamont and Thaler, 2003), treasury bonds (Cornell and Shapiro, 1989; Longstaff, 1992), options (Ofek et al., 2004), and primes and scores (Jarrow and O'Hara, 1989).

[3] Before October 2017 Huobi was a Chinese exchange which traded primarily in Chinese Yen. However after the Chinese government made exchanges between cryptocurrencies and CNY illegal the exchanges pivoted to only trading in cryptocurrencies and stablecoins. This paper only uses blockchain transaction and price data from January 2018 onward for Huobi.

Poloniex) and stablecoins which are primarily USD versions (USD Tether, TUSD, USDC, DAI, USDS, HUSD, Binance USD, and PAX). HITBTC also trade Euro stablecoins (EURS). For the analysis I use the minute closing price of BTC-USDT from Cryptocompare.

Panel A in Figure 1 shows that an arbitrageur trading between stablecoin exchanges have a very short and simple round-trip as all transactions between the exchanges occur on blockchains. The figure shows an example of an arbitrage process where the arbitrageur buys bitcoin with USDT on Exchange A, sends the bitcoin to Exchange B where she sells her bitcoin for USDT. She then returns the USDT to Exchange A with another blockchain transaction.

The duration of the round-trip depends primarily on the stablecoin used as a quote currency. As a block of bitcoin transactions are verified every ten minutes, the first transaction from Exchange A to Exchange B takes approximately 10 minutes. However, most exchanges require three blocks to be verified before the trader can sell her bitcoin on Exchange B. This is to ensure that the bitcoin blockchain transaction is not rejected because the bitcoin have been double spent. By waiting three blocks the risk of this occurring reduces from 20.5% to 1.3% (Nakamoto, 2009). Sending bitcoin from Exchange A to Exchange B therefore takes approximately 30 minutes. The duration of the return transaciton depends on which blockchain the stablecoin uses. As USDT uses the bitcoin omni layer[4] Exchange A will require a three block wait time and the transaction will take 30 minutes. Alternatively, if the arbitrageur uses USDC or one of the other Ethereum based stablecoins as the quote currency, the return transfer can take 7 minutes. This is because blocks on ethereum network take 14 seconds to verify and exchanges require 30 block confirmations before traders can sell the coins on the exchange. Regardless of which quote currency is used, the arbitrageur is able to complete multiple round-trips within a day.

2.1.2 Fiat currency exchanges

The second category increases the market frictions as these exchanges trade exclusively in cryptocurrencies and fiat currencies, not stablecoins. These exchanges have historically had country specific ties but many of them exchange multiple fiat currencies which are available to most traders.[5] The

[4]The bitcoin omni layer is a protocol built on top of the bitcoin blockchain to increase the types of assets users can trade. Transactions on the omni layer therefore have the same speed as bitcoin transactions.

[5]There are often specific rules for US residents and which currencies they can trade. For example Lake-BTC do not allow US residents to trade at all. After Bittrex listed USD and EUR in addition to their stablecoins, US residents are only able to exchange in USD,

exchanges in this category include Bitbay, Bitfinex, Bitstamp, CEX, Kraken, LakeBTC and TheRockTrading. Compared to the stablecoin exchanges, these exchanges list substantially fewer cryptocurrencies (29 on Bitbay, 7 on Bitstamp, 26 on CEX, 38 on Kraken, 5 on LakeBTC, and 12 on TheRock-Trading). Bitfinex is the exception, as it currently trades 152 cryptocurrencies. The exchanges trade in a variety of fiat currencies which have separate order books. For instance, BTC-USD is traded separately from BTC-EUR. The minute closing prices from Cryptocompare include: EUR, PLN and USD for Bitbay, CAD, EUR, GBP, JPY and USD for Kraken, AUD, CAD, EUR, GBP, JPY and USD for LakeBTC, EUR for TheRockTrading, and EUR and USD for Bitfinex, Bitstamp and CEX. As I do not see how the bitcoin are traded once they arrive at the exchange, it is unclear which fiat currency the arbitrageur is using as a quote currency. I therefore use the average price of the BTC-fiat exchange rates on the exchange, weighted by the dollar volume traded on the exchange in that minute for each exchange rate to get one price of bitcoin on each exchange.

To take advantage of price differences between exchanges in this category the arbitrageur needs to take additional steps to complete the round-trip, which increases the arbitrage transactions' duration. The arbitrage process example in Panel B in Figure 1 shows that after the arbitrageur sends her bitcoin to Exchange B and exchanges the bitcoin to Euro, the arbitrageur now has to withdraw the fiat currency from Exchange B to a bank account. The arbitrageur then has to exchange the fiat currency and send it internationally to a bank in the originating country, before depositing the fiat currency in Exchange A, completing the round-trip.

As the exchanges do not trade in stablecoins, the duration of the arbitrage round-trip is substantially longer. The bitcoin transaction from Exchange A to Exchange B still takes approximately 30 minutes. However, the arbitrageur has to wait for the bank transfers to clear where international bank transfers can take from one day to a few days. If both exchanges operate in the same fiat currency the arbitrageur can skip the international bank transfer, but she still has to withdraw and deposit fiat currency into the cryptocurrency exchanges using bank transfers. This means that the arbitrageur will only be able to complete a round trip at most once a day.

Importantly, this friction of slow transactions between banks also affects institutions. Institutions may have fiat currency deposits in multiple countries which allows them to avoid fiat currency frictions when arbitraging stocks for example. However, institutions have to make bank transfers when depositing and withdrawing fiat currencies to and from the cryptocurrency

not EUR. However non-US residents are able to exchange both USD and EUR on Bittrex.

exchange if the cryptocurrency exchanges do not offer margin trading, which few exchanges do. The institutions therefore have to wait the 1-2 days for the bank transfer to clear just like retail investors. This may explain why Makarov and Schoar (2020) observe price differences between bitcoin denominated in US dollar versus Euro of 3% on average. The authors find the magnitude of the price difference surprising as they expect that institutions should be able to exploit the price differences.

2.1.3 Capital control exchanges

The last category has the highest level of frictions and include transactions between fiat currency exchanges and exchanges in countries with capital controls. The exchanges that operate in countries with capital controls are OkCoin[6] (China), MercadoBitcoin (Brazil), and Yobit (Russia). The countries have varying rules on capital inflows and outflows (Fernández et al., 2016). This category includes transactions between the fiat currency exchanges (Bitbay, Bitfinex, Bitstamp, CEX, and Kraken), which are not restricted by capital controls, and exchanges with capital controls (MercadoBitcoin, OkCoin, and Yobit). Users in other countries can set up an account on OkCoin and Yobit[7] while users outside of Brazil are not able to set up an account on MercadoBitocin as the exchange requires a government identification number. Importantly, arbitrageurs cannot avoid the capital control regulation by using stablecoins, as none of the exchanges have stablecoins listed.

The transaction round-trip of the arbitrageur is further restricted by the capital control regulation as shown in the arbitrage prices example in Panel C of Figure 1. The duration of the arbitrage process increases as the arbitrageur now has to comply with capital control regulation on the return leg of the round-trip. The blockchain transaction still takes 30 minutes and the domestic bank transfers remain similar to the fiat currency exchanges in the previous category. However the international transfer may take longer. In addition, the volume the arbitrageur is able execute on each round-trip may also be restricted. This category therefore has the longest arbitrage process with the most frictions.

[6]OkCoin exchanged cryptocurrencies for Chinese Yen until October 2017 when the Chinese government made such trading illegal. I only include blockchain transaction and price data before October 2017 for OkCoin.

[7]Users from North Korea, Syria, Iran, Sudan, Bangladesh, Bolivia, Ecuador, Kyrgyzstan and the USA cannot set up an account an OkCoin.

2.2 Exchange specific frictions

Independently of which category of market frictions the arbitrageur experiences, she will incur some exchange specific costs. Market access is generally low cost. Depending on the cryptocurrency exchange, the setup time varies based on the level of Know Your Customer and Anti Money Laundering regulation the exchange enforces.[8] Once the arbitrageur has access to the exchange, the trading is organized similarly to stock exchanges. The exchanges have centralized limit order books with no intermediaries. Traders can submit market orders and limit orders, and some exchanges offer more advanced order types. All orders are ranked by price and time priority and matched and settled by the exchange's internal matching engine. As trading is organized internally by the exchange the transaction speed resembles that of stock exchanges.

The exchanges in the sample are highly liquid, but the liquidity varies throughout the day depending on the time zone of when the majority of traders are awake (Dyhrberg et al., 2018). Most exchanges do not have designated market makers and rely on endogenous market makers to provide liquidity (Dyhrberg et al., 2019). Depending on the liquidity, the arbitrageur will pay a liquidity cost equal to the effective spread to have immediate execution. Additionally, the arbitrageur will pay any explicit costs such as maker/taker fees. To withdraw fiat currencies the arbitrageur sometimes has to pay a withdrawal fee (10-50 basis points per withdrawal) and most exchanges also have withdrawal limits ($2,000 to unlimited depending on the trading account). The exchange specific frictions are therefore liquidity costs such as spreads and explicit trading fees as well as withdrawal fees and limits for fiat currencies.

In addition to a longer round-trip duration arbitrageurs between fiat currency exchanges will incur additional costs such as the bank fees for international transfers, foreign exchange conversion fees, the foreign exchange spread, the wait time for the fiat to be withdrawn from and deposited into the exchange, and the wait time of the international transfer.

[8] All of the exchanges in the sample requires some form of identification verification. However, the extent of the identification verification requirements varies. Most exchanges require contact information and a photo of a passport. Other exchanges additionally require proof of address, bank statements, source of funds information, and a photo of yourself with your id and a note stating the name of the cryptocurrency exchange. Having set up accounts and completed the identification verification on all exchanges in the sample except for MercadoBitcoin, the process varies between 15 minutes and 6 hours including processing time.

2.3 Blockchain specific frictions

All the trading on the cryptocurrency exchanges occur independently of the bitcoin blockchain. The transactions are matched, settled, and recorded internally by the exchange. To move the bitcoin to a different exchange the arbitrageur has to interact with the blockchain. To transfer the bitcoin the arbitrageur submits a transfer with information on the receiving wallet address (the bitcoin address linked to the arbitrageur's account on the receiving exchange), the amount to transfer, and the mining fee the arbitrageur would like to pay. The transaction information is comparable to a bank transfer where the user enters the account number of the receiver and the amount to be transferred. In contrast to bank transfers where the fee is set by the bank, the fee users pay the miners is voluntary and used to incentivize the inclusion of their transactions in the next block.[9] The fee can be of any size, but most exchanges suggests a fee amount.

When the transaction has been submitted it enters the pool of unverified transactions (called the memory pool or mempool). The time it takes for the transaction to be verified depends on the mining fee paid relative to the size of the transaction in bytes, the fees on the other transactions in the pool, and how many other transactions are waiting to be verified (Easley et al., 2019). Miners are incentivized to verify the transactions that pay the highest fee relative to how much space it takes up in the block, as the block has a finite size. During the sample period the median wait time of a transaction is 6.8 minutes.

In addition to the explicit mining fee, the arbitrageur is also subject to mempool wait time uncertainty. The wait time varies and the arbitrageur cannot secure a certain wait time by paying a specific fee (Hautsch et al., 2020). During the wait time the arbitrageur is exposed to spot price volatility risk as cryptocurrencies in general, and bitcoin specifically, is known for high price volatility (Hautsch et al., 2020). Once the transaction has been verified and included in a block, the bitcoin is transferred to the receiving exchange. The blockchain specific frictions thus include the mining fee, the mempool wait time, mempool wait time uncertainty, and spot price volatility risk.

3 Price differences under different market frictions

To identify how price differences and trading activity changes when the level of financial integration changes I calculate the average price difference across

[9] For more details about mining see Easley et al. (2019) and Huberman et al. (2019).

the exchange pairs as well as the transaction volume flowing between the exchanges in each category and plot the variables over time in Figures 2 to 4.

3.1 Stablecoin exchanges

The price differences and blockchain transactions between stablecoin exchanges, which have the fewest frictions of the three categories, is shown in Figure 2. Given that the arbitrage round-trip is relatively short, it is not surprising that the price differences between the stablecoin exchanges are close to zero. Panel A in Figure 2 shows the average daily price difference across the exchange-level flows in this category between 22 July 2017 and 8 September 2019. The daily price difference is rarely above (below) 2.5% (-2.5%). When the price differences spike, it occurs in both directions, indicating that no one exchange is persistently more expensive or cheaper than the others. The price difference decreases over time, especially since the end of 2018 where the price differences are very close to zero. This development indicates that as the market matures, the variation in the price differences decreases.

Panel B and Panel C in Figure 2 shows the price of bitcoin in USD and the bidirectional blockchain transaction volume between the stablecoin exchanges. The panels indicate that the blockchain volume positively correlates with the bitcoin price as bidirectional volume increases when the price of bitcoin appreciates and vice versa. Specifically, after June 2017 the transaction volume increases substantially to approximately 10 million USD daily in both directions and remains at that level until March 2018. During this period (mid 2017 to mid 2018) the cryptocurrency market experienced a boom in Initial Coin Offerings (ICO), where companies issue tokens to raise capital (Howell et al., 2019). Bittrex and Poloniex are known for listing smaller alternative coins, which explains the increase in activity in 2017 and the subsequent decrease in transaction flows between the exchanges as the ICO popularity reduces. This increase in activity is mirrored in the rapid increase in the bitcoin price during the same period where the price of bitcoin reached nearly 20,000 USD in December 2017. After the ICO boom, the bitcoin price stabilizes and the daily transaction volume decreases to under $1 million in both directions until the price starts to appreciate again in May 2019 and the volume increases. When plotting transaction volume between fiat currency exchanges and stablecoin exchanges[10] a similar pattern

[10] The transactions and graphs are not included in the analysis as these cannot be arbitrage transactions. To conduct arbitrage both exchanges have to have the same quote

emerges as these transactions are likely transactions to gain access to the wider selection of coins available on stablecoin exchanges.

Insert Figure 2 here

Trading exclusively in cryptocurrencies and stablecoins has benefits. As arbitrageurs can complete multiple round-trips throughout the day, the price deviations remain close to zero. The exchanges have also historically been subject to lower levels of regulation, as they do not interact with the traditional financial markets. However, stablecoins can cause issues depending on how the supply of the stablecoin is managed and how the peg to the respective fiat currencies are ensured. As stablecoins are backed and managed by companies and not central banks, the reliability of the peg and the trust that the fiat reserve covers the issuance of the stablecoin one to one is less transparent. For example, Griffin and Shams (2020) show that USDT is being printed, unbacked by USD, and exchanged for bitcoin to drive up the price following periods of negative bitcoin returns. Due to the issues around security and stability not all exchanges have listed stablecoins.

3.2 Fiat currency exchanges

When the market frictions increase, arbitrageurs have to exchange bitcoin for fiat currencies, withdraw the fiat currencies and transfer the fiat currencies between exchanges. The additional frictions of exchanging and transferring fiat currency between bank accounts makes it slower and more expensive to take advantage of price deviations between fiat currency exchanges.

The result of the increased frictions can be seen in Panel A of Figure 3, which shows the average daily price differences through time between the fiat currency exchanges. Compared to stablecoin exchanges, the price deviations have similar magnitudes, remaining within $\pm 2.5\,\%$. However, unlike the stablecoin exchanges, the price deviations are more frequently above zero and remain positive for extended periods of time. This price difference suggests that the arbitrageurs are not able to correct the mispricing because of the additional fees and the longer round-trip durations. Interestingly, the price difference is primarily positive which indicates that some exchanges are persistently more expensive than others. The exchanges driving this result are CEX, Kraken, LakeBTC and TheRockTrading.

currency listed which is not the case between fiat currency exchanges and stablecoin exchanges. Fiat currency exchanges only exchange bitcoin for fiat currencies and stablecoin exchanges only exchange bitcoin for stablecoins.

Panel B shows the price of bitcoin over the sample period. When comparing the price differences and the bitcoin price throughout time it is clear that the price difference increases in 2017 as the price of bitcoin appreciates rapidly. This relation supports the finding by Makarov and Schoar (2020) who find that price deviations between bitcoin and fiat currencies occur when the bitcoin price appreciates quickly. However, the price deviation converges towards the end of the time-series after May 2019 and, importantly, does not widen as the bitcoin price appreciates in May 2019. This indicates that the relationship between the appreciation of the bitcoin price and the price deviations may be a specific characteristic of the 2017 boom. A possible explanation could be more competition among arbitrageurs as the bitcoin market matures, for example by increased participation of institutions in arbitrage activities.

The transaction flows between the exchanges trading fiat currencies is significantly smaller than between the stablecoin exchanges, as shown in Panel C of Figure 3. Daily transaction volumes frequently passes $10,000 and occasionally $100,000, but is far from the millions transferred between stablecoin exchanges. Interestingly, the vast majority of the transaction volume is in one direction, which aligns with the positive price difference as users are transferring bitcoin from the cheap to the expensive exchanges.

The results show that as market frictions increase and users have to interact with traditional bank transfers rather than blockchains exclusively, the price differences increase and the overall trading activity decreases. This indicates that if bank transfers were made faster through higher integration between banks, the price differences might reduce resulting in increased activity.

The low transaction volumes between fiat currency exchanges also indicate that bitcoin is not being widely used as an alternative to international bank transfers. The arbitrage process example in Figure 1 shows that to deposit and withdraw fiat currencies into cryptocurrency exchanges, users have to complete traditional banking transfers. Using bitcoin as an alternative to international bank transfers may therefore only provide a marginal improvement as bank transfers are not eliminated entirely. To get the full benefit of the speed (and low frictions) of international transfers on the blockchain users would need a central bank digital currency to replace fiat currencies. This may be the reason why bitcoin has not disrupted the remittance industry as it was predicted to do.

Insert Figure 3 here

3.3 Capital control exchanges

When one of the exchanges are subject to capital control regulations, the duration of the arbitrage round-trip increases as the arbitrageur has to complete additional steps to comply with or avoid the regulation. These additional frictions are clearly reflected in the magnitudes of the price deviations shown in Panel A of Figure 4. Throughout the sample period the exchanges which operate in countries with capital controls have prices that are frequently more than 5% higher than the exchanges without capital controls. The price differences also persist for long periods of time ,and reach 10% several times. Similarly to the price differences between fiat currency exchanges, the price difference is most frequently positive as the exchanges in the countries with capital controls have higher prices.

As the price deviation is most frequently positive, the transaction volume in Panel C is correspondingly positive (i.e. flowing into the exchange with capital controls and higher prices). The daily transaction volume is however larger (frequently reaching $1 million) and more persistent than between fiat exchanges. Interestingly, around March 2019 when the price deviation flips from being primarily positive to being negative the transaction flows do not change direction, which indicates that the arbitrageurs may be delayed or restricted in moving their inventory and reversing the arbitrage round-trip direction. Panel C also shows that the majority of the blockchain transaction volume flowing out of the countries with capital controls occur in 2016 and 2017.

The persistent and high daily transaction volume between fiat currency exchanges and exchanges in countries with capital controls indicate that the additional costs of bank transfers may make bitcoin a more valuable alternative to international transfers compared to transactions between fiat currency exchanges discussed in the previous section.

Insert Figure 4 here

To test the effect of the market frictions on the price differences I estimate the regressions in Eq. (1).

$$\begin{aligned} PriceDifference_{i,t} = \alpha_m &+ \beta_1 FiatExchange_{i,t} \\ &+ \beta_2 CapitalControlExchange_{i,t} \\ &+ \beta_3 AbsBitcoinReturn_{i,t} \\ &+ \beta_4 IntradayVolatility_{i,t} + \epsilon_t \end{aligned} \tag{1}$$

where $PriceDifference_{i,t}$ is the price difference in percent between exchange pair i at minute t, α_m is month year fixed effects, $FiatExchange_{i,t}$ is a dummy variable which equals one for the exchange-level flows which are in the fiat exchange category and zero otherwise, $CapitalControlExchange_{i,t}$ is a dummy variable which equals one if the exchange-level flow is between a fiat exchange and an exchange with capital controls and zero otherwise, $AbsBitcoinReturn_{i,t}$ is the daily absolute bitcoin return[11] and $IntradayVolatility_{i,t}$ is the average intraday volatility of the two exchanges in exchange pair i.

The regression results in Table 1 show that the price differences between fiat currency exchanges and to exchanges with capital controls is 2.48% and 5.35% higher than between stablecoin exchanges. The result shows that the additional frictions imposed by transacting in fiat currencies and adhering to capital control regulations limits the activities of arbitrageurs and their effect on the prices. This indicates that if international fiat currency transactions were made faster, the price differences would reduce as arbitrageurs could complete round-trips more frequently.

The result is consistent when segmenting the sample period into before and after 1 Jan 2018 which indicates that even as the market for bitcoin matures, the market frictions are still limiting the activities of arbitrageurs. As the time series graphs showed in the previous sections the bitcoin network has experienced periods of high and low activity. Models (4) and (5) show that the results are consistent when the network is more or less congested (if the number of transactions in the mempool is above or below the median).

Insert Table 1 here

3.4 Price difference duration under different market frictions

The arbitrageurs' round-trip transaction varies depending on the level of market integration, and that the duration of this round-trip increases as more frictions are introduced. Given that the prices vary between exchanges in all three categories, the question becomes if the price differences persist for long enough for the arbitrageur to react. I investigate this question by analyzing the duration when the price difference is outside a percentage threshold ($\pm 2\,\%$, $\pm 5\,\%$, $\pm 10\,\%$ and $\pm 20\,\%$).

Table 2 shows that when the frictions increase and the arbitrage round-trip takes longer to complete the price differences persist for longer periods

[11] The bitcoin price used for the return variable is the daily volume weighted average price of BTC-USD on Kraken. This is to have a general measure of return instead of it depend on the exchanges in the specific exchange pair. The BTC-USD exchange rate is used as it is traded throughout the entire sample period. It is also representative of the global bitcoin price as it is included in the CME Bitcoin Reference Rate.

of time as well. Specifically, the maximum number of consecutive days the price difference is above/below ±2 % is 8 days, 123 days and 542 days between stablecoin exchanges, fiat currency exchanges, and to capital control exchanges respectively. This relationship between increasing duration and increasing frictions persists as the price differences increase to ±5 %, ±10 %, and ±20 %. When comparing the total number of days and the frequency with which the price difference is above/below the thresholds a similar pattern emerges. As frictions increase the price difference is outside ±2 % more frequently, persists for longer in single occurrences and in total.

This result indicates that when frictions increase and the arbitrage roundtrip takes days instead of hours due to the long clearing time for bank transfers arbitrageurs are restricted in executing enough volume to adjust the mispricing quickly. Consequently, if the speed of bank transfers increases the price difference should reduce in both frequency and length. This result has implications for international financial integration as it indicates that price differences of the same asset traded on multiple exchanges could be reduced if the settlement time decreases and integration between exchanges directly and between exchanges and the banking system increases.

Insert Table 2 here

4 Transaction types under different market frictions

One of the advantages of using the global market for bitcoin is that I can observe all the bitcoin the transactions between exchanges as they have to be recorded on the blockchain. This allows me to compare the variations in the price differences to the variation in the transactions and specifically the arbitrage transactions between the exchanges. This section segments the transactions into types and analyzes how they change as frictions increase.

The transaction volume between exchanges in Figures 2 to 4 will not be exclusively arbitrage volume. There are several reasons why a user would transfer bitcoin between exchanges besides arbitrage. This means that the users' sensitivity to the price differences between the exchanges will vary. It is therefore important to segment the transactions into different types, so I can isolate the arbitrage activity and identify if the transaction activity changes as frictions increase.

I categorize the transactions into three types based on two factors: the price difference when the transaction entered the mempool and the direction of the transaction (e.g. from Huobi to Poloniex). I use the price when the transaction entered the mempool as it shows the price the user reacted to, rather than the price when the transaction arrives at the receiving exchange.[12]

The first transaction type is a *liquidity transaction*. These transactions flow in both directions between exchanges, but only when the price difference is close to zero. For the analysis I include all transactions that occur when the price difference is between $\pm 2\,\%$. These transactions can be motivated by the liquidity needs of the user. For example if a user wants to trade in different cryptocurrencies she can move the bitcoin to an exchange with a wider selection of alternative coins. She is however mindful of the price deviation to minimize the cost of having to move the coins. Alternatively, a liquidity transaction can also be a user using bitcoin to make international transfers as an alternative to using banks and other financial service companies. The user will similarly be sensitive to any price differences between the sending and receiving exchange.[13]

The second type of transaction is *arbitrage transactions*. These transactions occur when the price difference is above (below) some price difference threshold and flow in the direction of the price deviation. For example, if the price of bitcoin is 5% higher on Poloniex than on Huobi, all transactions that flow from Huobi to Poloniex are categorized as arbitrage transactions. The user may not actively be arbitraging but will gain from the price deviation nonetheless.

The third and last type of transaction is *market access transactions*. These transactions occur when price deviations are greater than $\pm 2\,\%$ similarly to arbitrage transactions. However, they flow in the opposite direction of the price deviation (i.e. from the expensive to the cheap exchange). On the surface, these transactions seem uneconomic, but users can have reasons for disregarding the price deviation or be willing to incur this cost to gain market access. For example, during the ICO boom in 2017 users might be in a hurry to invest in newly listed cryptocurrencies. The possible gains from accessing the new cryptocurrencies therefore outweigh the costs of a worse bitcoin exchange rate. Alternatively, a user in a country with capital controls or high transaction costs for international transfers might be willing to get a worse bitcoin exchange rate to move the bitcoin to an exchange with unre-

[12]The mempool data is from 04/22/2014 - 06/24/2018 from blockchain.info. For transactions outside of the time-series, I use the price 6.8 minutes prior to the transaction being verified, which is the median mempool wait time. Using the median wait time is more accurate than using the price at the time the transaction was verified, as that would assume a mempool wait time of zero.

[13]It is important to note that even though I can observe transactions between exchanges, I cannot observe how the bitcoin is then traded on the receiving exchange.

stricted access to traditional banking (Hu et al., 2018). In addition, traders may transfer their bitcoin to different exchanges to obfuscate the ownership of the coins and will therefore be less sensitive to price differences. Foley et al. (2019) find that 46% of bitcoin transactions are involved in illegal activity amounting to $76 billion per year. For example hackers who extort money from individuals using ransomware often request payment in bitcoin (Sokolov, 2018).

4.1 Transaction types change as frictions change

Figure 5 shows the total net transaction volume (outflows minus inflows) in USD by minute (y-axis), the number of transactions (color scale) and the price difference in that minute (x-axis) for all transactions between stablecoin exchanges. As Figure 5 plots the price differences by minute for each exchange-level flow the variation is higher than the average daily price differences in Figure 2. The figure shows that the transaction flow is fairly symmetric around the x-axis except for smaller transactions below $10 which flow mostly in one direction (from Poloniex to Bittrex). Most of the transaction volume is *liquidity transactions*, as shown by the cluster of activity at volumes greater than $10,000 close to the y-axis. These clusters are typically 100+ individual transactions in that minute.

The *arbitrage transactions* are visible in the top right and bottom left quadrant. In these areas the net transaction volume is positive when the price difference is positive and vice versa, indicating that the majority of transactions in that minute flow to the expensive exchange. Interestingly, the transaction volume is similar in size to the *liquidity transactions* at over $10,000, but consist of fewer transactions. This suggests that when the price deviation is small there are many smaller transactions. As the price deviation increases the transactions per minute become fewer but larger, resulting in the same total dollar volume.

The *market access transaction* volume is shown in the top left and bottom right quadrant as the transaction volume flows in the opposite direction of the price difference. The cluster of large transactions in the bottom right quadrant flow primarily from the exchanges HITBTC, Bittrex and Huobi to Poloniex. Poloniex has historically listed many alternative cryptocurrencies which suggests that these transactions might be *market access transactions* to alternative cryptocurrency markets on Poloniex.

Insert Figure 5 here

Similarly to the transaction volume between stablecoin exchanges, the largest transaction volumes and most activity between fiat currency exchanges occur when the price difference is close to zero as shown in Figure 6. This *liquidity transaction* volume ranges in size and clusters at above \$10,000 in both directions. This result indicates that most of the transactions between the fiat exchanges are likely alternatives to international transfers using traditional bank transfers or other financial service providers.

As indicated by the transactions in Figure 3, the *arbitrage transactions* flow primarily in one direction as the price difference is most frequently positive. However, even though the price differences are larger when including individual exchange level flows instead of the average across all exchange-level flows, Figure 6 only show a small cluster of arbitrage transactions. This indicates that arbitrageurs are constrained by the longer duration of the arbitrage round-trip to take advantage of the price differences.

The *market access transaction* volume, which occurs in the opposite direction of the price difference when the price difference is outside of $\pm 2\,\%$, is less pronounced than between stablecoin exchanges. This is to be expected, as the fiat currency exchanges do not trade a wide variety of cryptocurrencies beyond the most popular.

Insert Figure 6 here

Figure 7 confirms that the majority of the transactions between fiat currency exchanges and exchanges with capital controls are *arbitrage transactions* and occur when the price difference is positive. The cluster of transactions in the top right quadrant is therefore more pronounced than the transaction flows between stablecoin or fiat exchanges. The *arbitrage transactions* primarily flow in one direction (from the fiat currency exchange to the exchange in a country with capital controls with higher prices), which is not surprising as the price difference is rarely negative.

Similarly to the stablecoin and fiat exchanges, there is a clear cluster of *liquidity transaction* volume when the price difference is close to zero. These transactions vary in size from less than \$10 to \$100,000 and flow in both directions. The *market access transactions* are clustered in the bottom right quadrant, flowing from the exchange with capital controls to the exchange without capital controls, even when the price difference is positive. These transactions are likely motivated by avoiding the capital controls.

Insert Figure 7 here

Overall the analysis indicates that the transaction activity and the types of transactions that are being sent between exchanges change as the market frictions increase. When frictions are low, as between stablecoin exchanges, transaction volumes are large and users send both *liquidity transactions*, *arbitrage transactions*, and *market access transactions* between exchanges. As frictions increase and users have to exchange fiat currencies for bitcoin the activity is almost exclusively *liquidity transactions* and total the volume being transferred reduces. As the frictions increase further and users have to comply with capital control regulations most of the activity is *arbitrage transactions* or likely *liquidity transactions* to avoid these capital control regulations. These results suggest that not only may the price differences and price difference duration reduce if the market frictions are reduced, but the transaction volumes between exchanges will increase and open up for a wider variety of transaction activity.

5 Transaction volume and arbitrage volume under different frictions

As expected from Figures 2 through 7 the total transaction volume changes as frictions change both in total and daily. The daily transaction volume transferred between stablecoin exchanges is 3.6 million USD on average and 4.1 billion USD in total over the sample period. The majority of this volume is non arbitrage volume which means the transaction enters the mempool when the price deviation is between $\pm 2\,\%$ or the direction of the transaction is against the price deviation (from the expensive to the cheap exchange). This is not surprising as the price deviation duration is short and occurs infrequently and as the exchanges are known for trading many alternative cryptocurrencies which may show up as these uneconomical arbitrage transactions as discussed previously in section 4. The daily transaction volume between fiat exchanges is much lower at 28,000 USD on average and 14 million USD in total. Almost all of the transaction volume (12.7 million USD) occurs when the price difference is between $\pm 2\,\%$. Interestingly, the daily transaction volumes between fiat currency exchanges and exchanges with capital controls is more than three times higher on average at 89,000 USD (95.7 million USD in total) compared to transaction between fiat currency exchanges.

When the prices start to deviate and exceed $\pm 2\,\%$, arbitrageurs on stablecoin exchanges are able to transfer \$835,000 daily on average and \$295 million in total to exploit the mispricing. By contrast, arbitrageurs on fiat currency exchanges only transfer \$9,700 on average daily and \$1.6 million in total when prices are above/below $\pm 2\,\%$. Arbitrageurs between fiat currency and capital control exchanges transfer \$91,000 daily and \$67.2 million in total throughout the sample period. These differences suggest that because the frictions are low between stablecoin exchanges, arbitrageurs can easily transfer bitcoin and exploit any price deviations. However, the price deviations are either not large enough to cover the additional costs of exchanging and transferring fiat currencies or the price differences do not persist for long enough for arbitrageurs to exploit the price deviations between fiat currency exchanges. The results suggest that the opposite is true for arbitrageurs between fiat currency exchanges and capital control exchanges. Even though the costs are higher for arbitrageurs, the price differences are large enough and persist for long enough for arbitrageurs to exploit the price differences.

Insert Table 3 here

5.1 Arbitrage and non-arbitrage transactions

As *arbitrage transactions* have a different sensitivity to price differences than *liquidity transactions* and *market access transactions*, it is likely that the volume and fees are different. This section explores these differences.

Arbitrage transactions are larger in dollar volume than non-arbitrage transactions (liquidity and market access transactions) between stablecoin exchanges (8,900 USD vs 7,500 USD) and between exchanges with and without capital controls (17,300 USD vs. 9,500 USD) on average as shown in Table 3. This difference is intuitive as arbitrageurs have an incentive to transfer larger volumes per transaction to maximize the arbitrage profits before the price deviation is eliminated, while non-arbitrage transactions do not have that incentive. The average transaction size increases as the price difference increases from $\pm 2\,\%$ to $\pm 5\,\%$ and $\pm 10\,\%$. By contrast, as the non-arbitrage activity is higher between fiat currency exchanges compared to arbitrage activity, the transactions when the price difference is between $\pm 2\,\%$ are three times larger (16,000 USD) than transactions when the price difference is outside of $\pm 2\,\%$ (5,4000 USD) on average. The difference is even more striking when comparing the median transaction sizes.

As arbitrageurs have an incentive to transfer bitcoin quickly between the exchanges to exploit price differences, arbitrage transactions are expected to pay higher mining fees to shorten the wait time in the mempool and get faster verification. This is confirmed when comparing the mining fees paid on arbitrage transactions and non-arbitrage transactions between stablecoin exchanges (5.89 USD and 3.48 USD) and between fiat exchange exchanges and exchanges with capital controls (2.50 USD and 0.87 USD). However, when considering the mining fee relative to the dollar volume of the transaction the proportion for arbitrage transactions (0.1 %) is smaller than for non arbitrage transactions (0.43%) between exchanges with and without capital controls. This indicates that as the dollar volume of arbitrage transactions between exchanges with and without capital controls is larger than non arbitrage transactions and as arbitrageurs require faster transactions it makes economic sense to give a higher fee to the miner. As a result the mempool wait time for arbitrage transactions between exchanges with and without capital controls is 18 minutes compared to 31 minutes for non-arbitrage transactions.

To get a more detailed view of the difference in fees and mempool wait time between arbitrage transactions and non-arbitrage transactions I estimate the regression in Eq. (2)

$$\begin{aligned} DependentVariable_{j,t} = \beta_0 + \beta_1 ArbitrageTransaction2 \\ - 5\%_{j,t} + \beta_2 ArbitrageTransaction5 \\ - 10\%_{j,t} + \beta_3 ArbitrageTransaction \\ > 10\%_{j,t} + \beta_4 AbsBitcoinReturn_{j,t} + \epsilon_t \end{aligned} \tag{2}$$

where the dependent variables are $TransactionFee_{j,t}$, which is the transaction fee paid on transaction j at time t in US Dollars, $TransactionFee OverVolume_{j,t}$, which is the transaction fee relative to the volume of the transaction, $MempoolWaitTime_{j,t}$ which is the number of minutes the transaction waited in the memory pool, and $MemoryPoolCongestion_{j,t}$ which is the number of transactions already waiting in the mempool as the transaction enters as used by Foley et al. (2020). The independent variables are dummy variables which equal one if the transaction occurs when the price difference is between 2% and 5%, 5% and 10% and greater than 10%. The control variable $AbsBitcoinReturn_{i,t}$ is the daily absolute bitcoin return. The regression is run for each of the friction categories.

Table 4 shows the coefficient estimates of the dummy variables for each of the regressions and friction categories. The results show that the arbitrage transactions between stablecoin exchanges and between fiat currency exchanges do not pay a higher transaction fee in USD compared to non-arbitrage transactions. Only transactions when the price difference is greater than 5% between fiat exchanges and capital control exchanges pay \$1.6 more than non-arbitrage transactions on average. As arbitrage transactions have a higher dollar volume than non arbitrage transactions between fiat currency exchanges and capital control exchanges, the transaction fee relative to the volume is significantly lower. The higher fee, translates into a lower mempool wait time for arbitrage transactions of 5.9 to 8.4 minutes on average.

While the arbitrage transactions between stablecoin exchanges and between fiat currency exchanges do not pay a significantly higher fee, they occur when the mempool is significantly more congested. When arbitrage transactions between stablecoin exchanges enter the mempool, there are between 8,900 and 42,700 more transactions waiting to be verified relative to when non-arbitrage transactions enter the mempool. For arbitrage transactions between fiat currency exchanges and between fiat currency exchanges and capital control exchanges the mempool has 2,600 to 6,000 and 13,400 to 33,300 more transactions respectively relative to non-arbitrage transactions. This result suggests that larger price differences coincide with higher congestion levels.

Insert Table 4 here

6 Conclusion

This paper identifies how different cross border market frictions (currency conversions, international bank transfers, and capital controls) limit the activities of arbitrageurs and affect the price differences between exchanges. As cryptocurrency exchanges are heterogeneous, I segment the exchanges into three categories with increasing market frictions: stablecoin exchanges, fiat currency exchanges, and exchanges in a country with capital controls.

The results show that for the categories with greater frictions the price differences between exchanges and the duration of these price differences increase. In addition, the overall transaction volume decreases and the types of transactions between exchanges become more specialized as frictions increase. Arbitrage volume in particular decreases when arbitrageurs have to use fiat currencies as quote currency as international bank transfers can take days to clear. The results suggest that increasing the speed of domestic and international bank transfers could lead to smaller price differences that resolve more quickly due to increased trading activity.

This paper makes three major contributions. First, the analysis contributes to the extensive literature on the limits to arbitrage (Shleifer and Vishny, 1997; Gromb and Vayanos, 2010; Mitchell et al., 2002; Lamont and Thaler, 2003) and cross border arbitrage specifically (Rosenthal and Young, 1990; Froot and Dabora, 1999; De Jong et al., 2009; Gagnon and Karolyi, 2010) by showing how the frictions of traditional bank transfers and capital controls limit the activities of arbitrageurs. The paper is able to isolate the effect of different market frictions on the size and duration of arbitrage opportunities as the same asset is traded under different levels of financial integration. This approach remedies the limitation of previous literature which is not able to isolate the effect of financial frictions from the frictions trading in American Depository Receipts and Dual Listed Companies impose such as lack of fungability. The results also suggest why Makarov and Schoar (2020) find that price differences in bitcoin occur between US and European exchanges, as I show that institutions are not able to circumvent the market frictions of trading in fiat currencies.

Second, the results contribute to the practical discussion of how international financial markets can be made more efficient by increasing the level of integration. Specifically, the results suggests that price differences can be reduced if the speed of transactions are increased. One way to achieve this is to have all transactions occur on the blockchain using stablecoins or central bank digital currencies instead of fiat currencies (Hautsch et al., 2020; ECB and BOJ, 2018; BIS, 2017).

References

Alsayed, H. and McGroarty, F. (2012). Arbitrage and the law of one price in the market for american depository receipts. *Journal of International Financial Markets, Institutions and Money*, 22(5):1258–1276.

Aquilina, M., Budish, E. B., and O'Neill, P. (2020). Quantifying the high-frequency trading "arms race": A simple new methodology and estimates. *Chicago Booth Research Paper*, (20-16).

BIS (2017). Distributed ledger technology in payment, clearing and settlement: An analytical framework. *Bank of International Settlement*.

Boar, C., Holden, H., and Wadsworth, A. (2020). Impending arrival–a sequel to the survey on central bank digital currency. *BIS Paper*, (107).

Budish, E., Cramton, P., and Shim, J. (2015). The high-frequency trading arms race: Frequent batch auctions as a market design response. *The Quarterly Journal of Economics*, 130(4):1547–1621.

Cornell, B. and Shapiro, A. C. (1989). The mispricing of us treasury bonds: A case study. *The Review of financial studies*, 2(3):297–310.

De Jong, A., Rosenthal, L., and Van Dijk, M. A. (2009). The risk and return of arbitrage in dual-listed companies. *Review of Finance*, 13(3):495–520.

Dyhrberg, A. H., Foley, S., and Svec, J. (2018). How investible is bitcoin? analyzing the liquidity and transaction costs of bitcoin markets. *Economics Letters*, 171:140–143.

Dyhrberg, A. H., Foley, S., and Svec, J. (2019). When bigger is better: The impact of a tiny tick size on undercutting behavior. *Working Paper*.

Easley, D., O'Hara, M., and Basu, S. (2019). From mining to markets: The evolution of bitcoin transaction fees. *Journal of Financial Economics*, 134(1):91–109.

ECB and BOJ (2018). Securities settlement systems: Delivery-versus-payment in a distributed ledger environment. *STELLA - a joint research project of the European Central Bank and the Bank of Japan.*

Fernández, A., Klein, M. W., Rebucci, A., Schindler, M., and Uribe, M. (2016). Capital control measures: A new dataset. *IMF Economic Review*, 64(3):548–574.

Foley, S., Hinzen, F. J., John, K., and Saleh, F. (2020). Why you don't buy coffee with bitcoin: The micropayments myth. *Working paper*.

Foley, S., Karlsen, J. R., and Putniņš, T. J. (2019). Sex, drugs, and bitcoin: How much illegal activity is financed through cryptocurrencies? *The Review of Financial Studies*, 32(5):1798–1853.

Froot, K. A. and Dabora, E. M. (1999). How are stock prices affected by the location of trade? *Journal of financial economics*, 53(2):189–216.

Gagnon, L. and Karolyi, G. A. (2010). Multi-market trading and arbitrage. *Journal of Financial Economics*, 97(1):53–80.

Griffin, J. M. and Shams, A. (2020). Is bitcoin really untethered? *The Journal of Finance*, 75(4):1913–1964.

Gromb, D. and Vayanos, D. (2010). Limits of Arbitrage. *Annual Review of Financial Economics*.

Hautsch, N., Scheuch, C., and Voigt, S. (2020). Building trust takes time: Limits to arbitrage in blockchain-based markets. *Working Paper*.

Howell, S. T., Niessner, M., and Yermack, D. (2019). Initial Coin Offerings: Financing Growth with Cryptocurrency Token Sales. *The Review of Financial Studies*, 33(9):3925–3974.

Hu, M. R., Lee, A. D., and Putniņš, T. J. (2018). Capital flight: Evidence from the bitcoin blockchain. *STELLA - a joint research project of the European Central Bank and the Bank of Japan.*

Huberman, G., Leshno, J., and Moallemi, C. C. (2019). An economic analysis of the bitcoin payment system. *Columbia Business School Research Paper*, (17-92).

Jarrow, R. A. and O'Hara, M. (1989). Primes and scores: An essay on market imperfections. *The Journal of Finance*, 44(5):1263–1287.

Kryzanowski, L. and Zhang, H. (2002). Intraday market price integration for shares cross-listed internationally. *Journal of Financial and Quantitative Analysis*, pages 243–269.

Lamont, O. A. and Thaler, R. H. (2003). Can the market add and subtract? mispricing in tech stock carve-outs. *Journal of Political Economy*, 111(2):227–268.

Liu, J. and Longstaff, F. A. (2004). Losing money on arbitrage: Optimal dynamic portfolio choice in markets with arbitrage opportunities. *The Review of Financial Studies*, 17(3):611–641.

Ljungqvist, A. and Qian, W. (2016). How constraining are limits to arbitrage? *The Review of Financial Studies*, 29(8):1975–2028.

Lok, E. and Kalev, P. S. (2006). The intraday price behaviour of australian and new zealand cross-listed stocks. *International Review of Financial Analysis*, 15(4-5):377–397.

Longstaff, F. A. (1992). Are negative option prices possible? the callable us treasury-bond puzzle. *Journal of Business*, pages 571–592.

Lu, K. (2020). Coin metrics' state of the network: Issue 53. *Coinmetrics*.

Makarov, I. and Schoar, A. (2020). Trading and arbitrage in cryptocurrency markets. *Journal of Financial Economics*, 135(2):293–319.

Mitchell, M., Pulvino, T., and Stafford, E. (2002). Limited arbitrage in equity markets. *The Journal of Finance*, 57(2):551–584.

Nakamoto, S. (2009). Bitcoin: A peer-to-peer electronic cash system.

Ofek, E., Richardson, M., and Whitelaw, R. F. (2004). Limited arbitrage and short sales restrictions: Evidence from the options markets. *Journal of Financial Economics*, 74(2):305–342.

Rosenthal, L. and Young, C. (1990). The seemingly anomalous price behavior of royal dutch/shell and unilever nv/plc. *Journal of Financial Economics*, 26(1):123–141.

Shkilko, A. and Sokolov, K. (2020). Every cloud has a silver lining: Fast trading, microwave connectivity and trading costs. *Working paper*.

Shleifer, A. and Vishny, R. W. (1997). The limits of arbitrage. *The Journal of finance*, 52(1):35–55.

Sokolov, K. (2018). Ransomware activity and blockchain congestion. *Available at SSRN 3175986*.

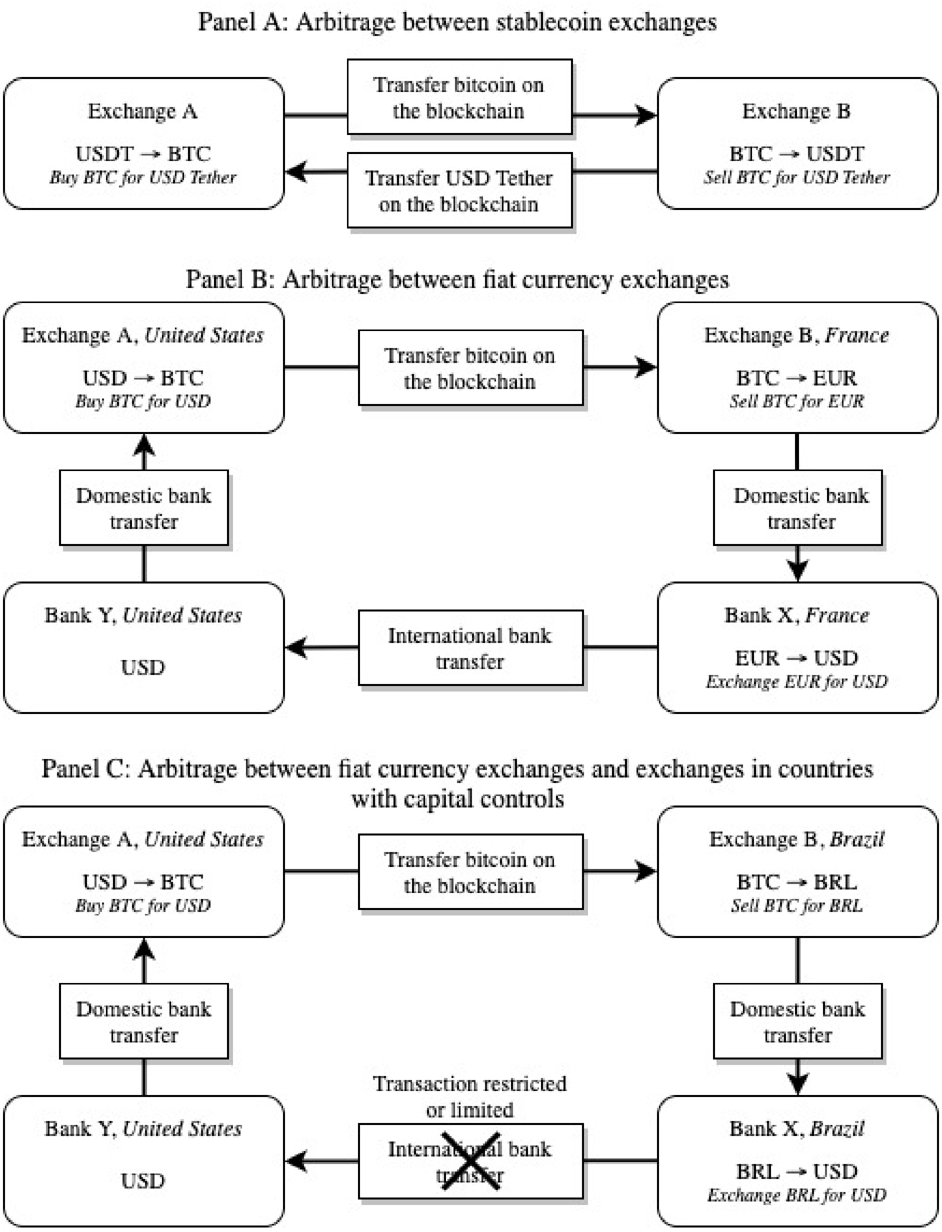

Figure 1: Frictions to arbitrage in bitcoin

The figure shows examples of the steps involved in carrying out arbitrage using bitcoin. Panel A shows the arbitrage round-trip with the fewest frictions; when the quote currency is a stablecoin. Panel B shows the additional steps necessary for the arbitrageur to complete a round-trip. Panel C shows the arbitrage round-trip with the highest level of frictions. In this situation one of the exchanges operate in a country with capital control regulation which restricts the international banking transfer back to the originating exchange.

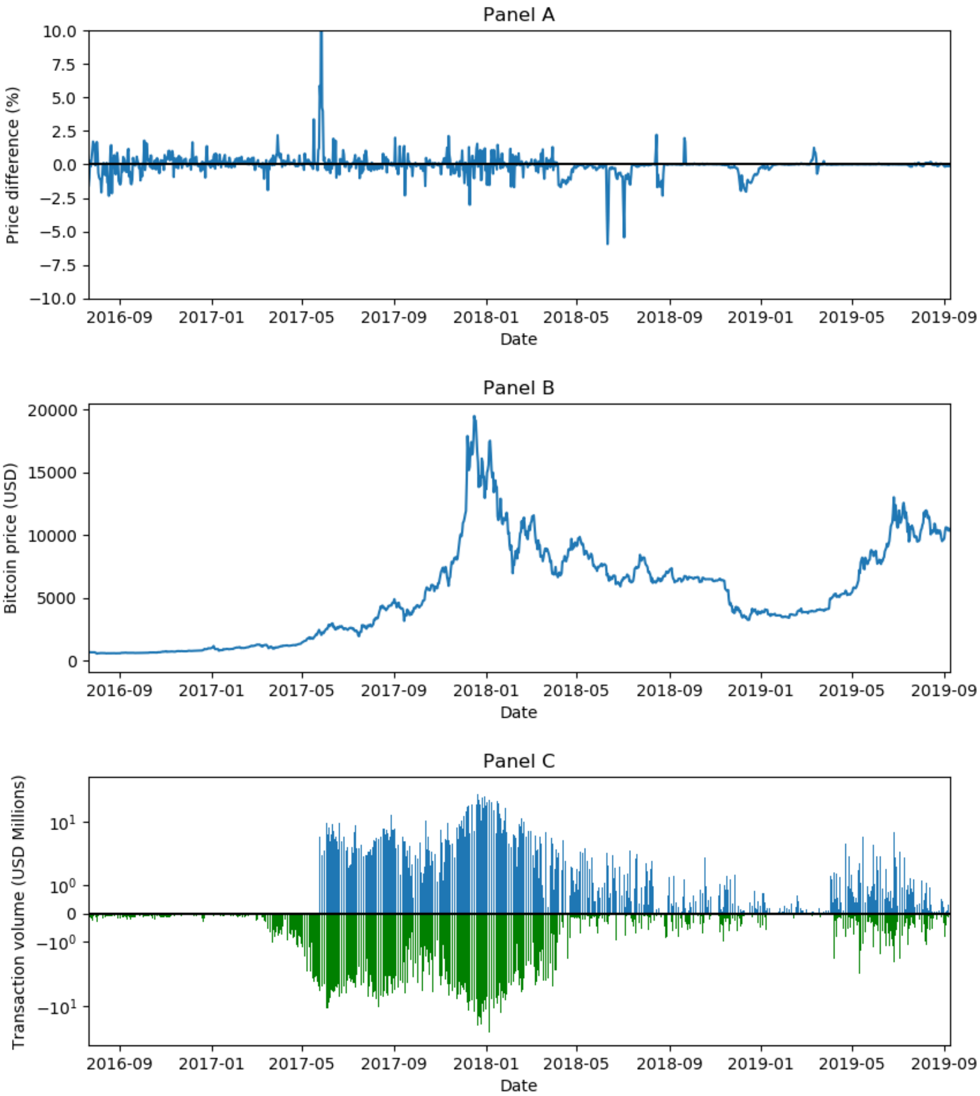

Figure 2: Average daily price difference and transaction flows between exchanges trading only stablecoins

Panel A of the figure shows the average daily price difference between exchanges trading only cryptocurrencies and stablecoins between 22 July 2016 and 8 September 2019. The price difference is calculated daily for each exchange flow (e.g. Bittrex to HITBTC) and then averaged across the exchange flows in this category. Panel B shows the daily closing price of bitcoin from Coinmarketcap.com over the same time period. Panel C shows the transaction flows between the exchanges from 22 July 2016 to 8 September 2019. As the transaction flows are bidirectional, the sign of the transaction indicates the direction in which it flows. The y-axis is logarithmic.

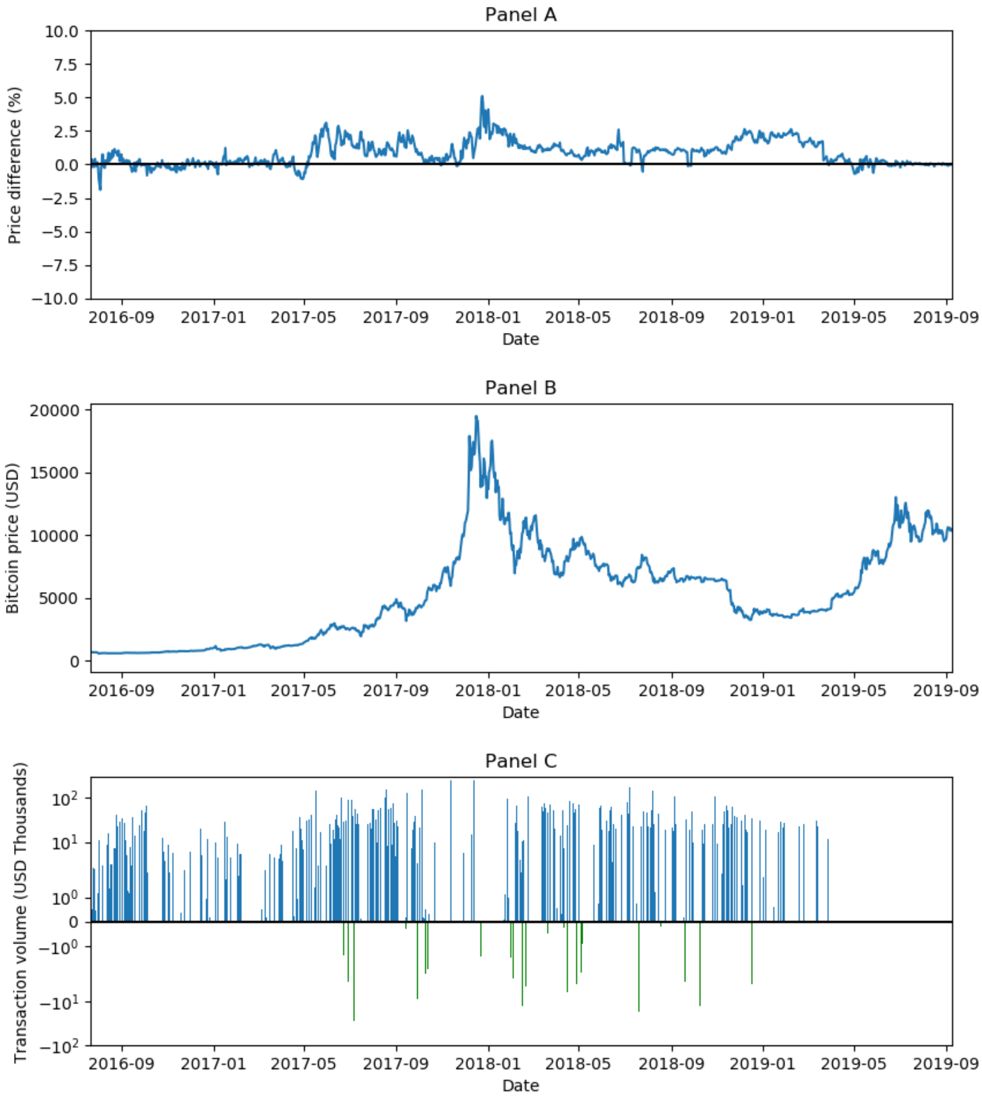

Figure 3: Average daily price difference and transaction flows between exchanges trading cryptocurrency for fiat currency only

Panel A of the figure shows the average daily price difference between exchanges trading only cryptocurrencies and fiat currencies between 22 July 2016 and 8 September 2019. The price difference is calculated daily for each exchange flow (e.g. Bitstamp to Bitfinex) and then averaged across the exchange flows in this category. Panel B shows the daily closing price of bitcoin from Coinmarketcap.com over the same time period. Panel C shows the transaction flows between the exchanges from 22 July 2016 to 29 March 2019. As the transaction flows are bidirectional. The sign of the transaction volume indicates the direction in which it flows.

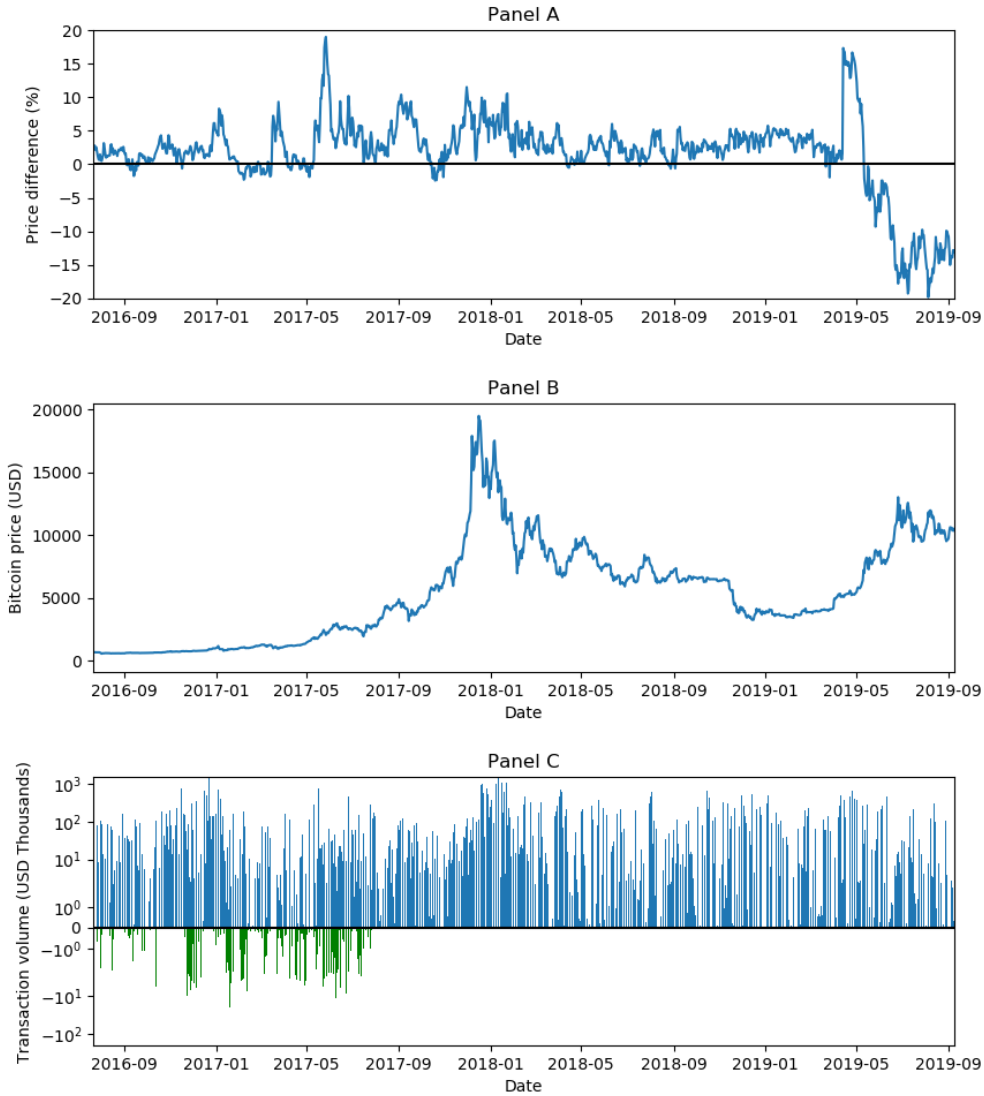

Figure 4: Average daily price difference and transaction flows between exchanges without capital controls and those with

Panel A of the figure shows the average daily price difference between exchanges which trade in fiat currency which is not subject to capital control regulation and those exchanges that trade in fiat which is subject to capital controls between 22 July 2016 and 8 September 2019. The exchanges which trade in fiat which is subject to capital controls is MercadoBitcoin (Brazil), OkCoin (China) and Yobit (Russia). OkCoin stopped exchanging CNY for cryptocurrency in October 2017 after the Chinese government made such trading illegal. For this analysis I only include transactions and prices for OkCoin prior to the ban. The price difference is calculated daily for each exchange flow (e.g. Bitfinex to MercadoBitcoin) and then averaged across the exchange flows in this category. Panel B shows the daily closing price of bitcoin from Coinmarketcap.com over the same time period. Panel C shows the transaction flows between the exchanges from 22 July 2016 to 8 September 2019. As the transaction flows are bidirectional, the sign of the transaction indicates the direction in which it flows.

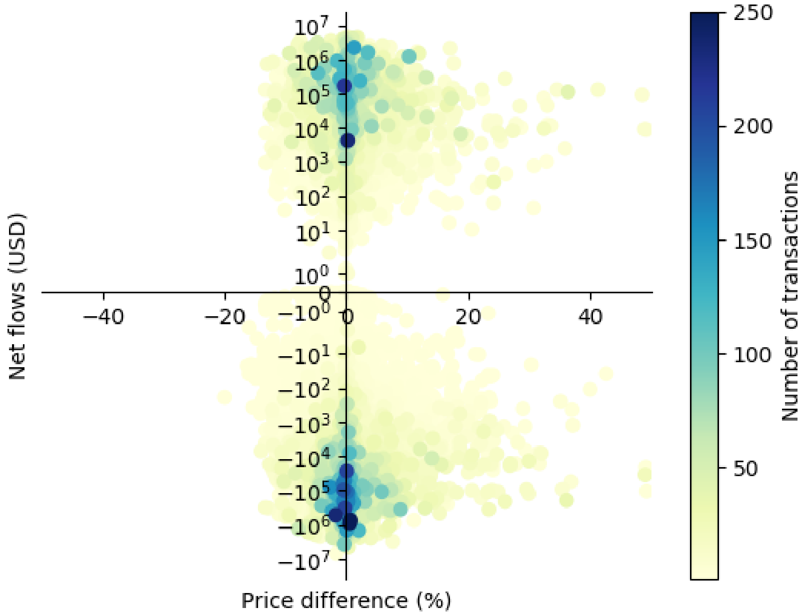

Figure 5: Net transaction flow and price difference for exchanges trading only stablecoins

The figure shows the total net transaction flow by minute on the y-axis and the price difference in that minute on the x-axis. The y-axis is symmetrically logarithmic. Each circle represents a minute and the color gradient shows the number of transactions in that minute. The figure includes all transactions from 23 February 2015 to 8 September 2019 between the exchanges Bittrex, HITBTC, Huobi and Poloniex.

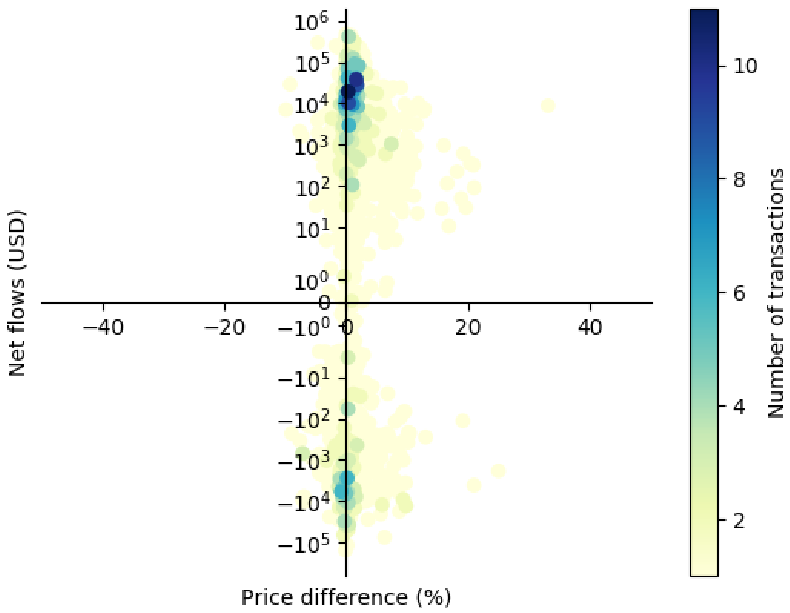

Figure 6: Net transaction flow and price difference between exchanges trading cryptocurrency for fiat currency only

The figure shows the total net transaction flow by minute on the y-axis and the price difference in that minute on the x-axis. The y-axis is symmetrically logarithmic. Each circle represents a minute and the color gradient shows the number of transactions in that minute. The figure includes all transactions from 18 May 2014 to 29 March 2019 between exchanges that only exchange cryptocurrencies for fiat currencies and not stablecoins specifically Bitbay, Bitfinex, Bitstamp, CEX, Kraken, LakeBTC and TheRockTrading.

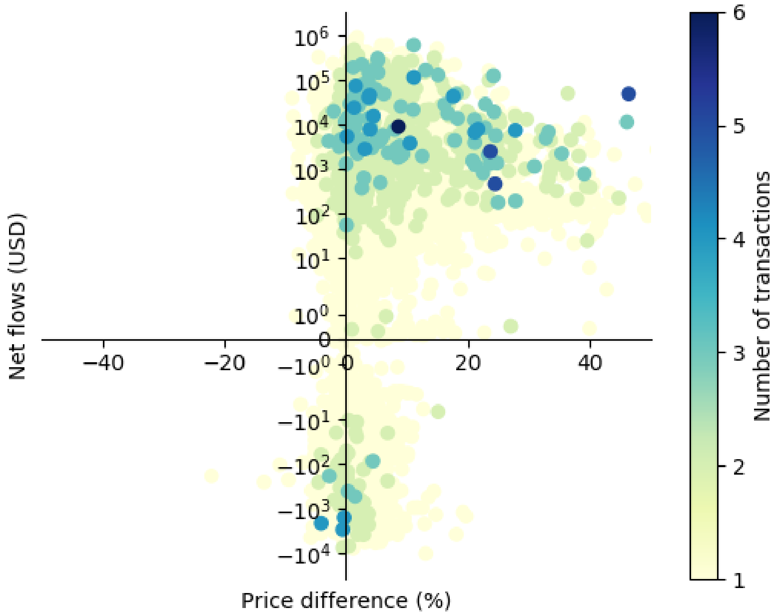

Figure 7: Net transaction flow and price difference between exchanges trading in fiat without capital controls and exchanges trading in fiat with capital controls

The figure shows the total net transaction flow by minute on the y-axis and the price difference in that minute on the x-axis. The y-axis is symmetrically logarithmic. Each circle represents a minute and the color gradient shows the number of transactions in that minute. The figure includes all transactions from 27 November 2013 to 8 September 2019 from exchanges that trade in fiat currency which is not subject to capital controls to exchanges that trade in fiat currency which are subject to capital controls. A positive price difference indicates that the exchanges trading in fiat currency which is subject to capital controls is more expensive. Positive net flows shows transactions going into the exchanges trading in fiat which is subject to capital controls. The exchanges which trade in fiat which is subject to capital controls is MercadoBitcoin (Brazil), OkCoin (China) and Yobit (Russia). OkCoin stopped exchanging CNY for cryptocurrency in October 2017 after the Chinese government made such trading illegal. For this analysis I only include transactions and prices for OkCoin prior to the ban.

Table 1: Price differences with different frictions

This table shows the regression results of $PriceDifference_{i,t} = \alpha_m + \beta_1 FiatExchange_{i,t} + \beta_2 CapitalControlExchange_{i,t} + \beta_3 AbsBitcoinReturn_{i,t} + \beta_4 IntradayVolatility_{i,t} + \epsilon_t$ where α_m is month year fixed effects. $PriceDifference_{i,t}$ is the price difference in percent between exchange-level flow i at minute t. $FiatExchange_{i,t}$ is a dummy variable which equals one for the exchange-level flows which are in the fiat exchange category. $CapitalControlExchange_{i,t}$ is a dummy variable which equals one if the exchange-level flow is between a fiat exchange and an exchange with capital controls and zero otherwise. $AbsBitcoinReturn_{i,t}$ is the daily absolute bitcoin return. The bitcoin price used for the return variable is the Kraken BTC-USD. $IntradayVolatility_{i,t}$ is the average intraday volatility of the two exchanges in exchange flow i. Model (1) is the baseline model with all available data. Model (2) uses the time series before Jan 1 2018, where Model (3) uses the time series after. Model (4) and (5) segments the time series into periods with below (low congestion) and above (high congestion) median blockchain congestion levels. The congestion level is the number of transactions in the mempool waiting to be verified. The standard errors are clustered on date. ***, ** and * indicate the statistical significance at the 1%, 5% and 10% levels, respectively.

	(1) All data	(2) Pre 2018	(3) Post 2018	(4) Low congestion	(5) High congestion
Between fiat exchanges	2.475***	1.673***	3.153***	2.203***	2.242***
	(0.240)	(0.236)	(0.323)	(0.196)	(0.416)
To capital control exchanges	5.352***	6.841***	2.389***	3.523***	9.158***
	(0.400)	(0.561)	(0.116)	(0.286)	(0.890)
Abs bitcoin return	0.243	0.233	4.584**	-0.706	2.021
	(2.297)	(2.877)	(2.141)	(2.382)	(3.676)
Intraday volatility	18.887***	20.456***	5.744***	10.364***	22.066***
	(5.141)	(5.582)	(1.762)	(2.072)	(6.668)
Month year fixed effects	Yes	Yes	Yes	Yes	Yes
Adjusted R-squared	0.256	0.279	0.145	0.186	0.295
Observations	552,802	468,770	84,032	276,344	276,458

Table 2: Price difference duration

The table shows statistics on the price difference duration of the exchange categories between July 22 2016 and September 8 2019. All metrics are averaged across the exchange-level flows in the categories. The variables are: the maximum number of consecutive days, the total number of days and the frequency with which the price difference is outside a specific percentage threshold ±2 %, ±5 %, ±10 %, ±20 %.

	Maximum consecutive days			Total days			Frequency		
	Stablecoin	Fiat currency	Capital control	Stablecoin	Fiat currency	Capital control	Stablecoin	Fiat currency	Capital control
Outside ±2 %	8	123	542	371	3,261	5,501	16,168	205,302	199,616
Outsude ±5 %	6	81	53	71	1,351	2,281	3,133	69,920	86,140
Outside ±10 %	2	14	49	21	271	840	754	43,353	24,403
Outside ±20 %	0	1	23	4	11	240	180	1,828	4,169

Table 3: Summary statistics of blockchain transaction volume, mining fees and mempool wait time

The table shows summary statistics of the exchange categories between July 22 2016 and September 8 2019. All metrics are averaged across the exchange-level flows in the categories. Daily transaction volume measures the average daily transactions between the exchanges in the category in USD thousands. Daily non-arbitrage volume measures the daily volume between the exchanges which occurs when the price difference is within ±2 % or in the opposite direction of the price difference (e.g. from the expensive to the cheap exchange). Daily arbitrage volume is the average daily transaction volume between exchanges that occur when the price difference is above or below a percentage threshold and the transaction flows with the price difference (e.g. from the cheap to the expensive exchange). The per transaction statistics measures the average size of a non-arbitrage and arbitrage transaction. The mining fee is the voluntary fee the user pays the miner to verify the transaction include it in a block. The mining fee is calculated in USD and relative to the volume of the transaction. The mempool wait time is the number of minutes the transaction waits in the mempool before being verified and included in a block.

	Between stablecoin exchanges				Between fiat currency exchanges				To exchanges with capital controls			
	Min	Median	Mean	Max	Min	Median	Mean	Max	Min	Median	Mean	Max
Daily volume ('000 USD)	7E-01	878.25	3,660.94	55,115.76	3E-04	16.30	28.24	337.65	7E-05	16.02	89.31	2,792.65
Daily non-arbitrage volume ('000 USD)	7E-01	870.69	3,402.46	51,586.68	3E-03	18.04	29.29	337.65	7E-05	4.66	36.49	1,949.09
Daily arbitrage volume ('000 USD)												
Price difference above 2%	6E-03	165.12	835.47	9,928.75	3E-04	1.58	9.73	153.12	6E-04	11.51	91.23	1,508.10
Price difference above 5%	5E-03	184.28	763.20	6,339.85	5E-03	0.84	4.41	37.19	7E-04	10.09	90.31	1,500.04
Price difference above 10%	7E-02	141.85	584.20	4,541.95	1E-02	0.37	2.79	27.68	1E-04	12.80	69.98	1,013.95
Price difference above 20%	3E+00	137.30	495.80	1,466.06	4E-01	0.41	0.41	0.41	6E-02	17.71	30.86	247.46
Non-arbitrage volume per transaction(USD)	0.04	602.83	7,582.70	6,978,707.54	0.85	9,414.78	16,084.93	337,638.79	0.03	475.41	9,545.30	885,853.51
Arbitrage volume per transaction (USD)												
Price difference above 2%	0.06	630.36	8,954.68	2,279,627.07	0.29	988.81	5,406.17	91,931.92	0.07	1,019.72	17,293.16	780,719.23
Price difference above 5%	0.24	776.86	11,245.50	2,279,627.07	0.50	647.65	2,596.73	28,621.00	0.14	987.98	14,727.61	599,665.07
Price difference above 10%	0.30	577.56	10,072.38	2,122,792.81	10.69	346.83	1,801.79	9,944.96	0.14	818.09	9,216.09	595,628.81
Price difference above 20%	3.58	463.20	8,039.94	1,354,371.00	90.67	206.79	206.79	322.91	0.25	385.53	2,612.04	101,635.51
Mining fees on non-arbitrage volume (USD)	0.00	0.04	3.48	6,432.12	0.00	0.16	1.33	83.47	0.00	0.12	0.87	347.71
Mining fees relative to non-arbitrage volume (%)	0.00	0.01	0.05	10.00	0.00	0.00	0.03	4.04	0.00	0.01	0.43	30.81
Mining fees on arbitrage volume (USD)	0.00	0.06	5.89	4,820.08	0.00	0.04	0.62	23.66	0.00	0.09	2.50	548.34
Mining fees relative to arbitrage volume (%)	0.00	0.01	0.06	9.30	0.00	0.00	0.02	0.78	0.00	0.01	0.10	13.60
Mempool wait time of non-arbitrage volume (minutes)	0.00	5.40	8.67	1,296.15	0.00	7.78	25.90	2,978.80	0.00	7.20	30.87	2,800.72
Mempool wait time of arbitrage volume (minutes)	0.00	5.72	8.79	590.73	0.00	7.70	19.05	617.93	0.00	6.13	17.74	5,182.07

Table 4: Characteristics of arbitrage transactions

The table shows the regression estimates of the regression $DependentVariable_{j,t} = \beta_0 + \beta_1 ArbitrageTransaction2-5\%_{j,t} + \beta_2 ArbitrageTransaction5-10\%_{j,t} + \beta_3 ArbitrageTransaction > 10\%_{j,t} + \beta_4 AbsBitcoinReturn_{j,t} + \epsilon_t$. The dependent variable in Model (1) $TransactionFee_{j,t}$ is the transaction fee paid on transaction j at time t in US Dollars. The dependent variable in Model (2) $TransactionFeeOverBytes_{j,t}$ is the transaction fee relative to the size of the transaction in bytes. The dependent variable in Model (3) $MempoolWaitTime_{j,t}$ is the number of minutes the transaction waited in the memory pool The dependent variable in Model (4) $MemoryPoolCongestion_{j,t}$ is the number of transactions already waiting in the mempool as the transaction enters as used by Foley et al. (2020). The standard errors are clustered on date. ***, ** and * indicate the statistical significance at the 1%, 5% and 10% levels, respectively.

	(1) Transaction Fee	(2) Transaction fee over volume	(3) Mempool wait time	(4) Mempool congestion level
Panel A: Stablecoin exchanges				
Arbitrage transaction 2-5% price difference	0.981	0.002	0.262	8949.033**
Arbitrage transaction 5-10% price difference	1.35	0.01	-0.507	24595.963**
Arbitrage transaction +10% price difference	0.266	0.01	0.295	42665.743***
Panel B: Fiat currency exchanges				
Arbitrage transaction 2-5% price difference	0.172	0.006	-1.012	2660.291**
Arbitrage transaction 5-10% price difference	-0.043	-0.002	3.257	6036.102***
Arbitrage transaction +10% price difference	0.311	-0.002	3.57	610.859
Panel C: Capital control exchanges				
Arbitrage transaction 2-5% price difference	-0.089	-0.144***	-5.883**	1630.523
Arbitrage transaction 5-10% price difference	1.565***	-0.255***	-6.143**	13486.304***
Arbitrage transaction +10% price difference	1.606**	-0.276***	-8.423***	33309.172***