

Trends, Tips, Tolls: A Longitudinal Study of Bitcoin Transaction Fees

Malte Möser¹ and Rainer Böhme²(✉)

¹ Department of Information Systems, University of Münster, Münster, Germany
`malte.moeser@uni-muenster.de`

² Institute of Computer Science, University of Innsbruck, Innsbruck, Austria
`rainer.boehme@uibk.ac.at`

Abstract. The Bitcoin protocol supports optional direct payments from transaction partners to miners. These “fees” are supposed to substitute miners’ minting rewards in the long run. Acknowledging their role for the stability of the system, the right level of transaction fees is a hot topic of normative debates. This paper contributes empirical evidence from a historical analysis of agents’ revealed behavior concerning their payment of transaction fees. We identify several regime shifts, which can be largely explained by changes in the default client software or actions of big intermediaries in the ecosystem. Overall, it seems that rules dominate ratio, a state that is sustainable only if fees remain negligible.

1 Introduction

Bitcoin is a protocol claimed to enable a decentralized cryptographic currency [25]. The amount of bitcoin “in circulation”, that is the book value managed in a distributed transaction ledger, is worth about 4–5 billion USD, converted at current market prices [7]. A selling proposition of Bitcoin is that it enables cheap online payments independent of the geographical location of the transaction partners. Therefore, Bitcoin directly competes with established payment systems on the Internet, such as credit cards or PayPal.

Factors influencing the adoption of innovative payment systems are primarily risks and costs [3, 21]. While there is already some work on technical and financial risks of using Bitcoin (e.g., [1, 9, 19, 22–24]), the actual costs of the system are not extensively studied yet. Edelman [13] and Böhme et al. [9] note that, disregarding intangible factors of (in)convenience, Bitcoin may not be as cheap for consumers as it appears. The authors argue that most purchases settled in bitcoin require costly conversions from and to conventional currencies, and consumers forgo kickbacks offered by many credit cards. On top of that, Bitcoin users are encouraged to pay fees to miners, up to 10 cents (of USD) per transaction, irrespective of the amount paid. This is in the same order of magnitude as recently imposed caps on interchange fees for conventional card-based payment systems [12].

Transaction fees are designed to gradually replace the minting revenue as a compensation to miners for contributing to the distributed consensus mechanism that maintains the (probabilistic) consistency of the global system state.

The long-term level of fees is uncertain, yet the question is highly relevant given its connection to the security and sustainability of the system as a whole. Several authors speculate that high fees will render Bitcoin uneconomical for micro payments [14, 20, 29]. Other plausible scenarios include vast variations in fees paid depending on users' time preferences, a low-fee equilibrium with altruistic action to keep the system alive for niche demands [17], or a combination of both with a system of off-blockchain compensation arrangements. Predicting the future regime is hard because it depends not only on properties of the protocol, but also on agent behavior and resulting path dependencies in the Bitcoin ecosystem.

To explore the space of possible future developments, we conduct a longitudinal study of past conventions by analyzing the transaction fees paid with all 55.5 million transactions recorded in the public block chain from the inception of Bitcoin until the end of December 2014. To the best of our knowledge, this first systematic account reveals several regime shifts concerning the payment of transaction fees in Bitcoin's short history. We try to explain these shifts and extract evidence that allows us to test several hypotheses that belong to the conventional wisdom of the Bitcoin community, including:

1. Do higher transaction fees lead to faster confirmation? (yes)
2. Do impatient users offer higher fees? (yes)
3. Do mining pools systematically enforce strictly positive fees? (rather not)

The rest of this paper is structured as follows. Section 2 recalls important properties of Bitcoin with regard to transaction fees. Section 3 documents how we collect and analyze data from the Bitcoin block chain and external sources. Section 4 presents our findings. We discuss limitations and design options for optimal fees in Sect. 5, and conclude in Sect. 6.

2 Background and Research Questions

We refrain from explaining Bitcoin and its terminology in detail and refer the reader to existing high-level [2, 9] or technical [25] descriptions.

Bitcoin's security builds on the block chain, a distributed data structure that allows everyone to look up account balances and to verify unspent transactions.¹ Arguably, the block chain can be seen as a public good, defined by the properties non-excludability and non-rivalry. Exclusion is hard because everyone can anonymously connect to a number of peers and download the block chain. Non-rivalry follows from the block chain being an information good that does not wear out from being shared.

The demand of public goods is characterized by concurrent consumption of all members of a community. This raises issues about the incentives to supply a public good, in particular if the provision incurs costs that cannot be socialized to all members of the community [15]. This is exactly the case in Bitcoin. Miners

¹ More precisely: to verify that all inputs of a transaction one is about to receive reference to so far unspent outputs of past transactions.

unilaterally bear the cost of solving the proof-of-work puzzle,² but all potential transaction partners benefit from the consistency and security of the block chain.

A critical success factor behind Bitcoin's adoption was the reward mechanism that couples, albeit loosely [16], the provision of the public good with newly minted units of currency [8]: 25 BTC per block in 2014. However, this reward mechanism is incompatible with an upper limit of money supply, another stated design goal of Bitcoin. Therefore, the protocol prescribes a transition from minting rewards to transaction fees offered by the sender of a transaction to the miners. By definition, the fee is encoded as difference between the sum of all inputs and the sum of all outputs of a transaction. Miners are free to accept the offer by including the transaction in the block chain, or to ignore it. This creates a market mechanism to find the price of Bitcoin transactions.

In *theory*, perfectly competitive miners will include transactions as long as the fee exceeds the marginal cost of inclusion. Production costs are fixed per block (but may vary between miners depending on access to technology and energy/cooling) and the protocol defines a maximum block size (1 megabyte at the time of writing). As a result, the marginal cost of inclusion is zero if there are fewer unconfirmed transactions than capacity in the block, and it is determined by the opportunity cost of foregone fees from competing transactions as soon as the capacity is reached. Competitive miners make positive expected profits only if transactions compete for space in the block chain. Hence, Houy [17] argues that a maximum block size is necessary for the stability of Bitcoin. However, dominant mining pools or cartels may extract excess profits from reduced competition.

If space in the block chain is scarce and the transaction partners' benefit does not emerge from merely looking up information in the block chain, but depends on the ability to *permanently include* data, then space in the block chain changes its characteristic from a public to something close to a private good. Rivalry comes with the space constraint and excludability with the miners' discretion to exclude unprofitable transactions. However, what remains is that space in the block chain generates substantial externalities: positive ones for parties who benefit from the information and negative externalities for parties who store redundant copies of the block chain in a distributed network.

In *practice*, historical transaction fees in Bitcoin were so small that senders and miners did not care a lot. Many users kept the default value for the transaction fee that is hard-coded in the client software, thereby following a sort of social norm, like for tipping, rather than economic calculus [26]. Likewise, miners followed hard-coded rules [6] to include zero-fee transactions even against their own best interest. Over time, the hard-coded defaults have been changed several times, allegedly to discourage tiny payments (by adding complicated calculation rules) and to offset the rising exchange rate. The latter, in particular, puts consumers' interest over miners', who had to struggle with even steeper increases of the proof-of-work difficulty. A group of programmers went even further and created a fork of the client software that does not offer fees at all [27].

² We suggest that a probabilistic *summation* function, in Hirshleifer's terminology [15], is a reasonable approximation in the short run.

This leads us to the first (open-ended) research question (RQ):

Research Question 1. *How did transaction fees develop and change over time?*

If the client software leaves the users freedom to choose the amount of the transaction fees, then users may follow conventional wisdom about how miners react upon being “tipped” or not.³

Research Question 2. *Do higher fees offered to miners reduce the time until a transaction is first confirmed?*

If RQ 2 is supported with evidence, then it would be rational for users to adjust fees to their time preference.

Research Question 3. *Do impatient users offer higher fees?*

The last research question tests the rationality of the miners, who have no incentive in general to confirm zero-fee transactions. We concentrate on the major mining pools to identify potential differences in their behavior.

Research Question 4. *Do any major mining pools systematically exclude zero-fee transactions?*

In summary, while many are talking about the importance of transaction fees, we are not aware of a comprehensive overview of how fees have changed in the past and why users might decide to deviate from the default. We set out to close this gap with the available data.

3 Data and Method

To study trends of Bitcoin transaction fee conventions over the past couple of years, we combine data from four sources (cf. Table 1). First, we load the block chain by parsing the block files of the Bitcoin Core reference client and extract information on the size of blocks and transactions. To analyze transaction fees as a function of the relation between transactions in the transaction graph, we import all relevant transaction information into an instance of the Neo4j graph database, from which we then extract output amounts, transaction fees, and the duration (based on the blocks’ time stamps) until the first output was reused. We also estimate the net amount of bitcoin transferred, that is total outputs minus estimated change, based on a set of heuristics.

Some analyses require additional data gathered from the website [blockchain.info](#). We use this source to identify the mining pool (if any) that solved a given

³ The default client implements soft rules reflecting part of this wisdom. But uncertainty remains as users cannot anticipate enforcement of these rules. Unlike hard rules (for instance, the requirement to verify signatures), soft rules do not decide the validity of a block. Moreover, miners organized in pools are less likely to heed the defaults than individuals who use the standard client to manage their own transactions.

block and to obtain the time stamps for when a transaction was first seen on the network. This information is not included in the block chain.

Data on the bitcoin exchange rate is taken from coindesk.com, which provides an average bitcoin price in USD. This price index is based on the exchange rates of multiple global exchanges since July 2013, and on the exchange rate of the former exchange Mt. Gox for the time before [11].

Table 1. Data sources and information gathered

Source	Entity	Information
Block files	Block	Height, time stamp, #transactions, size
	Transaction	#inputs, #outputs, size
Graph database	Transaction	Output volume, fee, unused period, net amount, heuristics
Blockchain.info	Block	Relayed by (mining pool)
	Transaction	Time first seen, time included in block
Coindesk.com	Price	USD value

We select the time range from January 2011 to December 2014 for our analysis. Although the Bitcoin block chain exists since 2009, the popularity of the system was low in the first years and interpreting this early data would not be very instructive to understand agent behavior.

In our longitudinal plots, each data point visualizes aggregated data of 1008 blocks, i.e., about one week. The time axis is defined in these epochs of block time with calendar dates added for readability, always using the closest time stamp in the block chain. The constant 1008 was chosen to divide the fixed interval of 2016 blocks of the difficulty control loop that adjusts the proof-of-work requirements. As a result, each pair of consecutive epochs represents blocks mined with the same difficulty. When appropriate, we plot a fitted smoothing spline (with six degrees of freedom) besides the raw data.

To answer RQ 2, we compare the time when a transaction was first seen on the network and the time stamp of the block that includes the transaction. We call the difference transaction latency. Both clocks are not necessarily in sync, but it is reasonable to assume that clock differences are not correlated with our dependent variable. The time when a transaction was first seen on the network has to be extracted by crawling and parsing the blockchain.info website. To limit the amount of requests, we analyze a representative subset of 9,000 transactions randomly chosen from all eligible transaction between June 2012 and May 2013, a period in which the conventions of fee offers remained relatively stable (see Fig. 3 below). Eligible transactions are defined as transactions that offer a fee of 0, 0.0005, or 0.001 BTC and have a size between 200 and 300 bytes. 60.6% or, in absolute terms, 9.17 of all 15.1 million transactions in the chosen time range are eligible by these criteria. Limiting our analysis to this homogenous subset removes the need to control for the influence of third variables.

For better comparability, we use the same subset of 9.17 million transactions to answer RQ 3. For each transaction, we compute the holding time, which is the period until one of the outputs was spent again. The computation of this time interval is based on the time stamps of the original block and the block that contains the transaction spending the output. A time interval of zero means, that the output was spent in the same block, i.e., without confirmation. Again, the clocks used for the timestamps of different blocks may not be in sync, but deviations from the true value should not correlate with our variable of interest.

Answering RQ 4 requires information about the mining pool that won each particular block race. We use the information on blockchain.info, parsed from 168,530 HTML pages, as baseline and cross-check against two additional data sources. First, we make use of the fact that some mining pools include a signature in the coinbase transactions of their blocks. This way, we are able to learn the origin of 75,750 blocks mined by the pools 50BTC, AntPool, ASICMiner, BitMinter, BTC Guild, EclipseMC, Eligius, KnCMiner, Polmine, and Slush. This information matches the baseline data from blockchain.info for 99.98 % of all relevant blocks. A second cross-check against the website blockorigin.pfoe.be, which maps pools to blocks based on the announced blocks on the pools' websites, confirms 99.92 % of the entries. However, this website only provides information for the latest 2016 blocks. All this indicates that our data is pretty reliable when it comes to the attribution of blocks to the major mining pools.

4 Results

4.1 Trends: Descriptive Analysis

We start with an exploratory analysis of transaction fees. The black lines in Fig. 1 show the average sum of transaction fees per block from January 2011 until December 2014. It grew from about 0.1 BTC in early 2012 to 0.25 BTC by mid 2013, with occasional spikes up to 0.5 BTC. In the course of 2014, it fell back to about 0.1 BTC. Overall, miners' revenue from transaction fees is small compared to the minting reward (50 BTC until November 2012, then 25 BTC).

The blue lines visualize the relative transaction fees as percentage of the (estimated) net amount. This value is of interest when looking at the competition between online payment systems. Overall, Bitcoin transaction fees are lower than 0.1 % of the transmitted value, which is significantly below the fees charged by conventional payment systems even if one accounts for the fact that some payments settle in two or more Bitcoin transactions.

The red lines show the average block size (in MB), which grew steadily to about 0.3 MB in December 2014. In the recent past, the default block size limits were increased from 250 KB to 350 KB in September 2013, and from 350 KB to 750 KB in March 2014. Although some blocks get close to the limit, it appears that hard size limits do not (yet) significantly drive the level of transaction fees.

When comparing the total transaction fees per block in USD to the Bitcoin exchange rate against USD, we see substantial co-movement (cf. Fig. 2). This indicates that BTC is the dominant unit of account when deciding about fee

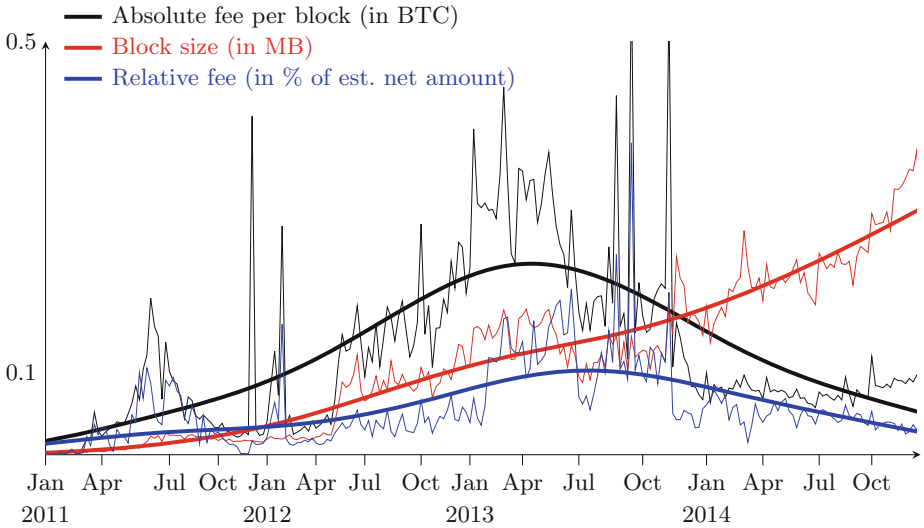


Fig. 1. Transaction fees per block (in BTC) and block size (in MB) (Color figure online)

offers, unlike prices for many goods and services paid with Bitcoin but fixed in a conventional currency. The smoothed curve shows that total fees have stabilized at about 45 USD per block in 2014.

Next, we explore changes in the nominal values of fees. Figure 3 shows trends for the fees paid *per transaction* over time. Each region represents the percentage of transactions with a specific nominal fee. Starting in January 2011, almost no transaction pays a fee. In the following months, a growing share of transactions started to include a fee of 0.01 BTC. The first notable change occurs after June 2011. Transactions with a fee of 0.0005 BTC appear and account for about 20–30 % of all transactions. In the second quarter of 2012, the share of zero-fee transactions drops significantly and 60–70 % of all transactions pay a fee of 0.0005 BTC. In the fourth quarter of 2012, this dominant share registers a sharp decrease, with a fee of 0.001 BTC now accounting for 30–40 % of all transactions. In May 2013, the nominal value of 0.001 BTC makes space for a tenth: 0.0001 BTC. This fee level stays on and gains a share of more than 70 % towards the end of the sample. The second largest nominal fee paid at the time of writing is 0.0002 BTC. This value started to appear in late 2013 and has a share of 15–20 %. It is very evident from Fig. 3 that the conventions on transaction fees are not static, but exhibit distinct trends over time.

In order to reason about these changes, we map important events in the Bitcoin ecosystem to the timeline (cf. Fig. 3). Generally, there seem to be two main reasons for shifts in trends: changes to the Bitcoin reference implementation and actions by large intermediaries in the ecosystem.

The emergence of 0.0005 BTC fees in June 2011 can be mapped to the release of version 0.3.23 of the Bitcoin Core client, which reduced the default transaction

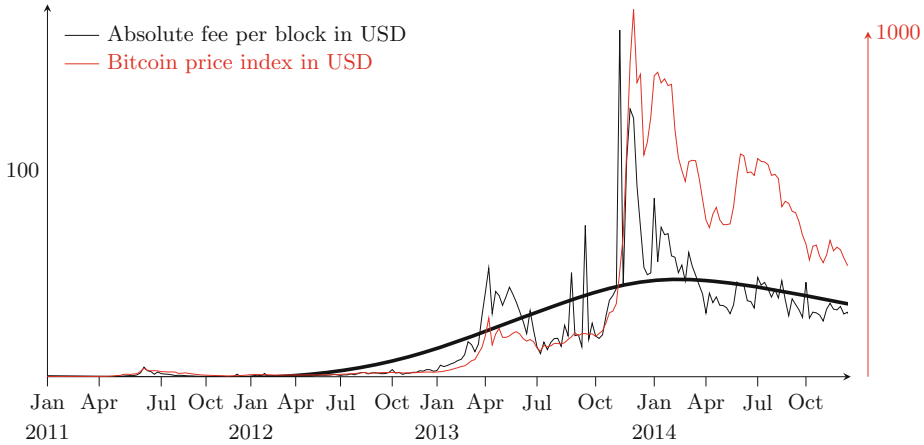


Fig. 2. Transaction fees per block (in USD)

fee from 0.01 BTC to 0.0005 BTC. The rise of transactions with a 0.0005 BTC fee in the second quarter of 2012 is probably due to the launch of the gambling website SatoshiDice. This service works as follows. A user can send a hand-picked amount of bitcoin to an address controlled by SatoshiDice. The service owns several deposit addresses with different associated win and payout ratios. For every incoming transaction, SatoshiDice instantly creates a new transaction to the incoming transaction’s source address. This new transaction returns the prize to the user in case he is lucky, or a very small output value to signal a loss.⁴ After its announcement on 24 April 2012, the service quickly gained popularity. It started to flood the block chain with transactions, leading to allegations of being a “DDoS attack against the Bitcoin network” [5].

While we could not find a plausible reason for the drop of the 0.0005 BTC nominal fee in late 2012, we found a possible explanation when looking at the payout transactions of SatoshiDice before and after this shift. Prior to it, SatoshiDice added a transaction fee of 0.0005 BTC to each payment. Then, in the fourth quarter of 2012, it doubled the fee to 0.001 BTC, while everyone else still paid the Bitcoin client’s default fee of 0.0005 BTC.

On 29 May 2013, version 0.8.2 of Bitcoin Core, the reference implementation, was released. In this update, the default transaction fee was lowered from 0.0005 BTC per KB to 0.0001 BTC per KB. Hence, the growing share of 0.0001 BTC fees might also visualize the adoption rate of both the new version of the reference client and other clients following this change.

The emergence of 0.0002 BTC fees starting in November 2013 can possibly be attributed to the release of version 1.9 of the Electrum wallet, which set this default fee in order to account for larger transactions due to the use of uncompressed addresses.

⁴ It was one Satoshi initially, then increased to 0.00005460 BTC after the default client required a minimum output value of 0.00005430 BTC to fight transaction spam [10].

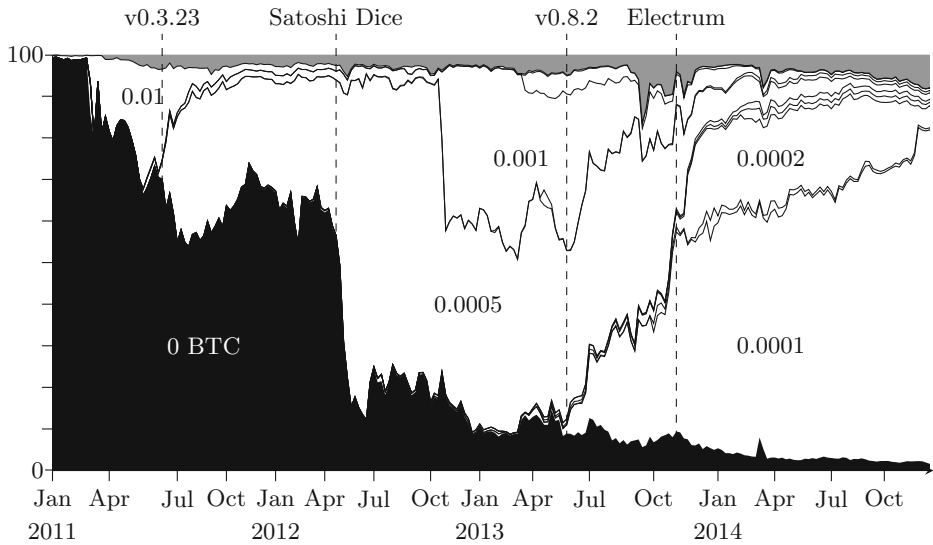


Fig. 3. Distribution of transaction fees

4.2 Tips: Explaining the Decision to Offer a Fee

Even at the time of writing there is a small share of transactions that does not offer a transaction fee to miners. Many of those paying a fee adhere to the default, but some were even willing to pay a higher fee. A plausible rationale is that paying a fee provides incentives for miners to prioritize a transaction, leading to faster confirmation. If this holds true, impatient users would be more willing to pay a fee, i. e., if transaction outputs are to be spent again soon after inclusion.

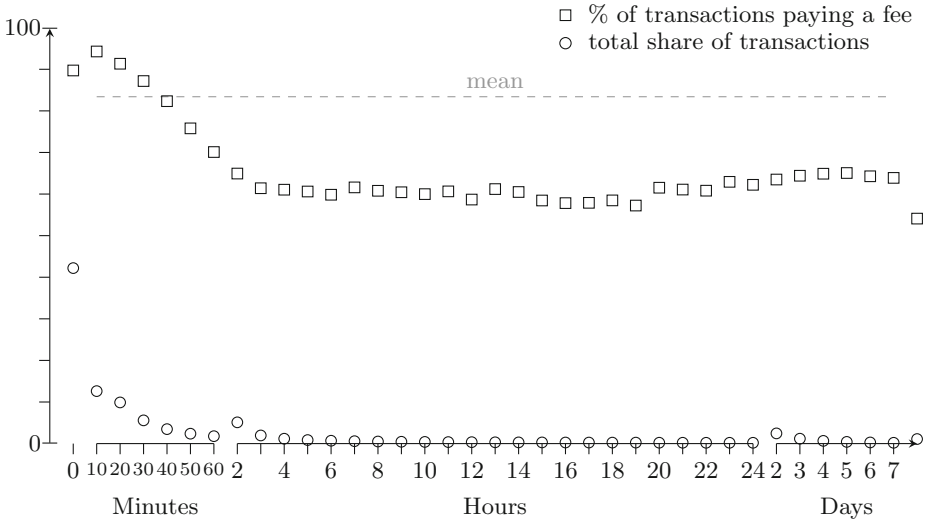
Table 2 shows the quantiles of transaction latencies for different fees. Half of all zero-fee transactions had to wait more than twenty minutes for their first confirmation. In contrast to that, paying a fee of 0.0005 BTC lead to an inclusion into a block in half of the time. While this seems acceptable for less time-critical transactions, the 90 % quantile shows a more extreme difference. Ten percent of all zero-fee transactions took almost 4 hours to confirm, in contrast to 40 min for transactions paying a 0.0005 BTC fee. The difference between paying a fee of 0.0005 or 0.001 BTC is not as pronounced, but the difference in medians is still statistically and economically significant.

Figure 4 reports the amount of transactions that include a fee dependent on the holding time. It is easy to see that the percentage of transactions including a fee is higher for those where outputs are spent shortly after being included in a block. The curve levels off to about 60–70 % for holding times of more than one hour. Another observation is that the amount of transactions whose outputs are reused in the same block amounts to slightly more than 40 %. We suspect that many of these transactions belong to SatoshiDice’s zero-confirmation transactions.

Table 2. Transaction latency in seconds by transaction fee

Fee	# Tx	Quantiles of the latency distribution				
		10 %	25 %	50 %	75 %	90 %
		(median)				
0	1503	180	444	1339	4270	13927
0.0005	5735	106	255	600	1244	2440
0.001	1905	90	212	520	1129	2135

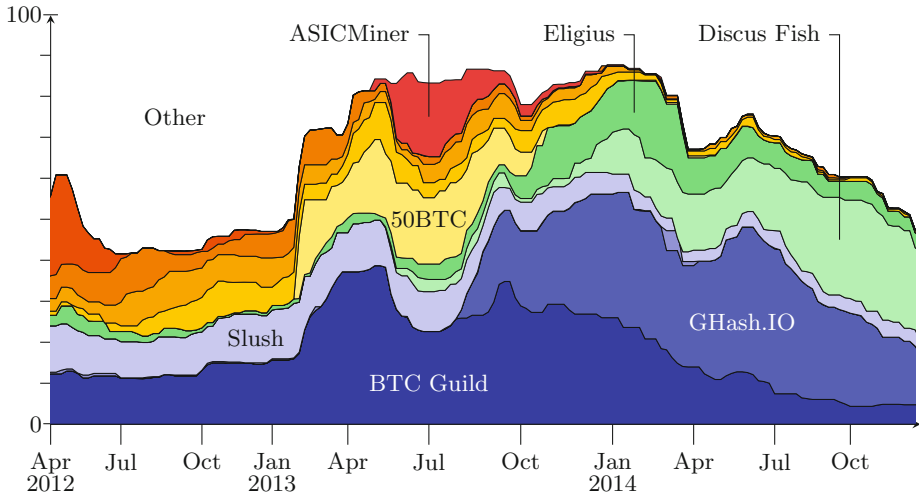
Sample period: June 2012 to May 2013. See text for details.

**Fig. 4.** Distribution of holding times and propensity to pay a fee (June 2012–May 2013)

4.3 Tolls: Mining Pools as Gatekeepers

Finally, we analyze pool behavior regarding a possible systematic exclusion of zero-fee transactions. Figure 5 shows the block solution share of each mining pool over time. Shares have shifted between pools quite extensively. In 2013, BTC Guild had a market share of up to 40 %. In 2014 both GHash.IO – which triggered controversial discussions when reaching almost a share of 50 % for a short time (cf. [4]) – and Discus Fish ousted this pool. Also, the share of “other” pools has risen in 2014. Previous incumbents like Slush or 50BTC have lost popularity. Possible reasons include economic and technical factors, like pool fees, service availability, or robustness against attacks (cf. [18, 28]).

Given the dominance of a few mining pools, we now tackle the question whether some pools systematically enforce fees. Table 3 shows the share of zero-fee transactions as well as the share of blocks without any zero-fee transaction (excluding the always present coinbase transaction) for the ten biggest pools.

**Fig. 5.** Block solution share of mining pools**Table 3.** Enforcement of transaction fees by mining pools

	Blocks solved (%)	% of zero-fee transactions		% of blocks w/o any zero-fee transaction	
		Apr 2012–	Jan 2014–	Apr 2012–	Jan 2014–
All miners	100.0	7.2	2.7	8.5	17.7
BTC Guild	18.0	6.5	2.2	1.5	4.1
GHash.IO	13.0	4.0	3.4	2.0	2.3
Slush	7.2	5.6	3.4	6.9	2.7
Discus Fish	7.0	0.7	0.3	66.3	72.5
Eligius	5.2	4.1	0.7	26.1	29.2
50BTC	3.9	8.2	11.9	0.4	3.3
BitMinter	3.5	10.4	14.9	3.5	0.8
EclipseMC	3.3	22.3	3.8	2.0	2.6
OzCoin	2.8	8.0	3.3	1.2	7.7
ASICMiner	1.9	8.8	5.9	1.7	0.0

Excluding coinbase transactions. Pool data before Apr 2012 is unreliable.

To account for developments over time, we contrast a longer sample (since April 2012) to the more recent past (since January 2014). The results show that two pools, Discus Fish and Eligius, have a considerably higher share of blocks without any zero fee-transaction: 29.2% for Eligius and 72.5 % for Discus Fish (since January 2014) – in contrast to an average of 17.7%. Other than that, there is no clear evidence for enforcement of strictly positive transaction fees.

A reason for the high number of blocks without zero-fee transactions for Discus Fish and Eligius could be that these blocks do not contain any transactions (besides the unavoidable coinbase transaction). Empty blocks appear on the block chain every now and then (one in 117 in 2014). To control for this, we calculate the median number of transactions within these blocks. For Eligius, the median number of transactions amounts to 83, for Discus Fish to 352. Hence, blocks without zero-fee transactions are not completely empty. These two pools seem to take a stricter line at enforcing transaction fees in their blocks than the other big pools.

5 Discussion

We interpret the heterogeneity and instability over time in transaction fees as an indication that the protocol's built-in market mechanism fails to set a fair price for transactions. This may be tolerable as long as minting rewards dominate miners' revenue and set the right incentive to defend the system, e.g., by keeping the cost of 51 % attacks high at any point in time. Two questions with relevance for the future of Bitcoin remain: 1. What factors influence a fair level of transaction fees? 2. Which mechanism can (approximately) find and enforce this level of fees?

A discussion section of an empirical paper is not the right place for a formal theoretical model. But it is safe to state that a fair price for transactions should internalize the externalities (cf. Sect. 2). Costs to others arise in two forms, born by two different types of agents in the system. First, miners bear the cost of solving the proof-of-work puzzle for the first confirmation. This cost is one-off, fixed per block, and thus depends on the number of transactions seeking confirmation at the same time. Second, relays in the network (that are all clients who store the entire block chain) bear the cost of storing the transaction record. It is current practice to store transactions forever, but in theory records can be pruned after all outputs are spent [25]. Cost of this second kind are incurred over time and depend on the size of the transaction (storage space), the time until all outputs are spent, and the size of the network (number of redundant copies).

It is conceivable that an internalization of the costs of the first kind can be enforced by miners (with some caveats, e.g., [17]). But there remains a free-riding problem regarding the provision of a public good with uninternalized costs of the second kind. Two out of three factors driving the costs of the second kind are not predictable at the time when the transaction is created. Taking averages over many transactions is no solution. It will lead to cherry-picking and other frictions. The time dimension makes it particularly challenging to find a mechanism that internalizes these externalities, as well as the *positive* externalities to longterm investors and potential transaction partners who extract utility from the very existence of the block chain although they rarely make transactions. In a fee-only regime, those with higher transaction demand and time preference subsidize others who can silently sit on their assets. Against this backdrop, it seems that the devaluation of stock, as implemented through monetary inflation

in the minting era, could be a closer approximation of the optimal mechanism than taxing transaction activity.

A limitation of our empirical approach is that off-blockchain payments and other agreements are unobservable. For instance, mining pools could allow exceptions for their own transactions used for reward redistribution or accept other forms of compensation from business partners, such as large intermediaries. (Such compensations are attractive because they can also be hidden from the miners and need not be redistributed.) As a result, what we identify as not rational may indeed be rational under the hidden agenda.⁵ Another limitation is that this initial analysis relies on central moments (mean, median) and subsamples of homogeneous transactions. This hides many particularities in a total of 55.5 million heterogeneous transactions. We suspect that various other factors influence the transaction fees in subsets of transactions too small to isolate in this analysis.

6 Concluding Remarks

A longitudinal analysis of 55.5 million transaction records reveals several regime shifts in agents' behavior related to the payment of transaction fees. This calls for caution against the risk of unobserved heterogeneity in all analyses that do not explicitly consider the time dimension.

Throughout Bitcoin's history, it appears that the level of transaction fees is primarily driven by social norms and conventions formed by key actors in the ecosystem rather than set by the protocol's implied market mechanism, which in principle could match miners' supply with transaction partners' demand. In other words, most agents seem to follow rules instead of economic ratio.

This history, however instructive it may be, is unlikely to offer good predictions for a (distant) future. Fees were generally low in the past, so that agents' ignorance can be explained with information, search, and decision costs. (In simple terms: they do not care.) At least agents will need to revisit their behavior when transaction fees replace minting rewards as the incentive for miners to maintain the system secure. Possibly, the Bitcoin stakeholders may also need to revisit the protocol's incentive system.

Acknowledgements. We thank the anonymous reviewers for their feedback and the hint on the emergence of 0.0002 BTC fees. We also thank blockchain.info for providing us with an API key to bypass their request limit.

References

1. Ali, R., Barrdear, J., Clews, R., Southgate, J.: Innovations in payment technologies and the emergence of digital currencies. In: Digital Currencies: Quarterly Bulletin 2014 Q3. Bank of England (2014)

⁵ We appreciate hints and anecdotes which might lead to testable hypotheses.

2. Ali, R., Barrdear, J., Clews, R., Southgate, J.: The economics of digital currencies. In: *Digital Currencies: Quarterly Bulletin 2014 Q3*. Bank of England (2014)
3. Anderson, R.: Risk and privacy implications of consumer payment innovation. In: *Federal Reserve Bank Payments Conference* (2012)
4. Bershidsky, L.: Trust Will Kill Bitcoin (2014). <http://www.bloombergtview.com/articles/2014-07-17/trust-will-kill-bitcoin>. Accessed 16 Oct 2014
5. Bitcoin Wiki. SatoshiDice. <https://en.bitcoin.it/wiki/SatoshiDice>. Accessed 17 Sept 2014
6. Bitcoin Wiki. Transaction Fees (2014). https://en.bitcoin.it/w/index.php?title=Transaction_fees&oldid=45501. Accessed 15 Oct 2014
7. Blockchain.info. Bitcoin Market Capitalization (2014). <https://blockchain.info/charts/market-cap>. Accessed 08 Oct 2014
8. Böhme, R.: Internet protocol adoption: learning from Bitcoin. In: *IAB Workshop on Internet Technology Adoption and Transition (ITAT)*, Cambridge, UK (2013)
9. Böhme, R., Christin, N., Edelman, B., Moore, T.: Bitcoin: economics, technology, and governance. *J. Econ. Perspect.* (2014). Available at SSRN: <http://ssrn.com/abstract=2495572>. Forthcoming; Harvard Business School NOM Unit Working Paper No. 15–015
10. Buterin, V.: Bitcoin Developers Adding \$0.007 Minimum Transaction Output Size (2013). <http://bitcoinmagazine.com/4465/bitcoin-developers-adding-0-007-minimum-transaction-output-size/>. Accessed 17 Oct 2014
11. Coindesk. About the Bitcoin Price Index (2014). <http://www.coindesk.com/price/bitcoin-price-index/>. Accessed 23 Oct 2014
12. The Economist. Plastic stochastic (2014). <http://www.economist.com/news/finance-and-economics/21621882-capping-fees-card-transactions-has-not-worked-out-planned-plastic-stochastic>. Accessed 22 Oct 2014
13. Edelman, B.: Consumers Pay More When They Pay with Bitcoin (2014). <http://www.pymnts.com/in-depth/2014/consumers-pay-more-when-they-pay-with-bitcoin/>. Accessed 15 Jan 2015
14. Gavin Andresen comments on Bitcoin 0.8.6 Released, Updates to Block Size Limit, Free Transactions, OSX Bugs (2013). <http://www.reddit.com/r/Bitcoin/comments/1sk3df/bitcoin.086-released-updates-to-block-size-limits/cdyrab7>. Accessed 13 Oct 2014
15. Hirshleifer, J.: From weakest-link to best-shot: the voluntary provision of public goods. *Public Choice* **41**(3), 371–386 (1983)
16. Houy, N.: The Bitcoin Mining Game. Working Paper GATE 2014–12 (2014)
17. Houy, N.: The Economics of Bitcoin Transaction Fees. Working Paper GATE 2014–07 (2014)
18. Johnson, B., Laszka, A., Grossklags, J., Vasek, M., Moore, T.: Game-theoretic analysis of DDoS attacks against Bitcoin mining pools. In: Böhme, R., Brenner, M., Moore, T., Smith, M. (eds.) *FC 2014 Workshops*. LNCS, vol. 8438, pp. 72–86. Springer, Heidelberg (2014)
19. Karame, G.O., Androulaki, E., Capkun, S.: Two bitcoins at the price of one? double-spending attacks on fast payments in Bitcoin. In: *Proceedings of the ACM Conference on Computer and Communications Security (CCS)* (2012)
20. Kaskaloglu, K.: Near zero Bitcoin transaction fees cannot last forever. In: *The International Conference on Digital Security and Forensics (DigitalSec 2014)*, pp. 91–99 (2014)
21. Luther, W.J.: Cryptocurrencies, Network Effects, and Switching Costs. *Mercatus Center Working Paper No. 13–17* (2013)

22. Meiklejohn, S., Pomarole, M., Jordan, G., Levchenko, K., McCoy, D., Voelker, G.M., Savage, S.: A fistful of Bitcoin: characterizing payments among men with no names. In: Proceedings of the ACM Internet Measurement Conference (IMC), pp. 127–140. ACM, New York (2013)
23. Moore, T., Christin, N.: Beware the middleman: empirical analysis of Bitcoin-exchange risk. In: Sadeghi, A.-R. (ed.) FC 2013. LNCS, vol. 7859, pp. 25–33. Springer, Heidelberg (2013)
24. Möser, M., Böhme, R., Breuker, D.: Towards risk scoring of Bitcoin transactions. In: Böhme, R., Brenner, M., Moore, T., Smith, M. (eds.) FC 2014 Workshops. LNCS, vol. 8438, pp. 16–32. Springer, Heidelberg (2014)
25. Nakamoto, S.: Bitcoin: A Peer-to-Peer Electronic Cash System (2008)
26. Sherif, M.: The Psychology of Social Norms. Harper, New York (1936)
27. [UPDATE: 2014–10-05] Bitcoin Core soft-fork “No Forced TX Fee” v0.9.3. <https://bitcointalk.org/index.php?topic=22434.0>. Accessed 23 Oct 2014
28. Vasek, M., Thornton, M., Moore, T.: Empirical Analysis of Denial-of-Service Attacks in the Bitcoin Ecosystem. In: Böhme, Rainer, Brenner, Michael, Moore, Tyler, Smith, Matthew (eds.) FC 2014 Workshops. LNCS, vol. 8438, pp. 57–71. Springer, Heidelberg (2014)
29. Wong, J.I.: New Study: Low Bitcoin Transaction Fees Unsustainable (2014). <http://www.coindesk.com/new-study-low-bitcoin-transaction-fees-unsustainable/>. Accessed 13 Oct 2014