Empirical Analysis of EIP-1559:

Transaction Fees, Waiting Time, and Consensus Security

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Abstract

Transaction fee mechanism (TFM)

- 블록체인 프로토콜에서 필수적인 요소
- 실제 세상에서의 시스템적 분석이 없었음

이더리움 블록체인의 풍부한 데이터를 이용해 EIP-1559의 영향을 분석

- Mempool
- Exchanges (가격) 등

EIP-1559

- 전통적인 First-price 옥션에서 벗어난
- 최초의 TFM 중 하나

다음에 대한 관찰을 수행

- Transaction fee dynamics
- Transaction waiting time
- Security

그 결과 EIP-1559가 다음을 개선

- Fee estimation
- Mitigating intra-block difference of gas price paid
- Reducing users' waiting times

그러나 다음에는 영향이 없거나 아주 사소

- Gas fee levels
- Consensus security

추가적으로

- ETH 가격이 변덕스러울수록 대기 시간이 유의미하게 높아짐
- 큰 블록 사이즈가 siblings의 등장 가능성을 더함

Introduction

TFM is an essential component of a blockchain protocol

- Fundamentally affect incentive compatibility
- User experience
- Security of a blockchain system

Ethereum

- Used to employ first-price auctions as the transaction fee mechanism

On August 5th, 2021, Ethereum London Hardfork

- Implemented EIP-1559 together with several other EIPs

EIP-1559

- Maintaining backward compatibility
- Overhauled the Ethereum TFM
- 메이저 블록체인에서의 최초의 First-price 옥션을 벗어난 시도

EIP-1559에 대한 실질적 관측 및 검증은 없는 상황

- Reijsber- gen et al. observed the volatile gas usage after EIP-1559
- The Ethereum community had analyzed the EIP informally
  - and expected
  - to mitigate the economic inefficiencies due to fee volatility,
  - to avoid over-paid transaction fees,
  - and to lower transaction waiting time

저자들은 이더리움의 TFM 리폼에 대해, 다음 세 질문에 답변하는 것을 초점

1. Does EIP-1559 affect the transactions fee dynamics?
    - TFM 적용 이후 수수료 예측이 쉬워질 것으로 예상
    - TFM의 SEE(Symmetric Ex-post Equilibrium)가 First-price 옥션의 BNE(Bayesian Nash Equilibrium) 보다 풀기 쉬움
        - 이성적 참여자가 가정되어야 하는데,
        - 이더리움의 참여자들이 실제로 이성적인가?
2. Does EIP-1559 affect transaction waiting time?
3. Does EIP-1559 affect consensus security?
    - EIP-1559에서는 블록 사이즈(정확하게는 가스 사용량)가 크게 변화함

Background

Transaction Fees in Ethereum

- To prevent malicious users from spamming the network
- or deploying hostile infinite loops
- every operation is charged a fee

$$GasFee = GasUsed \times GasPrice$$

the amount of gas needed for a transaction is usually unknown before execution

- users could specify a gas limit with their transactions
- Unconsumed gas is refunded

Ethereum has a block gas limit

- 15 (30) million before (after) the implementation of EIP-1559

The sum of the gas limit of transactions included in a block

- cannot exceed this block gas limit

EIP-1559 전,

- A first-price auction
- Users submit a gas price bid for their transactions to outbid competitors
- Miners are incentivized to include those with the highest gas prices in a block first

The first-price auction

- does not have a Bayesian-Nash equilibrium
- so users need to make assumptions on their competitors' bids
- to optimize their bid strategy
- which is impractical and user-unfriendly
- 그 결과: overpaid and volatile gas fees, long inclusion time of transaction 문제 발생

The new TFM in EIP-1559

Block Size

- EIP-1559 changes the fixed-sized blocks to variable-sized blocks
- The block gas limit is doubled from 15 million to 30 million
- while the block gas target is still set at 15 million.
  - block gas used remains around block gas target on average

Base Fee

- EIP-1559 introduces a base fee parameter determined by network conditions
- The minimum gas price that every transaction must pay to be included in a block

Base fee adjusts

- in a dynamic Markov process
- according to the block gas used in the previous block

If the block gas is greater than the target

- the base fee for the next block increases, and vice versa.

$$\text{BaseFee}_{h+1} = \text{BaseFee}_{h}\left(1 + \frac{1}{8}\frac{\text{GasUsed}_{h} - \text{GasTarget}}{\text{GasTarget}}\right)$$

User Bidding

- max priority fee per gas and max fee per gas

Priority fees per gas

- are the tips

Max fees

- are the fee caps

The difference

- between the max fee and the sum of the base fee and priority fee
- will be refunded to the user

$$\text{GasPrice} = \min\{\text{BaseFee} + \text{MaxPriorityFee}, \text{MaxFee}\}.$$

if a user bids (MaxFee, MaxPriorityFee) = (60, 2)

(1) If BaseFee > 60
- the transaction must not be included in this block
- It waits in the mempool until base fee falls.

$$\text{GasPrice} = \min\{\text{BaseFee} + \text{MaxPriorityFee}, \text{MaxFee}\}.$$

if a user bids (MaxFee, MaxPriorityFee) = (60, 2)

(2) If 58 < BaseFee < 60

- the miner can choose whether to include this transaction
- the user pays 60 – Basefee Gwei as a priority fee to miners
- Users pay 60 Gwei per gas in total

$$\text{GasPrice} = \min\{\text{BaseFee} + \text{MaxPriorityFee}, \text{MaxFee}\}.$$

if a user bids (MaxFee, MaxPriorityFee) = (60, 2)

(3) If BaseFee < 58

- the miner can choose whether to include this transaction
- the user pays 2 Gwei as a priority fee to miners
- Users pay BaseFee + 2 Gwei per gas in total

DATA

저자들은 이더리움의 많은 데이터를 수집

- Mempool for computing waiting time
  - We set up a distributed data collection system to monitor the mempool of Ethereum
- Exchanges (intra-day ETH prices)

EIP-1559의 블록체인에서의 효과는 다른 요소들과 많이 엮여있음

- Price volatility
- Network instability
- Time trend

To isolate the effect of EIP-1559 from those of confounding factors, 다음을 적용

- Event study

Regression Discontinuity Design (RDD) framework

$$Y = \alpha_0 + \alpha_1 \mathbb{1}(\text{London Hardfork}) + \alpha_2 r_{\text{EIP}} + \alpha_3 \mathbf{X} + \mu_h + \epsilon.$$

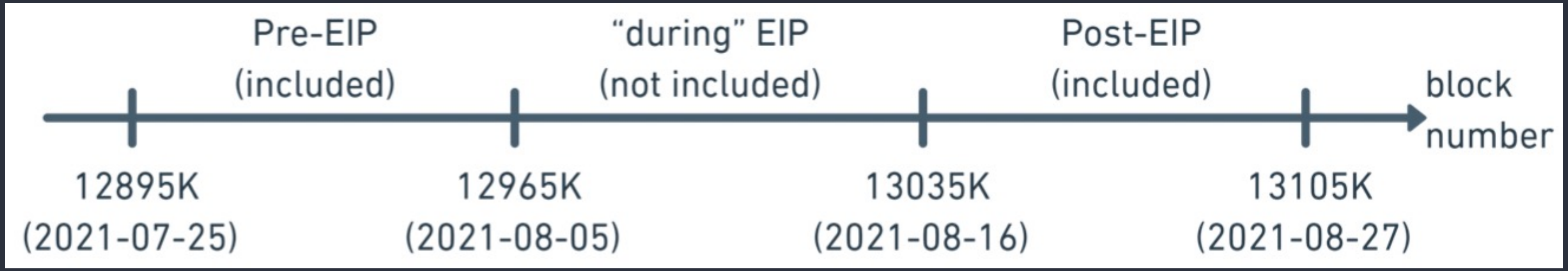
- $\alpha 1$ is the coefficient for the indicator variable on whether London Hardfork happened (block number ≥ 12965000)
- $\alpha 2$ is the coefficient for rEIP the percentage of transactions that adopts EIP-1559 after the London Hardfork
- a set of control variables represented as X
- hour fixed-effect term μh to account for the seasonality
- ϵ is an error term

Three data sources

1. Google Bigquery
   - the block-level characteristics and transaction-level characteristics from Ethereum
2. Run four Ethereum full nodes
   - geographically distributed around the world
   - North Carolina, Los Angeles, Montreal, and Germany
   - to monitor the mempool
3. ETH price data at a one-minute granularity from Bloomberg Terminal
   - to compute minute level price volatility of ETH price as a control variable

We do not use data from the blocks immediately after EIP-1559

- because it takes time for users and miners to upgrade their software to adapt to the London Hardfork change
- The Start Block of the post-EIP 1559 period is chosen when the adoption reaches 20%



We obtained blockchain data

- including the gas price paid for each transaction (legacy and EIP-1559)
- max fee and max priority fee bids for each EIP-1559 transaction from Google Bigquery

Representative transaction

- To measure the gas price of a “representative transaction” in the block
- we use the **median** of gas prices

Intra-block variance

- measures like median and inter-quartile range (IQR) are much more robust to outliers
- use the **standardized IQR** of gas prices in blocks
- to measure intra-block variance of gas prices

$$\text{standardized IQR} = \frac{Q_{75}(\text{GasPrice}) - Q_{25}(\text{GasPrice})}{Q_{50}(\text{GasPrice})}$$

$$\text{Waiting time of TX} = T^{\text{TX}}_{\text{block}} - T^{\text{TX}}_{\text{mempool}}$$

- T^TX_mempool is the time when the transaction first appears in the mempool
- T^TX_block is the time when the transaction is mined

Estimating T^TX_mempool

- we modified the Ethereum Geth client
- so that our nodes connect to up to 1,000 peers
- distributed nodes in Durham, Los Angeles, Montreal, and Helsinki
- Our modified Geth client stores a log of mempool
  - whenever they receive a new transaction from the P2P network
  - use the earliest time when TX is observed in mempool across all servers

$$\text{Waiting time of TX} = T^{\text{TX}}_{\text{block}} - T^{\text{TX}}_{\text{mempool}}$$

- T^TX_mempool is the time when the transaction first appears in the mempool
- T^TX_block is the time when the transaction is mined

Estimating T^TX_block

- block timestamp given by miners, but that is vastly inaccurate

Azevedo-Sousa et al

- calculated waiting time in this fashion
- which led to the wrong conclusion that 50% of transactions have negative waiting times

Block timestamps given by miners

- are typically when the miner starts the mining process

We bypass this difficulty

- by using the timestamp of the next block
- we reduce the proportion of transactions
  - with negative waiting time from 50% to less than 5%
  - we set the waiting time of those (negative) transactions to 0

Miners' revenue (MR) includes

- block rewards, transaction fees
- and "extracted values"

use the revenue from Flashbots

- by far the largest MEV extraction services,
- as an approximation of the total MEV

Fork Rate Data

To understand how the new transaction fee mechanism may affect consensus security

- we collected data about past forks in Ethereum

The Ethereum blockchain

- contains pointers to uncle blocks
- from which we derive the number of “siblings”
- to show the specific time when forks happen

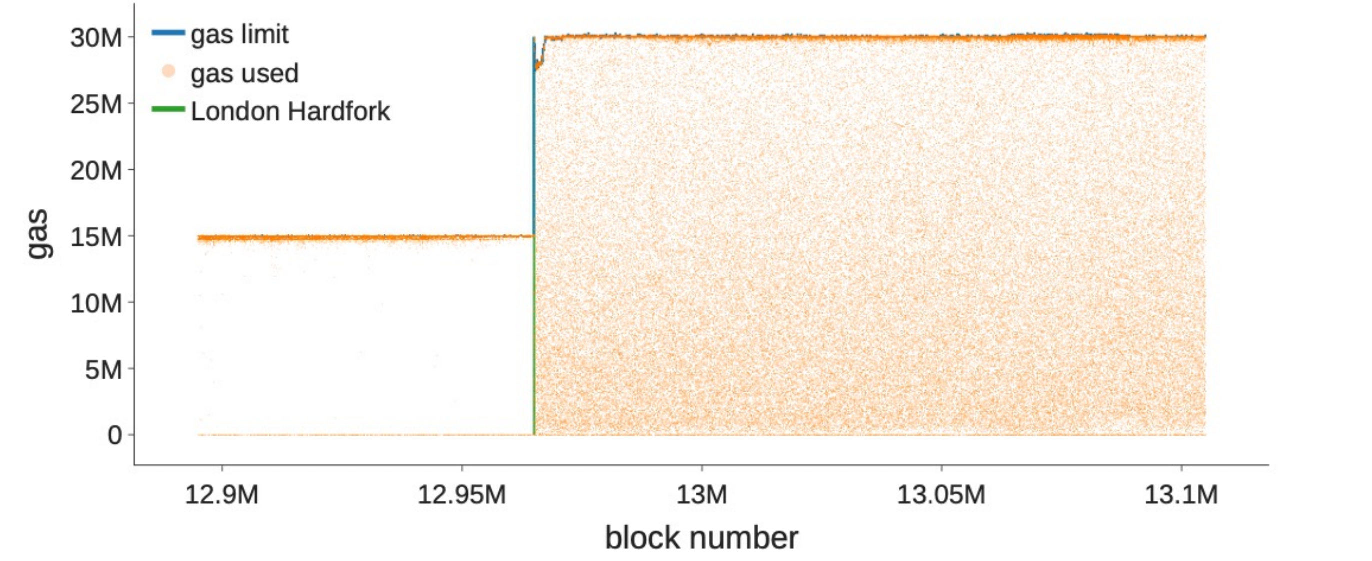
Sibling count can reflect

- how many different blocks compete at a specific height at a given time

Empirical Results

Distribution of Block Gas Used

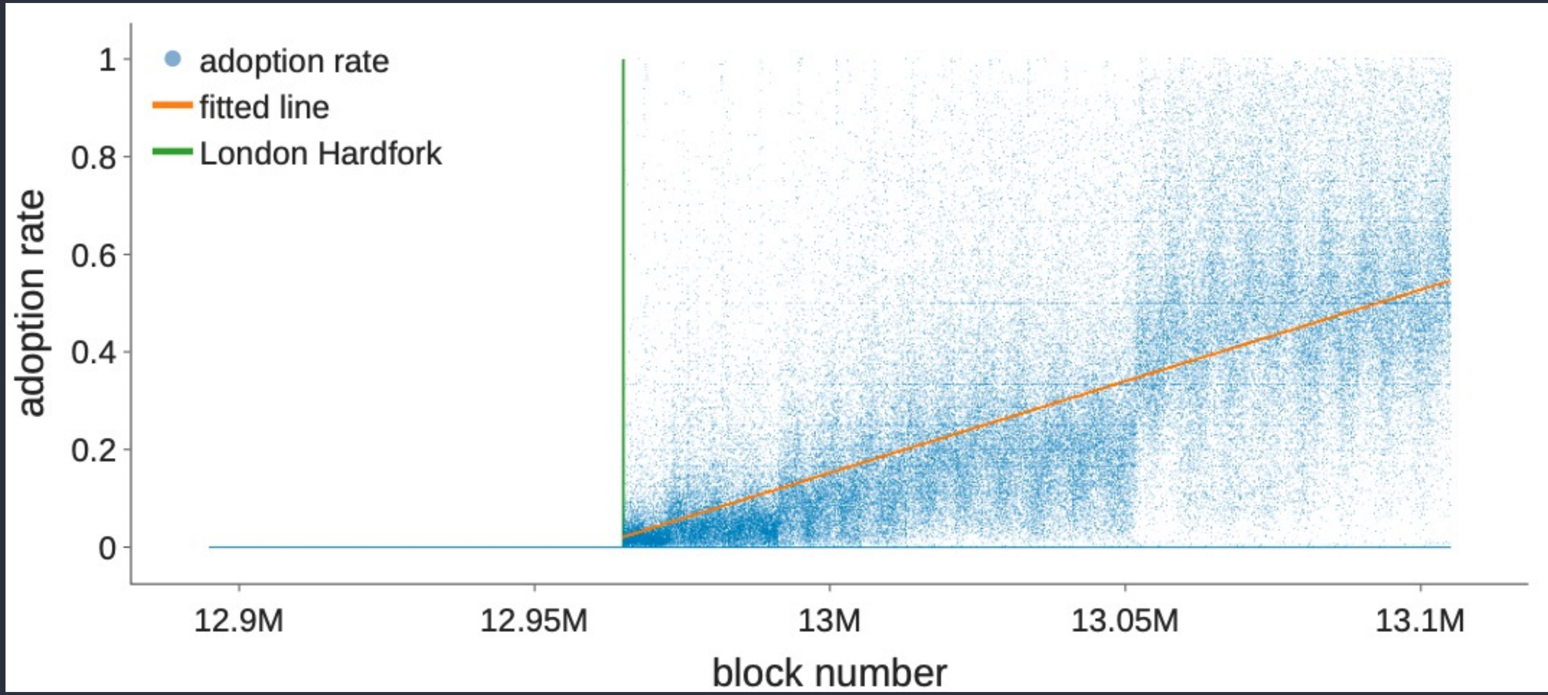
- Increasing base fee screens users with lower intrinsic values
- and leads to fewer transactions included in a block
- until the block gas used is lower than the target



(a) Before London Hardfork, almost all blocks used 15 million gas; after London Hardfork, block gas used varies between 0-30 million. Each dot represents a block.

Adoption rate

- We notice a sharp increase in adoption rate around block number 13.05 million, which is possibly related to the adoption as default on MetaMask



1. Transaction fees
2. Transaction waiting time
3. Consensus security

Transaction fees

- EIP-1559 did not lower the transaction fee level
- Enabled easier fee estimation for users

Before EIP-1559

- users pay the entirety of their bids
- risk overpaying transaction fees if the network turns out less congested after they bid
- With the new TFM, however, such risks are avoided

because users can set two parameters in their bids

- a cap on the total fees they will pay per gas (called “max fee per gas”)
- and a tip for the miner on top of the base fee (called “max priority fee per gas”).

이러한 수수료 분리는

- enables a simple yet optimal bidding strategy
- users just set the max fee per gas to their intrinsic value for the transaction
- set the max priority fee per gas to the marginal cost of miners

Who adopt EIP-1559 bidding

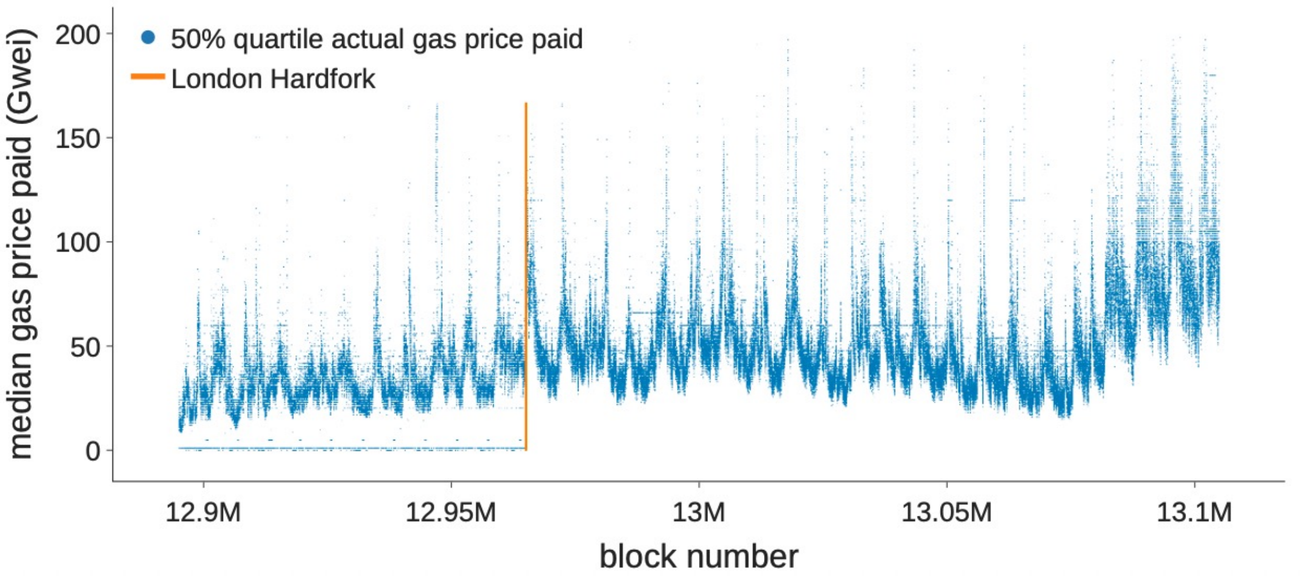
- pay a lower fee than those who stick to the legacy bidding
- estimation is easier with the new gas fee bidding style

The gas price paid by users did not change much immediately after London Hardfork

But it started to rise about two weeks later

- We can not conclude whether this was caused by EIP-1559

Each dot represents a quartile of the gas price paid for a block.

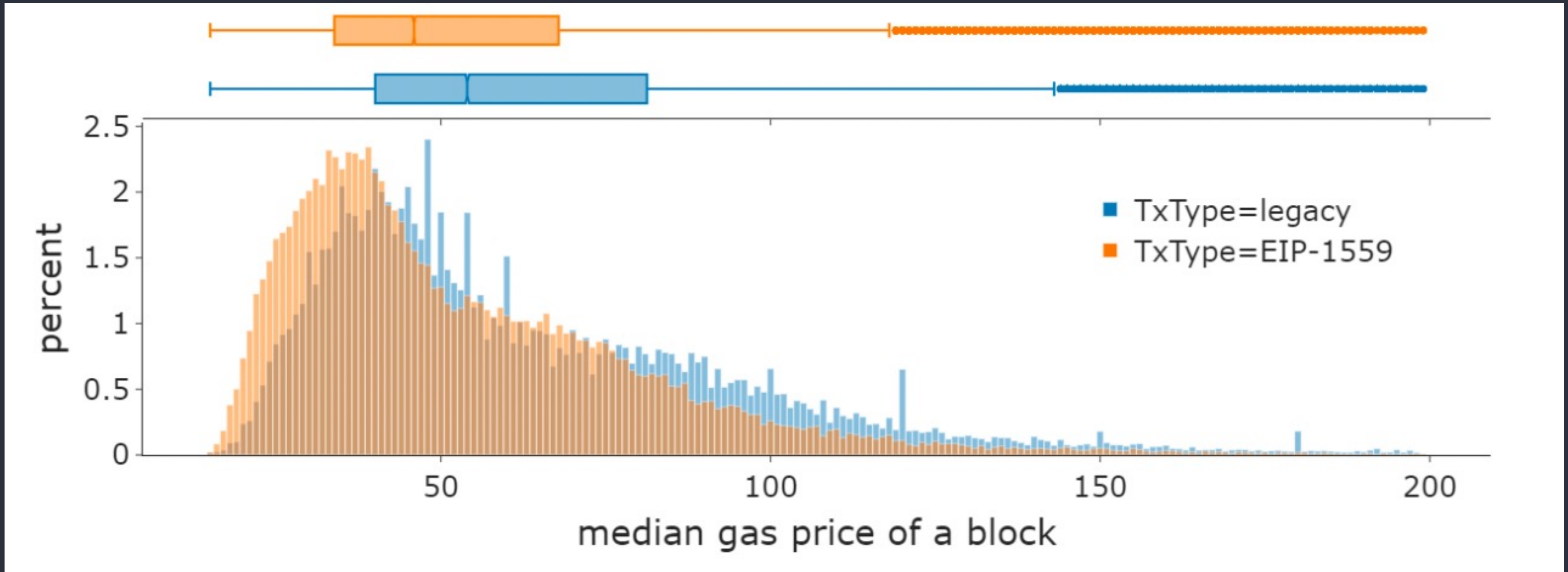


Intra-block gas price variance

- measured by standardized interquartile range (IQR)
- becomes significantly lower as more users adopt EIP-1559 transactions
- Also implies easier fee estimation and less overpaying for users

Distributions of median gas prices of a block

- The distribution of EIP-1559 transactions is overall to the left
- which means that users who adopt EIP- 1559 pay a lower gas price



Transaction waiting time

- EIP-1559 lowers transaction waiting time

Waiting time significantly reduces after London Hardfork

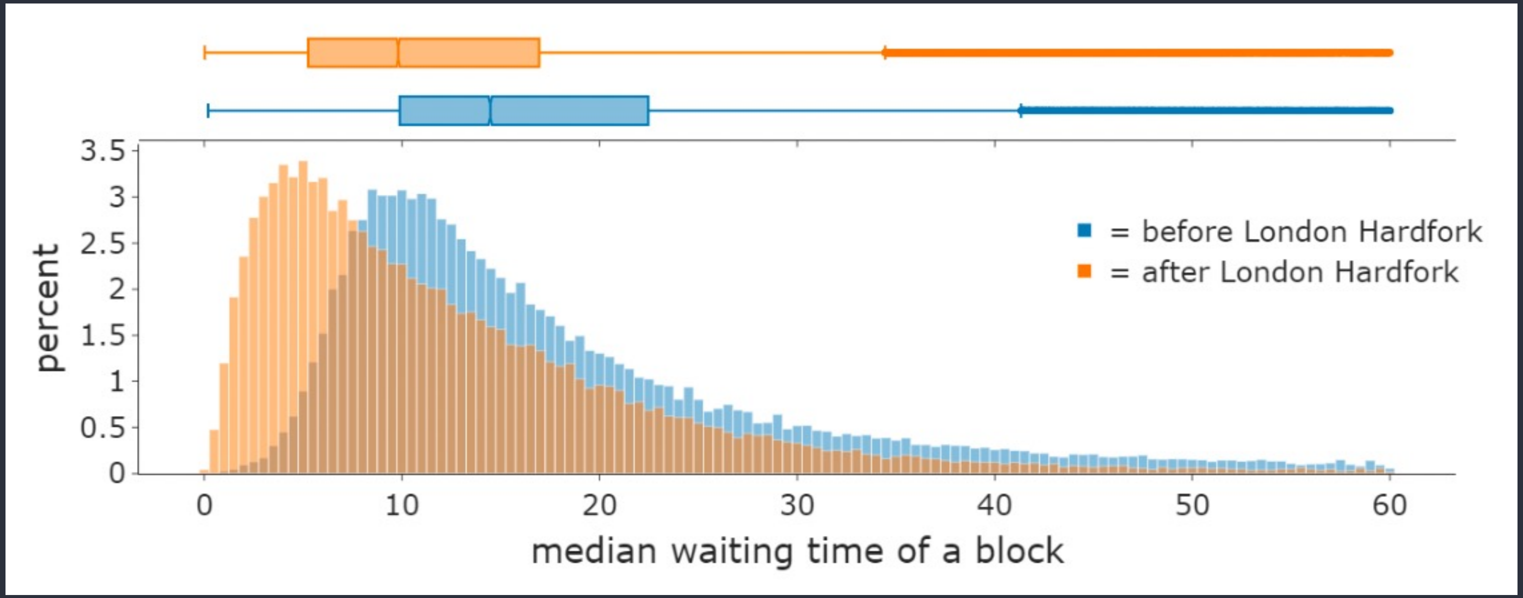
- possibly as a result of easier gas price bidding and variable-sized blocks

The reduction in waiting time

- might also be a consequence of the easier fee estimation

Distributions of median waiting time

- It moved left after the London Hardfork
- Users experience a much lower transaction waiting time with EIP-1559



Consensus security

- EIP-1559 changes important consensus parameters
- such as the block size and the incentive of miners and users

다음의 세 가지에 집중

1. Forkrate
2. Network load
3. Miner Extractable Value (MEV)

Forkrate

- Larger blocks may take more time to propagate through the p2p
- leading to more forks

In EIP-1559 the block size is variable and dynamically adjusted

- thus its impact on fork rate is not well understood

Our results

- empirically show that London Hardfork increased block size on average,
- and it also led to an about 3% rise in fork rats

Network load

- 블록체인에 참여하기 위해 노드가 가져야/수행해야 할 computational, networking, and storage work

Whether variable block sizes will increase the network load

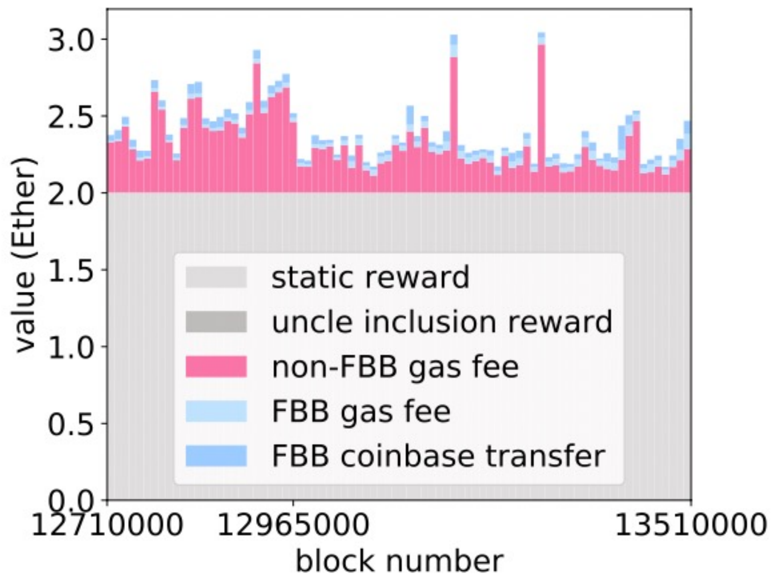
- since processing larger blocks consumes more resources

Our results show that EIP-1559

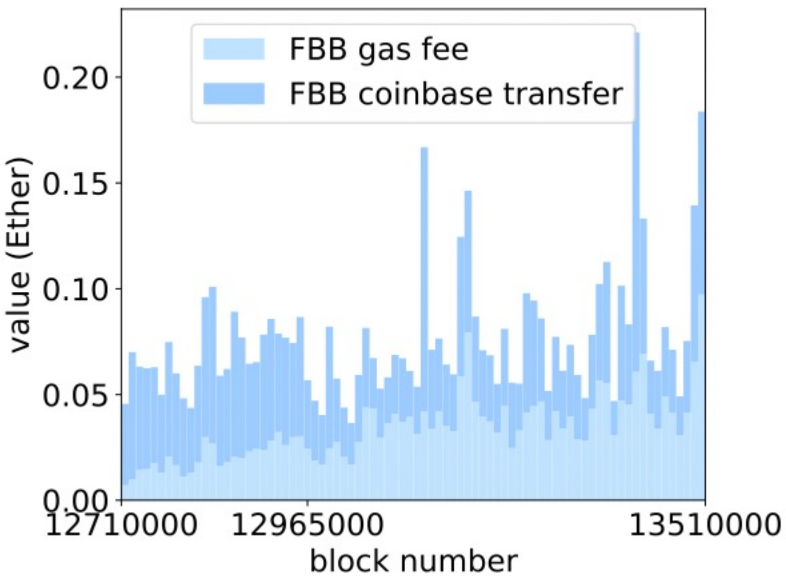
- does not put the blockchain system under a significantly higher load

Miner Extractable Value

- MEV becomes a much larger share of miners' revenue after EIP-1559
- mainly because the base fees are burnt



(a) Source of miners' revenue



(b) MEV from Flashbots

Conclusion

We show

- that the volatility of intra-block gas prices decreases significantly
- as more users adopt EIP- 1559 transactions,
- which implies easier fee estimation and better user experience

EIP-1559 increases user experience by reducing waiting time significantly

We also verify that a larger block size increases the presence of siblings