Economic Determinants of Ethereum Transaction Fees in the Priority Fee and Proof of Stake Periods

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Abstract

We analyze the economic determinants and dynamics of transaction fees in the Ethereum blockchain before and after two significant platform updates. The first is the August 2021 EIP-1559 "London" upgrade, a switch from user-bid *gas price* (transaction fee per unit of complexity) to a fee model in which the gas price is the sum of an algorithmically determined base fee and an optional priority fee (tip) chosen by the user. The second update ("the Merge") is the switch from proof-of-work to proof-of-stake transactions validation in September 2022. We estimate the impact on Ethereum transaction fees of both demand factors (block utilization, transaction type, ETH price in USD) and algorithmic supply-side factors (the block gas limit and base fee). Using data from nearly 900 million blockchain transactions, we find that the gas price is statistically significantly positively associated with the block utilization rate. A larger share of contract call transactions or legacy (user-bid gas price) transactions is linked with higher gas prices on average. On the supply side, a higher block gas limit is statistically significantly associated with lower gas prices.

Keywords: transaction fees, Ethereum blockchain, gas price, supply and demand factors, time series analysis

JEL codes: G10, G19, G29, C58

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1 Introduction

Ethereum, established in 2015, is the second-largest blockchain platform by market capitalization, with a valuation of $452 billion as of May 22, 2024. Unlike other digital platforms mainly focused on cryptocurrency investment or trading (e.g., Bitcoin), Ethereum distinguishes itself with a broad range of applications and flexibility, by enabling users to create and deploy automatized digital "smart contracts" for diverse purposes including decentralized applications (DApps), decentralized financial services (DeFi), non-fungible tokens (NFTs), etc.

Transferring digital funds or deploying and interacting with digital smart contracts on the Ethereum blockchain requires paying a transaction fee determined in terms of the platform's internal resource unit called *gas* and the price per unit of gas, *gas price*. Each use of the blockchain (transaction) has an algorithmically specified gas requirement which depends on the transaction's computational complexity and number of operations.[1] The transaction fee that a user pays equals the transaction's gas requirement multiplied by the gas price.

Before August 5, 2021 the Ethereum gas price was determined in a way similar to a first-price auction – users submit gas price bids and the transactions of the users with the highest bids are prioritized for validation and execution, that is, included in more immediate data blocks. As of August 5, 2021, the economic mechanism for determining Ethereum transaction fees was changed significantly with the implementation of Ethereum Improvement Proposal EIP-1559, also known as 'the London upgrade'.[2] This platform code upgrade was introduced with the goal to rein in rising transaction fees and to reduce network congestion and delays in transaction processing.

Combined with a doubling of the gas supply (the gas limit per block), the major change introduced in the London upgrade was a switch from gas prices fully bid by the users to a new transaction fee mechanism in which the gas price is formed as the sum of two components: a 'base fee' and a 'priority fee'. Specifically, the base fee of each block is algorithmically determined by the blockchain code (see Appendix B) as a function of two variables: the base fee of the immediately preceding block and the block utilization (gas used) in the immediately preceding block. Higher utilization (above 50% of the block gas limit) in block $t-1$ automatically triggers a proportional increase (capped at 12.5%) of the base fee in the following block t, while lower block utilization in block $t-1$ (below 50%) results in a proportional decrease of the base fee in block t, again by at most 12.5%. By design, the base fee therefore acts to stabilize Ethereum transaction costs, since the block-on-block gas price growth rate is capped and depends on the gas usage (reflecting demand) in the immediately preceding block. Paying the base fee is mandatory – a transaction

[1]For instance, the gas requirement for a simple bilateral ETH transfer between two addresses is 21,000 gas. More complex transactions, for example deploying a digital contract, require substantially larger amounts of gas.

[2]See https://github.com/ethereum/EIPs/blob/master/EIPS/eip-1559.md for complete details.

which does not provide sufficient Ether (ETH, Ethereum's digital currency unit) to pay the base fee would be rejected by the platform.

In addition to the base fee, users can optionally offer to pay a so-called "priority fee" (akin to a tip), chosen in a similar way to the pre-London gas price bid. All submitted transactions must pay the base fee and transactions with higher priority fees are more likely to be included on the blockchain and executed sooner. Users are also allowed to continue to adhere to the old pre-London transaction format, i.e., set the full gas price for their transaction, however, such transactions would be valid only if their user-submitted gas price equals or exceeds the platform-determined current block base fee. We refer to such transactions as "legacy transactions". In contrast, users who adopt the new EIP-1559 fee mechanism (we refer to such transactions as "non-legacy transactions") choose two parameters ('max fee per gas' and 'max priority fee per gas') and the resulting gas price they pay is determined as the smaller value of 'max fee per gas' and the sum of the base fee and 'max priority fee per gas'. Consequently, following the London upgrade, in addition to the gas price, we also analyze the economic demand and supply determinants of the priority fees chosen by the users.

A second major change in the Ethereum platform ('the Merge upgrade') was implemented on September 15, 2022 by switching from *proof of work* (also known as "mining") – the original and most commonly used consensus algorithm for verifying and recording transaction data securely on a blockchain,[3] see Nakamoto (2008) – to *proof of stake*, a protocol in which major ETH holders, who have posted collateral in a smart contract deployed on the blockchain, validate submitted transactions.[4] Unlike the computationally and electricity consumption heavy proof of work mechanism, proof of stake validation requires drastically lower computer processing power. For example, Kapengut and Mizrach (2023) and De Vries (2023) estimate that the 'Merge' transition to proof of stake in Ethereum reduced electric energy consumption by 99.84% to 99.99%, a magnitude similar to the electric power requirement of a country as large as Ireland or Austria.[5] We analyze the Merge's impact on transaction fee determination and levels and find that the switch to proof-of-stake led to an approximately 12%–15% increase in the daily gas supply by reducing and stabilizing the time interval between consecutively created blocks to 12 seconds. As a result, both the level and variation of median transaction gas prices as of the end of 2022 was

[3]In 'proof of work', miners (special users contributing computing power to operate the platform) compete to solve a computationally-hard cryptographic problem. The first miner to find a solution wins the right to add a new block of transactions to the blockchain and is rewarded with newly-minted ETH currency and the transaction fees (priority fees post-London) of all transactions included in the block.

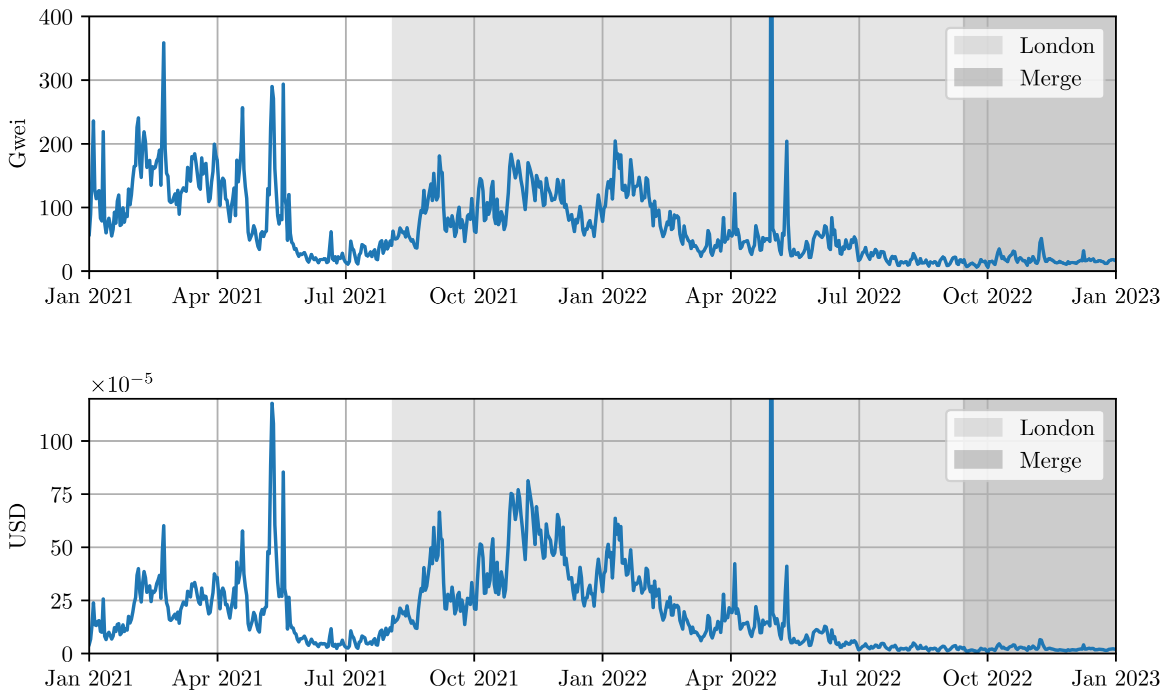
[4]To qualify as a validator, a user must deposit 32 ETH into a designated smart contract. A single validator is randomly selected to serve as the current block builder/proposer and is responsible for constructing and broadcasting the block to the Ethereum platform, along with updating the virtual machine state.

[5]See Jermann (2023) and Kose et al. (2024) for further analysis of users' economic incentives under proof of stake validation.

significantly reduced.

To illustrate the impact of the 2021 London upgrade and the 2022 Merge upgrade on Ethereum gas prices, in Figure 1, we display the daily-aggregated average values of our main variable of interest – the Ethereum gas price, in Gwei and in US dollars (USD), over our period of analysis January 1, 2021 to December 31, 2022.[6] The block median gas price reached more than 200 Gwei in early 2021, was about 60 Gwei on August 5, 2021, the date of transition to base fee plus priority fee gas price ('London upgrade'), rose again to about 180 Gwei in September-October 2021, then fell to about 18 Gwei on September 15, 2022, the date of transition to proof-of-stake ('Merge upgrade') and stayed at similarly low values until the end of 2022.[7]

Figure 1: Gas price



Notes: The Figure plots the daily average of the block median gas price over the studied period, measured in Gwei (10^{-9} ETH) in the top panel, and in US dollars (USD) in the bottom panel. The vertical red lines mark the August 5, 2021 London upgrade and the September 15, 2022 Merge upgrade. The May 1, 2022 'Bored Ape' NFT release caused a gas price spike to 797 Gwei (truncated in the Figure), see also Ante and Saggu (2024).

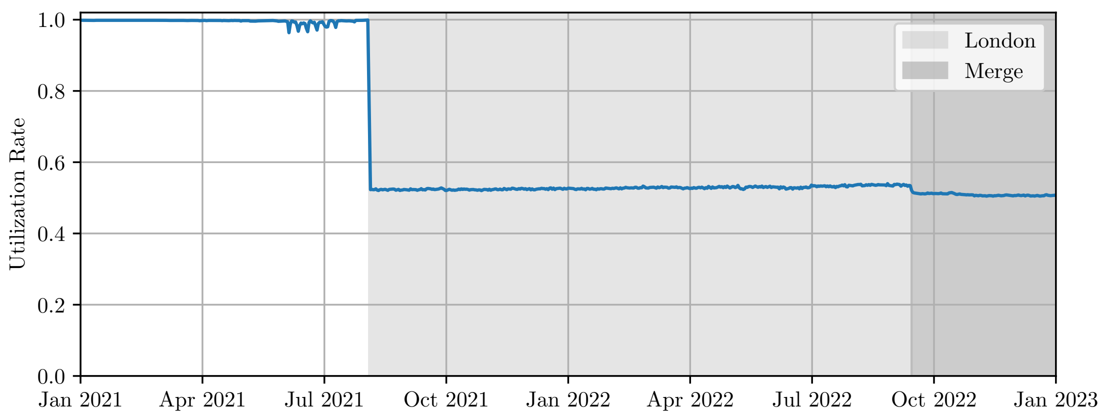
In Figure 2, we display the daily average *block utilization rate*, defined as the total gas used by all transactions included in a given block divided by the block gas limit. As defined, the block

[6]One Gwei equals 10^{-9} Ether (ETH). 1 ETH was worth about $2,700 on August 5, 2021 and about $1,600 on September 15, 2022 (see Figure A1).

[7]On May 1, 2022 the Bored Ape Yacht Club released 100,000 non-fungible tokens (NFTs), a type of digital asset hosted on Ethereum, which caused a significant surge of transaction demand by crypto investors and drove the median gas price from 47 Gwei on April 30, 2022 to 797 Gwei on May 1, 2022.

utilization rate reflects the demand for Ethereum services (in units of gas) relative to the available gas supply (the block gas limit, a system parameter) at a given moment of time. Figure 2 shows that the block utilization rate underwent a substantial and sustained decrease and stabilization immediately after the London upgrade, as intended by the algorithmic fee determination in which deviations above and below 50% utilization trigger upward or downward changes in the block base fee (see Appendix B1). Prior to the August 5, 2021 London upgrade most Ethereum blocks exhibited extremely high congestion, with utilization rates close to 100%. The block utilization fell to 53% immediately after the London upgrade. Following the proof-of-stake (Merge) upgrade on Sep. 15, 2022, the block utilization rate decreased further and stabilized at around 51% on average until the end of our period of analysis.[8]

Figure 2: Block utilization



Notes: the Figure plots the daily average of the block utilization rate, defined as the total gas used by all transactions included in a block divided by the block gas limit (maximum capacity).

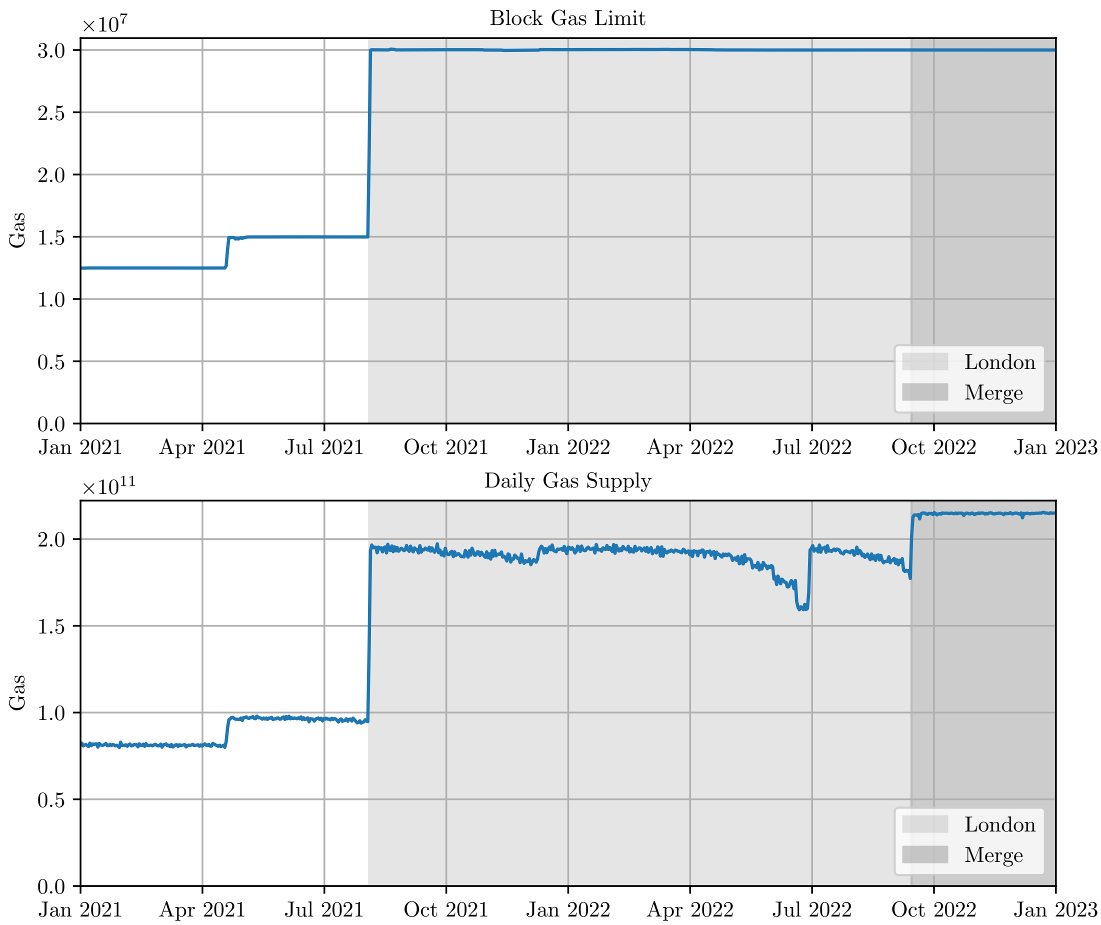
Figure 3 plots the gas supply at the block level and at the daily level over the studied period. The top panel plots the daily average of the *block gas limit*, the algorithmically determined gas supply per block. The sum of the gas requirements of all transactions included in a block cannot exceed the block gas limit. The transaction gas requirement and the gas limit are essential for the operation of Ethereum's Turing-complete virtual machine code and prevent potential issues such as infinite loops, coding errors, network disruptions, and more. The block gas limit was increased from 12.7 million gas to 14 million gas on April 21, 2021 and further to 15 million gas by the end of April 2021. The limit was then doubled to 30 million gas on August 5, 2021 as part of the London upgrade and remained at that level until the end of the studied period.

The bottom panel of Figure 3 plots the average *daily gas supply*, computed by multiplying the

[8]See also Leonardos et al. (2023) who analyze the stability of Ethereum base fees and block utilization and derive near-optimal upper and lower bounds for the time-average block utilization in the EIP-1559 mechanism despite its possibly chaotic evolution.

block gas limit by the daily number of blocks created. The daily gas supply tracks the changes in the block gas limit (the top panel of the figure), with two exceptions. First, the daily gas supply experienced two decreases, one in June 2022 and one right before the Sep. 2022 Merge upgrade as the mining difficulty was intentionally increased as part of the preparatory phase for the transition to proof-of-stake protocol encouraging miners to move away from energy-intensive proof-of-work mining. Second, the daily gas supply increases with the Merge upgrade since more blocks are created per day due to the fixed and predictable block-creation rate (see also Figure 5).

Figure 3: Gas supply



Notes: The Figure plots the daily average of the block gas limit (top panel) and the daily gas supply (bottom panel) over the studied period. The block gas limit is algorithmically determined and defines the total gas available to be used by all transactions included in a block. The daily gas supply is computed by multiplying the block gas limit by the number of blocks created in a day (24 hours) and corresponds to the total daily gas amount available.

We use the observed variation of the Ethereum gas price (transaction fee per unit of complexity) over the studied period, including the major London and Merge platform upgrades, to identify and analyze its demand-side and supply-side determinants using a time-series regression model.

Importantly for identification and for separating demand and supply factors, we use that changes in the gas supply in Ethereum are exogenous, as they arise from algorithmic adjustments to the block gas limit and/or the block creation rate.

We find that in the pre-London period, the median gas price is higher on average when the platform experiences higher block utilization rate, which aligns with economic theory. After the London upgrade, when the algorithmically determined base fee is the predominant part (about 92%) of the gas price, lagged block utilization plays a similar role, that is, a higher utilization rate in the previous block (which leads to a higher base fee in the current block, all else equal) is associated with higher gas prices (see Appendix B2). Second, we find that gas prices are statistically significantly positively associated with the proportion of contract calls in a block, both before and after the London upgrade, with a mitigated effect in the post-London period. Third, we find that in the post-London period, users of legacy transactions pay higher gas prices on average compared to the users of non-legacy transactions. Fourth, the gas price decreases on average as the gas supply within each block (the gas limit) is increased. Overall, we find that the London and Merge upgrades resulted in a sizable reduction of median gas prices as of the end of 2022 and significantly stabilized the variability of Ethereum transaction fees over time.

Related literature

Donmez and Karaivanov (2022) use daily-averaged data to analyze the determinants of the Ethereum gas price and transaction fees in the period Nov. 2017 – Jan. 2019, prior to the 2021 London upgrade, and find that changes in demand are the key gas price determinant. Specifically, when there is high daily platform utilization the gas price increases on average, with a strong positive nonlinear effect above 90% utilization. The authors also find that a larger daily fraction of direct transfers between users is associated with a higher gas price on average.

Liu et al. (2022) study the effect of the London upgrade on Ethereum transaction fees and waiting times using a regression discontinuity approach. Similar to our findings, they document a decrease in the volatility of fees in the post-London period. However, our results further reveal a significant impact on the overall gas price level through changes in the gas price determination mechanism – specifically, the algorithmically determined base fee anchoring gas prices, along with the importance of the block utilization rate as a measure of demand and the block gas limit as measure of gas supply. Brown et al. (2021) empirically show that the Segwit (segregated witness) protocol, which increased the Bitcoin block size, led to a reduction in the congestion rate and transaction fees. Their findings indicate that congestion causes users to bid higher fees to have their transactions processed sooner, consistent with our results for Ethereum. The authors also find that higher Bitcoin price in USD and its volatility lead to higher transaction fees.

Jain et al. (2023) study the impact of network congestion, the six-month return of the platform currency, and the Merge upgrade on transaction fees in Bitcoin and Ethereum using daily-level data. The authors find that transaction fees in USD sharply increase with congestion (measured by the 'mempool' count of waiting transactions), and that the Merge upgrade led to lower transaction fees.[9] Our results, using block-level data and a different measure of congestion (the block utilization rate), characterize the dynamics of transaction fees across three different time periods (pre-London, London, and Merge) and demonstrate the effect of additional demand and algorithmic/supply factors on gas prices. Also using daily-level Ethereum data and first-difference quantile regressions, Koutmos (2023) shows that the count of daily transactions (a measure of demand or congestion) is the factor most consistently associated with the transaction fee level across all gas price quantiles, unlike other variables such as the ETH price or block size. This is consistent with our finding about the positive association between the block utilization rate (a more direct measure of congestion at the block level) and the Ethereum gas price.

Our paper contributes to this literature in several ways. First, unlike previous papers which use data aggregated at the daily level, we use granular block-level data constructed from the universe of more than 900 million transactions directly downloaded from the Ethereum blockchain over the two-year period January 1, 2021 to December 31, 2022. Using block-level data is especially important in the post-London upgrade period, since key gas price determinants such as the base fee and the block utilization rate are determined and vary at the block level. Second, we analyze the changes in the Ethereum gas price and its determinants preceding and following both major recent platform changes, the 2021 London upgrade and the 2022 Merge upgrade, thus spanning a longer time horizon than the papers which focus on the short-term effects of these upgrades. Third, we use time-series regressions and analyze the effect on the gas price of multiple economic factors, both from the demand and the supply side.

2 Data

2.1 Data sources

We downloaded the complete block-level and transaction-level data directly from the Ethereum blockchain for the period January 1, 2021 to December 31, 2022. The block-level data include the block timestamp, block number, miner, size, gas limit (representing the block capacity), gas used

[9]See also Pierro and Rocha (2019) who examine the effect of the number of pending transactions, the ETH price in USD, and the number of miners, on Ethereum transaction fees in the pre-London period and conclude that the number of pending transactions and the number of miners significantly impact transaction fees compared to other variables. On predicting and optimizing gas price fees, see Laurent et al. (2022), Bhatt and Pandey (2024) and Meister and Price (2024).

(the total gas consumed by all transactions included in the block), difficulty level (pre-Merge), number of transactions, and the block base fee (after August 5, 2021).

The transaction-level data contain information about each transaction, including the transaction index within its block, a "nonce" (count of the number of previous transactions originated from the sender's address), the sender's address, the receiver's address, the transaction value in Wei (10^{-18} ETH), the maximum gas for the transaction, the gas price, the transaction type, the maximum fee per gas, the maximum priority fee per gas, and legacy (pre EIP-1559 format) or non-legacy transaction type indicator. We combine the blockchain data with hourly-level data on the USD price of Ether (ETH), the internal digital currency of Ethereum in which the transaction fees are paid, obtained from Cryptocompare.

The main data variables which we use in our empirical analysis are the gas price, the priority fee, the block base fee, the block gas limit, total gas used per block, the transaction type (one of: 'regular' transfer between two addresses, 'contract call', and 'contract creation'), and the ETH price in USD. Our sample period includes 4,657,807 blocks and 870,350,631 transactions in total. We aggregate the raw transaction data at the block level and perform all statistical analysis with block-level data.

2.2 Variables and definitions

Our main variable of interest is the median *block gas price*, defined as the median of the gas prices of all transactions recorded in a given block. We use the median block gas price as a representative statistic of the transaction fees paid by users at a specific moment of time (block). The median is also robust to outliers and extreme values.[10] Additionally, we perform robustness analysis using the bottom 5-th percentile of within-block gas prices in Section 4.3.

We define the *block utilization rate* as the ratio of the total gas used by all transactions in a block to the *block gas limit*. We use the block utilization rate as the variable measuring transaction service demand in the Ethereum platform at the block level, i.e., demand at a specific moment of time, and therefore a key economic factor affecting the block gas price. An alternative measure used by several authors (e.g., Jain et al. (2023), Pierro and Rocha (2019)) is the number of pending transactions ('mempool' size), that is, transactions that have been submitted but not yet validated and executed on the platform.[11] While both variables reflect demand conditions,[12] we chose the

[10]We also ran our main empirical specifications using the mean block gas price and obtained very similar results.

[11]Zhang and Zhang (2023) find that the Merge upgrade significantly reduced transaction waiting times and identify block interval shortening (captured by our daily gas supply variable) as the main contributing factor.

[12]E.g., Pacheco et al. (2023) find that that pending transactions are processed within a median time of 57 seconds and 90% are processed within 8 minutes.

block utilization rate as our preferred measure because it directly reflects the actual usage of block capacity at a given time, thus providing an immediate and precise estimate of transaction demand or congestion. In addition, data on pending transactions is not directly obtainable from the blockchain (third-party sources must be used) and, being a stock variable, the mempool size may not accurately represent current platform conditions. For example, transactions in the mempool may have too low gas fees or be invalid (duplicate or submitted with errors).[13]

As a measure of gas supply, the second key economic factor affecting the gas price, we use the *block gas limit*, which is the total (maximum) gas that all transactions in a block can use. The block gas limit is mostly algorithmically fixed by the platform code, with discrete increases in April 2021 and August 2021, see Figure 3.

Ethereum transactions can be classified into three main types: (i) simple bilateral ETH transfer between two accounts, which we call 'regular' transaction; (ii) 'contract call' transaction, a type of transaction that triggers the execution of a pre-defined function of a smart contract deployed on the platform, e.g., an exchange of a token into ETH; and (iii) 'contract creation' transaction, which deploys a smart contract on the platform. The transaction type and its associated time sensitivity, intent, or function can influence the gas price a user is willing to pay. Since contract creations are a very small fraction of all transactions (about 0.1%), we use the *block contract call share*, defined as the ratio of all contract call transactions to the total number of transactions in a given block, as a measure capturing the effect of changes in the composition of transactions within a block between the two major transaction types (regular transfers vs. contract calls) and, as such, another potential determinant of the gas price.[14]

As previously discussed, the EIP-1559 London upgrade changed how the transaction fee (gas price) is determined and recorded on the blockchain, as the sum of an algorithmic base fee and a user-chosen priority fee. However, pre-London format ('legacy') transactions with fully user-determined gas price, remained valid on the platform, as long as their submitted gas price is not lower than the block base fee. To account for this change in transaction composition and its potential effect on gas prices, we use the *block legacy share*, defined as the proportion of legacy transactions among all transactions in a block (all transactions are legacy prior to August 5, 2021).

We also control for the *ETH price in USD*, as a variable measuring the cost of Ethereum transactions in real (dollar) terms. Since we only have hourly data on the ETH price in USD, we match and merge these price data with the block-level Ethereum data using the block timestamps.

[13] Sousa et al. (2021) use data from 7.2M Ethereum transactions prior to 2020 and find no stable correlation between transaction pending time and the gas price.

[14] Similarly, Ante and Saggu (2024) study the interplay between transaction fees and transaction classification based on different economic subsystems on the Ethereum platform, e.g., cross-blockchain bridges, centralized and decentralized cryptocurrency exchange transactions, NFT and stablecoin transactions.

Table A1 displays summary statistics of the main variables used in our empirical analysis.

2.3 Descriptive findings

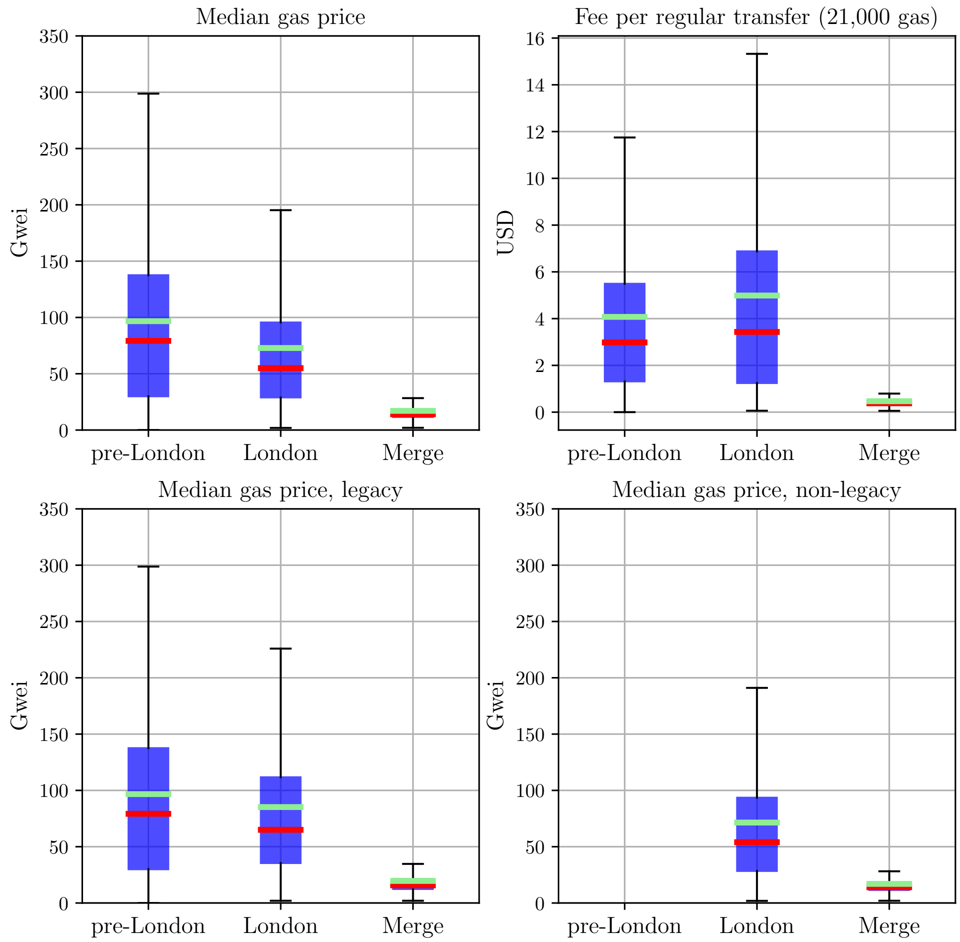
Figure 4 illustrates the gas price distribution in the three time periods we analyze: 'pre-London' (January 1, 2021 to August 4, 2021), 'London' (August 5, 2021 to September 14, 2022), and 'Merge' (September 15, 2022 to December 31, 2022), including separately for legacy and non-legacy transactions. We observe that the median block gas price decreases from approximately 79 Gwei (pre-London) to 55 Gwei after the EIP-1559 switch to base fee plus priority fee model (London), and further to 14 Gwei in the Merge period. The significantly reduced level and volatility of median ETH gas prices after the London and Merge upgrades compared to the pre-London period indicates that the upgrades have helped users in predicting the going transaction fee / gas price level and preventing overpayment.

We also find that users who continue to submit legacy transactions (using the pre-London bid gas price format) after the London upgrade pay higher gas prices (both average and median) compared to the users who submit non-legacy (the new, London format) transactions – 65 Gwei vs. 54 Gwei in the London period and 15.7 Gwei vs. 14 Gwei in the Merge period. In the top-right panel of Figure 4 we display the transaction fee for a 'regular transaction' (ETH transfer between two addresses) in USD. The transaction fee rose on average in the London period, because of the higher price of ETH in USD (see Figure A1) but then decreased in the Merge period as both the ETH price in USD and the gas price fell.

Figure 5 displays the distributions of the block base fee, the block utilization rate, the daily block creation rate, and the ETH price in USD, before and after the London and Merge upgrades. Comparing the London and Merge sub-periods in the top left panel, we note a significant decrease in both the magnitude and the dispersion of the block base fee, which is the main factor determining the gas price level.[15] The block utilization rate (top right panel) experiences a substantial reduction after the London upgrade, from more than 99% on average in the pre-London period to 51% on average as of December 2022. The block utilization rate varies significantly around its average value, notably in the London period. We explore this variation in our empirical analysis in Section 3. While the block gas limit was not changed in the Merge upgrade, the block creation rate (bottom left panel of Figure 5), defined as the number of new blocks created per day, went up from 6,305 blocks per day on average before the Merge to 7,153 blocks per day after the Merge, representing an increase in gas supply per unit of time. The ETH price in USD (bottom right panel) increased from 2,006 USD on average in the pre-London period to 2,994 USD in the London

[15]There is no algorithmic base fee in the pre-London period; instead the whole gas price is bid by the users.

Figure 4: Gas prices by period

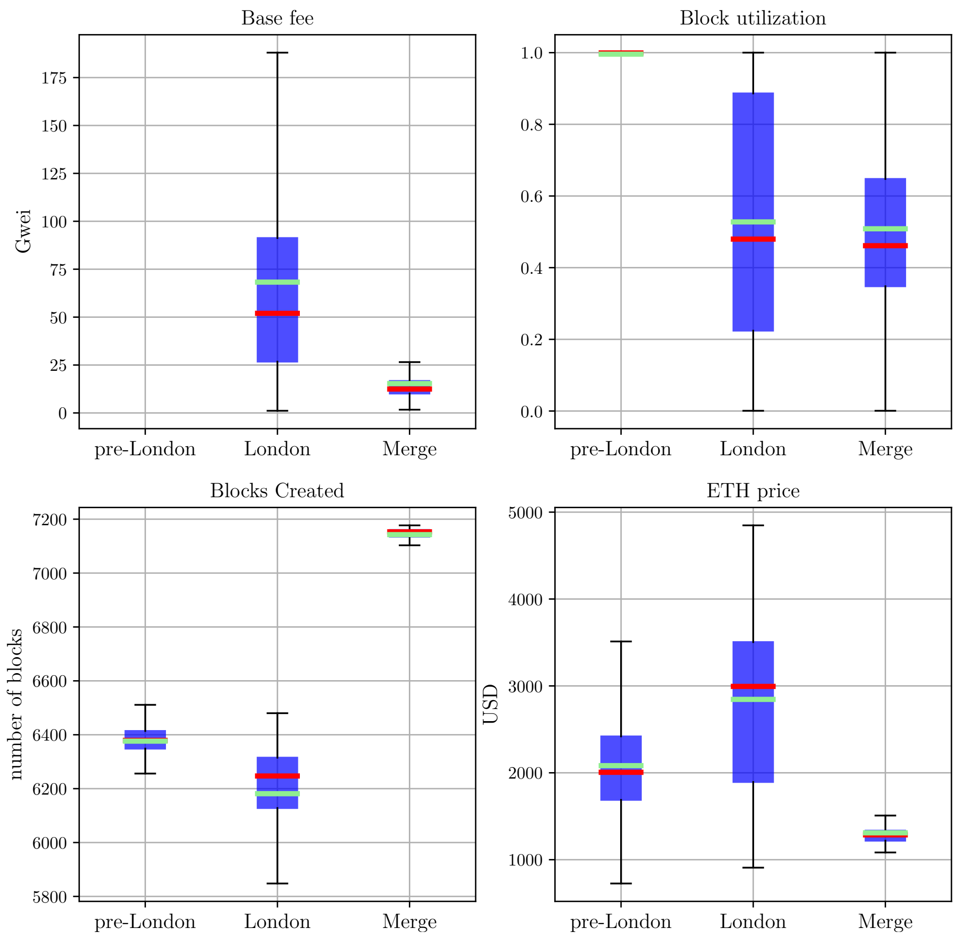


Notes: the top-left panel displays the distribution of the median block gas price in the pre-London, London, and Merge periods. The top-right panel displays the distribution of the US dollar transaction fee per regular transfer, computed by multiplying the median gas price by 21,000 and by the ETH price in USD. The bottom panels display the distribution of the median block gas price for legacy transactions (bottom left) and for non-legacy transactions (bottom right). In each panel and for each time period the blue boxes display the interquartile range (IQR) of the plotted data; the green and red lines denote respectively the data mean and median; and the whiskers extend to all first and fourth quartile observations that are within 1.5 times the IQR.

period and declined to 1,286 USD on average after the Merge upgrade.

In Figure 6 we illustrate the time series behaviour over the studied period of the two transaction type composition variables we consider. The top panel displays the daily average of the contract call share. It remains steady before and after the London upgrade at about 65% on average but increases after the Merge upgrade to about 71% on average. A possible explanation is that the transition from proof of work to proof of stake improved the platform's efficiency and reduced transaction costs and confirmation times, making it more attractive for users to interact with smart/DeFi contracts. Moreover, the Merge upgrade and switch away from energy-intensive mining plausibly spurred greater interest and confidence in Ethereum's long-term viability, lead-

Figure 5: Data Descriptives



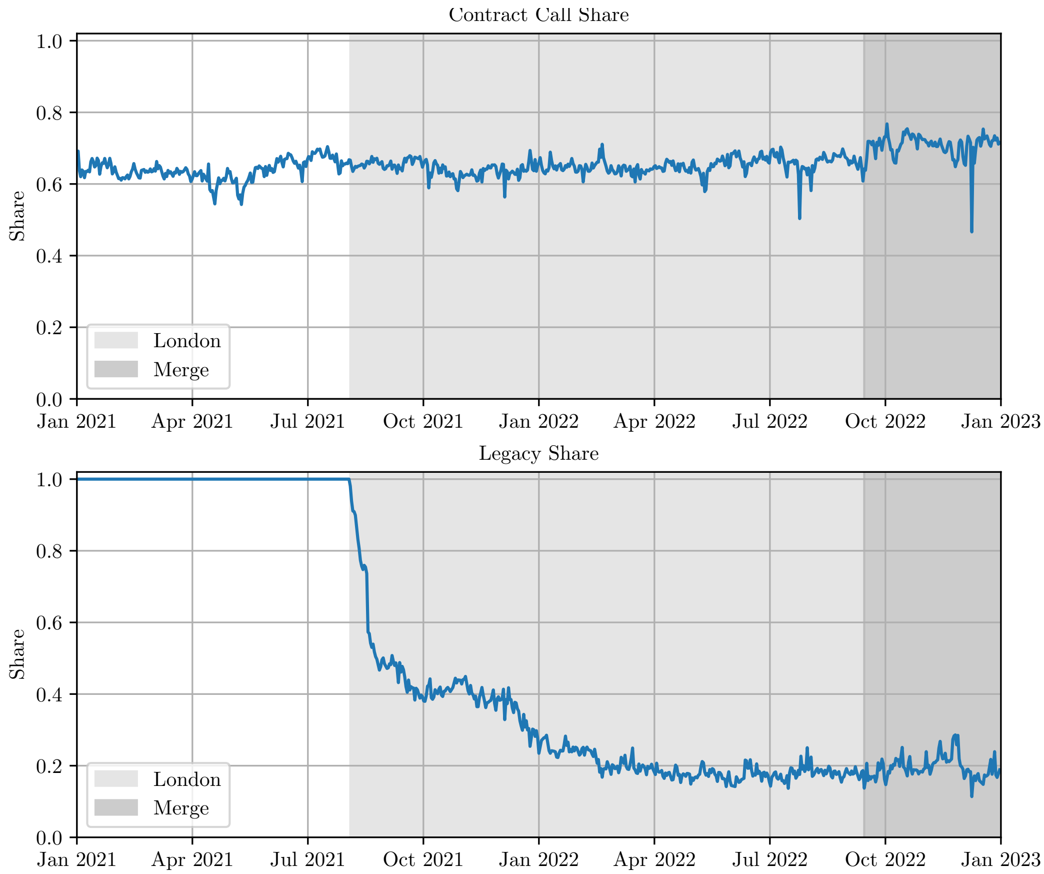
Notes: The Figure plots the distribution of the block base fee, block utilization rate, blocks created per day, and the ETH price in USD in the pre-London, London, and Merge periods. In each panel and for each time period the blue boxes display the interquartile range (IQR) of the plotted data; the green and red lines denote respectively the data mean and median; and the whiskers extend to all first and fourth quartile observations that are within 1.5 times the IQR.

ing to increased development and use of decentralized applications relying on contract calls and contributing to the observed post-Merge contract call share increase.

The bottom panel of Figure 6 plots the daily average of the share of legacy transactions over the studied period. The London upgrade improved the user experience by making transaction fees more predictable and reducing the likelihood of overpaying. This encouraged users to adopt the new EIP-1559 transaction format, leading to a sharp at first and then steady decline in the share of legacy transactions.

Prior to the London upgrade, users bid the gas price they were willing to pay considering their transaction's complexity and gas requirements. If a miner selected a specific transaction to be included in the current block, the user would ultimately pay a total transaction fee calculated

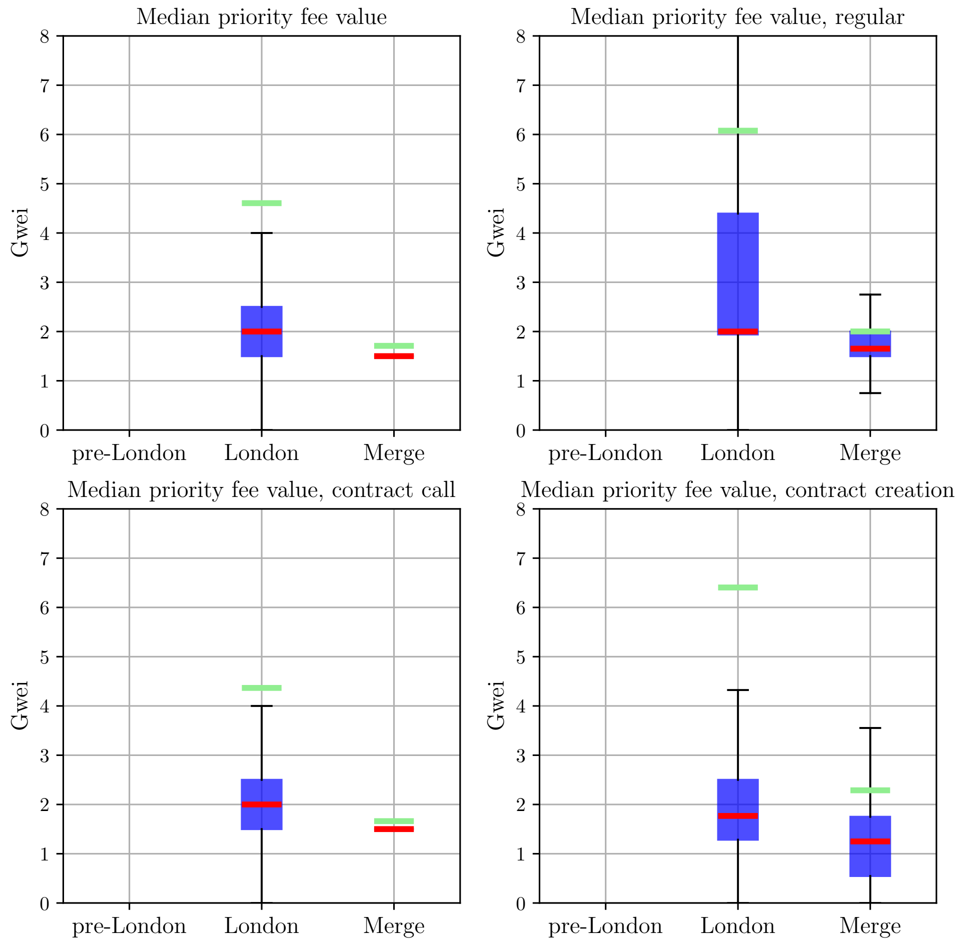
Figure 6: Contract call share and Legacy share over time



Notes: The Figure plots the daily average of the contract call share (top panel) and the legacy transactions share (bottom panel) over the studied period. The light grey shaded area indicates the London period and the darker shaded area indicates the Merge period.

as the *gas price* bid by the user multiplied by the transaction's *gas requirement*. Following the London upgrade, users submitting non-legacy transactions can bid a priority fee, factoring in the mandatory base fee of the current block and the transaction's gas requirement. The sum of the priority fee and the algorithmically determined base fee forms the actual gas price paid by the user. Figure 7 illustrates the distribution of the priority fees per unit of gas submitted by the users, overall and for different transaction types. Priority fees did not exist in the pre-London period. We observe that the median block priority fee decreases from around 2 Gwei in the London period to 1.5 Gwei in the Merge period across all transactions, from 2 Gwei to 1.7 Gwei for regular (ETH transfer) transactions, from 2 Gwei to 1.5 Gwei for contract calls, and from 1.8 Gwei to 1.3 Gwei for contract creations.

Figure 7: Priority fees



Notes: The Figure displays the distribution of priority fees in the pre-London, London, and Merge periods. The top left panel displays the median block priority fee; the top right panel displays the median block priority fee for regular transactions (direct ETH transfer between users); the bottom left panel displays the median block priority fee for contract calls, and the bottom right panel displays the median block priority fee for contract creations. In each panel and for each time period the blue boxes display the interquartile range (IQR) of the plotted data; the green and red lines denote respectively the data mean and median; and the whiskers extend to all first and fourth quartile observations that are within 1.5 times the IQR.

3 Empirical analysis

3.1 Estimation

Our goal is to analyze and quantify the economic determinants of Ethereum transaction fees before and after the London and Merge platform upgrades. Our main dependent variable is thus the gas price which is the transaction fee per unit of computational complexity (gas) in Ethereum. Our baseline empirical specification uses the median block gas price, as a representative and robust to outliers statistic of the fee magnitude paid by users at a specific moment in time.[16]

We consider three main factors that affect gas prices at the block level: gas demand, gas supply, and the composition of transaction types within the block. As explained in Section 2.2, we use the *block utilization rate*, defined as the ratio of the total gas used by all transactions in a block to the *block gas limit*, as a measure of transaction service demand at the block level. We use the *block gas limit* as the algorithmically-determined measure of gas supply (maximum total gas that included transactions can use) at the block level.[17] To account for changes in the within-block transaction type composition which can reflect user or service needs heterogeneity at a specific moment, we use the *contract call share* and the *legacy share*, as defined and justified in Section 2.2. Finally, we control for the real cost of posting transactions by including the *ETH price in USD*. Overall, this leads to the following baseline empirical specification that we estimate for both the pre-London upgrade (pre EIP-1559) and post-London periods:

$$\log(g_t) = \beta_0 + \beta_1 u_t + \beta_2 l_t + \beta_3 c_t + \beta_4 x_t + \epsilon_t \tag{1}$$

where g_t denotes the median gas price[18] in block t, u_t is the block utilization rate in block t, and l_t is the log of the algorithmically determined block gas limit. The variable c_t denotes the contract call share in block t, as defined in Section 2.2, and x_t denotes all other included variables, such as the hourly ETH price in USD and the block legacy transactions share (the latter for the post-London period only). We estimate equation (1) at the block level using OLS with Newey-West (HAC) standard errors robust to heteroskedasticity and serial correlation, including a constant.

We next discuss the expected signs of the regression coefficients in (1) based on the hypothesized economic mechanism of gas price determination. On the demand side, when the platform utilization rate is high, there is greater competition among users to have their transactions recorded in the current block. The reason is that transactions with higher gas prices are prioritized for inclusion because the miners or validators receive the fees for the transactions included in the created block, thus maximizing their profits by sorting submitted transactions in descending order of their bid gas price. Therefore, the predicted effect of the block utilization rate, as an indicator of demand conditions, on the gas price is positive.

On the supply side, the number and complexity of transactions that can be included in a block is constrained by the block gas limit (total supply of gas per block, see Figure 3), which is algorithmically set by code and determines the platform's service rate capacity. A higher block

[16] We also present robustness results using the bottom 5-th percentile of gas prices in Section 4.

[17] See also Section 4.1 where we perform a robustness check using daily gas supply.

[18] To account for observations with zero median gas price (4,535 observations or 0.3% of the pre-London period sample), we add 1 Wei to all block median gas prices before taking logs.

gas limit allows for recording more transactions in a block, all else held equal. Therefore, the predicted effect of the block gas limit on the gas price is negative.

Additionally, we study the effect of the share of contract calls among all transactions included in a block. Our hypothesis is that contract calls are relatively more urgent on average, as they often involve automated time-sensitive interactions with smart contracts, such as token purchases or DeFi trades or exchanges. Consequently, the predicted effect of the block contract call share on the gas price is positive.

We also analyze the impact of the changing share of legacy (pre EIP-1559 format) transactions per block during the post-London period. Figure 4 suggests that, despite having the ability in principle to set a gas price equal to or slightly above the block base fee, users who continued to submit legacy transactions after the London upgrade tend to overpay in fees relative to users who switched to non-legacy (EIP-1559 format) transactions. We thus expect a positive association between the 'legacy share' and the gas price (see Section 3.3 for further discussion).

Finally, since the gas price is paid in ETH (the platform's internal digital currency), a higher ETH price in US dollars increases the users' real monetary cost. This suggests a negative association between the gas price and the ETH price in USD. On the other hand, a higher ETH price in USD can indicate higher interest or demand for Ethereum transactions and services, leading to higher gas prices. The sign of the association between the ETH price in USD and the gas price is therefore undetermined ex-ante and will be estimated in the empirical analysis.

After the London upgrade, the gas price is constructed as the sum of an algorithmically determined base fee and a user-bid priority fee. The block base fee accounts for about 92% of the block gas price on average in our data and is a deterministic function of the utilization rate and the base fee of the immediately preceding block (see Appendix B). In the post-London period we estimate specification (1) using the first lag of the block utilization rate, u_{t-1} (see Table 2). The reason for using the lagged utilization rate is the dependence of the algorithmically determined base fee, which constitutes the major part of the gas price, on the utilization rate of the immediately preceding block. Therefore, by using the lagged block utilization rate in the post-London period, we account for the variation in the base fee resulting from demand conditions.

In the post-London period the user has no direct control over the base fee component of the gas price. Therefore, after the London upgrade, the users' choice variable is the priority fee rather than the full gas price. For the post-London period, we thus estimate the following priority-fee specification in addition to the gas-price specification (1):

$$\log(\pi_t) = \gamma_0 + \gamma_1 \log(b_t) + \gamma_2 u_t + \gamma_3 l_t + \gamma_4 c_t + \gamma_5 x_t + \nu_t \tag{2}$$

where π_t is the median priority fee in block t. The variable b_t denotes the base fee in block t, which is included in equation (2) since the base fee level may affect the magnitude of the priority fee paid by users. For example, when the base fee is relatively high, users may have to submit a relatively higher priority fee in nominal terms to maintain a target 'tip percentage'. The definitions of u_t, l_t, c_t, and x_t are the same as in specification (1) and ν_t is the error term.

In Section 4, we additionally analyze the robustness of our results to alternative variable definitions and specifications: using daily gas supply instead of the block gas limit, an alternative method for accounting for zero gas price and priority fees, and using the bottom 5-th percentile of the gas price instead of the median gas price, as a proxy for the gas price of a marginally included transaction.

3.2 Results

In Table 1 we present estimation results for the pre-London period, using specification (1). The dependent variable is the natural logarithm of the median gas price in each block, measured in Wei (10^{-18} ETH). We find that the block utilization rate (total gas used in the block divided by the block gas limit), which is a proxy for the demand for Ethereum services, is positively and statistically significantly associated with the median gas price, consistent with economic theory. Quantitatively, the estimated coefficient of 4.384 in Table 1, column (1), implies that a 1 percentage point increase in block utilization is associated with a 4.48% increase in the median gas price in Wei, calculated as $100(e^{0.01\times 4.384} - 1)$. Considering that the average value of the block median gas price in our sample is 96.6 Gwei (see Table A1), this implies that a user submitting a transaction with gas requirement (complexity) of 100,000 gas would pay, on average, $96.6 \times (100,000) \times (4.48\%) =$ 432,768 Gwei (about 1 USD) more following a 0.01 increase in block utilization in the pre-London period.

We also find that the block gas limit, defined as the total gas supply per block (an algorithmically determined quantity) is negatively and statistically significantly associated with the median gas price. The estimate of -11.10 in column (1) of Table 1 indicates that a 1% increase in the block gas limit is associated with an 11.10% lower median gas price on average.

The block contract call share, defined as the fraction of all contract call transactions among all transactions in the block, has a positive and statistically significant coefficient estimate. This suggests that contract call transactions are associated with higher gas prices bid by the users, on average. The estimate of 1.347 in column (1) means that a 1 percentage point increase in the contract call share is associated with a 1.36% increase in the median gas price. The estimated coefficient on the ETH price in USD (the ETH/USD exchange rate) is also positive and statistically

Table 1 Pre-London Results, Gas Price
January 1, 2021 to August 4, 2021

	log median gas price, Wei	
	(1)	(2)
	levels	first differences
block utilization	4.384***	3.394***
	[0.127]	[0.138]
log block gas limit	-11.10***	-27.42***
	[0.059]	[2.496]
block contract call share	1.347***	1.835***
	[0.037]	[0.041]
log ETH price in USD	1.344***	n.a.
	[0.018]	–
adj. R-squared	0.187	0.032
sample size	1,377,279	1,377,278

p-values: $^{*}\ p < 0.1$, $^{**}\ p < 0.05$, $^{***}\ p < 0.01$

Notes: OLS regressions with block-level data including a constant. Newey-West (HAC) standard errors robust to heteroskedasticity and serial correlation are reported in the square brackets (Newey and West (1987)). In column (1) the dependent variable 'log median gas price' is the natural logarithm of the median gas price in Wei (10^{-18} ETH) of all transactions within a block; 'block utilization' is the ratio of the total gas used by all transactions in a block to the gas limit of that block; 'log block gas limit' is the natural logarithm of the block gas limit; 'block contract call share' is the number of contract call transactions in a block divided by the total number of transactions in that block; 'log ETH price in USD' is the natural logarithm of the hourly Ether (ETH) price in USD. In column (2) the dependent and independent variables are the first differences of the respective block-level variables from column (1). To account for the observations with zero median gas price (4,535 observations or 0.3% of the sample) we add 1 Wei to all block median gas prices before taking logs.

significant, consistent with the hypothesis that higher Ether prices may be associated with higher demand for blockchain transactions. For example, an increase in the dollar price of ETH may attract more traders or investors to Ethereum, leading to a higher transaction volume. The resulting increase in demand for block space would drive gas prices up, as the users compete by offering higher fees to have their transactions processed quicker.

To ensure robustness against possible non-stationarity issues, in Table 1 column (2) we also report estimation results from a specification in which all variables are the first differences of the respective block-level variables from column (1), excluding the ETH price in USD which is measured hourly.[19] Our results from column (1) on the relationship between block utilization, the block gas limit, the contract call share, and the median gas price in the pre-London period remain robust.

In Table 2 we estimate a modified version of specification (1) using data from the time period

[19] We also performed the augmented Dickey-Fuller (ADF) test (Dickey and Fuller (1979)) for stationarity with the time series variables used in Tables 1 and 2. We reject the null hypothesis that a unit root is present for all series at the 95% or higher confidence level, except for the ETH price in USD in the post-London period.

Table 2 Post-London Results, Gas Price
August 6, 2021 – December 31, 2022

	log median gas price, Wei			
	London		London + Merge	
	(1)	(2)	(3)	(4)
	levels	first differences	levels	first differences
L.block utilization	0.108***	0.131***	0.110***	0.129***
	[0.001]	[0.0001]	[0.001]	[0.0001]
log block gas limit	-8.875***	-4.247***	-7.979***	-4.294***
	[0.987]	[0.078]	[1.008]	[0.078]
block contract call share	0.174***	-0.026***	0.150***	-0.025***
	[0.009]	[0.0006]	[0.009]	[0.0007]
log ETH price in USD	1.410***	n.a.	1.379***	n.a.
	[0.007]	–	[0.0077]	–
block legacy share	0.084***	0.162***	0.095***	0.149***
	[0.008]	[0.0007]	[0.008]	[0.0008]
adj. R-squared	0.418	0.292	0.557	0.281
sample size	2,503,393	2,503,392	3,267,660	3,267,659

p-values: $^{*}\, p < 0.1$, $^{**}\, p < 0.05$, $^{***}\, p < 0.01$

Note: OLS regressions with block-level data including a constant. Newey-West (HAC) standard errors robust to heteroskedasticity and serial correlation are reported in the square brackets. In columns (1) and (3) the dependent variable 'log median gas price' is the natural logarithm of the median gas price in Wei (10^{-18} ETH) of all transactions within a block; 'L.block utilization' is the first lag of block utilization, defined as the ratio of the total gas used by all transactions in a block to the gas limit of that block; 'log block gas limit' is the natural logarithm of the block gas limit; 'block contract call share' is the number of contract call transactions in a block divided by the total number of transactions within that block; 'log ETH price in USD' is the natural logarithm of the hourly Ether (ETH) price in USD; 'block legacy share' is the number of transactions in a block using the pre-London legacy (bid gas price) format divided by the total number of transactions in that block. In columns (2) and (4), the dependent and independent variables are the first differences of the respective block-level variables from columns (1) and (3). To control for the algorithmic increase in the block creation rate in the Merge period, in columns (3) and (4) we also include a dummy variable which equals 0 before Sep. 15, 2022 and 1 from Sep. 15 onward. Columns (1) and (2) use data from the period Aug. 6, 2021 to Sep. 14, 2022; columns (3) and (4) use data from the period Aug. 6, 2021 to Dec. 31, 2022.

after the London upgrade. We divide this period into two: "London period", spanning from August 6, 2021 to September 14, 2022 and "Merge period", from September 16, 2022 to December 31, 2022.[20] According to the algorithmic base fee formula (see Appendix B for details), the base fee of block t is determined by the utilization rate and the base fee of the immediately preceding block, $t-1$. Since the base fee is very persistent and makes up for about 92% of the gas price on average, in our post-London analysis in Table 2, instead of the time-t block utilization rate which does not affect the time-t base fee, we use the first lag (time $t-1$) of block utilization (L.block utilization) in equation (1) to capture the impact of demand conditions on the gas price.

[20]We omit from the sample the date of the London upgrade, August 5, 2021 and the date of the Merge upgrade, September 15, 2022 since there is a mix of regimes on these dates.

In Table 3 we additionally estimate the impact of the time-t block utilization rate on the priority fee component of the gas price.

In Table 2, column (1) we find that the (lagged) block utilization rate is positively and statistically significantly associated with the median gas price in the post-London period. The estimate of 0.108 in column (1) implies that a 1 percentage point increase in the previous block's utilization is associated with a 0.11% higher median gas price. A larger block gas limit (larger gas supply) is associated with a lower median gas price, in line with economic theory and with the pre-London results in Table 1. A larger share of contract call transactions and larger ETH price in USD are each associated with a higher gas price in columns (1) and (3), as in our pre-London results.

In Table 2 we additionally control for the 'block legacy share', defined as the fraction of legacy (pre-London format) transactions in the block. This captures the post-London change in the composition of legacy format (bid gas price) vs. new format (base fee plus priority fee) transactions submitted by users. We find that a larger legacy share is associated with a higher median gas price on average, consistent with our findings in Figure 4 that legacy users tend to submit higher gas prices in the post-London period compared to non-legacy users. The estimate of 0.084 in column (1) suggests that a 1 percentage point increase in the block legacy share is associated with a 0.084% larger median gas price in Wei. Taking into account that the average block median gas price in this period is 72.8 Gwei (see Table A1), a user executing a transaction with complexity 100,000 gas would pay on average $72.8 \times (100,000) \times (0.084\%) =$ 6,115 Gwei (about 1.7 US cents) more when the block legacy share is higher by 0.01.

In Table 2, columns (2) and (4), we also report estimation results for a first-differences specification of our empirical model. Our main results remain robust, with the only exception being the estimate of the block contract call share which turns negative in the first-differenced specification. In columns (3) and (4) of Table 2 (the combined London+Merge period) we additionally control for the algorithmic increase in the block creation rate after the Merge upgrade (see Figure 5) by including a dummy variable that equals 0 before Sep. 15, 2022 and 1 from Sep. 15 onward.

In Table 3, we present the results from estimating equation (2) for the post-London period, using the priority fee component of the gas price as the dependent variable.[21] This specification isolates the current demand conditions driven user-bid effect on the gas price. In columns (1) and (3) we find that a larger block utilization rate is associated with a higher priority fee on average, consistent with our earlier results but with lower magnitude. The estimate of 0.094 in column (1) implies that a 1 percentage point increase in the block utilization rate is associated

[21]The priority fee is directly recorded in the blockchain data for all non-legacy transactions. For the legacy (pre-London format) transactions, we compute the implied priority fee as the difference *gas price - base fee*, where *gas price* is the user-bid gas price and *base fee* is the base fee of the block in which the transaction is recorded.

Table 3 Post-London Results, Priority Fee
August 6, 2021 to December 31, 2022

	log median priority fee, Wei			
	London		London + Merge	
	(1)	(2)	(3)	(4)
	levels	first differences	levels	first differences
block utilization	0.094***	-0.002	0.066***	-0.032***
	[0.003]	[0.004]	[0.003]	[0.003]
log block gas limit	-20.83***	-33.91***	-22.83***	-34.69***
	[1.012]	[1.755]	[1.025]	[1.793]
block contract call share	2.119***	2.601***	1.837***	2.306***
	[0.037]	[0.044]	[0.032]	[0.040]
log ETH price in USD	-0.282***	n.a.	-0.216***	n.a.
	[0.006]	–	[0.005]	–
block legacy share	2.631***	3.865***	2.429***	3.467***
	[0.011]	[0.024]	[0.011]	[0.024]
log block base fee	0.177***	1.493***	0.159***	1.242***
	[0.003]	[0.025]	[0.002]	[0.023]
adj. R-squared	0.170	0.165	0.165	0.145
sample size	2,503,394	2,503,393	3,267,661	3,267,660

p-values: $^{*}\,p < 0.1$, $^{**}\,p < 0.05$, $^{***}\,p < 0.01$

Note: OLS regressions with block-level data including a constant. Newey-West (HAC) standard errors robust to heteroskedasticity and serial correlation are reported in the square brackets. In columns (1) and (3) the dependent variable 'log median priority fee' is the natural logarithm of the median priority fee in Wei (10^{-18} ETH) among all transactions within a block (imputed for legacy transactions as the difference between the gas price and the block base fee); 'block utilization' is the ratio of the total gas used by all transactions in a block to the gas limit of that block; 'log block gas limit' is the natural logarithm of the block gas limit; 'block contract call share' is the number of contract call transactions in a block divided by the total number of transactions in that block; 'log ETH price in USD' is the natural logarithm of the hourly Ether (ETH) price in USD; 'block legacy share' is the number of legacy transactions in a block divided by the total number of transactions in that block. 'log block base fee' is the natural logarithm of the base fee on a given block. In columns (2) and (4), the dependent and independent variables are the first differences of the respective block-level variables in columns (1) and (3). To control for the algorithmic increase in the block creation rate in the Merge period, in columns (3) and (4) we include a dummy variable which equals 0 before Sep. 15, 2022 and 1 for Sep. 15 onward. Columns (1) and (2) use data from Aug. 6^{th}, 2021 to Sep. 14^{th}, 2022 while columns (3) and (4) use data from Aug. 6^{th}, 2021 to Dec. 31^{st}, 2022. To account for the observations with zero median priority fee (9,289 observations or 0.3% of the sample) we add 1 Wei to all median priority fees before taking logs.

with a 0.094% increase in the median priority fee in Wei, holding the block base fee constant. Given that the average value for the block median priority fee in the 'London' period is 4.6 Gwei (see Table A1), a user executing a transaction with complexity 100,000 gas would pay on average $4.6 \times (100,000) \times (0.094\%) = 432.4$ Gwei higher priority fee following a 0.01 increase in the block utilization rate. Comparing to our pre-London results in Table 1, this suggests a lower sensitivity of the gas price (holding the base fee constant) to the current block utilization rate in the post-London period.

The coefficient estimate for the block gas limit in Table 3 is statistically significantly negative and large in magnitude in all specifications – for example, the value -20.83 in column (1) means that a 1% increase in the block gas limit is associated with a 20.83% larger median priority fee paid by users. The block contract call share is positively and statistically significantly associated with the median priority fee on average, as in Tables 1 and 2. The estimate of 2.119 suggests that a 0.01 larger contract call transaction share is associated with a 2.14% higher priority fee on average.

We also find that the block median priority fee is negatively and statistically significantly associated with the ETH price in USD, holding all else constant and controlling for the block base fee. A higher ETH price in USD implies larger real costs of paying the transaction fee, the major share of which is the mandatory base fee. Our results suggest that users tend to offer lower priority fees (smaller tip) on average when the USD price of ETH is higher. For example, the estimate of -0.282 in column (1) of Table 3 implies that a 1% increase in the ETH dollar price is associated with a 0.3% lower priority fee on average.

As in our Table 2 results for the gas price in the post-London period, we find that a larger block legacy share is associated with higher priority fees on average and with larger coefficient estimates (higher elasticity). We also find that a higher base fee, which reflects higher demand in the immediately preceding blocks, is associated with higher priority fees on average, in line with the theoretical expectations. The first-difference specifications in columns (2) and (4) of Table 3 are consistent with the results in levels from columns (1) and (3), with one exception of an opposite sign for block utilization in column (4).

3.3 Discussion

Our empirical results can be summarized in the following main findings holding at the block level: (i) median gas prices are positively associated with the block utilization rate (a measure of platform demand), (ii) median gas prices have a negative association with the block gas limit (a measure of gas supply), (iii) median gas prices have a positive association with the within-block share of contract call transactions, (iv) legacy transactions pay higher gas fees on average than EIP-1559 transactions, and (v) the ETH price in US dollars is positively associated with the median gas price.

Findings (i) and (ii) indicate reassuringly that the basic economic laws of supply and demand hold on the Ethereum blockchain platform and the block utilization rate and block gas limit are useful proxies for system-level demand and supply at the block frequency (12-15 seconds). These findings suggest that Ethereum is a well-functioning digital marketplace with a gas price determination mechanism reflecting correctly the ongoing market conditions and individual user incentives and behaviour.

Finding (iii) shows a positive association between the gas price and the contract call share capturing the composition of transactions between regular bilateral transfers and contract calls at a given moment of time and controlling for all other factors included in our empirical specification. Since contract calls do not have significantly higher gas prices than regular transfers on average (see Figure A2), a possible behavioral mechanism consistent with this finding is that users choose to initiate more contract calls during periods of higher platform activity and fees, possibly reflecting increased trading or DeFi transactions (e.g., automated calls to exchanges, token purchases, and others). We also observe that the median gas price is more sensitive to the contract call share in the pre-London period than in the post-London period (compare Tables 1 and 2), likely explained by the base fee anchoring effect on the gas price after the EIP-1559 upgrade.

Finding (iv) documents that users posting legacy transactions tend to pay higher gas fees on average. A possible behavioral explanation could be that legacy users set a static gas price, unlike EIP-1559 users who set a max priority fee and a max fee, which together provide a safety net against overpaying. Consequently, risk-averse legacy users may be likely to bid higher gas prices to avoid their transactions being stuck during periods of high service demand. The difference between the gas prices of legacy vs. nonlegacy transactions is illustrated on Figure A3, expressed as a multiple of the median base fee and smoothed at the monthly level for clearer visualization. We observe that the degree of 'overpayment' for legacy transactions (both regular and contract calls) relative to EIP-1559 non-legacy transactions stays in the range of 15-20% of the base fee until May 2022 (a period of high fees, see Figure 1), then rises to 50% of the base fee in summer 2022 and falls back to 20% or less after the Sep. 2022 Merge upgrade. The persistence of about 18-22% daily share of legacy transactions as of the end of 2022 observed on Figure 6 may be explained by a fraction of users operating outdated software clients or being otherwise unaware of the platform upgrades.

Finally, finding (v), the positive association between the US dollar price of Ether and gas prices, is consistent with the behavioral hypothesis that a higher ETH price in USD may indicate or correlate with higher interest or utility from Ethereum services offsetting the larger real-terms transaction cost.

4 Robustness analysis

4.1 Alternative supply measure – daily gas supply

In Table A2, for the pre-London period, and in Tables A3 and A4, for the post-London period, we estimate a variant of our main specifications in Tables 1, 2, and 3 where instead of using the block gas limit we use the *daily gas supply*, defined as the sum of the gas limits of all blocks recorded on a given calendar day. This specification accounts for variations in the gas supply on a daily scale by capturing both the impact of the block gas limit (gas supply per block), as in the baseline tables, and in addition the *number of blocks created* per day. Our main results from Tables 1–3 remain robust and we find that the daily gas supply has the expected negative association with the gas price or the priority fee.

4.2 Alternative accounting for zeros

The median bid gas price in the pre-London period equals 0 for 0.3% of the observations in our sample. Since the dependent variable in our empirical specification is log of the gas price in Wei, in our baseline regressions in Table 1 we add 1 Wei (10^{-18} ETH) to all gas prices (in comparison the median gas price over the pre-London period is 79.2 Gwei = 79.2bln Wei, see Table A1), so that we retain these observations in our sample and keep them as close to the raw data as possible. Alternatively, in Table A5 we deal with the zero gas price observations in the pre-London period in a different way, by replacing log(0) with zero. Our main results from Table 1 regarding the positive association between the block median gas price and the block utilization, the block contract call share and the ETH price in USD and the negative association between the block median gas price and the block gas limit remain essentially identical. In Table A6, we perform the same robustness check for the priority fee model in the post-London period where 0.3% of the priority fee observations equal zero. Our baseline results from Table 3 remain unchanged.

4.3 Alternative dependent variable – 5-th percentile of the gas price

In our baseline results we used the block median gas price, as a representative and robust-to-outliers statistic of block-level gas prices. Given the users' incentive to have their transactions executed with the lowest possible fee, we also perform a robustness check targeting transactions that are low-cost or at the margin of being included in a block. Furthermore, low- vs. high-fee transactions may respond differently to demand and supply conditions. Specifically, we re-estimate our baseline specifications using the within-block bottom 5-th percentile gas price instead of the median gas price. We chose the 5-th percentile instead of the minimum gas price in the block to avoid any abnormally low-fee transactions or outliers.

In Tables A7 and A8, we present results using the bottom 5-th percentile of the block gas price as the dependent variable in specifications (1) and (2). The estimates in Table A7 for the pre-London period have the same signs and are similar to our baseline estimates using the block median gas price in Table 1, with slightly larger estimated coefficients. In Table A8, we perform the same robustness exercise for the post-London gas price specification. Our baseline results from Table 2 remain robust, except for the estimate of the block legacy share, which in Table A8 is negatively associated with the 5-th percentile gas price in columns (1) and (3), however, this result is not robust, as seen in the first-differenced specifications in columns (2) and (4).

5 Conclusions

The Ethereum blockchain recently underwent two significant code updates (the 'London' and 'Merge' upgrades), which represent a pivotal shift in the platform's economic model of transaction fee determination and operational dynamics. We analyze the economic implications of these platform upgrades by focusing on the Ethereum gas price, that is, transaction fee per unit of computational complexity. We use a large dataset of block and transaction level data directly downloaded from the Ethereum blockchain and spanning two years and nearly 900 million transactions. We consider both demand-driven factors such as the utilization/congestion rate and the transaction type composition, as well as supply factors, such as the block gas limit and block creation rate.

We document the impact of the London upgrade on the gas price determination mechanism through the introduction of a base fee plus priority fee model which significantly reduced block congestion and stabilized the transaction fees paid by users. These effects were further enhanced by the Merge upgrade, a shift from proof-of-work to a proof-of-stake consensus mechanism, which drastically reduced the platform's energy consumption and enhanced its transaction processing efficiency.

Our empirical analysis reveals key economic determinants influencing the Ethereum gas price. Prior to the August 2021 London upgrade, when the gas price was fully determined by users' bids/offers, we document very high block utilization rates (nearly 100%) and elevated gas prices. These high utilization rates and prices were mitigated after the London upgrade through the algorithmic determination of the base fee which rises when utilization is high and falls when utilization is low, and an increase in the block gas limit. In the post-London period we show that the variability of gas prices substantially decreased and there was an overall reduction in the gas price, affirming the upgrades' effectiveness in addressing the pre-London platform congestion and inefficiencies.

Using time-series regression analysis, we find that the block utilization rate is significantly and positively associated with gas prices prior to the London upgrade. After the London upgrade, the first lag of block utilization has a similar effect, attributable to the algorithmic determination of the base fee which is a direct function of the prior-block utilization rate. We also analyze the impact of the within-block transaction type composition on gas prices and find that a larger fraction of contract call transactions is associated with higher gas prices, suggesting that contract call transactions may be more urgent on average. Additionally, we find that 'legacy transactions', that is, transactions that continue using the pre-London gas price bidding format, pay higher gas prices on average in the post-London period. Consistent with economic theory, a higher block gas limit, reflecting increased gas supply, is statistically significantly associated with lower gas prices in both the pre-London and post-London periods.

We contribute to the growing economics literature on blockchain platforms by providing a granular, block-level data analysis of Ethereum's transaction fee dynamics and the underlying supply and demand economic factors affecting them. The transition toward a more predictable, stable, and efficient transaction fee mechanism, coupled with the drastic reduction in electric energy consumption after the London and Merge upgrades enhances Ethereum's scalability and sustainability and sets a leading example for future blockchain and digital platform innovations.

Declaration of funding

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Disclosure of interest

The authors declare that they have no competing interests.

Data availability statement

All data used are in the paper are publicly available and accessible from the Ethereum blockchain, e.g., via the infura.io API. The USD price of ETH data is publicly available from https://min-api.cryptocompare.com/.

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Appendix A – Additional tables and figures

Table A1 Summary statistics

	Full sample, January 1, 2021 – December 31, 2022					
Variables	Obs.	Mean	Std	25^{th} pctile	50^{th} pctile	75^{th} pctile
Median gas price, Gwei	4,657,807	70.6	115.8	19	47	99
Base fee, Gwei	3,277,292	55.8	105.3	14.6	37	77.3
Block utilization	4,657,807	0.66	0.34	0.35	0.74	0.99
Contract call share	4,657,807	0.65	0.13	0.59	0.67	0.74
Legacy share	4,657,807	0.48	0.37	0.16	0.31	1.00
ETH price, 10^3 USD	4,657,807	2.36	0.99	1.51	2.13	3.11
Gas limit, 10^6 gas/block	4,657,807	25.1	7.47	15	30	30
	Pre-London period, January 1, 2021 – August 4, 2021					
	Obs.	Mean	Std	25^{th} pctile	50^{th} pctile	75^{th} pctile
Median gas price, Gwei	1,377,279	96.6	90.4	30	79.2	137.5
Base fee, Gwei	n.a.	-	-	-	-	-
Block utilization	1,377,279	0.99	0.03	0.99	0.99	0.99
Contract call share	1,377,279	0.63	0.15	0.56	0.66	0.74
Legacy share	1,377,279	1.00	0.00	1.00	1.00	1.00
ETH price, 10^3 USD	1,377,279	2.08	0.06	1.68	2.00	2.41
Gas limit, 10^6 gas/block	1,377,279	13.7	1.24	12.4	12.5	14.9
	London period, August 6, 2021 – September 14, 2022					
	Obs.	Mean	Std	25^{th} pctile	50^{th} pctile	75^{th} pctile
Median gas price, Gwei	2,503,394	72.8	138.1	29	55	95.5
Median priority fee, Gwei	2,503,394	4.6	63.6	1.5	2	2.5
Base fee, Gwei	2,503,394	68.2	117.4	26.7	51.9	91.2
Block utilization	2,503,394	0.52	0.33	0.22	0.48	0.88
Contract call share	2,503,394	0.64	0.13	0.58	0.66	0.73
Legacy share	2,503,394	0.28	0.21	0.13	0.23	0.39
ETH price, 10^3 USD	2,503,394	2.84	0.98	1.89	2.99	3.50
Gas limit, 10^6 gas/block	2,503,394	30	0.04	30	30	30
	Merge period, September 16, 2022 – December 31, 2022					
	Obs.	Mean	Std	25^{th} pctile	50^{th} pctile	75^{th} pctile
Median gas price, Gwei	764,267	17	18.5	11.6	14	18.3
Median priority fee, Gwei	764,267	1.7	12.5	1.5	1.5	1.5
Base fee, Gwei	764,267	15.3	13.3	10.1	12.4	16.6
Block utilization	764,267	0.50	0.24	0.34	0.46	0.64
Contract call share	764,267	0.70	0.10	0.66	0.72	0.77
Legacy share	764,267	0.19	0.10	0.12	0.17	0.23
ETH price, 10^3 USD	764,267	1.31	0.12	1.21	1.28	1.33
Gas limit, 10^6 gas/block	764,267	30	0.001	30	30	30

Note: Summary statistics aggregated to the block level. The base fee was introduced on August 5, 2021; before that, the entire gas price was bid by users.

Table A2 Pre-London, Gas Price – Robustness (using daily gas supply)
(January 1, 2021 to August 4, 2021)

	log median gas price, Wei	
	(1)	(2)
	levels	first differences
block utilization	4.341***	3.383***
	[0.127]	[0.139]
log daily gas supply	-11.74***	n.a.
	[0.064]	–
block contract call share	1.319***	1.837***
	[0.037]	[0.041]
log ETH price in USD	1.351***	n.a.
	[0.018]	–
adj. R-squared	0.183	0.032
sample size	1,377,279	1,377,278

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

Notes: OLS regressions with block-level data including a constant. Newey-West (HAC) standard errors robust to heteroskedasticity and serial correlation are reported in the square brackets. The dependent variable 'log median gas price' is the natural logarithm of the median gas price in Wei (10^{-18} ETH) of all transactions within a block; 'block utilization' is the ratio of the total gas used by all transactions in a block to the gas limit of that block; 'log daily gas supply' is the natural logarithm of the gas limit of all blocks recorded on a given day; 'block contract call share' is the number of contract call transactions in a block divided by the total number of transactions in that block; 'log ETH price in USD' is the natural logarithm of the hourly Ether (ETH) price in USD. To account for the observations with zero median gas price (4,535 observations or 0.3% of the sample) we add 1 Wei to all block median gas prices before taking logs.

Table A3 Post-London, Gas Price – Robustness (using daily gas supply)
(August 6, 2021 – December 31, 2022)

	log median gas price, Wei			
	London		London + Merge	
	(1)	(2)	(3)	(4)
	levels	first differences	levels	first differences
L.block utilization	0.111***	0.131***	0.114***	0.129***
	[0.001]	[0.0001]	[0.001]	[0.0001]
log daily gas supply	-4.597***	n.a.	-4.302***	n.a.
	[0.086]	–	[0.089]	–
block contract call share	0.179***	-0.025***	0.153***	-0.025***
	[0.009]	[0.0006]	[0.009]	[0.0007]
log ETH price in USD	1.589***	n.a.	1.543***	n.a.
	[0.007]	–	[0.007]	–
block legacy share	0.100***	0.163***	0.112***	0.149***
	[0.008]	[0.0008]	[0.007]	[0.0008]
adj. R-squared	0.443	0.291	0.571	0.280
sample size	2,503,393	2,503,392	3,267,660	3,267,659

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

Note: OLS regressions with block-level data including a constant. Newey-West (HAC) standard errors robust to heteroskedasticity and serial correlation are reported in the square brackets. In columns (1) and (3) the dependent variable 'log median gas price' is the natural logarithm of the median gas price in Wei (10^{-18} ETH) of all transactions within a block; 'L.block utilization' is the first lag of block utilization, defined as the ratio of the total gas used by all transactions in a block to the gas limit of that block; 'log daily gas supply' is the natural logarithm of the total gas supplied on the day block t is recorded; 'block contract call share' is the number of contract call transactions in a block divided by the total number of transactions within that block; 'log ETH price in USD' is the natural logarithm of the hourly Ether (ETH) price in USD; 'block legacy share' is the number of transactions in a block using the pre-London legacy (bid gas price) format divided by the total number of transactions in that block. In columns (2) and (4), the dependent and independent variables are the first differences of the respective block-level variables from columns (1) and (3). To control for the algorithmic increase in the block creation rate in the Merge period, in columns (3) and (4) we also include a dummy variable which equals 0 before Sep. 15, 2022 and 1 from Sep. 15 onward. Columns (1) and (2) use data from the period Aug. 6, 2021 to Sep. 14, 2022; columns (3) and (4) use data from the period Aug. 6, 2021 to Dec. 31, 2022.

Table A4 Post-London, Priority Fee – Robustness (using daily gas supply)
(August 6, 2021 to December 31, 2022)

	log median priority fee, Wei			
	London		London + Merge	
	(1)	(2)	(3)	(4)
block utilization	0.092***	-0.009***	0.064***	-0.038***
	[0.003]	[0.004]	[0.003]	[0.003]
log daily gas supply	-0.215***	n.a.	-0.346***	n.a.
	[0.046]	–	[0.044]	–
block contract call share	2.119***	2.604***	1.837***	2.309***
	[0.037]	[0.044]	[0.032]	[0.040]
log ETH price in USD	-0.281***	n.a.	-0.209***	n.a.
	[0.007]	–	[0.006]	–
block legacy share	2.642***	3.866***	2.440***	3.468***
	[0.011]	[0.024]	[0.011]	[0.024]
log block base fee	0.175***	1.470***	0.157***	1.222***
	[0.003]	[0.025]	[0.003]	[0.023]
adj. R-squared	0.170	0.165	0.165	0.145
sample size	2,503,394	2,503,393	3,267,661	3,267,660

P-values: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Note: OLS regressions with block-level data including a constant. Newey-West (HAC) standard errors robust to heteroskedasticity and serial correlation are reported in the square brackets. In columns (1) and (3) the dependent variable 'log median priority fee' is the natural logarithm of the median priority fee in Wei (10^{-18} ETH) among all transactions within a block (imputed for legacy transactions as the difference between the gas price and the block base fee); 'block utilization' is the ratio of the total gas used by all transactions in a block to the gas limit of that block; 'log daily gas supply' is the natural logarithm of the total gas supplied on the day block t is recorded; 'block contract call share' is the number of contract call transactions in a block divided by the total number of transactions in that block; 'log ETH price in USD' is the natural logarithm of the hourly Ether (ETH) price in USD; 'block legacy share' is the number of legacy transactions in a block divided by the total number of transactions in that block. 'log block base fee' is the natural logarithm of the base fee on a given block. In columns (2) and (4), the dependent and independent variables are the first differences of the respective block-level variables in columns (1) and (3). To control for the algorithmic increase in the block creation rate in the Merge period, in columns (3) and (4) we include a dummy variable which equals 0 before Sep. 15, 2022 and 1 for Sep. 15 onward. Columns (1) and (2) use data from Aug. 6^{th}, 2021 to Sep. 14^{th}, 2022 while columns (3) and (4) use data from Aug. 6^{th}, 2021 to Dec. 31^{st}, 2022. To account for the observations with zero median priority fee (9,289 observations or 0.3% of the sample) we add 1 Wei to all median priority fees before taking logs.

Table A5 Pre-London, Gas Price – Robustness (replace log(0) with 0)
(January 1, 2021 to August 4, 2021)

	log median gas price, Wei	
	(1)	(2)
	levels	first differences
block utilization	4.384***	3.395***
	[0.127]	[0.139]
log block gas limit	-11.10***	-27.44***
	[0.060]	[2.497]
block contract call share	1.347***	1.835***
	[0.037]	[0.041]
log ETH price in USD	1.344***	n.a.
	[0.018]	–
adj. R-squared	0.187	0.032
sample size	1,377,279	1,377,278

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

Notes: OLS regressions with block-level data including a constant. Newey-West (HAC) standard errors robust to heteroskedasticity and serial correlation are reported in the square brackets. In column (1) the dependent variable 'log median gas price' is the natural logarithm of the median gas price in Wei (10^{-18} ETH) of all transactions within a block; 'block utilization' is the ratio of the total gas used by all transactions in a block to the gas limit of that block; 'log block gas limit' is the natural logarithm of the block gas limit; 'block contract call share' is the number of contract call transactions in a block divided by the total number of transactions in that block; 'log ETH price in USD' is the natural logarithm of the hourly Ether (ETH) price in USD. In column (2) the dependent and independent variables are the first differences of the respective block-level variables from column (1). To account for the observations with zero median gas price (4,535 observations or 0.3% of the sample) we replace the natural logarithm of zero with zero.

Table A6 Post-London Results, Priority Fee – Robustness (replace log(0) with 0)
(August 6, 2021 to December 31, 2022)

	log median priority fee, Wei			
	London		London + Merge	
	(1)	(2)	(3)	(4)
	levels	first differences	levels	first differences
block utilization	0.093***	-0.002	0.066***	-0.032***
	[0.003]	[0.004]	[0.003]	[0.003]
log block gas limit	-20.84***	-33.93***	-22.85***	-34.72***
	[1.031]	[1.758]	[1.026]	[1.795]
block contract call share	2.121***	2.604***	1.839***	2.309***
	[0.038]	[0.044]	[0.033]	[0.040]
log ETH price in USD	-0.282***	n.a.	-0.216***	n.a.
	[0.006]	–	[0.005]	–
block legacy share	2.632***	3.868***	2.429***	3.469***
	[0.012]	[0.024]	[0.011]	[0.024]
log block base fee	0.177***	1.495***	0.159***	1.244***
	[0.003]	[0.025]	[0.002]	[0.023]
adj. R-squared	0.170	0.165	0.165	0.145
sample size	2,503,394	2,503,393	3,267,661	3,267,660

P-values: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Note: OLS regressions with block-level data including a constant. Newey-West (HAC) standard errors robust to heteroskedasticity and serial correlation are reported in the square brackets. In columns (1) and (3) the dependent variable 'log median priority fee' is the natural logarithm of the median priority fee in Wei (10^{-18} ETH) among all transactions within a block (imputed for legacy transactions as the difference between the gas price and the block base fee); 'block utilization' is the ratio of the total gas used by all transactions in a block to the gas limit of that block; 'log block gas limit' is the natural logarithm of the block gas limit; 'block contract call share' is the number of contract call transactions in a block divided by the total number of transactions in that block; 'log ETH price in USD' is the natural logarithm of the hourly Ether (ETH) price in USD; 'block legacy share' is the number of legacy transactions in a block divided by the total number of transactions in that block. 'log block base fee' is the natural logarithm of the base fee on a given block. In columns (2) and (4), the dependent and independent variables are the first differences of the respective block-level variables in columns (1) and (3). To control for the algorithmic increase in the block creation rate in the Merge period, in columns (3) and (4) we include a dummy variable which equals 0 before Sep. 15, 2022 and 1 for Sep. 15 onward. Columns (1) and (2) use data from Aug. 6, 2021 to Sep. 14, 2022 while columns (3) and (4) use data from Aug. 6, 2021 to Dec. 31, 2022. To account for the observations with zero median priority fee (9,289 observations or 0.3% of the sample) we replace the natural logarithm of zero with zero.

Table A7 Pre-London Results, Gas Price – Robustness (5th percentile gas price)
(January 1, 2021 to August 4, 2021)

	log pct5 gas price, Wei	
	(1)	(2)
	levels	first differences
block utilization	5.612***	4.525***
	[0.171]	[0.185]
log block gas limit	-11.77***	-34.32***
	[0.067]	[3.861]
block contract call share	3.051***	3.742***
	[0.038]	[0.042]
log ETH price in USD	1.665***	n.a.
	[0.020]	–
adj. R-squared	0.139	0.059
sample size	1,377,279	1,377,278

P-values: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Notes: OLS regressions with block-level data including a constant. Newey-West (HAC) standard errors robust to heteroskedasticity and serial correlation are reported in the square brackets. In column (1) the dependent variable 'log pct5 gas price' is the natural logarithm of the 5th percentile gas price in Wei (10^{-18} ETH) of all transactions within a block; 'block utilization' is the ratio of the total gas used by all transactions in a block to the gas limit of that block; 'log block gas limit' is the natural logarithm of the block gas limit; 'block contract call share' is the number of contract call transactions in a block divided by the total number of transactions in that block; 'log ETH price in USD' is the natural logarithm of the hourly Ether (ETH) price in USD. In column (2) the dependent and independent variables are the first differences of the respective block-level variables from column (1). To account for the observations with zero 5th percentile gas price (7,958 observations or 0.6% of the sample) we add 1 Wei to all block 5th percentile gas prices before taking logs.

Table A8 Post-London Results, Gas Price – Robustness (5th percentile gas price)
(August 6, 2021 – December 31, 2022)

	log pct5 gas price, Wei			
	London		London + Merge	
	(1)	(2)	(3)	(4)
	levels	first differences	levels	first differences
L.block utilization	0.093***	0.118***	0.098***	0.119***
	[0.001]	[0.00009]	[0.001]	[0.0001]
log block gas limit	-8.639***	-4.720***	-7.639***	-4.734***
	[1.003]	[0.065]	[1.024]	[0.065]
block contract call share	0.185***	-0.009***	0.158***	-0.013***
	[0.009]	[0.0004]	[0.009]	[0.0004]
log ETH price in USD	1.454***	n.a.	1.420***	n.a.
	[0.007]	–	[0.007]	–
block legacy share	-0.068***	0.004***	-0.050***	0.001***
	[0.008]	[0.0004]	[0.008]	[0.0004]
adj. R-squared	0.414	0.361	0.556	0.360
sample size	2,503,393	2,503,392	3,267,660	3,267,659

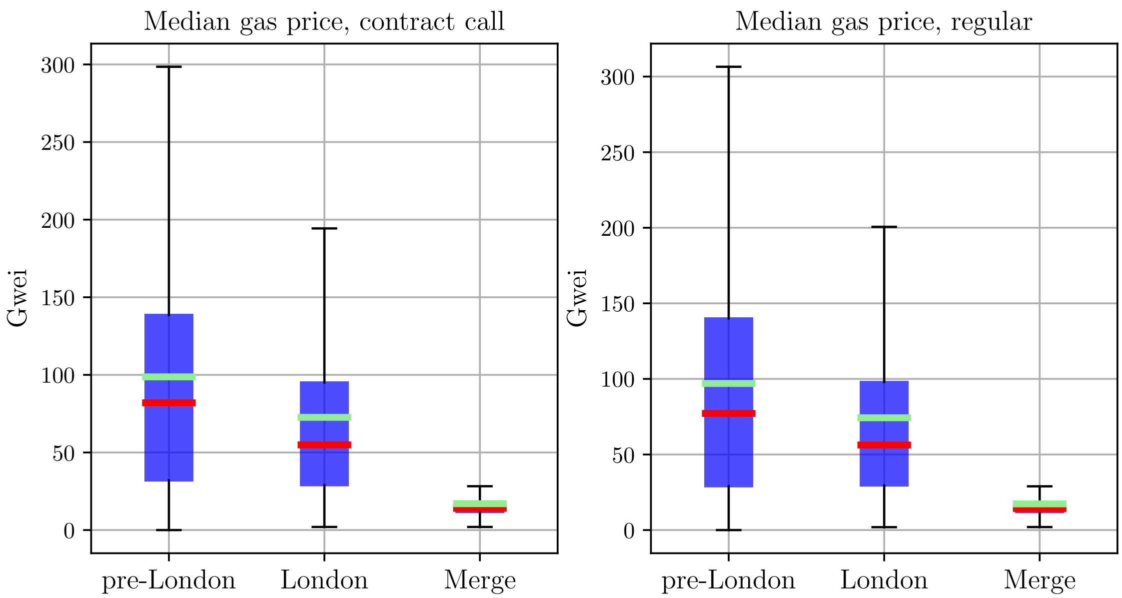
P-values: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Note: OLS regressions with block-level data including a constant. Newey-West (HAC) standard errors robust to heteroskedasticity and serial correlation are reported in the square brackets. In columns (1) and (3) the dependent variable 'log pct5 gas price' is the natural logarithm of the 5th percentile gas price in Wei (10^{-18} ETH) of all transactions within a block; 'L.block utilization' is the first lag of block utilization, defined as the ratio of the total gas used by all transactions in a block to the gas limit of that block; 'log block gas limit' is the natural logarithm of the block gas limit; 'block contract call share' is the number of contract call transactions in a block divided by the total number of transactions within that block; 'log ETH price in USD' is the natural logarithm of the hourly Ether (ETH) price in USD; 'block legacy share' is the number of transactions in a block using the pre-London legacy (bid gas price) format divided by the total number of transactions in that block. In columns (2) and (4), the dependent and independent variables are the first differences of the respective block-level variables from columns (1) and (3). To control for the algorithmic increase in the block creation rate in the Merge period, in columns (3) and (4) we also include a dummy variable which equals 0 before Sep. 15, 2022 and 1 from Sep. 15 onwards. Columns (1) and (2) use data from the period Aug. 6, 2021 to Sep. 14, 2022; columns (3) and (4) use data from the period Aug. 6, 2021 to Dec. 31, 2022.

Figure A1: ETH Price in USD

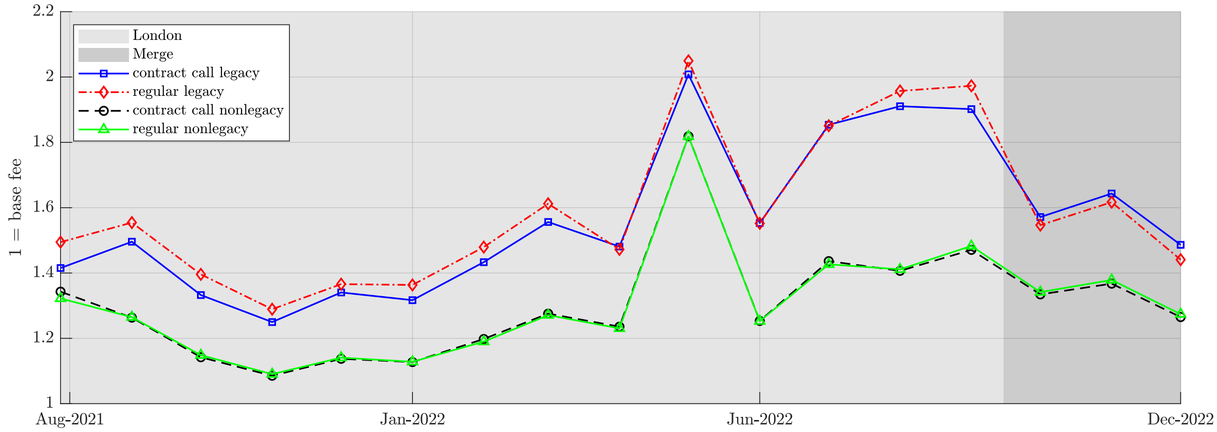
Notes: The Figure plots the daily average ETH price in US dollars (USD) over the sample period.

Figure A2: Gas prices by transaction type



Notes: The Figure plots the distribution of the median gas price for contract calls and regular transfers in the pre-London, London, and Merge periods. In each panel and for each time period the blue boxes display the interquartile range (IQR) of the plotted data; the green and red lines denote respectively the data mean and median; and the whiskers extend to all first and fourth quartile observations that are within 1.5 times the IQR.

Figure A3: Gas price relative to base fee (monthly averages)



Notes: The Figure plots the median gas price by transaction type normalized by the median block base fee, averaged from daily data over each month.

Appendix B

B1. Base fee determination

As of the August 5, 2021 London upgrade, the Ethereum gas price consists of a “base fee” and a “priority fee”. The base fee of block t is algorithmically determined by the utilization rate and the base fee in the previous block $t-1$,

$$BaseFee_t = BaseFee_{t-1} \times (1 + \frac{1}{8} \times \frac{GasUsed_{t-1} - GasTarget}{GasTarget}) \tag{3}$$

where t is the block number and *GasTarget* is algorithmically set to 15 million (15M) gas which is half of the post-London block *GasLimit* (30M). By construction, the base fee can thus increase or decrease by a maximum of 12.5% from one block to the next, with the magnitude of the increase or decrease determined by the magnitude of the deviation between the observed block utilization and the 50% utilization target.

B2. Post-London gas price structure

After the London upgrade the Ethereum gas price, g_t equals the sum of an algorithmically determined base fee, b_t and a user-supplied optional priority fee, $\pi_t \geq 0$,

$$g_t = b_t + \pi_t \tag{4}$$

Using (3), the definition of the block utilization rate, $u_{t-1} = \frac{GasUsed_{t-1}}{GasLimit}$, and $GasLimit = 2 \times GasTarget = 30$M gas, we obtain:

$$\begin{aligned}\log(b_t) &= \log(b_{t-1}) + \log(1 + \frac{1}{8} \times \frac{GasUsed_{t-1} - GasTarget}{GasTarget}) \\ &= \log(b_{t-1}) + \log(1 + \frac{1}{4} \times \frac{GasUsed_{t-1} - 15M}{30M}) \\ &= \log(b_{t-1}) + \log(\frac{7}{8} + \frac{1}{4} \times u_{t-1})\end{aligned}$$

Thus, the block t base fee, b_t, which constitutes the major part of the gas price, is a deterministic function of the previous block's utilization rate, u_{t-1} and its base fee, b_{t-1}. Substituting for b_t into (4), we see that the gas price g_t can be expressed as a deterministic function f of the preceding block's (lagged) utilization rate and base fee, plus the priority fee,

$$g_t = f(u_{t-1}, b_{t-1}) + \pi_t \tag{5}$$