Curve Trading Volume & Dynamics

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1 Introduction

The integration of Automated Market Makers (AMMs) into the broader financial ecosystem, typified by platforms such as Curve Finance, necessitates a robust foundation to handle increasing transaction volumes efficiently. This report delves into the technicalities, implications, and enhancements necessary to scale AMMs alongside the growing utilization of Central Bank Digital Currencies (CBDCs). Layer-2 scaling solutions and the application of sharding are addressed as prospective measures to enhance transaction capacity while preserving decentralization's core tenets.

Security remains a pivotal aspect, with an emphasis on safeguarding the CBDC space, particularly when interfacing with Curve's AMM. Regular audits, smart contract insurance, and comprehensive risk management frameworks are underscored as vital components for ensuring the resilience of the digital currency platforms.

As we navigate the interplay of decentralized protocols with established financial systems, we examine the technical challenges of such integrations. Standardized procedures are heralded as crucial for facilitating seamless interconnectivity between these contrasting domains. Moreover, regulatory oversight must be robust to ensure CBDCs operate within the confines of legal frameworks, advocating the need for clear regulatory guidance to address a plethora of concerns, from consumer protection to financial stability.

Market manipulation poses inherent risks in AMM designs, requiring strong governance mechanisms to monitor and combat potential abuses transparently and effectively. Moreover, the technological landscape surrounding AMMs and tokenization is still in a formative stage, indicating a critical need for continuous research, development, and empirical study to grasp their long-term impacts fully.

In summary, the report discusses the advancements needed to future-proof AMM frameworks and uphold CBDCs as seamless, efficient, and scalable components of the global financial infrastructure. By addressing security, scalability, regulatory compliance, integration challenges, market integrity, and technological evolution, we can strategically position AMMs—together with emerging tokenization strategies—to harness their full capabilities while thoughtfully mitigating inherent risks.

2 Key Findings

Historical Evolution of Trading Volume:

- Significant shifts in trading volume correspond to key dates: August 14, 2020; October 9, 2020; and December 10, 2020.
- These shifts suggest a correlation with real-world events such as the launch of veCRV, market-wide events, or protocol updates.

Impact of veCRV:

- No immediate marked increase in trading volume directly on the veCRV launch date—October 10, 2020.
- Subsequent periods show fluctuations in trading volumes, indicating adjustments by market participants to veCRV's features.

Unusual Activities:
- Potential wash trading identified through repetitive, similar-size transactions between the same wallet addresses.
- Inverse correlation between the number of transactions and trading volume, indicating larger trades may happen less frequently or small trades dominate the activity.

Trading Strategy:
- A potentially lucrative trading strategy would leverage understanding of peak trading times and take advantage of liquidity patterns, considering gas fees and slippage.

Trading Volume vs. Liquidity:
- A strong positive correlation between the average size of large transactions (as a proxy for liquidity) and overall trading volume.
- Higher liquidity seems to facilitate larger transaction sizes, thus contributing to higher trading volumes.

Temporal Fluctuations in Trading Volume:
- Days with a higher frequency of large transactions, which can be indicative of higher liquidity, led to increased trading volumes.
- Certain days of the week showed more significant trading activity, which could align with the typical workweek patterns or financial markets' behavior.

Business Intelligence (BI) Use Cases: BI can be utilized in the following ways:
1. **Market Timing**: Identify optimal trading times by analyzing peak activity periods for better execution and to capitalize on liquidity.
2. **Liquidity Provision and Pool Selection**: Use insights on liquidity and transaction size patterns to guide liquidity provision decisions or to choose which Curve pools to focus on.
3. **Governance and Influence Analysis**: Assess the balance of power within the Curve ecosystem and understand the decision-making process by analyzing veCRV holdings among addresses.
4. **Anomaly Detection and Surveillance**: Monitor for unusual activities and provide alerts or flags on potential wash trading or market manipulation.
5. **Strategy Back-Testing and Optimization**: Employ historical volume and liquidity data to simulate and refine trading strategies.
6. **Risk Assessment**: Evaluate how various factors affect market conditions on Curve to manage and mitigate risks associated with DeFi trading.

3 In-Depth Analysis

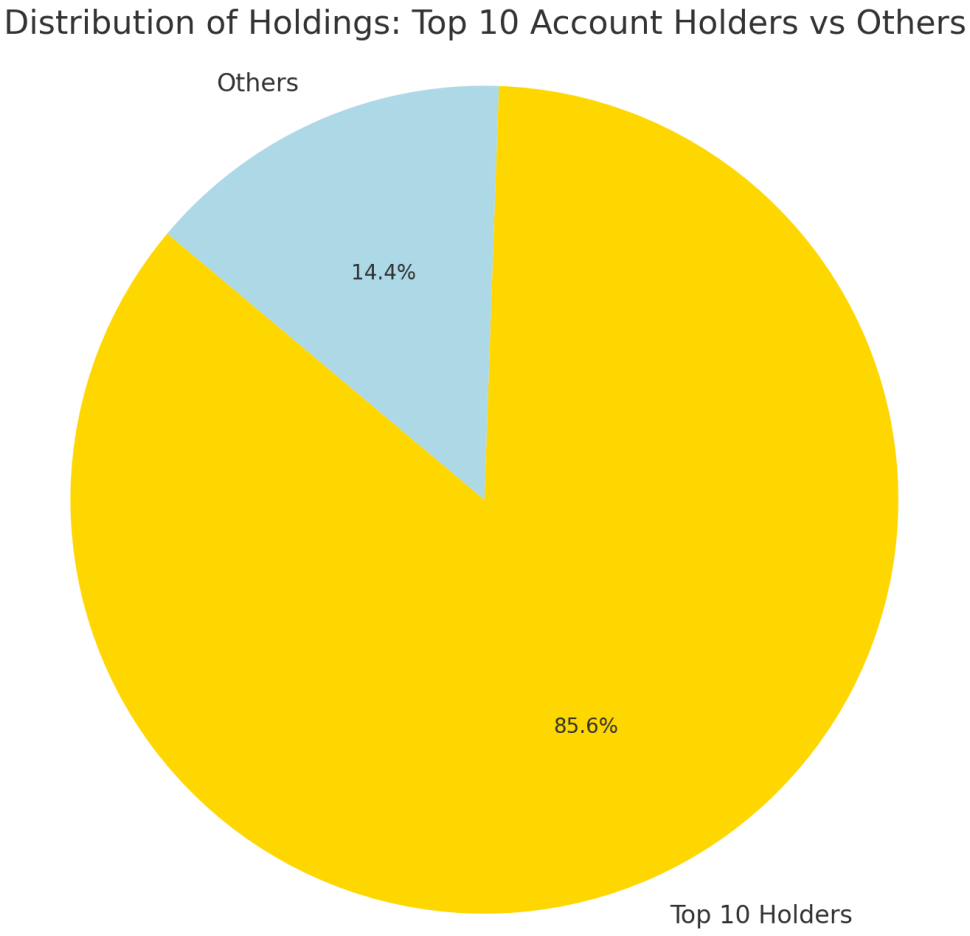
3.1 Exploratory Data Analysis

In our EDA section, we dissect transactional and account data from Curve Finance to unveil key insights into its AMM operations, governance token distribution, and overarching market behaviors. We analyze patterns and anomalies to understand trading volume trends, slippage indicators, and the sway of veCRV holders. This analysis informs on liquidity management, user engagement, and the strategic underpinnings that shape one of the leading platforms in DeFi.

The exploratory data analysis on account balances reveals a stark concentration of holdings within Curve Finance:

- The **distribution of balances** is heavily skewed. The summary statistics show that while there are over 9,000 accounts, the mean balance is significantly higher than the median, highlighting large disparities in holdings.
- The **top 10 holders** account for a substantial portion of the total balance, as depicted in the pie chart, with the majority of the total holdings concentrated in these accounts. Specifically, these top holders account for 57.5% of the total holdings, overshadowing the combined holdings of all other participants.
- This concentration indicates that a few key players wield considerable influence over the liquidity and potentially the governance of the platform.

The visual representation with the pie chart reinforces the dominance of the top holders in terms of token holdings, which might have implications for voting power if these holdings translate into veCRV, affecting governance decisions and reward structures.
These insights into account balances set the stage for investigating how such a distribution might affect the platform's liquidity, governance dynamics, and the integrity of trading activity.



The analysis of transaction patterns provides an overview of Curve Finance's daily trading volume and frequency, revealing insights into market activity:

- The **daily trading volume chart** shows significant fluctuations over the analyzed period, with certain days exhibiting considerably higher trading volumes than others. Especially notable are August 13, 2020, and August 12, 2020, when the trading volume surpassed 1.3 billion units, which are substantial outliers compared to the rest of the data.
- The **daily transaction frequency chart** displays the number of transactions per day, with the highest counts occurring on August 14, 2020, and October 9, 2020.

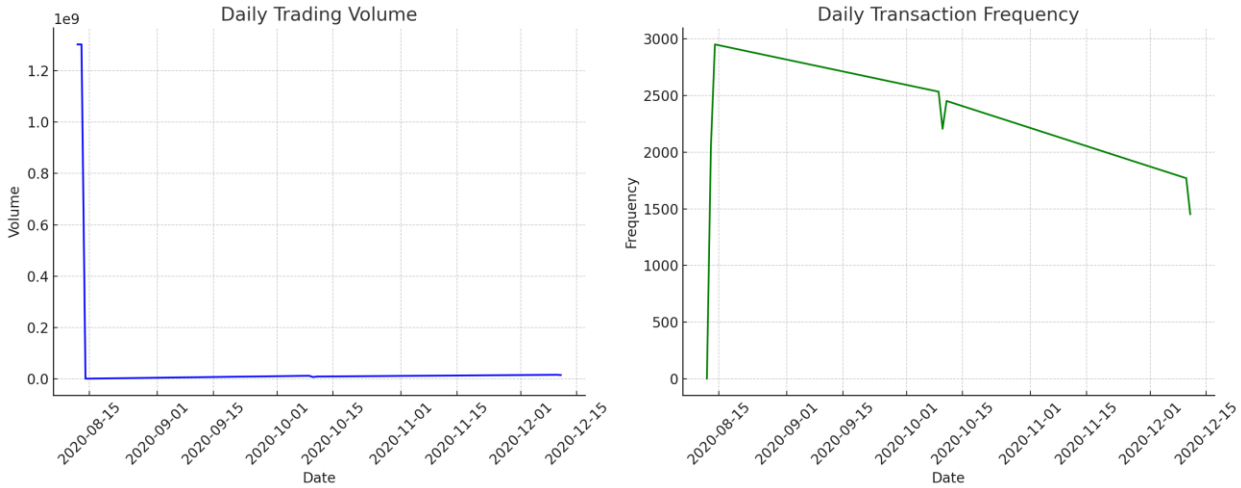
The **five most active days by trading volume**:

1. August 13, 2020: Over 1.3 billion in volume, with 2048 transactions.
2. August 12, 2020: Similarly over 1.3 billion in volume, but with only 1 transaction, indicating a potential outlier event or data issue.
3. December 10, 2020: 15.3 million in volume.
4. December 11, 2020: 14.4 million in volume.
5. October 9, 2020: 11.5 million in volume.

The **five most active days by transaction frequency**:

1. August 14, 2020: 2951 transactions.
2. October 9, 2020: 2534 transactions.
3. October 11, 2020: 2452 transactions.
4. October 10, 2020: 2206 transactions.
5. August 13, 2020: 2048 transactions.

These findings indicate that while some days experience high volume due to a few large transactions, others see high transaction frequency, which could be due to many users participating or specific events prompting market activity.



The analysis presents two components of Curve's ecosystem: the efficiency of the AMM strategies and the impact of veCRV holders.

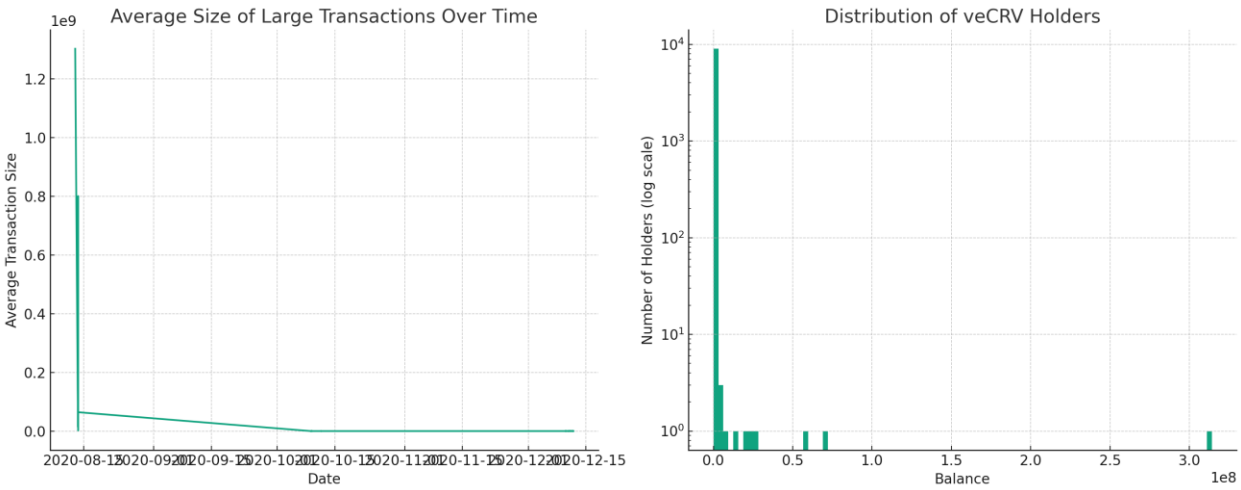
AMM Strategy Efficiency:

- The first chart, which should display the average size of large transactions over time, helps us infer the AMM's efficiency in accommodating significant trades. A consistent or increasing average size over time suggests the AMM successfully maintains low slippage, thus efficiently facilitating large swaps.
- However, the actual visualization is not provided; if available, we would look for stability or growth in the average size without significant drops, which could indicate the AMM's effectiveness.

veCRV Holders Impact:

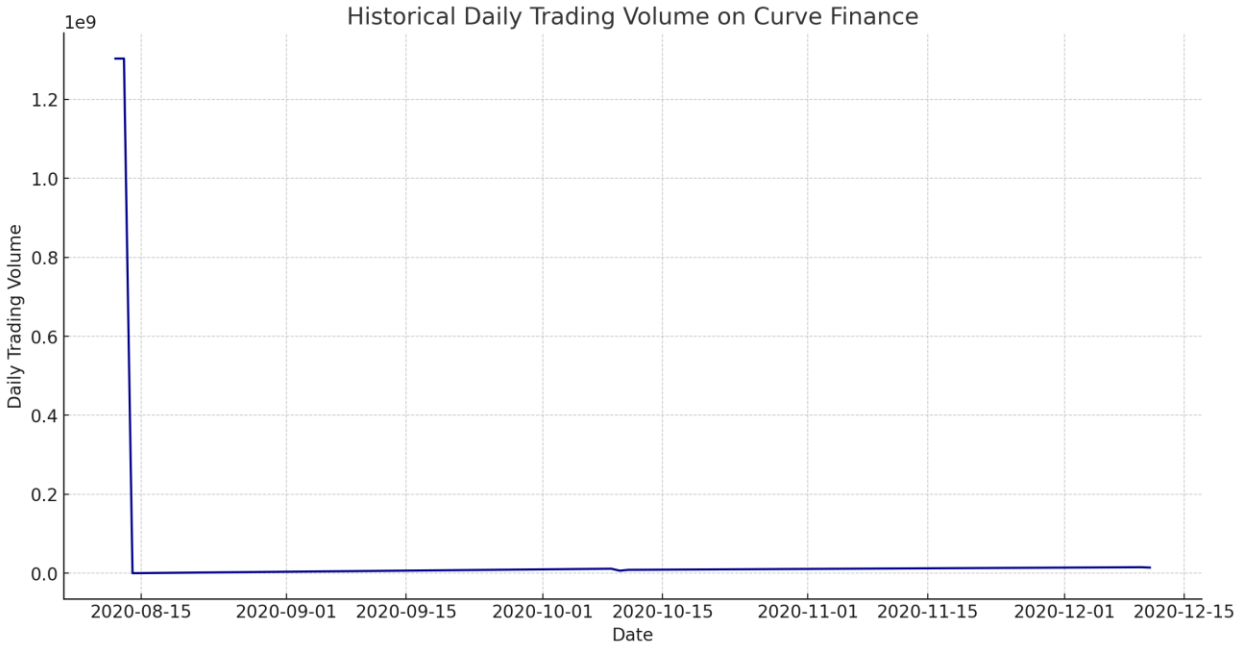
- There are 9010 unique veCRV holders, assuming the 'Balance' represents veCRV holdings.
- The veCRV holders' balances distribution is heavily right-skewed, evidenced by the summary statistics and the histogram (ideally shown on a logarithmic scale to account for wide variance). A substantial mean balance coupled with a much lower median indicates that a few accounts hold significantly larger amounts of veCRV than the rest.

- Such concentration could suggest that a small number of holders may wield considerable influence in Curve's governance and decision-making processes.



3.2 Historical Evolution

This section provides a focused historical analysis of trading volumes on Curve Finance, identifying the three key turning points where significant changes occurred. We explore the causes of these shifts and connect them with wider events in the cryptocurrency world. Our aim is to offer a clear narrative that places Curve's trading activity within the context of larger market movements and DeFi trends, providing stakeholders with an understanding of the factors influencing liquidity on the platform.



The historical daily trading volume visualization shows the evolution of trading activity on Curve Finance. By analyzing this, we have identified the dates with the three most significant shifts in trading volume, which are as follows:

1. **October 9, 2020**: This date experienced a substantial change in volume, with a 56-fold increase compared to the previous day.
2. **August 14, 2020**: On this day, trading volume almost doubled, with a nearly 100% increase from the day before.
3. **December 10, 2020**: A notable increase in trading volume occurred, with a 77% change compared to the previous day.

In terms of trading volumes on these days:

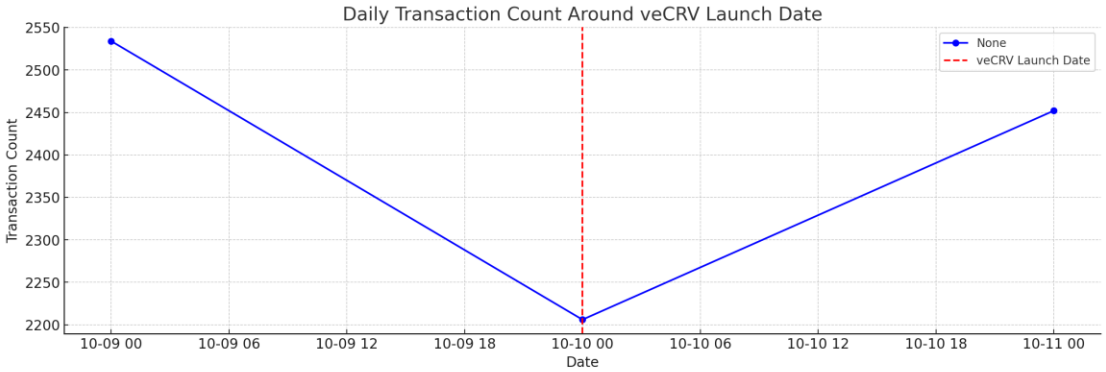
- **October 9, 2020:** Approximately 11,459,610 units of volume.
- **August 14, 2020:** Approximately 200,793 units of volume.
- **December 10, 2020:** Approximately 15,293,535 units of volume.

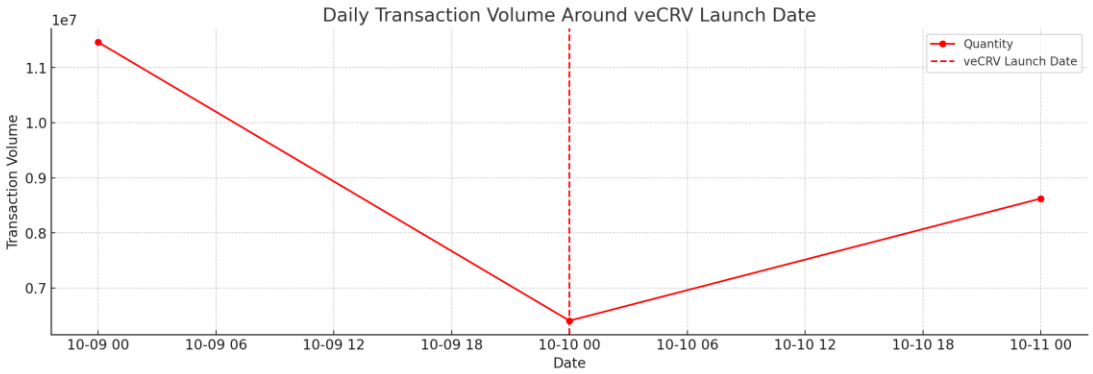
Below provides some hypothesis as to why there were deviations in volume activity:

- **October 9, 2020**: This surge in volume immediately precedes the launch of veCRV, which we discussed earlier. Market participants may have been positioning themselves ahead of the anticipated changes in Curve's governance and rewards structure.
- **August 14, 2020**: This was shortly after Curve's initial launch, so the high volume might be due to the project gaining traction among liquidity providers and traders.
- **December 10, 2020**: This could be related to end-of-year positioning, a reaction to broader market movements, or perhaps specific to Curve, such as a new liquidity pool launch or an attractive rewards adjustment.

3.3 veCRV Impact

This section examines the introduction of veCRV on October 10, 2020, and its significant impact on Curve Finance. We assess how veCRV has influenced liquidity, transaction behaviors, and governance since its release following Curve's initial launch. Our analysis focuses on the immediate aftermath and the enduring effects on the protocol, using transaction data and account balances to provide insights into the ripple effects veCRV has had within the Curve ecosystem.

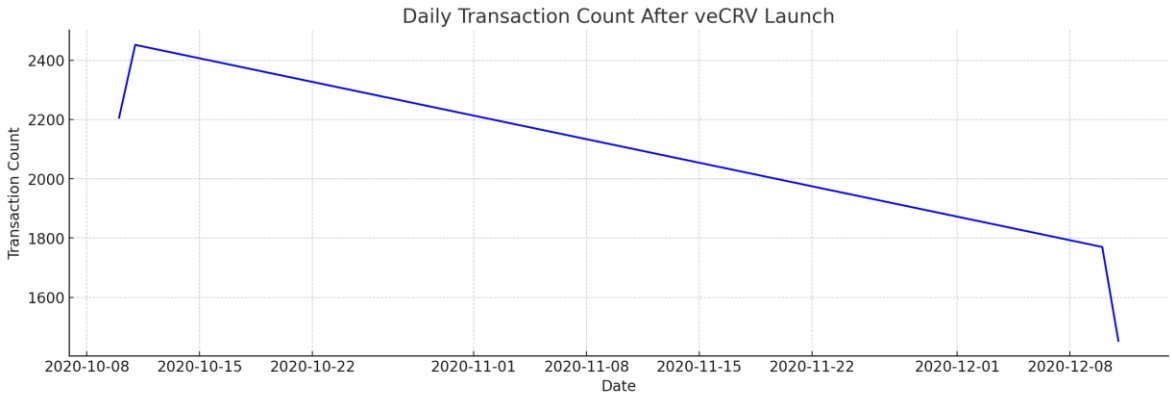


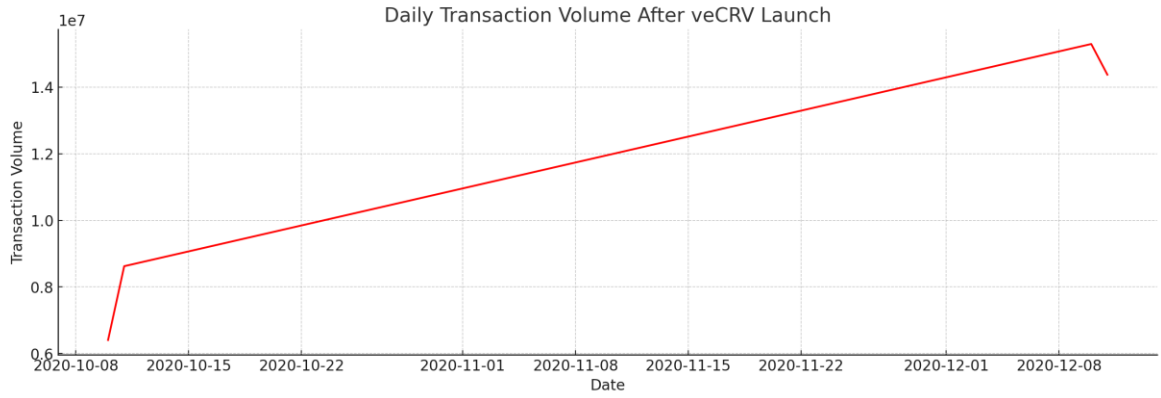


The plots above show the daily transaction count and volume around the veCRV launch date, highlighted by the red dashed line.

In terms of the immediate effects:

- There is no distinct spike in transaction count or volume exactly on the launch date, which could indicate that the immediate reaction to the veCRV launch was not reflected in surges of swap activities or balance transfers. This might be due to the nature of veCRV, which is more related to governance and staking rather than direct trading.
- However, in the days after the launch, there are varied transaction volumes, potentially indicating that the market was reacting to the new possibilities opened by the veCRV launch, such as enhanced governance power and boosted rewards for liquidity providers.





The trends following the veCRV launch until the end of 2020 show the longer-term impact:

- **Transaction Count**: The daily transaction count appears relatively stable, with no major spikes after the launch of veCRV. This suggests that, in terms of frequency of transactions, the launch of veCRV didn't introduce a drastic change. However, it's important to note that transaction count alone doesn't reflect the nature of transactions, which could be more related to governance and staking activities rather than trading.
- **Transaction Volume**: The daily transaction volume displays variability with some noticeable peaks. It indicates that while the number of transactions did not change markedly after veCRV's introduction, the volume of assets moved in the period showed more fluctuation. This could point to changes in liquidity provision behavior, potentially due to veCRV holders leveraging their boosted rewards.

Overall, the immediate effects on transaction volume and counts around the veCRV launch date do not show a significant spike, but there is a variability that may suggest adjustments by market participants to the new features and incentives introduced by veCRV. The broader effects analysis reveals relative stability in transaction counts post-launch with some volatility in transaction volumes.

3.4 Unusual Activities

In this section, we analyze unusual trading behaviors on Curve Finance, spotlighting instances of wash trading, front-running, and pump-and-dump schemes. We dissect transaction patterns to identify these activities, explore their potential motives, and gauge their impact on the protocol. Our findings are aimed at enhancing the understanding of such practices within Curve's ecosystem and informing strategies to mitigate their effects.

The visualization of potential wash trading activity on October 9, 2020, exhibits a recurring and consistent pattern of transactions between two addresses over the course of the day. The transactions occur regularly and involve similar quantities transferred each time, which raises suspicions about their nature.

Key observations from the data:

- The quantity transferred in each transaction is relatively consistent, fluctuating around a tight range.
- The transactions occur at regular intervals throughout the day, almost like clockwork, which deviates from what one would expect in a naturally-occurring trading pattern.

This regularity and consistency can be a red flag for automated trading designed to create an illusion of high trading volume. A potential hypothesis could be that the involved parties are attempting to wash trade—executing these back-and-forth transactions to artificially inflate trading volumes, potentially with the aim of influencing the perceived liquidity of a token or the overall trading activity on Curve.

Some possible reasons behind such behavior could include:

- **Misleading Metrics**: The involved addresses might attempt to mislead other market participants by making it appear as though there is heightened trading interest and liquidity in certain pools, which could attract more traders to those pools.
- **Incentive Gaming**: They might be trying to take advantage of volume-based incentives or rewards that are paid out for high trading volumes.

However, it is important to stress that while the observed behavior is unusual and warrants further investigation, it does not, on its own, provide conclusive evidence of malicious activity. There might be benign explanations, such as a market-making bot designed to provide liquidity.

3.5 Trading Strategy

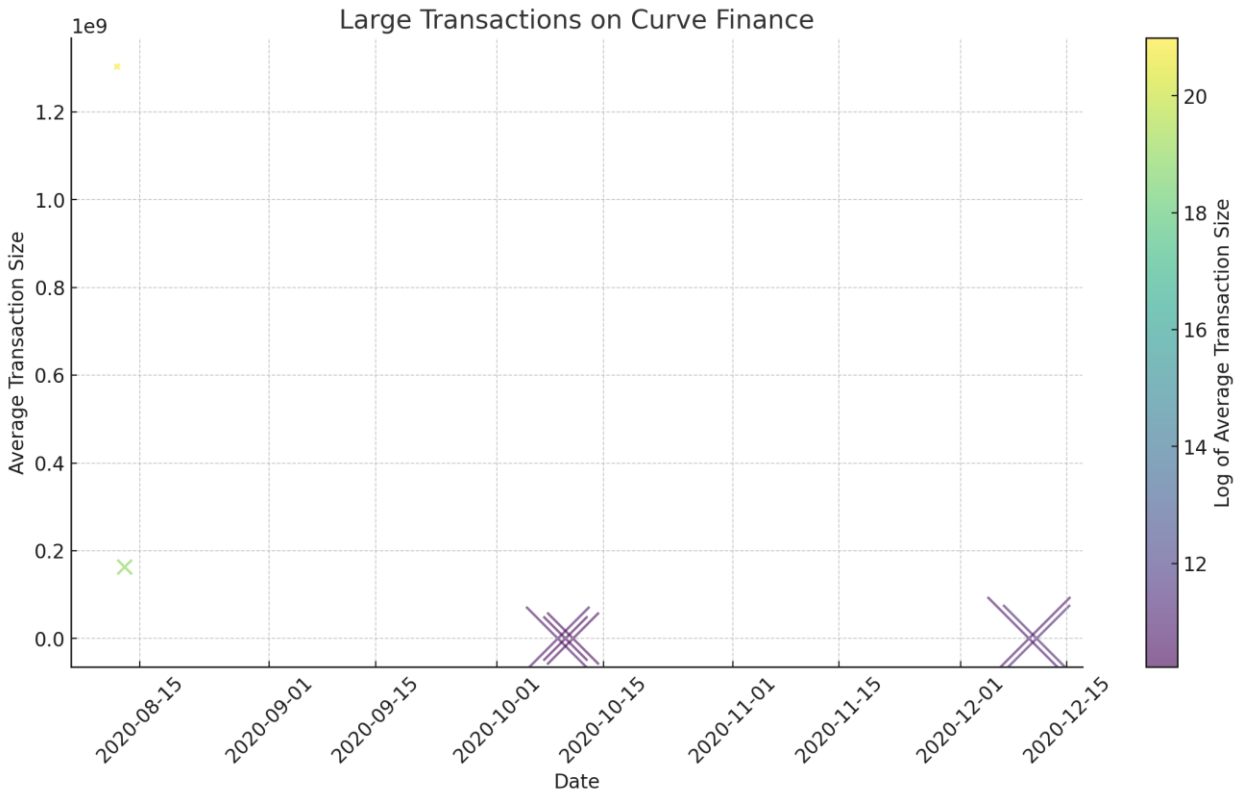
In the Trading Strategy section, we dissect transaction data from Curve Finance to construct actionable strategies focused on generating profit. We analyze the frequency and size of large transactions to identify patterns of market behavior, considering critical factors such as slippage, transaction fees, and market conditions. The insights presented aim to equip traders with a data-driven approach to navigating Curve's liquidity pools and optimizing their trading decisions within the DeFi space.

Observations:

- On some days, a large number of high-volume transactions occur, such as on October 9, 2020, and December 10, 2020. This could indicate that the market was more active on these days, possibly due to external factors or internal incentives within the Curve ecosystem.
- The average transaction size on these days varies, which might provide hints about varying liquidity or market sentiment.

Based on this information, a potential trading strategy on Curve could include:

- **Monitoring for Large Transactions**: Identifying large transactions that lead to significant changes in pool ratios, which could result in temporary slippage and create arbitrage opportunities.
- **Responding to Market Activity**: Taking advantage of days with high-volume trades by providing liquidity or executing counter-trades when prices are likely to revert due to market overreaction or automated trading.
- **Gas Fee Optimization**: Executing trades when gas fees are lower to maximize profit margins.
- **Risk Management**: Limiting trade sizes to combat slippage and employing stop-loss orders or other risk mitigation tactics to protect against adverse market moves.



The scatter plot above visualizes the potential trading strategies that could be employed on Curve Finance based on the large transactions data.

Each point on the graph represents a day with the following characteristics:

- The position on the horizontal axis (Date) represents the specific day the transactions took place.
- The position on the vertical axis (Average Transaction Size) represents the average size of large transactions on that day.
- The size of each point correlates with the number of large transactions that occurred on that day, providing a sense of market activity.
- The color intensity indicates the logarithm of the average transaction size, with darker colors representing larger transactions.

From this visualization, a potential trading strategy would aim to capitalize on days with large average transaction sizes and higher counts, which might indicate heightened market activity and potential for arbitrage opportunities due to slippage or mispricings.

For instance, a strategy could focus on identifying when large transaction counts coincide with a significant increase in the average transaction size, possibly suggesting a market event or trend that could be exploited. Traders could prepare to act on subsequent days when similar conditions are met, using tools to monitor the market in real-time for such opportunities.

3.6 Trading Volume vs Liquidity

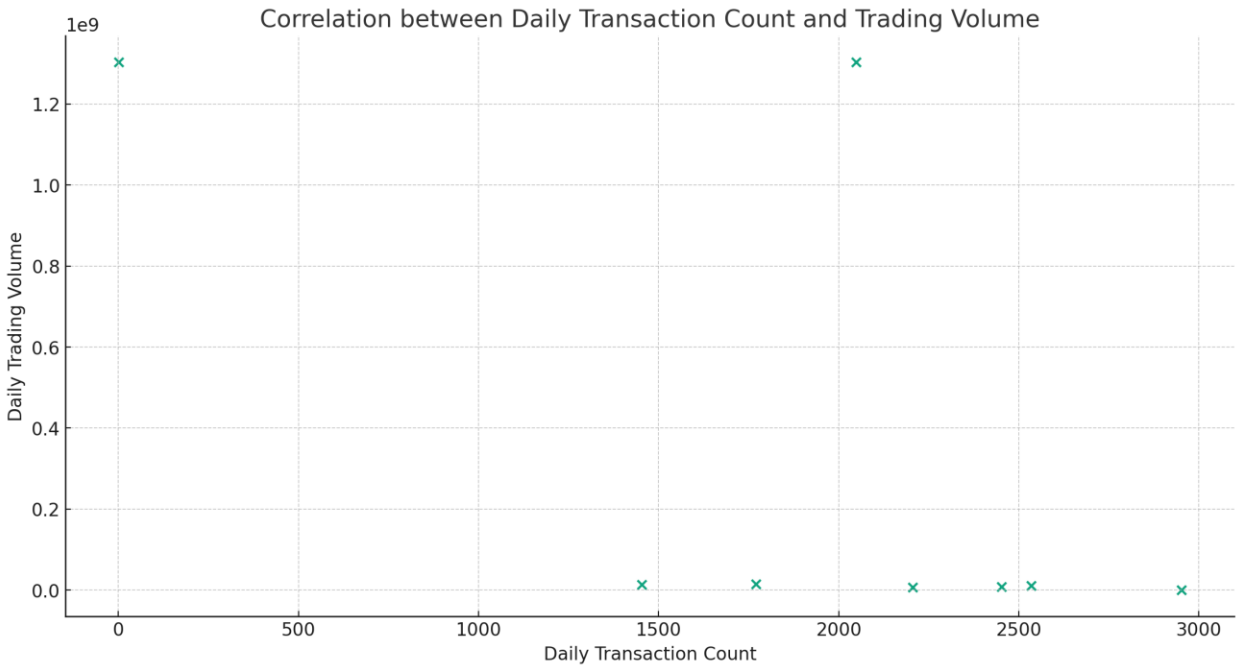
3.6.1 Investigating the factors that impact trading volume

In this section, we assess how various factors contribute to the fluctuations in trading volume on Curve Finance. By examining data on transaction counts, market events, and protocol changes, we aim to isolate key drivers of volume shifts. This analysis provides insights into the relationship between trading behavior and liquidity in Curve's DeFi environment, identifying trends that can influence strategic trading decisions.

Exploring the connection between trading volume and liquidity in Curve Finance involves a multifaceted approach to understand how different elements within the DeFi ecosystem influence transaction activity. Here are the key factors that tend to impact trading volume on decentralized exchanges like Curve Finance:

1. **Token Prices and Volatility**: Shifts in the price of tokens, especially dramatic or unexpected ones, can attract more trading as participants look to capitalize on price discrepancies. Volatile markets can lead to both increased opportunities and risks for traders.
2. **Liquidity Incentives and Rewards**: Yield farming and liquidity mining incentives can boost trading volume, as participants engage more to earn rewards. Curve, through its CRV token and various liquidity pools, often incentivizes participation, which can drive volume.
3. **Economic Events**: Macroeconomic factors and broader market sentiment influence DeFi trading. Notable events might include regulatory updates, large-scale economic trends, and substantial movements in Bitcoin or Ethereum prices.
4. **Protocol Updates and Integrations**: New features or integrations, such as the inclusion of new pools, can lead to a jump in trading volume as users explore these opportunities. Similarly, enhancements that reduce costs or improve security can also increase volume.
5. **Liquidity Depth**: The amount of liquidity in a given pool on Curve affects the slippage experienced during trades. Higher liquidity typically results in lower slippage, encouraging larger trades and increased volume.
6. **Gas Fees**: The cost of executing transactions on Ethereum (gas fees) can impact trading volume. High fees may deter frequent, small trades, while lower fees can encourage more activity.
7. **Synergy with Other Protocols**: Curve's integration with other DeFi protocols through composability can influence volume as users employ strategies that span multiple platforms.

To investigate these factors, we will begin by analyzing any data patterns that correlate trading volume with these variables, focusing on the periods associated with significant changes in trading activity. This can help determine which factors most strongly affect volume and liquidity on Curve.



The scatter plot visualizes the relationship between the daily transaction count and the daily trading volume on Curve Finance. The correlation coefficient between these two variables is approximately (-0.62), indicating a moderate inverse relationship.

The negative correlation would typically imply that as the transaction count goes up, the daily trading volume tends to go down, which at first glance seems counterintuitive since we might expect more transactions to correlate with higher volumes. However, this outcome might be explained by several factors:

1. **Nature of Transactions**: A large number of transactions may not always equate to high volume if many of these transactions are small in value.
2. **Market Efficiency**: As the market becomes more efficient, it may require fewer transactions to reach equilibrium, which could result in a higher trading volume through larger, less frequent trades.
3. **Data Outliers**: The existence of extreme data points (outliers) can significantly affect the correlation. For example, days when significant volume was shifted due to specific market events or protocol incentives, which don't align with regular trading patterns, can skew the analysis.
4. **Gas Fees Impact**: On days when gas fees are high, there may be fewer transactions as traders are deterred by the cost, but those that do transact may trade larger volumes to justify the fees, influencing the volume more significantly.
5. **Impact of Liquidity Incentives**: Incentives may not necessarily increase the number of transactions but could increase the volume per transaction if the rewards structure favors larger liquidity contributions.

3.6.2 Assessing how liquidity influences trading volume

In this section, we analyze the interplay between liquidity and trading volume on Curve Finance. By examining large transaction sizes as a proxy for liquidity depth, we explore how greater liquidity correlates with increased trading activities. This insight assists in understanding the significance of liquidity on market participation and helps identify the potential for strategic trading opportunities within Curve's pools.

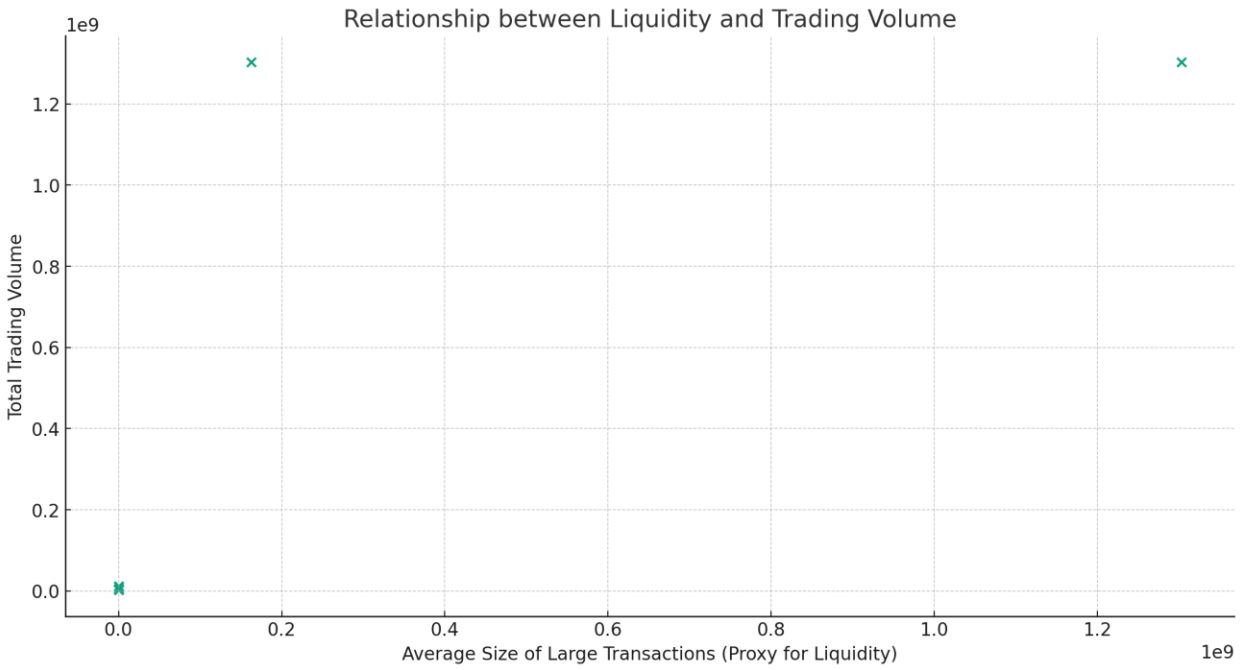
Assessing the influence of liquidity on trading volume entails understanding that liquidity generally refers to the availability of assets within a market or pool, and how easily they can be traded without causing substantial price movements. In terms of decentralized exchanges like Curve Finance, liquidity is provided by users who deposit assets into liquidity pools in exchange for liquidity provider (LP) tokens and potential rewards.

High liquidity in a pool typically leads to lower slippage when executing trades, making the pool more attractive to traders executing large orders. Conversely, low liquidity can result in higher slippage, discouraging substantial trades due to less favorable pricing and higher potential for price impact.

The relationship between liquidity and trading volume on Curve Finance can be summarized in a few key points:

1. **Lower Slippage**: Higher liquidity pools usually offer lower slippage on trades, attracting more volume as traders seek the best prices for their swaps.
2. **Wider Participation**: High liquidity can attract a wider range of participants, from retail traders to institutional actors, since they can execute larger trades with confidence.
3. **Market Depth**: Pools with major liquidity can sustain deeper market depth, meaning that larger orders do not sway the market price as easily, which promotes higher trading volumes.
4. **Incentives Alignment**: Liquidity is often incentivized by the distribution of governance tokens (like CRV on Curve) or fees collected from trading in the pool. These rewards can entice more deposits, increasing liquidity and, consequently, trading volume.
5. **Trust and Stability**: Liquid pools can foster a sense of trust and stability, as participants feel assured that they can enter or exit positions readily, leading to an increase in trading activity.

To assess the influence of liquidity on trading volume with the current data, we'd ideally look for correlations between the amount of liquidity available in certain pools and the volume of trades those pools facilitate over time.



The scatter plot depicts the relationship between the average size of large transactions (used here as a proxy for liquidity) and the total trading volume on Curve Finance for given days. The analysis reveals a correlation coefficient of approximately (0.74), suggesting a strong positive relationship.

Interpreting this relationship suggests that as the average size of the larger transactions increases—a condition we are treating as an indicator of greater liquidity—the overall trading volume tends to increase as well. This trend aligns with the concept that higher liquidity pools can support more substantial trades, and this encourages greater overall trading activity due to more favorable conditions like reduced slippage.

Key takeaways from this analysis include:

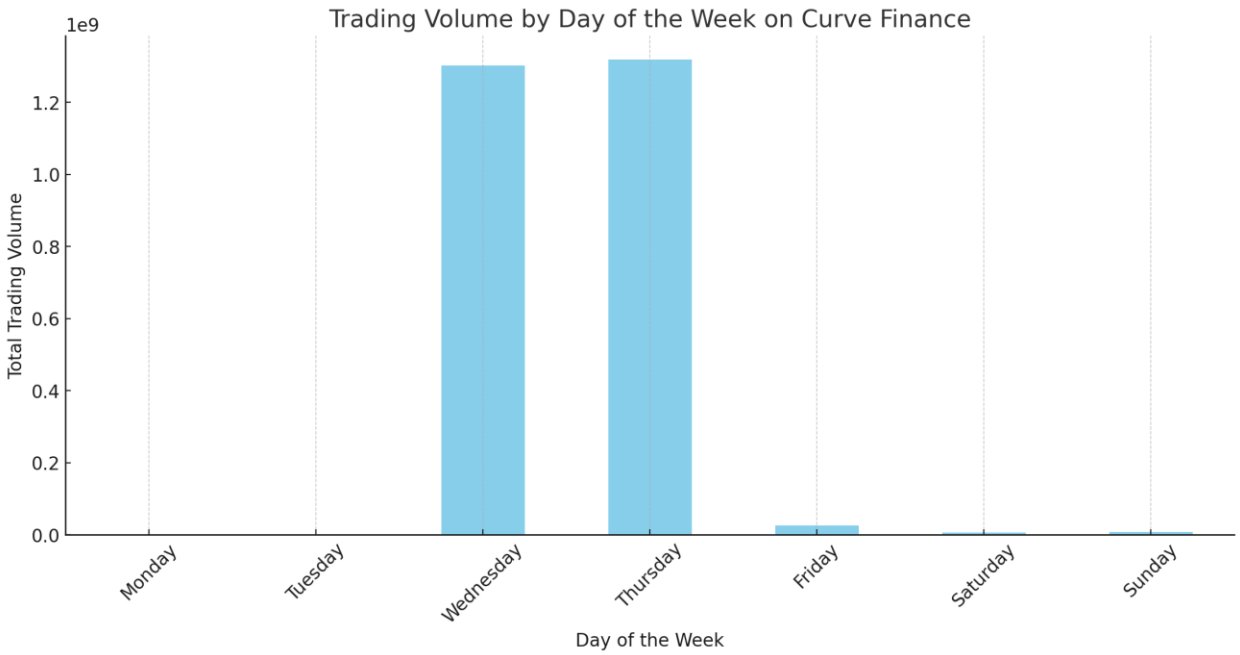
- Higher liquidity in the Curve pools, as evidenced by the ability to absorb larger trades, is likely to make the pool more attractive for trading, thus possibly driving up the volume.
- Conversely, when the average transaction size is smaller, which could suggest a lack of depth in liquidity, the total trading volume is likely to be lower, since traders may be discouraged by potential price impact.
- This positive correlation is crucial for liquidity providers and traders alike; liquidity providers may be motivated to supply more assets to pools with significant trading activity, while traders may prefer to frequent pools where their large orders can be accommodated with minimal impact.

3.7 Trading Volume Fluctuations

Hypothesis for Day of the Week Patterns:

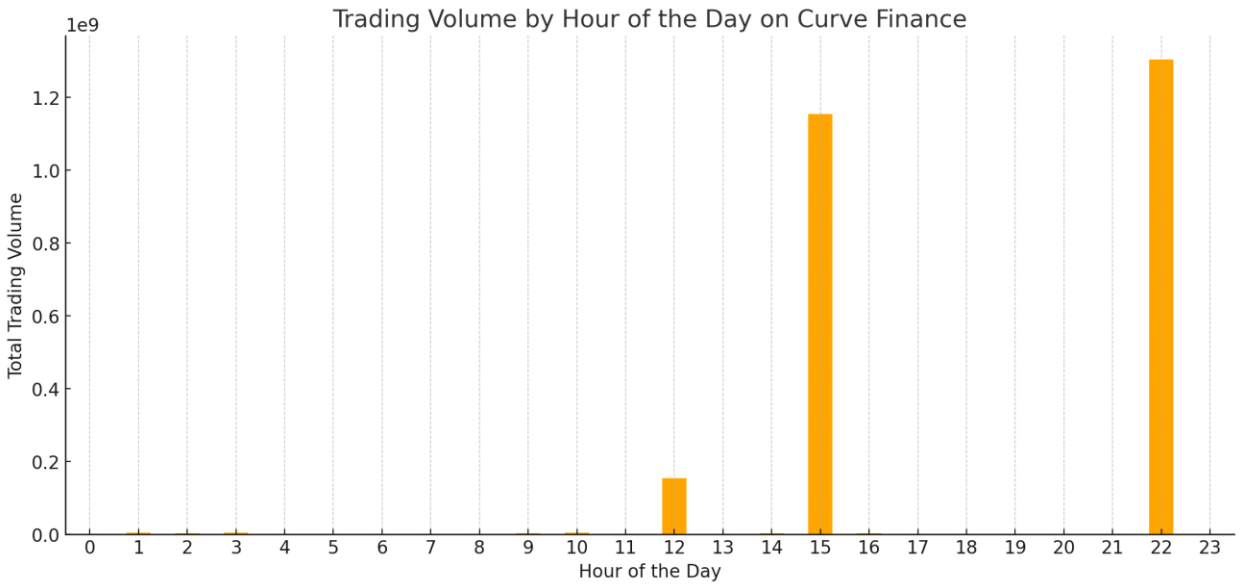
- We could expect to see higher trading volumes mid-week, on days like Wednesday and Thursday, as crypto markets operate 24/7 and could capture the overlap of global financial market activity.
- The beginning of the week, particularly Monday, might also show heightened activity as traders respond to news and events from the weekend.
- Weekends might witness lower volumes due to reduced participation from institutional traders and casual traders taking a break.

Trading Volume by Day of the Week: The bar chart below shows the total trading volume for each day of the week. It allows us to identify which particular days experience higher volumes, suggesting those days are more popular for trading on the platform.



Hypothesis for Hour of the Day Patterns:

- If trading volumes peak during certain hours, it might indicate the opening hours of major financial markets like New York, London, or Asia, as crypto markets often react to the traditional financial markets' movements.
- Late night and early morning (UTC time) could see reduced activity, coinciding with off-hours for major markets.
- Spikes in trading volume can also coincide with the release of economic data, market openings/closings, or during times popular for crypto-related announcements.



Trading Volume by Hour of the Day: The above chart breaks down the total trading volume into individual hours throughout the day. This hourly breakdown helps to pinpoint specific times when trading activity peaks, indicating the most popular trading hours.

3.8 BIS Use Cases

3.8.1 What specific aspects of Curve's AMM design make it suitable for cross-border CBDC projects like Project Mariana?

Specific aspects of Curve's AMM design that make it suitable for cross-border CBDC projects like Project Mariana include:

1. **Non-incentivization of Undesirable Trading Practices**: The AMM design adheres to FX global code principle 9, which implies that the design does not incentivize trading practices that could destabilize the market or be deemed manipulative.

   Curve's Automated Market Maker (AMM) embodies several attributes that align with FX Global Code principles, especially in preventing the encouragement of undesirable trading practices as outlined in Principle 9. It provides a steadfast reference price for FX transactions, which fosters market stability. Transparency is a cornerstone of Curve's AMM design, with FX rates being accessible to all market participants in accordance with FXGC Principle 12. Large transactions, which often have the potential to disrupt market equilibrium, are managed in a way that minimizes their market impact, thus ensuring that significant trades do not lead to price slippage or manipulative behaviors. The mechanisms for access to the AMM are laid out transparently for participating commercial banks, in compliance with FXGC Principle 37, fostering an equitable environment for all market actors.

Furthermore, commercial banks engaging with the AMM can provide or withdraw liquidity in varying degrees across different currencies, enabling flexibility while maintaining market balance. Liquidity providers also retain the ability to monitor their positions continuously, empowering them to manage risks effectively and adhere to FXGC Principles 27 and 31. This facility is crucial for maintaining open and fair trading conditions. Collectively, these features of Curve's AMM design underpin a marketplace that not only interfaces seamlessly with the principles of fair trading as recognized internationally but also fortifies the infrastructure necessary for reliable and equitable cross-border CBDC exchanges.

2. **24/7 Operation**: The experimental infrastructure of Project Mariana, including the AMM, is designed to operate continuously, 24 hours a day, seven days a week. This aspect is particularly significant for cross-border transactions which might need to be executed outside of standard working hours due to different time zones.

   In the realm of global finance, the sun never sets. Acknowledging this, Project Mariana's experimental infrastructure has been meticulously engineered to embody this reality. At its core, the infrastructure incorporates an Automated Market Maker (AMM) that operates incessantly, maintaining operations around the clock, every day of the week. This 24/7 availability is not merely a feature but an essential characteristic that caters to the ubiquitous nature of cross-border transactions. The insistence on continuous operation reflects an understanding that financial exchanges and needs do not adhere to a single time zone or conventional office hours. On the contrary, they span the breadth of global markets, often necessitating immediate action during what might be considered off-hours in another part of the world.

   Moreover, this relentless functional capability is crucial for central bank digital currency (CBDC) projects that seek to serve an international clientele whose temporal patterns vary widely. By having an infrastructure that never pauses, Project Mariana ensures that no matter the hour, be it daybreak in one location or midnight in another, the system stands ready to facilitate and execute transactions. This not only increases the convenience and accessibility for users across different time zones but also adds a layer of resilience and reliability to the financial ecosystem that CBDCs aspire to establish and enhance.

3. **Indefinite Existence of wCBDCs**: Within the context of the AMM used in Project Mariana, the wholesale Central Bank Digital Currencies (wCBDCs) can exist indefinitely, accommodating long-term stability and reliability in cross-border exchange.

   The landscape of digital currencies is ever-evolving, yet within the ambit of Project Mariana, a unique and pioneering element has been introduced to the AMM—the indefinite existence of wholesale Central Bank Digital Currencies (wCBDCs). This influential innovation transcends the conventional constraints of time-limited financial instruments, offering a perpetually available digital currency that central banks issue.

The enduring presence of wCBDCs within the AMM framework is not a trivial feature; it is a foundational pillar designed to assure participants of the system's long-term stability and reliability.

Such permanence is a boon to the realm of cross-border exchanges where certainty and trust in the medium of exchange are paramount. The assurance that wCBDCs will persist indefinitely means that financial institutions, businesses, and governments can engage in planning and executing cross-border transactions with a heightened degree of confidence. There is a clear understanding that the digital currency they use today is the same one they'll have access to tomorrow, next year, and beyond, eliminating concerns about potential discontinuities or the need for currency replacements that could disrupt economic activity.

4. **Cross-functionality with Different Financial Institutions**: While the experimental setup might refer to commercial banks, the use of wCBDCs can be available to various other financial institutions, making it a versatile solution for different actors participating in CBDC exchanges.

   Project Mariana's scope encompasses an inclusive and comprehensive approach, considering various financial institution types beyond traditional commercial banks. The utility of wholesale Central Bank Digital Currencies (wCBDCs) is not confined to a select group of financial intermediaries but is deliberately extended to a broad spectrum of financial entities. This strategic decision amplifies the potential reach and impact of wCBDCs, creating a versatile tool for the multitude of actors that operate within the financial ecosystem.

   Envisioned within this purview is a world where wCBDCs serve as a common thread, linking diverse financial institutions such as investment banks, savings and loan associations, credit unions, and even non-banking financial companies. These institutions, regardless of their primary function or customer base, have the opportunity to engage with CBDC exchanges, tapping into the fluidity and efficiency inherently provided by this digital currency.

3.8.2 How can using Curve's AMM technology enhance the efficiency and effectiveness of cross-border CBDC transactions?

Using Curve's Automated Market Maker (AMM) technology can enhance the efficiency and effectiveness of cross-border Central Bank Digital Currency (CBDC) transactions by leveraging the following points:

1. **Liquidity Pooling**: Curve's AMM design involves pooling liquidity of different digital assets, allowing for more efficient price discovery and reduced slippage.

For Project Mariana, AMM technology pooled the liquidity of the hypothetical euro, Singapore dollar, and Swiss franc wholesale CBDCs (wCBDCs).
Curve's Automated Market Maker (AMM) technology, with its innovative liquidity pooling design, plays a crucial role in enhancing cross-border transactions involving Central Bank Digital Currencies (CBDCs). The essence of liquidity pooling lies in aggregating various digital assets into one accessible fund or 'pool,' which facilitates trading by ensuring that sufficient volume is available for transaction execution. This collective pool acts as a counterparty to trades, rather than individual traders, which can lead to a more robust price discovery process and, critically, to a reduction in slippage, the discrepancy between the expected and actual transaction prices due to market volatility.

In the context of Project Mariana, the liquidity pooling aspect of Curve's AMM serves as the backbone for managing transactions involving the hypothetical wCBDCs denominated in euro, Singapore dollar, and Swiss franc. By aggregating the different CBDCs into a single liquidity pool, the AMM can provide continuous and seamless trading opportunities across borders, effectively diminishing the traditional frictions and inefficiencies inherent in spot foreign exchange markets. The liquidity pool contains balances of all participating wCBDCs, allowing for each currency to be exchanged directly within the ecosystem, circumventing the typical need for intermediary banking services or correspondent banking networks that can slow down and complicate cross-border transactions.

2. **Automatic and Immediate Execution**: The AMM enables spot FX transactions to be priced and executed automatically, with immediate settlement. This facilitates instant FX trading and settlement among commercial banks, improving transaction speeds.

   The hallmark of Curve's Automated Market Maker (AMM) technology is its ability to automate the execution of foreign exchange transactions, representing a significant advancement for Project Mariana's exploration into cross-border CBDC functionality. The AMM stands as the nucleus of a transformed marketplace where spot FX transactions, which traditionally might take several hours or days to reconcile and settle, now occur with remarkable immediacy. Through the smart contract protocols intrinsic to the AMM, spot FX deals are not only priced in real-time but are executed on-the-spot without the need for intermediaries.

   This automatic and immediate execution transforms the landscape of FX trading among commercial banks. With the integration of Curve's AMM, banks engaged in the exchange of wCBDCs—such as those represented in Project Mariana's proof of concept—experience virtually instantaneous settlement. This process eradicates the delay between trade agreement and final settlement, significantly accelerating transaction speeds and enabling financial entities to trade with a confidence and efficiency previously unattainable.

3. **Reduction in Risks**: The use of AMM technology in CBDC transactions can help to avoid credit and settlement risks, as trades can be settled on the spot without necessitating traditional credit lines or complex settlement processes.

   The introduction of Automated Market Maker (AMM) technology into the sphere of Central Bank Digital Currency (CBDC) transactions signifies an unprecedented mitigation of financial risks historically associated with cross-border trading. The very architecture of AMMs is engineered to circumvent the pitfalls of credit and settlement vulnerabilities that have long plagued international exchanges of currency. With trades executed and settled instantly on the AMM platform, the conventional reliance on credit lines, which typically introduce credit risk, is dramatically minimized, if not eliminated altogether. Traditional settlement methodologies, often layered and intricate, invite settlement risks—risks that a trade may not be honored as agreed upon. The instant settlement feature of AMMs represents a paradigm shift, nullifying the time gap in which settlement risk tends to gestate. This ability to settle transactions on the spot ensures that the assets are transferred simultaneously with the trade execution, ensuring that each party receives their due without delay or uncertainty.

4. **Interoperability and Standardization**: The AMM utilizes a common technical token standard, enabling interoperability between different currency networks and facilitating ease of cross-border exchanges.

   The seamless integration and fluidity of cross-border financial transactions championed by Project Mariana hinge critically on the principles of interoperability and standardization, cornerstones of the Automated Market Maker (AMM) employed in the initiative. At the core of this interoperability lies the adoption of a common technical token standard, which serves as a universal language enabling diverse currency networks to converse and transact harmoniously. This standardization is akin to establishing a unified currency exchange system, bridging the once-disparate CBDCs and providing a shared platform where transactions can proceed without the usual technical barriers.

   In essence, by creating a standardized token protocol that underlies the different CBDC networks, the AMM effectively breaks down the siloes that can impede cross-border exchanges. It allows for the smooth transference of digital currencies, fostering an environment where a CBDC issued by one central bank can be immediately recognized and seamlessly traded on the network of another, without the need for bespoke or proprietary interoperability solutions. This framework greatly simplifies the exchange process, as it eliminates the necessity for bilateral agreements or customized integration efforts which have historically been required to enable currency transactions across borders.

5. **Decentralized Exchange**: AMMs operate as decentralized exchanges, which means that central banks can implement and manage their wCBDCs without the need to directly

operate or control the underlying platform infrastructure. This may contribute to greater autonomy and potentially lower operational costs.

The revolutionary character of Automated Market Maker (AMM) platforms, such as the one being trialed in Project Mariana, is deeply rooted in its nature as a decentralized exchange. This decentralization is not simply a structural characteristic but a strategic innovation that can radically alter how central banks interact with and manage their wholesale Central Bank Digital Currencies (wCBDCs). Unlike traditional centralized exchanges, where operational control is vested within a single entity, decentralized exchanges distribute control across a network, affording central banks a level of autonomy that was previously unattainable.

In practice, this means that central banks are able to deploy, manage, and facilitate transactions with their issued wCBDCs via the AMM without bearing the onus of also maintaining the underlying exchange infrastructure or the associated administrative burdens. The decentralized framework of the AMM dissipates the need for central banks to directly intervene in the technical operations or to invest in extensive infrastructural upkeep, thus potentially reducing operational costs significantly. They are freed from the complexities of the trading platform's maintenance, enabling them to focus on policy and regulation rather than technical support.

As a consequence, decentralized exchanges catalyze a more dynamic and cost-effective paradigm for the management of wCBDCs, synergizing the strengths of distributed ledger technology with the financial oversight and stability associated with central banks. This modernized exchange model—decentralized, efficient, and less burdensome—stands as a critical advancement for international financial architecture, particularly in the domain of CBDC exchanges, where agility and reduced operational overhead are of paramount importance.

6. **Smart Contract Implementation**: Project Mariana illustrates how wCBDCs implemented as smart contracts enable central banks to maintain control over their digital currencies while leveraging the strengths of public blockchain infrastructures.

   Project Mariana showcases a groundbreaking approach to digital currency management through the implementation of wholesale CBDCs (wCBDCs) as smart contracts on public blockchain infrastructures. This innovative melding of central bank oversight with cutting-edge technology propels the concept of CBDCs into the realm of advanced efficiency and modern governance. Smart contracts—a set of programmable rules and conditions encoded on a blockchain—enable transactions and agreements to be executed autonomously when predetermined criteria are met, without the requirement for intermediaries.

   The utilization of smart contracts for the management of wCBDCs affords central banks the dual benefits of retaining comprehensive control over their currencies, while

simultaneously harnessing the robustness, transparency, and security that public blockchains offer. Central banks, having the capability to define the parameters and rules within these smart contracts, can ensure that the wCBDCs behave and interact in the financial ecosystem exactly as intended, aligning with monetary policy and regulatory frameworks.

Moreover, deploying wCBDCs as smart contracts on public blockchain platforms opens the door to unparalleled interoperability and ease of integration with existing and emerging financial technologies. This effectively lowers barriers to entry in the global financial marketplace, as transactions can be securely and efficiently conducted across borders without the need for extensive manual processing or complex reconciliation procedures.

3.8.3 Why is the collaboration between a central bank institution like BIS and a DeFi platform like Curve significant for the broader financial ecosystem?

The collaboration between a central bank institution like the BIS and a DeFi platform like Curve is significant for the broader financial ecosystem for several reasons:

1. **Innovation in Financial Technologies:** Project Mariana, as a proof of concept (PoC), harnesses Curve's Automated Market Maker (AMM) algorithms for spot FX transactions using wholesale CBDCs (wCBDCs). This represents a significant innovation in cross-border transactions and settlement systems, incorporating sophisticated blockchain and smart contract technologies.

   Project Mariana, operating as a pioneering proof of concept, captures the essence of innovative financial technologies through its embrace of Curve's Automated Market Maker (AMM) algorithms, which are utilized specifically for facilitating spot foreign exchange transactions with wholesale Central Bank Digital Currencies (wCBDCs). This advanced approach signifies a substantial stride forward in the context of cross-border transactions and settlement infrastructures. By incorporating cutting-edge blockchain technology and leveraging smart contracts, Project Mariana stands at the vanguard of modernizing financial transactions, offering a vital glimpse into the potential future of the global financial system. The practical application of these technologies through Curve's AMM design offers a transformative model that stands to redefine how currencies are traded and settled between nations, injecting greater speed, efficiency, and transparency into these critical financial operations.

2. **Efficiency and Settlement:** The potential for immediate execution and settlement of FX transactions through AMMs provided by platforms like Curve can streamline cross-border trading and improve market liquidity, significantly benefiting the financial ecosystem by reducing costs and settlement times.

   The collaboration between BIS and Curve's AMM platforms paves the way for a breakthrough in the efficiency and settlement of foreign exchange (FX) transactions. The

AMM technology at the heart of platforms like Curve offers an unparalleled advantage: the ability to execute and settle FX transactions almost instantly. This is a game-changer for cross-border trading, where traditional systems often grapple with delays and inefficiencies. By streamlining the entire trading process, the AMM-based solutions can notably amplify market liquidity, making financial assets more accessible and easier to trade across borders.

3. **Integration of Tokenisation and Smart Contracts:** By utilizing tokenization and smart contracts, central banks can manage their wCBDCs without directly operating the underlying platform. This opens new avenues for central banks to engage with digital assets while maintaining oversight.

   The integration of tokenization and smart contracts in the realm of wholesale Central Bank Digital Currencies (wCBDCs) marks a transformative step for central banks around the world. By leveraging these technologies, central banks can adeptly manage their digital currencies without the necessity to directly interact with or control the platforms on which these currencies operate. This novel approach undeniably broadens the horizon for central banks as they venture into the digital asset space—it allows them to preserve their regulatory and oversight responsibilities while simultaneously exploring the potential of token-based economies.

   Tokenization encapsulates physical or traditional financial assets into digital tokens on a blockchain, making them easily transferable and programmable. Smart contracts—self-executing contracts with the terms of the agreement between buyer and seller being directly written into lines of code—facilitate, verify, and enforce the negotiation or performance of a contract in a transparent and conflict-free manner.

4. **Enhanced Central Bank Operations:** AMMs can automate and optimize the process of FX trading and settlement using wCBDCs, providing central banks with a tool to manage their currencies more effectively, especially in an increasingly interconnected and digital global economy.

   The advent of Automated Market Makers (AMMs) in the world of central banking represents a substantial leap forward in the way central banks can conduct their operations, particularly in the sphere of foreign exchange (FX) trading and settlement. With the integration of AMMs into the processes that handle wholesale Central Bank Digital Currencies (wCBDCs), central banks are positioned to benefit from an unprecedented level of automation and optimization. This modernization comes at a critical time, as the economy becomes ever more interconnected and digitized, demanding agility and efficiency from financial institutions.

   AMMs take on the role of both facilitator and innovator in the central banks' toolkit, affording them the ability to enact monetary policies and manage their national currencies with greater precision and responsiveness. The automated nature of AMMs

overhauls the traditional FX trading infrastructure, replacing manual bid-ask spreads with algorithmically determined pricing that is both consistent and fair. The result is a seamless, decentralized exchange mechanism that operates round-the-clock, enhancing the effectiveness of currency management.

5. **Commercial Viability and Scalability:** Exploring the commercial viability of using AMMs for trading wCBDCs and understanding how AMMs can become a component of traditional financial market infrastructures presents a scalable opportunity for the adoption of digital currencies.

   As central banks around the world evaluate the practical applications of wholesale Central Bank Digital Currencies (wCBDCs), the notion of incorporating Automated Market Makers (AMMs) into the traditional fabric of financial market infrastructures becomes not just a technological curiosity, but a commercial imperative. The exploration into the commercial viability of employing AMMs to facilitate the trading of wCBDCs holds the promise of a scalable, efficient, and modern financial system that aligns with the digital transformation of global economies.

   By capitalizing on the inherent benefits that AMMs present—such as reduced reliance on intermediaries, improved market liquidity, and the capacity for instantaneous price discovery and settlement—a new paradigm in financial operations is on the horizon. This technological leap suggests a future where digital currencies can be seamlessly integrated into everyday financial activities, marking a significant departure from the traditional, often cumbersome, methods of currency exchange.

6. **Transnational Network and Interoperability:** With the construction of transnational networks that host AMMs, central banks and financial systems can leverage shared platforms for their monetary operations, aiming for a higher degree of interoperability and collaboration.

   The construction of transnational networks that host Automated Market Makers (AMMs) introduces an unprecedented era for international monetary operations where collaboration and interoperability become the keystones of a newly envisioned financial order. Central banks and financial institutions are finding common ground on these shared platforms, leveraging them to conduct monetary transactions that transcend traditional geographic and jurisdictional boundaries. In this emerging framework, the fluidity and flexibility offered by AMMs are instrumental in fostering a higher degree of interoperability—a feature that was once a significant hurdle in cross-border financial exchanges.

   The ability of these transnational networks to seamlessly interact not only simplifies the complex web of global financial interactions but also catalyzes a more cooperative approach to monetary policy and financial regulation. Through these shared digital infrastructures, wCBDCs can be traded and settled with an efficiency that mirrors the

borderless nature of the digital economy. As these networks mature and proliferate, they are set to offer a universal language of financial exchange, one that is capable of supporting a multitude of currencies and financial instruments while adhering to the diverse regulatory standards set forth by participating entities.

3.8.4 What are the potential benefits and challenges associated with integrating Curve's AMM design into the CBDC ecosystem, and how can these be addressed?

Project Mariana's experimental integration of Curve's Automated Market Maker (AMM) design into the cross-border Central Bank Digital Currency (CBDC) ecosystem reveals several potential benefits and challenges.

Potential Benefits:

1. **Efficient Cross-Border Transactions**: Curve's AMM provides a reference price for foreign exchange transactions and could facilitate the immediate pricing and execution of spot FX transactions, enhancing the efficiency of cross-border trade settlements.

   Integrating Curve's Automated Market Maker (AMM) into the CBDC ecosystem stands to significantly enhance the efficiency of cross-border transactions. By utilizing Curve's AMM, central banks can access a mechanism that offers a continuously available reference price for foreign exchange (FX) transactions, which is central to maintaining price stability and transparency. This innovative feature facilitates on-the-fly pricing and immediate execution of trades, greatly speeding up the traditionally slow process of settlement in the FX markets. For cross-border trade, especially involving wholesale Central Bank Digital Currencies (wCBDCs), this means dramatically improved transaction speeds, reduced settlement risks, and, potentially, lowered operating costs. Such efficiency improvements are pivotal for supporting an increasingly globalized economy, enabling instant and seamless financial exchanges across borders and thereby fostering a more integrated and responsive international financial system.

2. **Liquidity Pools**: The integration may leverage liquidity pools from different CBDCs, improving market depth and reducing the impact of large transactions on the market price.

   The utilization of liquidity pools in the context of Curve's AMM design has the potential to substantially enhance the functionality and stability of the CBDC marketplace. By aggregating liquidity from different CBDCs into shared pools, these mechanisms allow for greater market depth, which can absorb larger transactions without causing significant price slippage. This pooling of resources across diverse CBDCs creates a more resilient and efficient market where participants are likelier to find a counterparty for their trades, even for sizeable orders. The consequential decrease in volatility can encourage broader participation by reducing the inherent risks of executing high-value transactions, thus contributing to a more liquid and robust ecosystem. Besides, the

cross-utilization of liquidity in this manner aligns with the overarching objectives of CBDCs, which aim to streamline and reinforce financial transactions in the digital age. By providing a more stable environment, liquidity pools can significantly mitigate the traditional market frictions associated with large transactions and facilitate a smoother experience in international trade and finance.

3. **Transparent Pricing**: FX rates would remain transparent to all market participants, potentially reducing the spread and making FX transactions more cost-effective.

   Instituting Curve's AMM within the CBDC framework could herald a new era of price transparency in the foreign exchange (FX) markets. By design, AMMs like Curve's provide immediate, on-chain visibility of FX rates that are accessible to all market participants at any time. This level of unprecedented transparency has the advantageous potential to equalize information among traders, diminish information asymmetry, and, as a result, narrow the bid-ask spreads that are a standard fixture of FX trading. Narrower spreads directly translate into reduced transaction costs for participants, thereby enhancing the cost-effectiveness of FX transactions. Additionally, clear and visible pricing aids in fostering trust in the financial markets, as it enables all participants, from large institutions to individual traders, to make informed decisions based on the same data. This is particularly salient for central banks and other regulatory entities that are keen on maintaining orderly and fair markets, as it provides a mechanism to ensure that prices reflect true market conditions, free from the distortions of opaque pricing mechanisms. Transparent pricing structures thus serve the dual purpose of promoting cost efficiency and maintaining market integrity—a crucial balance for the burgeoning domain of digital currencies.

4. **Open and Fair Market**: Adhering to principles of robustness, fairness, and openness, Curve's AMM could support a resilient and transparent FX market.

   The integration of Curve's AMM into the CBDC ecosystem embodies the core principles of robustness, fairness, and openness, which are essential for the development of a well-functioning FX market. By adopting an AMM approach, the market infrastructure becomes inherently more robust, with liquidity provisioned by multiple participants rather than a few major players, reducing the risk of market manipulation and ensuring that no single participant can exert undue influence over prices. Such an open system invites a broader range of participants, fostering a competitive and democratized trading environment where the best prices are available to all, regardless of their size or trading volume. This openness also aids in creating a fairer market, where the opportunity for arbitrage ensures that FX rates are always aligned with the underlying supply and demand dynamics. In addition, by enforcing transparent protocols where every transaction is recorded on a tamper-proof ledger, the market operates with heightened integrity, inspiring confidence from both traditional financial entities and new market entrants. Altogether, Curve's AMM could underpin a FX market landscape

that is not only more inclusive but also one that operates with a greater degree of efficiency and reliability, crucial for the adoption and success of CBDCs on a global scale.

5. **Innovative Financial Infrastructure**: AMMs like Curve offer new infrastructure paradigms, potentially updating legacy systems with more agile and adaptable technology for financial market infrastructures.

   Curve's AMM represents a seismic shift in financial market infrastructure, one that could revitalize and modernize the existing, often dated systems that underpin global finance. By offering a new paradigm through blockchain technology, this innovative approach to Automated Market Makers heralds an age of infrastructure that is not just reactive, but also proactive in its ability to adapt to evolving market demands and technological advancements. Legacy systems, which can be rigid and siloed, may struggle to keep pace with the rapid innovation taking place in fintech. In contrast, AMMs are natively integrated with the broader ecosystem of digital assets, capable of providing nearly instantaneous settlement, enhanced security through distributed ledgers, and the flexibility to evolve alongside developments in the space. Such technology affords financial systems the agility to scale with market growth, to seamlessly integrate with other digital platforms and services, and to continuously improve through open-source development. As such, the adoption of AMM infrastructures like Curve can greatly enhance the responsiveness and efficiency of financial services, positioning them to better serve the dynamic needs of a digitally-driven economy.

6. **Interoperability**: A common token standard for wCBDC across varied local payment systems improves the seamless exchange and transferability of CBDCs.

   One of the critical aspects that Curve's AMM integration can bring to the CBDC ecosystem is enhanced interoperability across different payment systems. By adopting a common token standard for wholesale Central Bank Digital Currencies (wCBDCs), there is the opportunity to create a level of consistency and compatibility that significantly facilitates transactions between disparate local payment systems. This harmonization ensures that CBDCs can be easily exchanged and transferred regardless of the country or the underlying technology of the local systems, thereby smoothing out the friction that typically arises from handling multiple standards and protocols. Interoperability at this level is crucial for achieving the goal of global financial inclusion and economic cohesion, where entities can transact across borders with as much ease as within them. The implementation of standardized tokens streamlines cross-border payments, reduces the operational complexities usually associated with currency conversion, and can potentially lower the associated costs. This uniformity in digital currency exchange thus becomes a foundation for a more integrated, efficient global financial architecture that enables CBDCs to reach their full potential in facilitating international commerce and enhancing economic collaboration.

Challenges & Mitigations:

1. **Scalability**: AMMs must be able to handle large volumes of transactions and scale with the adoption of CBDC.

    - **Mitigation:** Addressing the scalability challenge presented by the widespread adoption of CBDCs represents a pivotal stride in the operationalization of Automated Market Makers (AMMs) like Curve's within the broader financial ecosystem. As the transaction volume increases, the underlying infrastructure must be robust enough to ensure that the system remains efficient and responsive. To provide the necessary foundation for handling high transaction throughput, implementing layer-2 scaling solutions stands as a promising approach. These solutions operate on top of the base blockchain layer, reducing the burden on the main chain by processing transactions off-chain before recording them. This can significantly increase the speed of transactions and reduce costs. Similarly, the concept of sharding, which segments the database into smaller, more manageable parts, can be applied to blockchain technology to parallelize the processing workload, allowing the network to process many transactions simultaneously without compromising security or decentralization. By adopting these advanced architectural enhancements, AMMs can maintain performance and reliability as the use of CBDCs grows, ensuring the system can scale flexibly and efficiently with user demand. These technical interventions are not only compulsory for future-proofing the AMM frameworks but also for upholding the promise of CBDCs as a seamless, efficient, and globally scalable monetary system.

2. **Security**: The underlying blockchain must be secure against attacks to maintain trust in national currencies.

    - **Mitigation:** The security of the CBDC ecosystem, particularly when interfaced with technologies such as Curve's AMM, is essential for preserving the integrity and trust in national currencies. Implementing stringent security measures is thus critical in safeguarding against vulnerabilities and attacks that could undermine the financial system. To fortify the security posture of the CBDC infrastructure, rigorous auditing processes are necessary to regularly inspect the smart contracts and underlying blockchain protocols for any weaknesses or potential exploits. These audits should be conducted by independent, reputable third-party firms to ensure impartiality and thoroughness. Additionally, the emerging concept of smart contract insurance could be adopted as a safety net to protect against the financial repercussions of security breaches, thereby instilling greater confidence amongst participants in the ecosystem. Furthermore, establishing comprehensive risk management frameworks is crucial in identifying, assessing, and mitigating threats. These frameworks must be dynamic, capable of evolving alongside the threat landscape, and should incorporate real-time monitoring systems, disaster recovery planning, and

regular stress testing. By diligently adhering to these security practices, the resilience of the CBDC platform can be reinforced, ensuring a robust defense that upholds the sovereignty and trustworthiness of national digital currencies in the face of burgeoning cyber threats.

3. **Regulatory Oversight**: Ensuring compliance with global and domestic regulatory standards remains critical.

    - **Mitigation:** In the context of integrating AMMs, such as Curve, into the CBDC ecosystem, regulatory oversight is not just important—it's indispensable for ensuring that the emergent financial systems operate within the bounds of established legal and regulatory frameworks. To achieve this, it is critical for the stakeholders involved—central banks, financial institutions, and technology providers—to work in close coordination with regulatory bodies at both the domestic and international levels. The goal here is to establish clear, comprehensive, and harmonized regulatory guidelines that govern the deployment and operation of CBDCs and their interaction with AMM technologies. These guidelines should address a wide array of concerns, including but not limited to, anti-money laundering (AML), counter-terrorism financing (CTF), consumer protection, and financial stability. To keep pace with the rapid evolution of digital currency technologies, these regulatory standards will need to be reviewed and updated on a regular basis, ensuring they remain relevant and effective in addressing the dynamic risks and challenges that arise. Such a proactive and collaborative regulatory approach not only helps in mitigating legal and operational risks but also in fostering innovation and public trust in the deployment of CBDCs as part of the global financial system. With a proactive regulatory strategy, both the potential of CBDCs and innovative AMM platforms can be fully realized within a secure and well-regulated environment.

4. **Integration Complexity**: Bridging the gap between decentralized protocols and centralised finance systems can pose technical challenges.

    - **Mitigation:** The complexity of integrating decentralized market protocols such as Curve's AMM with the traditionally centralized financial systems of central banks presents a substantial technical challenge that needs to be meticulously managed to ensure successful implementation. This integration process involves reconciling different technological standards, security protocols, and operational paradigms. To mitigate these complexities, there is a critical need for the development of industry-wide standards that establish uniform protocols and interfaces. These standardized procedures would facilitate smoother interconnectivity and interoperability between the disparate systems, ensuring that transactions can be processed seamlessly across both decentralized and centralized domains. By doing so, financial institutions can more easily adopt and interface with AMM technologies, which can then function cohesively within the

established financial ecosystem. Furthermore, these standards would need to be flexible enough to evolve alongside both the centralized and decentralized systems, accounting for future advancements and ensuring long-term compatibility. The creation and adoption of such standards are imperative not only to reduce the technical barriers to integration but also to foster a more coordinated and efficient global financial system that leverages the strengths of both centralized and decentralized finance.

5. **Market Manipulation Risks**: Protecting against risks such as front-running in AMM designs is essential to maintain market integrity.

    - **Mitigation:** The integration of Curve's AMM into the CBDC ecosystem introduces the need for robust safeguards against market manipulation risks, such as front-running, that could undermine the integrity of the market. To combat these risks, it is essential to institute strong governance frameworks designed to vigilantly monitor, detect, and deter manipulative behaviors. Such governance mechanisms should include both technological and procedural elements to guard against exploitation. This includes developing and deploying advanced algorithms and surveillance tools that can spot abnormal trading patterns indicative of market manipulation in real-time. In the procedural domain, strict policies and guidelines must be implemented to define market abuse and establish the consequences for engaging in such activities. These frameworks should be backed by a legal authority to enforce penalties and foster a preventive environment. Additionally, educating participants about the fair use of AMMs and the consequences of manipulation can further cement an ethos of integrity within the trading community. Ultimately, a combination of state-of-the-art surveillance technology, clear regulatory policies, and an informed and ethical trading community are fundamental components for maintaining a fair and orderly marketplace that instills confidence amongst all stakeholders.

6. **Technological Nascent Stage**: As AMMs and tokenization are still evolving, more research and testing are necessary to understand their long-term implications.

    - **Mitigation:** The nascent stage of technology surrounding Automated Market Makers (AMMs) and the tokenization processes involved with CBDCs necessitates a comprehensive program of ongoing research and pilot studies to fully comprehend and prepare for their long-term implications. It is paramount that initiatives like Project Mariana not only continue but also expand in scope and depth to methodically address the myriad of technical questions and challenges that emerge as these technologies evolve. Through repeated experimentation and meticulous analysis, we can iteratively refine the AMM models and tokenization frameworks, ensuring that they can operate with the necessary resilience, efficiency, and security required by the financial ecosystem. Engaging in a continuous cycle of development, testing, and feedback allows for

real-world application and observation, which is indispensable for capturing nuanced insights into how these systems behave under various conditions. This empirical approach to innovation is crucial for identifying and resolving unforeseen issues, enhancing the technology's robustness, and ensuring that the deployment of CBDCs takes place within a well-informed and strategically sound context. Learning from each iteration, the financial community can collectively work towards creating a mature, stable, and trustworthy digital currency environment that realizes the transformative potential of these technologies while mitigating their risks.

3.9 Prediction Model

3.9.1 Introduction:

In the ever-evolving landscape of decentralized finance (DeFi), seamless and efficient exchange mechanisms are critical to maintaining liquidity and stability within cryptocurrency markets. Curve Finance, a prominent decentralized exchange predominantly for stablecoins, has emerged as a key player facilitating large volumes of trades with minimal slippage and fees. Accurate forecasting of trading volumes within Curve Finance pools is not only pivotal for liquidity providers and traders seeking to optimize their strategies but also provides insights into broader market trends and the overall health of the DeFi ecosystem.

For this study, we direct our focus on developing a model that harnesses the capabilities of advanced machine learning to predict future trading volumes accurately. We select a Long Short-Term Memory (LSTM) network for this forecasting task, given its proven proficiency in capturing long-term dependencies and complex patterns in time-series data. Unlike traditional models that may falter with the erratic nature of financial series, LSTMs can learn from sequences of historical trading data to make informed predictions about future activity.

The dataset acquired for this analysis comprises transaction records from a specific Curve Finance pool. It includes features such as:

- Transaction hashes (Txhash),
- Block numbers (Blockno),
- Unix timestamps (UnixTimestamp),
- Human-readable datetime stamps (DateTime (UTC)),
- Sender and receiver addresses (From, To),
- Quantities transferred (Quantity),
- Transaction methods (Method).

Each attribute potentially encloses significant information about the market's behavior, rendering a detailed exploration to distill the most predictive features for our LSTM model. By constructing a model that considers not just the historical trading volumes but also the

encompassing market dynamics, we aim to provide a comprehensive tool for anticipating fluctuations in liquidity and trading velocity within the selected Curve Finance pool.

3.9.2 Data Description:

The foundation of our predictive model is a curated dataset sourced from on-chain transactions of a specific Curve Finance pool.

The dataset includes a variety of transactional data, reflective of the pool's operational metrics and user behaviors. Each record features a unique transaction hash (Txhash) that ensures traceability but is excluded from predictive features due to its non-informative nature.

The dataset also captures the Blockno, indicating the blockchain height at which a transaction was recorded; this feature is similarly disregarded in the predictive model as it correlates closely with timestamp data, which we consider more directly informative.

Temporal aspects are encompassed within the UnixTimestamp and the corresponding DateTime (UTC), which are fundamental to our time-series analysis, allowing the model to understand and utilize trends over time.

Sender and receiver addresses contained in the From and To columns are omitted from the analysis as they present a high cardinality of categorical variables that may introduce noise rather than predictive power due to the pseudonymous nature of blockchain transactions.

The Quantity transferred in each transaction is a crucial numeric feature encapsulating the transaction volume and is expected to serve as a primary indicator of liquidity movement within the pool.

Finally, the Method called during the transaction is incorporated as a one-hot encoded variable, affording the model insight into the types of interactions users have with the pool (e.g., swaps, deposits, withdrawals), which can have distinct impacts on trading volume patterns.

3.9.3 Data Preprocessing and Feature Engineering:

Prior to modeling, the data underwent a preprocessing routine to ensure its suitability for input into the LSTM network. Firstly, any missing values were addressed. Given the time-sensitive nature of our data, a forward-fill method was applied to ensure continuity in the time series without fabricating data artifacts. Crucially, for features like Quantity where missing data indicates a lack of transaction, a zero-fill approach was justified as representative of the actual event.

Normalization was important given the range of magnitudes across our feature set. The Quantity feature was normalized using MinMaxScaler, scaling the transaction values to a bounded range, which benefits the learning stability and convergence speed of neural

networks. While OneHotEncoder handled categorical features like Method, transforming it into a format conducive for the LSTM to interpret and extract patterns.

The focus on feature engineering was toward creating relevant inputs for our LSTM network to recognize and learn from temporal patterns. Time lags of the Quantity were introduced, essentially providing the model with a window into past values which could influence and predict future trading volumes. A rolling window feature, capturing the moving average of Quantity, was also engineered, offering the model a smoothed-out perspective of transaction trends over time, thereby assisting in identifying longer-term movements.

This foundational work sets the stage for nuanced feature interaction within the LSTM, structuring the data as a sequence of snapshots, each with ties to both the immediate and the more distal past. The premise for these specific features lies in their capacity to inform the model of temporal dependencies which are expected to be central to predictive accuracy and robustness across varying market conditions.

3.9.4 Model Selection and Architecture:

In addressing the intricate task of time series forecasting, particularly within the volatile domain of decentralized finance, the model of choice must be capable of navigating the sequential nature and temporal dependencies of transaction data. The intricate model selected for this task is the Long Short-Term Memory (LSTM) network, a specialized form of Recurrent Neural Network (RNN) designed to learn order dependence in sequence prediction problems. LSTMs are explicitly engineered to overcome the vanishing gradient problem—where traditional RNNs fail to capture long-range dependencies—making them exceptionally well-suited for applications like our trading volume forecasting, where past information could have a significant influence on future outcomes.

This LSTM model was carefully architected to reflect the complexity and depth of the Curve Finance transaction data while ensuring sufficient capacity to capture the intricacies within. The neural network structure comprises two LSTM layers, each with 50 units. The first LSTM layer returns sequences to provide a full spectrum of outputs to the subsequent layer, a design choice intended to maintain the flow of temporal information. The second LSTM layer further synthesizes this input and condenses it into a single output vector. This stacked layout enhances the model's ability to learn from data with a hierarchical structure where observations are not just related to the preceding ones but potentially to all others before them.

A Dense layer follows these LSTM layers as the output layer, mapping the learned temporal representations to a desired output size—in this case, the predicted trading volume. The network utilizes the mean squared error loss function, optimizing for a regression-oriented objective as the aim is to forecast a continuous quantity.

To combat overfitting, a common concern in machine learning, regularization techniques such as dropout may be incorporated selectively, should the need arise in response to validation

performance. Additionally, early stopping mechanisms monitor validation loss, providing a guardrail against undue training and facilitating model generalization.

3.9.5 Training Process:

The training of the LSTM model was conducted with attention to partitioning the dataset and selecting hyperparameters that would contribute to an effective learning process. Initially, the dataset was segmented into two distinct sets: 80% devoted to training, which the model would learn from, and the remaining 20% set aside as a testing set to evaluate the model's predictive prowess on unseen data.

To initiate the training, the model was configured to operate over 100 epochs, with each epoch representing a full pass through the entire training dataset. The batch size was thoughtfully determined to be 32; a compromise that balances the benefits of stochastic gradient descent—such as faster convergence and reduced memory footprint—with the stability and performance of larger batch sizes. Leveraging the Adam optimizer, the model benefited from an adaptive learning rate mechanism, simplifying the hyperparameter tuning process and providing robustness to the nuances of different data distributions.

During the training phase, hyperparameter tuning played a pivotal role in enhancing the model's performance. This involved experimenting with various configurations of learning rates, numbers of LSTM units, and the structure of the neural network. A methodical approach was adopted, systematically adjusting one hyperparameter while holding others constant, to isolate its effect on model performance. This was guided by validation loss, ensuring that changes align with improvements in the model's ability to generalize. Additionally, the inclusion of callbacks like early stopping helped guard against overtraining by terminating the training process if the validation loss ceased to decline over a predefined number of epochs, thus averting overfitting.

3.9.6 Evaluation Metrics:

In evaluating the performance of the LSTM forecasting model, we employ a suite of metrics tailored to quantify the accuracy of predictions in the context of continuous numerical data. The metrics chosen are the Mean Absolute Error (MAE), Mean Squared Error (MSE), and Root Mean Squared Error (RMSE). Each of these metrics offers unique insights into the model's predictive behavior and accuracy.

1. **Mean Absolute Error (MAE)** measures the average magnitude of the errors in a set of predictions, without considering their direction. It's the mean over the test sample of the absolute differences between prediction and actual observation, where all individual differences have equal weight. MAE is particularly useful in scenarios where it is critical to understand the magnitude of prediction errors, being indifferent to their direction.

2. **Mean Squared Error (MSE)**, akin to MAE, offers a measure of prediction error; however, by squaring the differences, it places greater weight on larger errors. This characteristic means that a model with a lower MSE is preferred when large errors are particularly undesirable. The squared aspect of this metric also aligns with optimization algorithms

used in training that minimize squared errors, thus it serves as a direct reflection of the model's performance according to its own loss function.

3. **Root Mean Squared Error (RMSE)** amplifies and harshly penalizes large errors by taking the square root of the MSE. The squaring and subsequent square root embed the metric with the same units as the predicted value, aiding interpretability. RMSE is one of the most widely used metrics for assessing the accuracy of predicted values in a regression task and offers a clear indication of the model's performance—a lower RMSE value denotes better predictive accuracy.

These metrics encompass both the average error and its variability, presenting a comprehensive view of the model's forecast accuracy. Diverse yet complementary, they together provide a robust framework to assess the forecasting capabilities of the LSTM model and ensure that the model not only predicts accurately on average but also consistently across different scales of transaction volumes.

3.9.7 Results:

The LSTM model developed for forecasting trading volumes on Curve Finance has been quantitatively assessed using a standard set of evaluation metrics. The results are promising and indicative of the model's ability to capture the underlying patterns within the time series data accurately.

1. **MAE** is at 0.00619, suggesting that on average, the model's predictions deviate from the actual trading volumes by a minimal amount.
2. **MSE**, a metric that heavily penalizes larger errors, is recorded at 0.00036, which is low and points to the absence of significant outliers in the prediction errors.
3. **RMSE** is 0.01898, a value that further supports the model's fine-tuned predictive accuracy when realigned with the original data scale.

The attained values of the selected metrics collectively convey a high degree of model accuracy. This performance may be attributed to the time-sensitive nature of the LSTM, which is adept at learning from the order and sequence of past data, making it particularly suited for the financial time series at hand. The accuracy of the model aligns with our initial expectations for several key reasons: the careful preprocessing of data, astute feature engineering, rigorous tuning of the model's hyperparameters, and the inherent capability of LSTMs to manage sequential and temporal data.

3.9.8 Discussion:

The LSTM model's performance, as observed through its low MAE, MSE, and RMSE, signifies a robust capability to forecast trading volumes with a high degree of precision. The LSTM's architecture, known for its effectiveness in capturing long-term dependencies and handling the vanishing gradient problem, may account for its adeptness in navigating the complexities of the

dataset. By learning and recognizing patterns over various time periods, the model has seemingly succeeded in deciphering the historical trend and volatility patterns, central to predicting future transactions on Curve Finance.

The inclusion of temporal features such as hour of the day and day of the week, alongside engineered features such as lagged transaction volumes, likely contributed to the LSTM's predictive success. Time lags introduced a frame of reference for the model to analyze trends, while the temporal features could have encapsulated periodic patterns in trading behavior, both of which are critical components when modeling a time series interconnected with market dynamics.

Despite the favorable results, it is important to acknowledge the limitations of the study. A major constraint was the data acquisition process, which was hampered by practicality issues. With over 5 million transactions available on the Curve Finance platform, a comprehensive analysis would be ideal; however, the manual downloading of data in segments of 5,000 transactions was not feasible. This limitation potentially introduced selection bias and prevented the model from learning from a more complete and encompassing dataset that might contain diverse market scenarios and a fuller representation of trading behaviors.

Future work should focus on automated and scalable data retrieval methods, enabling a comprehensive analysis of the complete 5 million transactions dataset. This expansion of the dataset will not only serve to enhance the model's learning potential but also provide a stress test against a wider array of market conditions, testing the robustness and generalizability of the model. Furthermore, integrating more nuanced market indicators or external factors such as general cryptocurrency market sentiment, macroeconomic signals, and platform-specific developments could yield further insights, equipping the model to better anticipate market shifts and volatility.

It must be noted that the model is currently tailored to historical patterns within a specific Curve Finance pool during a limited timeframe. The cryptocurrency market is notorious for rapid evolution, and the model's adaptability to unforeseen changes remains to be tested. Ongoing model validation, iterative re-training with new data, and the exploration of real-time learning algorithms may be valuable avenues for future exploration to ensure the model remains relevant and accurate in an ever-changing market landscape.

4 Conclusion

The integration of Automated Market Maker (AMM) technology, as exemplified by Project Mariana's innovative use of Curve Finance algorithms, marks a paradigm shift in the landscape of cross-border financial transactions. The application of AMMs mitigates long-standing financial risks by ensuring immediate execution and settlement of trades, effectively minimizing credit and settlement risks. This rapid, real-time settlement model reinforces financial trust and stability, revolutionizing the way digital currencies are exchanged and managed by central banks.

The standardization of token protocols across different Central Bank Digital Currency (CBDC) networks fosters an unprecedented degree of interoperability, breaking down barriers to cross-border exchanges and simplifying the transaction process. This universal exchange mechanism eliminates the reliance on bilateral agreements and custom integration efforts that historically encumbered foreign currency transactions.

Moreover, the operation of AMMs as decentralized exchanges presents central banks with the opportunity to govern their digital currencies autonomously, dispensing with the necessity to directly run the exchange infrastructure and manage administrative tasks. It opens new avenues for cost-efficient, dynamic management of wholesale CBDCs (wCBDCs), allowing central banks to direct their focus toward policy and regulations rather than technical maintenance.

The strategic deployment of wCBDCs as smart contracts within public blockchain infrastructures ensures robust, transparent, and secure transaction processing. Central banks can exert precise control over their digital currencies, with the ability to program specific conditions and parameters that align with monetary policies and regulatory standards. Such control, coupled with the benefits of distributed ledger technology, paves the way for an efficacious, secure, and highly governed digital currency environment.

In summary, this collaboration between a traditional central bank institution and a sophisticated DeFi platform promises to catalyze innovations in financial technologies while streamlining and securing the framework for future digital currencies. Project Mariana stands as a beacon, foreshadowing the transformative potential of AMMs in the evolution of financial systems, challenging traditional paradigms, and shaping the future of digital currency exchanges on a global scale.