Performance and Cost Trade-offs in Layer-2 Payment Channel Networks for Micromobility Systems

Balancing Reliability and Capital Efficiency in Urban Transport Infrastructure

POZNAŃ UNIVERSITY OF ECONOMICS AND BUSINESS

Department of Business Information

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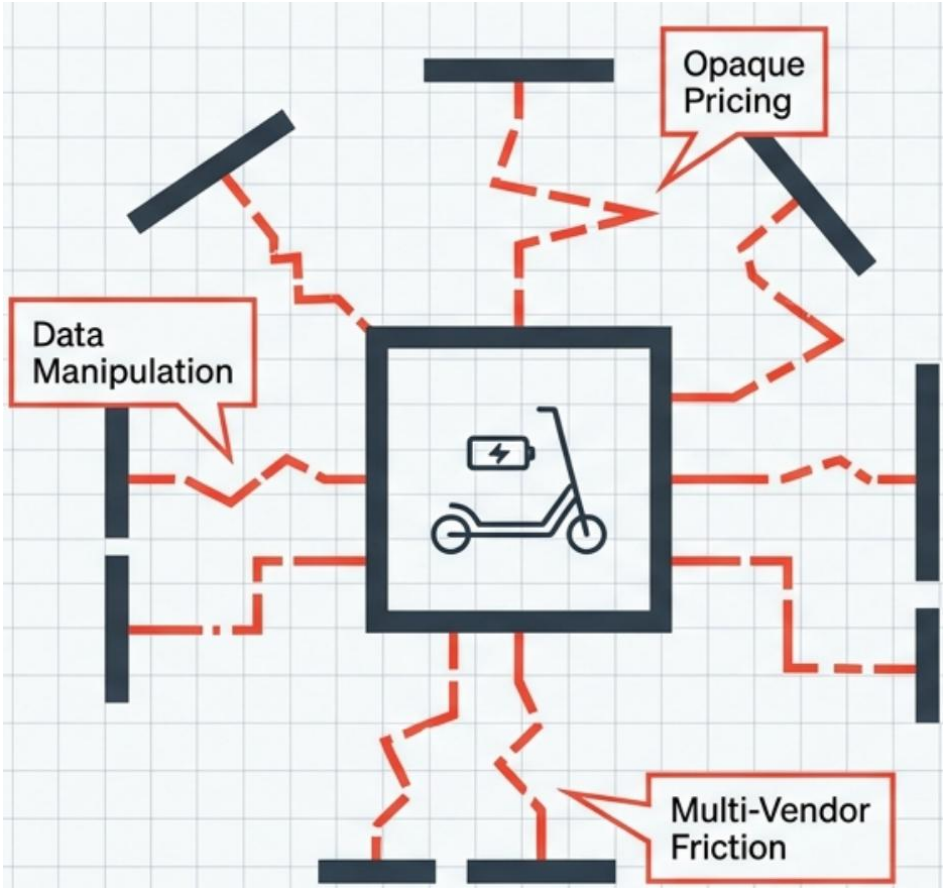
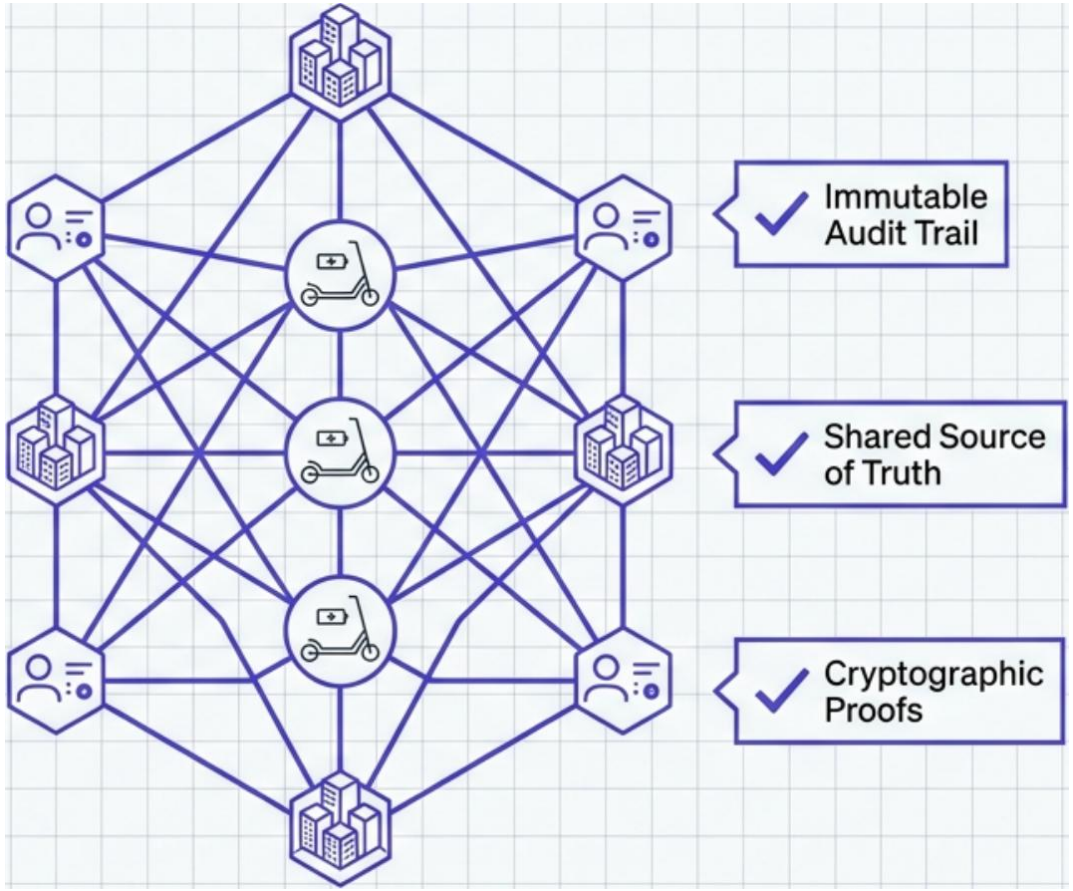
The Urban Context: Micromobility & The Trust Gap

The Problem: Centralized Silos



The Solution: Distributed Ledger Technology

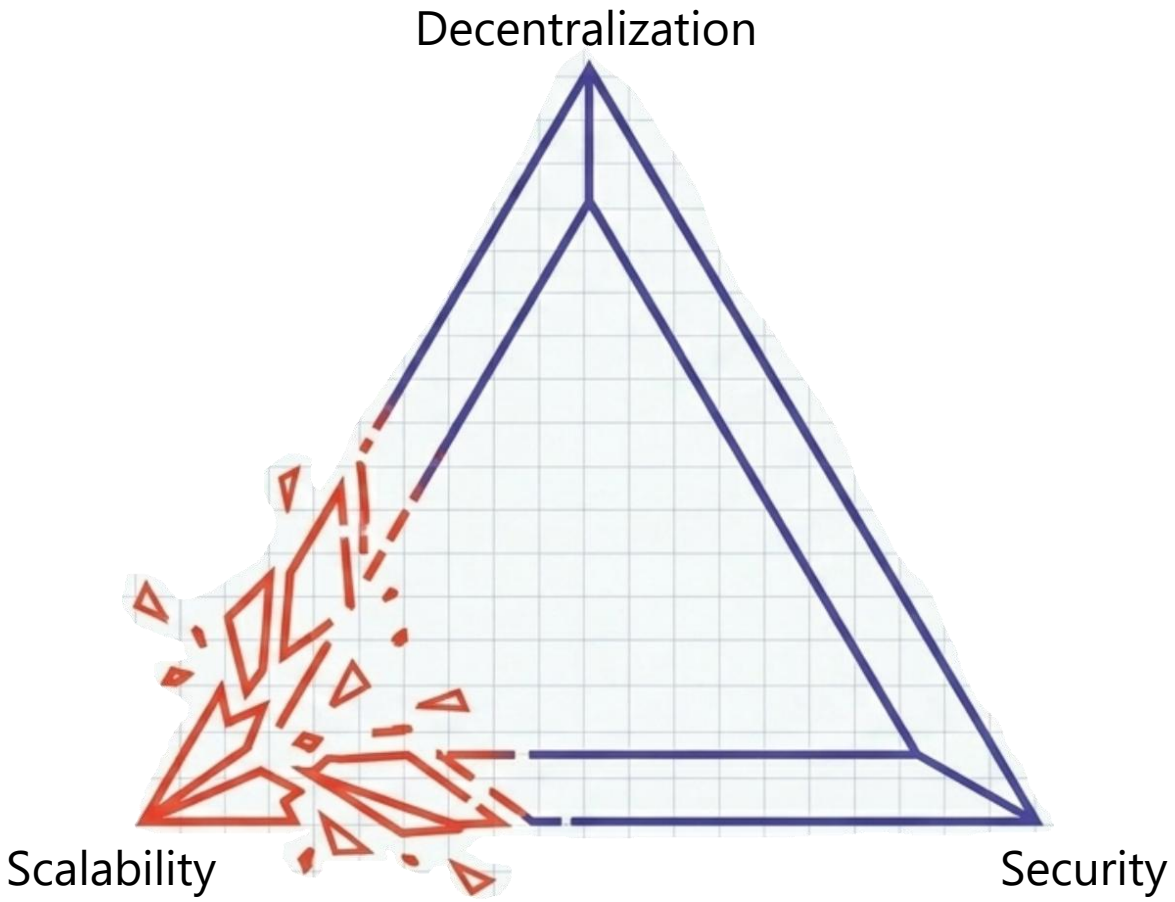


The Research Problem: The Scalability Trilemma

Low Throughput
Ethereum processes 15-30 TPS vs. Visa at ~8,500 TPS. Insufficient for city-scale telemetry.

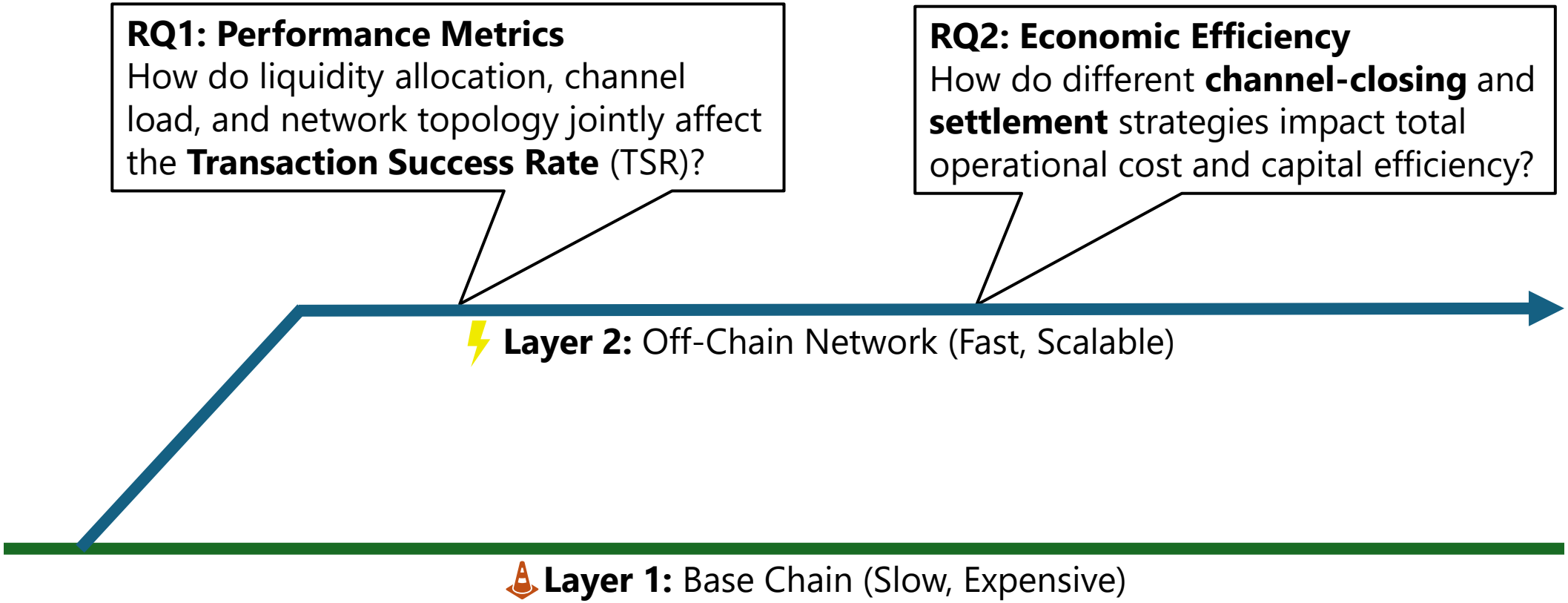
High Gas Fees
Spikes in network load push transaction costs above the actual value of the ride.

Latency
Confirmation times range from seconds to an hour - unacceptable for immediate vehicle unlocking.



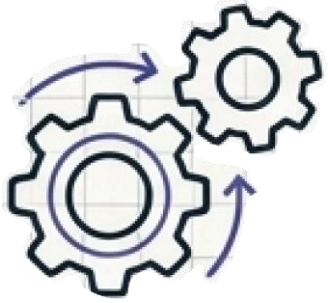
Enter Layer-2: Shifting High-Frequency Friction Off-Chain

Core Goal: Quantify the operational behavior of a hybrid L1/L2 Raiden-style architecture under realistic micromobility conditions.



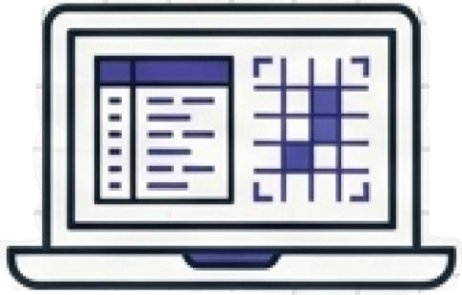
Methodology: Design Science Research Pipeline

STAGE 1:
BLOCKCHAIN PROTOTYPE



Smart-contract coordination and L1 ride summaries

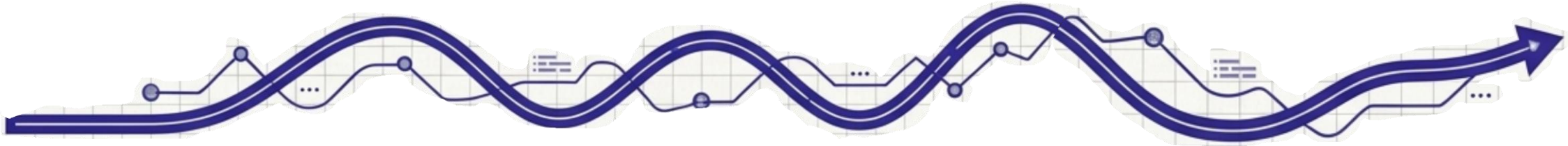
STAGE 2:
EXPERIMENTAL SIMULATOR



Parameterized using the real-world Chicago e-scooter trip dataset

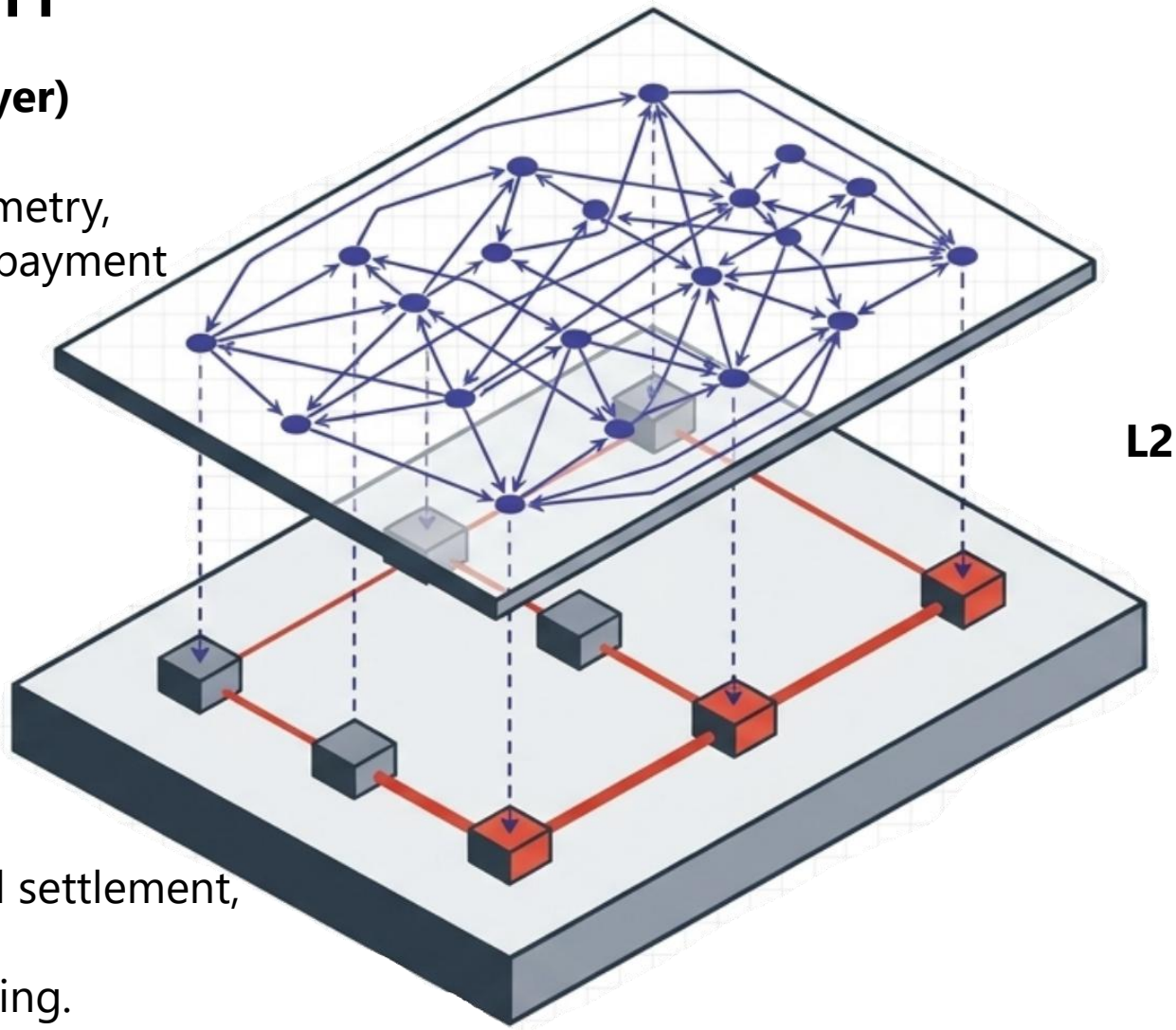
STAGE 3:
PROOF OF CONCEPT (PoC)

Evaluating private Ethereum L1 coupled with Raiden-style L2 nodes



Architectural Synthesis: Functional Stratification

Layer-2 (Operational Layer)
Handles high-frequency micromobility traffic, telemetry, and off-chain routing via payment channels.

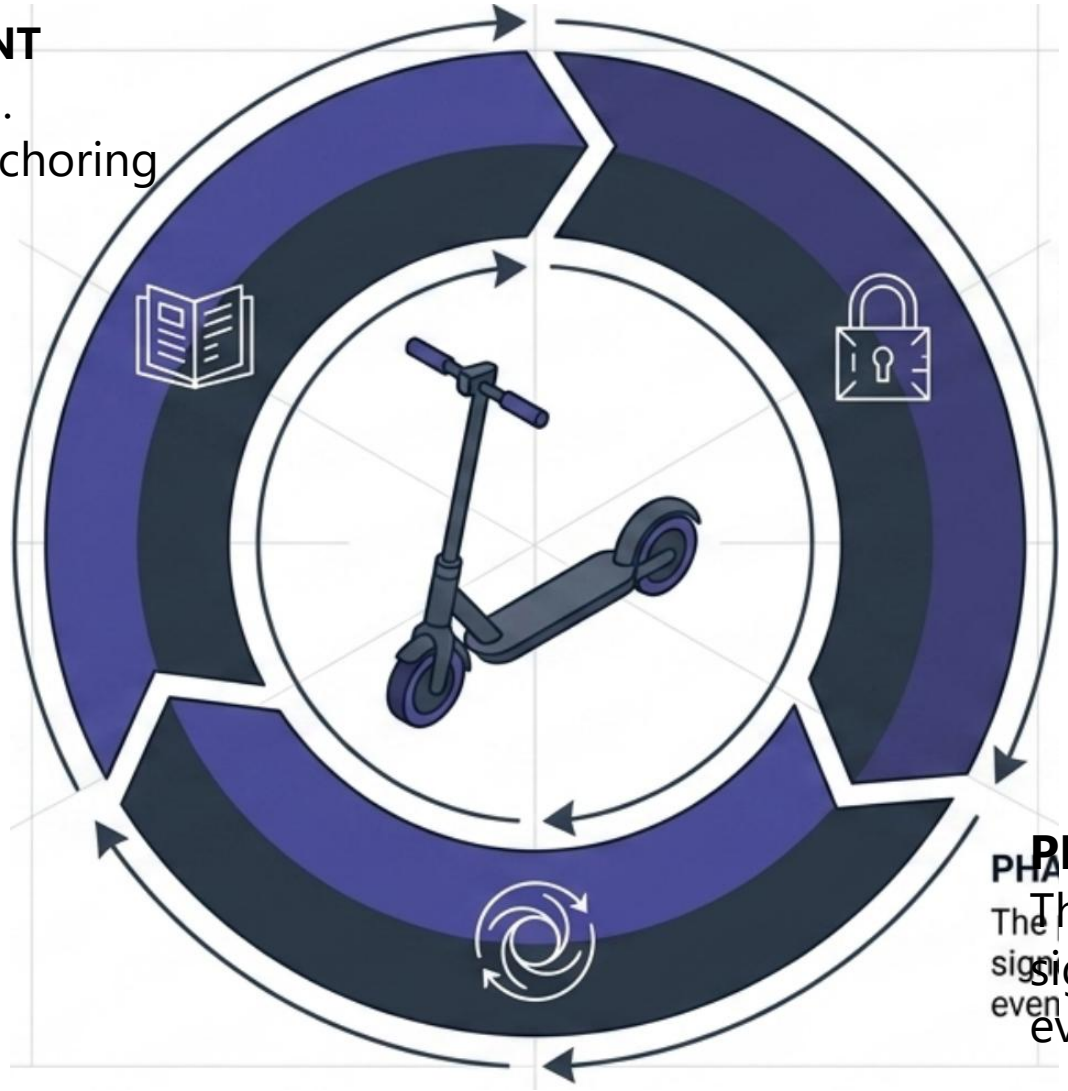


L2-L1 Anchor Mapping

Layer-1 (Base Layer)
Serves exclusively for final settlement, cryptographic anchoring, and regulatory audit logging.

Anatomy Of A Ride: The 3-phase Mechanism

PHASE III: SETTLEMENT
Final pricing calculated.
Scheduled L2-to-L1 anchoring and channel closure.

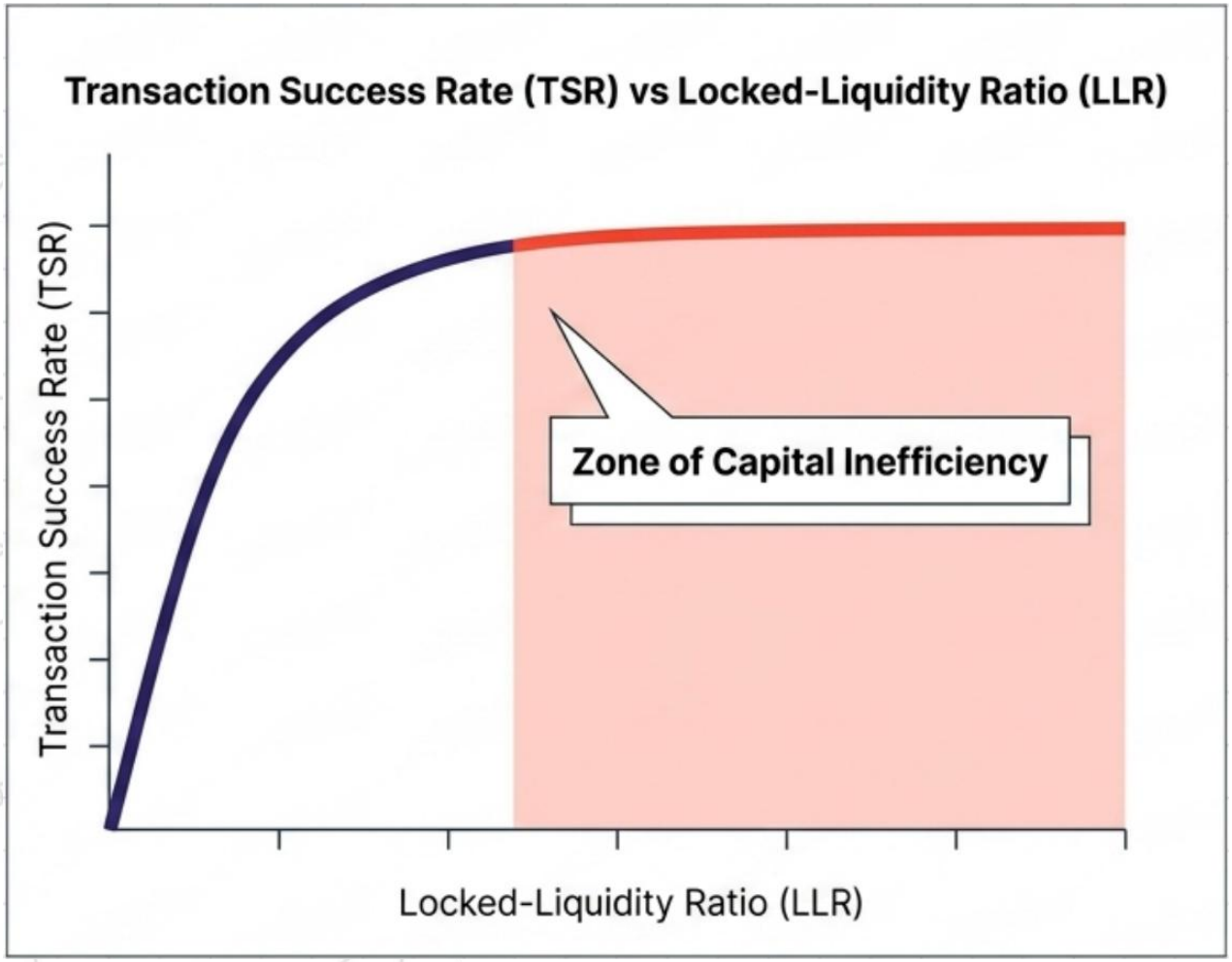


PHASE I: BOOKING & AUTHORIZATION
Verifying user L2 deposits and pre-authorizing funds off-chain.

PHASE II: EXECUTION & LOGGING
The physical ride generates off-chain signed updates mapping operational events to micro-transactions.

RQ1 Analysis: The Illusion of Infinite Liquidity

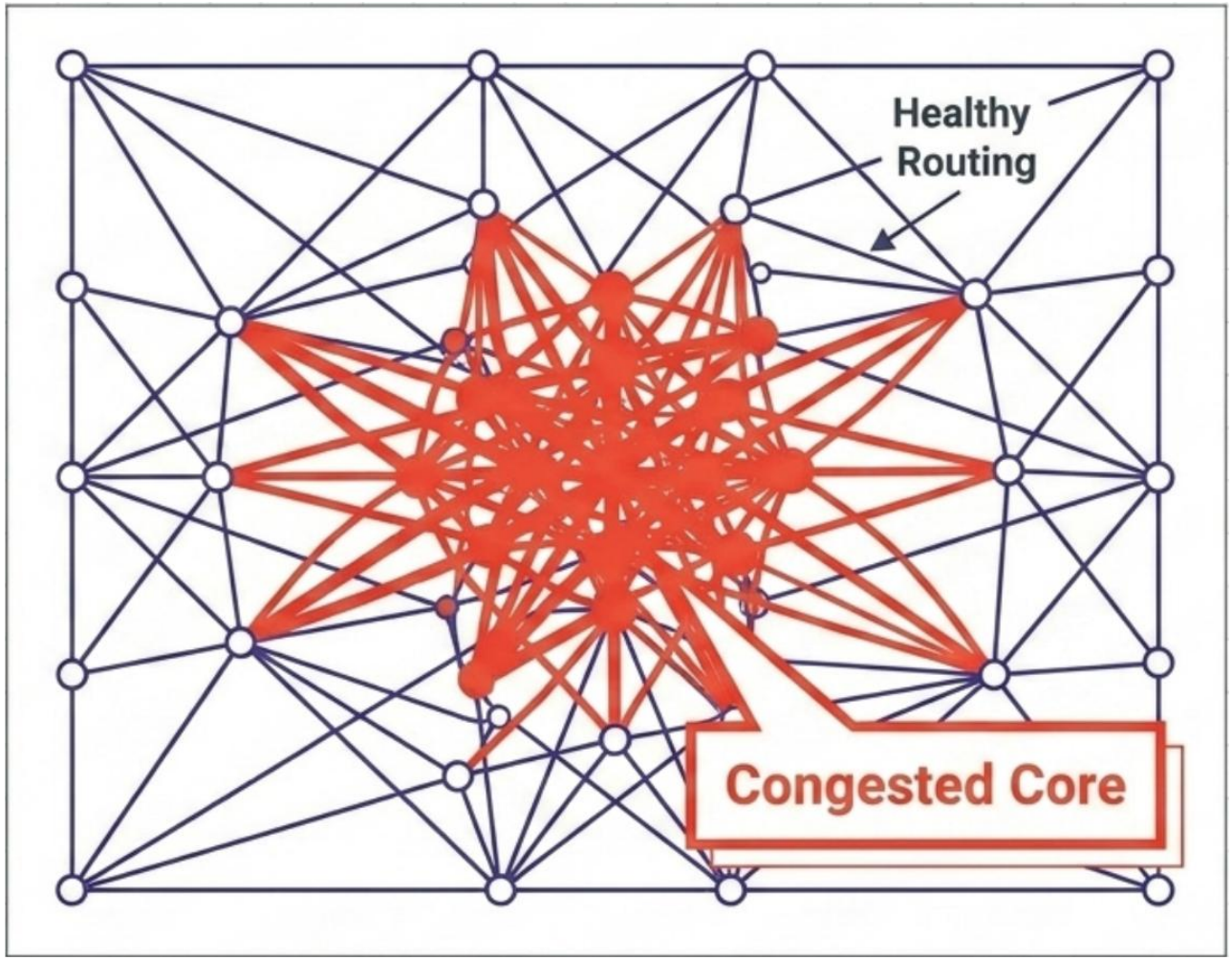
The Insight
Transaction Success Rate (TSR) vs Locked-Liquidity Ratio (LLR)
Increasing the liquidity-to-demand ratio improves reliability, but exhibits aggressive diminishing returns.
“Overfunding” channels results in a severe zone of capital inefficiency.



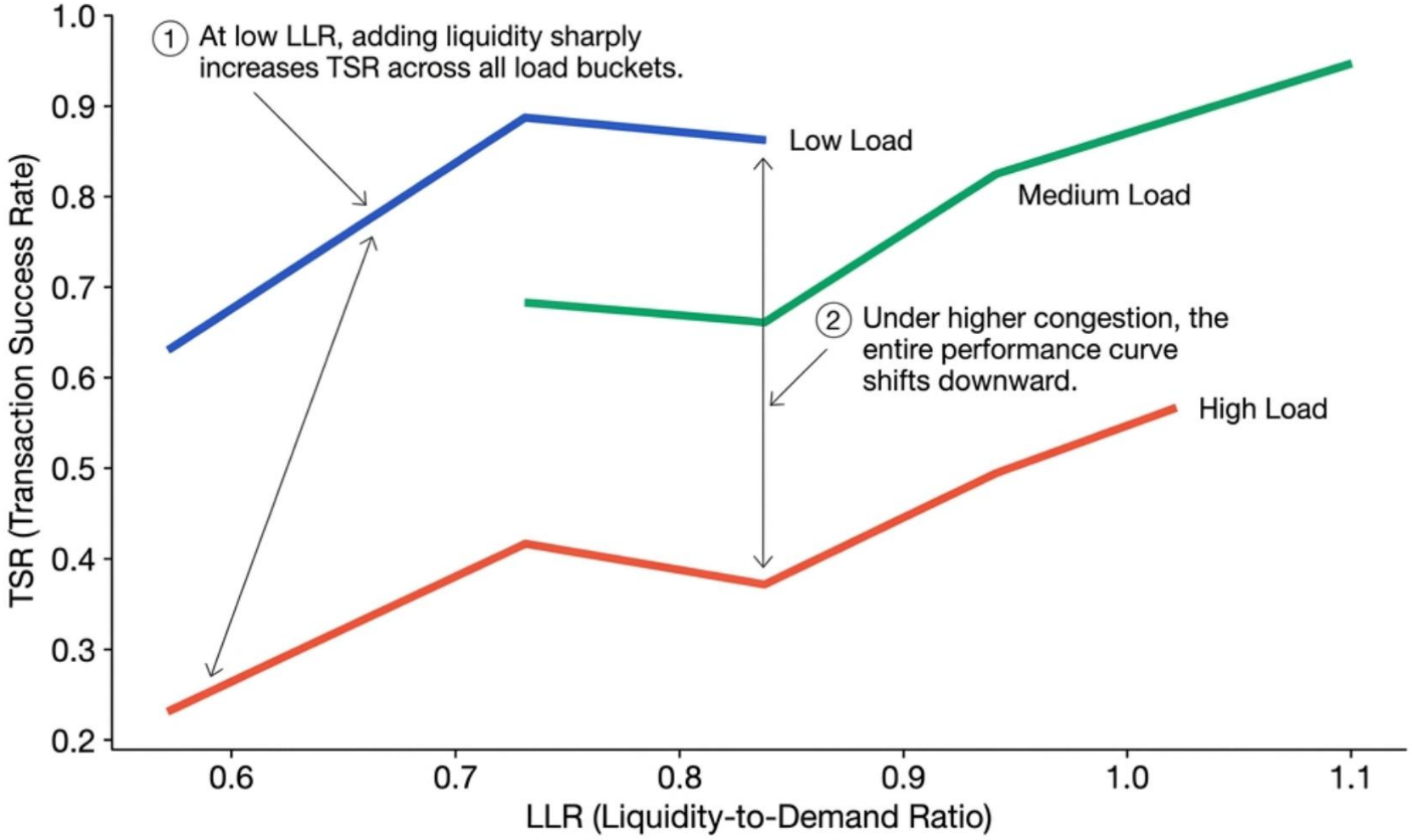
RQ1 Analysis: The True Bottleneck

The Root Cause
Reliability is primarily limited by channel-level load and structural constraints, not aggregate network liquidity.

The Implication
Unbalanced demand concentrates failures on a subset of channels. Massive liquidity reserves cannot overcome localized routing congestion.



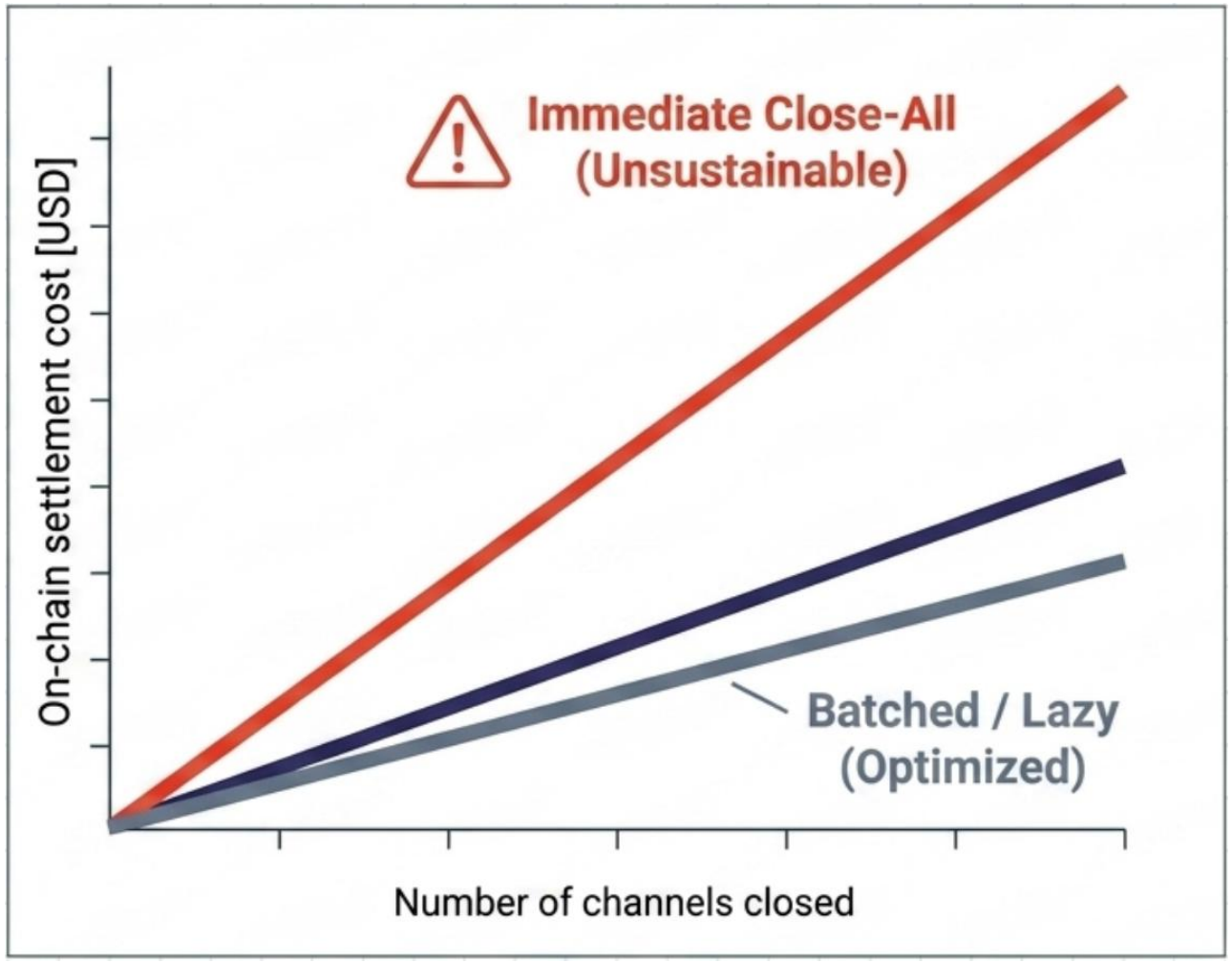
Congestion acts as a structural ceiling on Transaction Success Rate



Conclusion
"Overfunding" channels yields diminishing returns. Efficacy demands load distribution before liquidity expansion.

RQ2 Analysis: The Cost of Closure

The Threat
Immediate, ride-by-ride closure policies result in unsustainable gas fees, entirely negating the economic viability of the service. Settlement expenditure is driven by closure volume, not transaction volume.

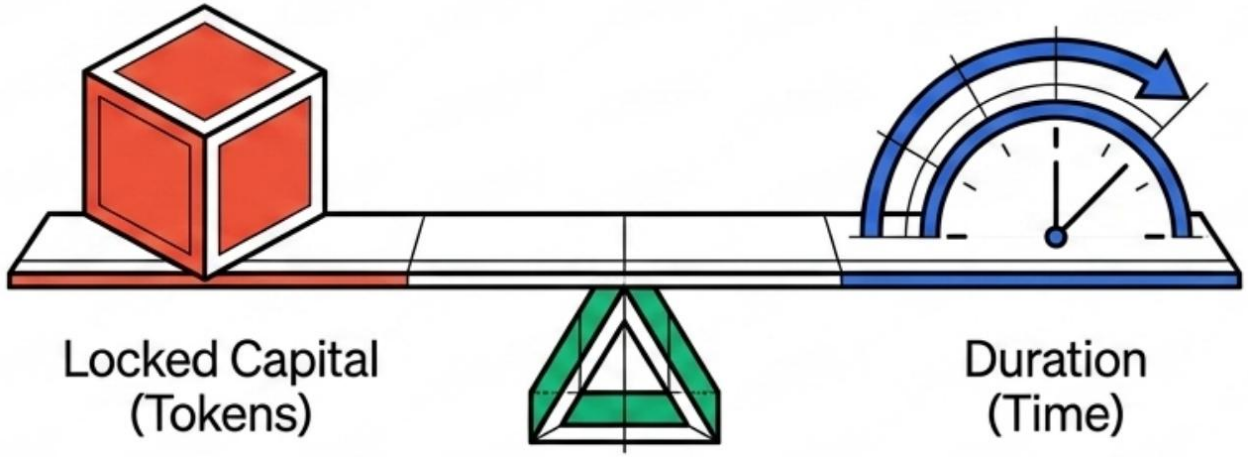


Comparison Matrix: Optimizing Settlement Strategies

Core Takeaway: Batched and lazy policies shift the operation toward a fundamentally superior cost-reliability envelope by amortizing gas expenditure across multiple rides.

Strategy	L1 Gas Cost	Operational Overhead	Capital Lock-up	Verdict
⚠️ Immediate Close-All	❌	High	Low	❌ **Unsustainable**
Batched Settlement	✔️ Low	Medium	Medium	✔️ **Recommended**
Lazy Settlement	✔️ Low	Low	High	✔️ Situational

The invisible cost of scaling: Locked-Value-Time (LVT)



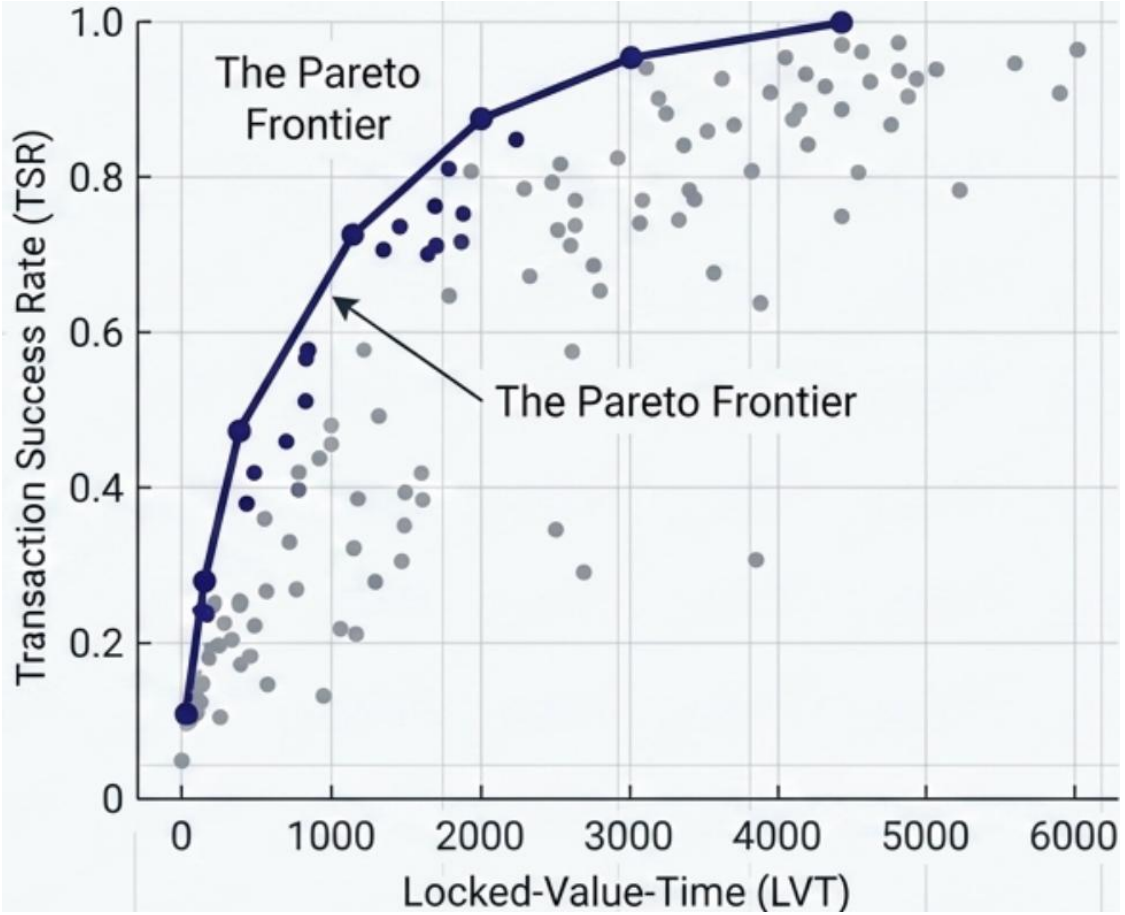
LVT = Locked Value x Lock Duration

LVT measures the true cost of off-chain scaling. A system might save money on L1 gas fees by deferring settlement, but it pays an equally steep hidden cost by paralyzing the operator's working capital.

Economic Efficiency: The LVT Pareto Frontier

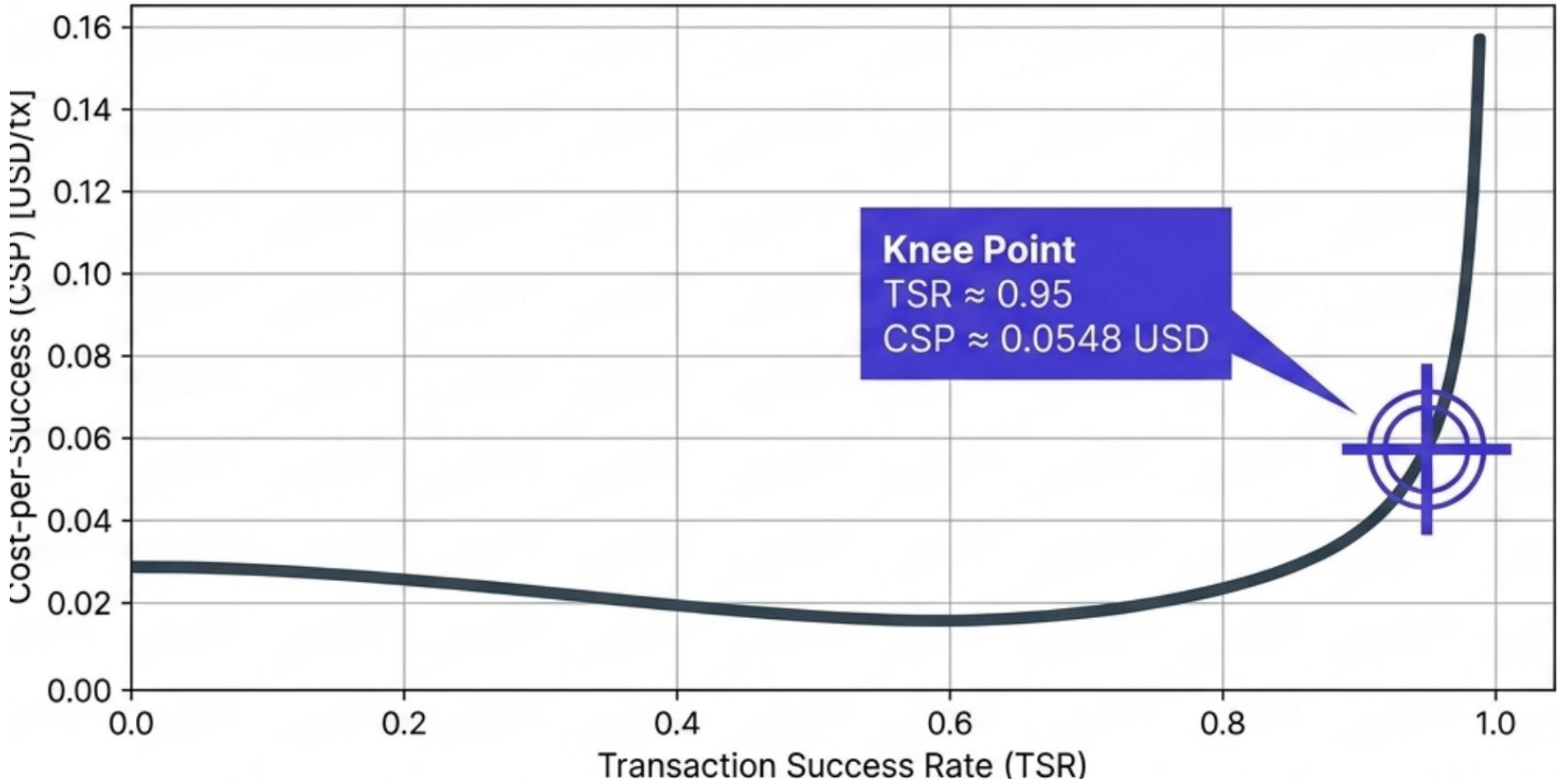
The Metric: Locked-Value-Time (LVT)
A hybrid metric capturing both the amount of frozen capital and its lock duration.

The Trade-off
Achieving higher reliability generally demands disproportionately more LVT. The frontier visualizes the exact boundary of what is mathematically possible.

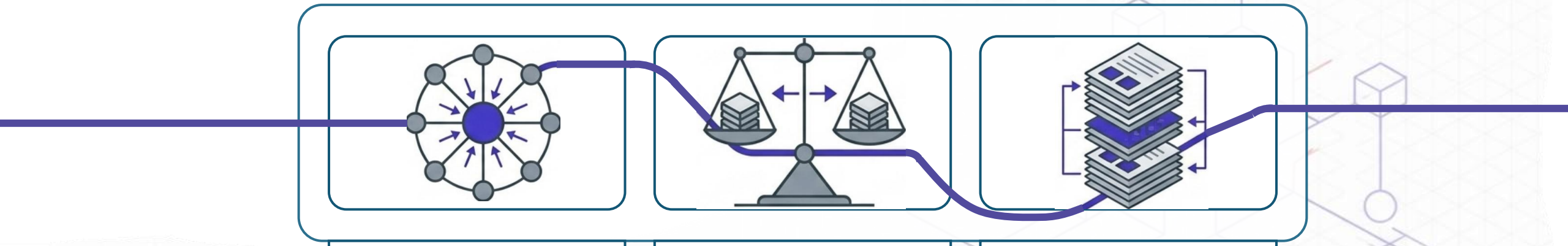


Synthesis: Identifying the Operational Knee Point

The Golden Mean. Pushing for 100% reliability results in an explosion of marginal LVT costs. Aim for the knee, not perfection.



Designer Guidelines: Building the Optimal City Grid



1. Hub-Oriented Topologies

- Prioritize load-aware routing structures over unconditional, brute-force liquidity increases.

2. Active Load Balancing

- Minimize load variance across channels to prevent catastrophic capital immobilization and localized congestion.

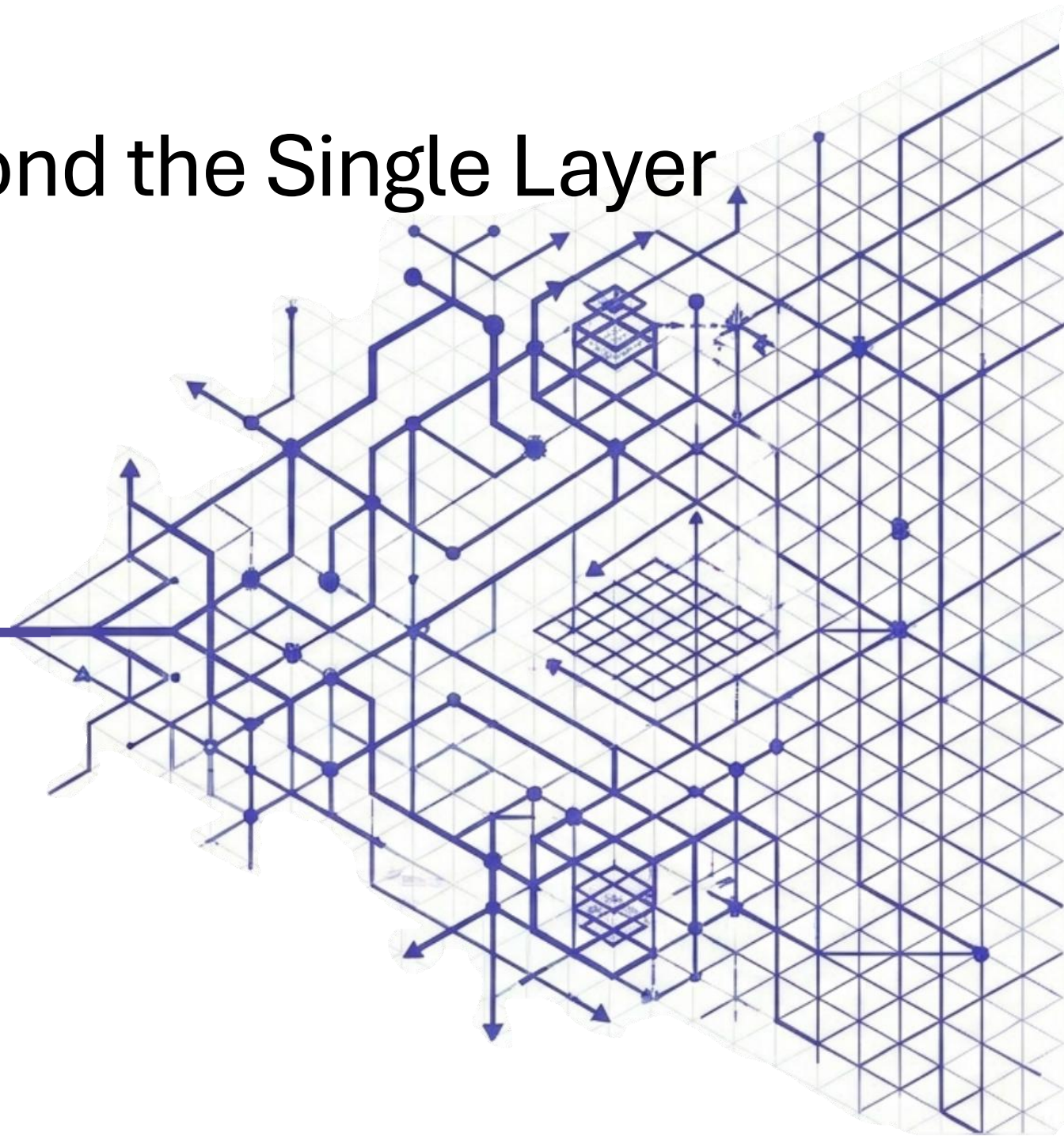
3. Aggressive Batching

- Rely on batched anchoring and settlement operations to maintain the system's economic cost-reliability envelope.

Future Horizons: Beyond the Single Layer

Automated Liquidity Rebalancing
Developing smart monitoring-driven systems to dynamically shift capital and mitigate congestion without human intervention.

L2 Symbiosis
Exploring the integration of payment channel networks with advanced rollup technologies to further compress data logic.



Thank you for attention

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Questions?