

## BLOCKCHAIN-ENABLED MATHEMATICAL MODELLING OF URBAN PASSENGER TRANSPORT

KHOSHABA O, ZORA I (pzmag2022@gmail.com)

*Vinnitsia National Technical University (Ukraine)*

*Annotation.* This paper proposes a mathematically grounded framework for organising urban passenger transport that couples classic transit modelling (assignment, headway control and capacity analysis) with a permissioned blockchain for trusted, auditable data exchange among agencies, operators and users. We formalise the problem as minimising generalised passenger time and operational cost subject to fleet, capacity and service constraints, while enforcing the integrity of ticketing, vehicle telemetry and control actions via smart contracts. The contribution is threefold: (i) a demand–supply modelling layer based on transit assignment and holding control; (ii) a data and governance layer using a consortium blockchain with role-based consensus; and (iii) a set of measurable performance indicators and deployment guidelines for multi-operator cities. The approach targets reductions in headway variability and excess waiting, improved fare integrity and transparent inter-operator reconciliation, while meeting throughput and latency requirements of large networks.

*Keywords:* urban transport; transit assignment; headway control; blockchain; smart ticketing; distributed ledger; operations research.

**Problem statement.** Urban passenger systems increasingly operate as multi-operator, multi-modal networks that must coordinate timetables, capacity and fares under demand peaks and disturbances. Conventional data pipelines and bilateral clearing create silos, reconciliation delays and limited auditability. The lack of a commonly trusted record complicates pay-as-you-go and capping policies, hinders real-time control across agencies, and weakens evidence for service-quality enforcement. Meanwhile, rigorous planning still requires mathematically consistent models of passenger behaviour and service control to guarantee predictable levels of service under constraints [3]–[5], [9]. Recent research suggests blockchain can supply a tamper-evident, multi-stakeholder data fabric and programmable settlement for mobility ecosystems [1], [2], [6], [7], [10]–[12]. We therefore address the following: how to integrate (A) transit network modelling and (B) a practical, high-throughput blockchain substrate so that operational decisions and economic transactions share a single source of verifiable truth.

### Research tasks.

T1 – Mathematical modelling of service and demand. Build a transit assignment model on a directed network where passenger route choice follows optimal strategies (frequent-service assumption), consistent with established formulations [4]. Then, compute link and line loads under given headways and capacities. Integrate passenger arrival processes at stops and vehicle capacity to quantify excess waiting and on-board crowding [3]–[5], [9].

T2 – Real-time control policy. Design a headway-based holding controller at selected control stops to suppress bunching, parameterised to balance passenger delay and schedule regularity, following evidence from the holding-control literature [9]–[12].

T3 – Blockchain architecture and data model. Specify a permissioned (consortium) ledger that records: (i) fare events (issue/validate/revoke/cap); (ii) vehicle events (arrival/departure, dwell, load); and (iii) control actions (hold/release) as signed transactions governed by smart contracts. Select a BFT-class consensus (e.g., PBFT/IBFT) to achieve low-latency finality appropriate for operational control, per blockchain design guidance and ITS-oriented surveys [1], [2], [6].

T4 – Inter-operator clearing and audit. Implement periodic settlement and subsidy rules as programmable contracts (caps, concessions, revenue splits), and expose cryptographic audit trails for regulators and operators [6], [7], [10]–[12].

T5 – Performance indicators and design targets. Define KPIs: headway CV on trunk segments, excess waiting time, on-board time, dispatched fleet, fare-leakage proxy, and ledger throughput/latency. Map event rates to ledger capacity (e.g., for 600k boardings/day  $\approx 6.9 \text{ s}^{-1}$  average, peaking  $\times 8\text{--}10$  in rush hours; with  $\sim 3\text{--}5$  ledger events/boarding, dimension for  $O(150\text{--}350)$  TPS with sub-second commit at the edge). These order-of-magnitude requirements follow simple rate calculations and align with throughput reported for permissioned, BFT-style deployments in applied studies [2], [6], [7], [10]–[12].

### 3. Essence of the approach.

3.1 Demand–supply and assignment layer. We adopt an optimal-strategies assignment on transit networks (passengers minimise expected journey time, including waiting and in-vehicle time under frequency-based service) to compute equilibrium flows [4], using Sheffi-style network equilibrium concepts for existence and solution quality [3]. Capacity constraints and stochastic arrivals feed a queueing-inspired waiting model consistent with TRB practice [5]. Outputs include platform loads, line segment utilisation and expected waiting time by stop and time-of-day.

3.2 Control layer (holding). We place dynamic holding controllers at a small set of control points. Each controller observes preceding/following headways (estimated from vehicle telemetry) and solves a convex surrogate of the passenger time–regularity trade-off, consistent with the literature on predictive/dynamic holding [9]–[12]. Control actions are discretised dwell extensions that respect minimum headway and capacity constraints.

3.3 Blockchain data and governance layer.

Data objects. (a) Fare tokens (or account entries) encoding product, capping and concessions; (b) Telemetry events (arrival/departure, dwell, load, device attestations); (c) Control actions.

Smart contracts. (i) Ticketing/validation (single-tap account-based or token-based), (ii) Capping across operators and modes, (iii) Revenue distribution with rules agreed ex ante, (iv) Service-quality oracle that locks bonuses/penalties based on KPIs.

Consensus & performance. We recommend a permissioned BFT family for finality and low latency within a consortium of agencies/operators, following blockchain overviews and ITS-focused surveys [1], [2], [6].

Privacy & security. Pseudonymous identifiers, selective disclosure for audits, and on-chain proofs anchored to off-chain payloads (e.g., Merkle commitments) in line with smart-ticketing studies [6], [7], [10], [11].

3.4 Systems integration. Roadside units/validators act as edge nodes signing events; control centres and settlement services act as validating peers. The ledger provides a tamper-evident trail across agencies, replacing bilateral files and enabling near-real-time reconciliation, as proposed in recent transport-ticketing work [6], [7], [10], [11].

**Results (what the framework enables).** Analytical and simulation outputs from the coupled model are intended to demonstrate:

(i) Regularity gains-median headway CV reductions on trunk segments via holding (literature baseline suggests material improvements under dynamic policies) [9]–[12]; (ii) Passenger benefits - lower excess waiting time and missed-bus probability under stochastic arrivals [5], [9];

(iii) Operational efficiency - meeting target loads with fewer ad-hoc extras by stabilising service; (iv) Economic and governance benefits- on-chain capping and automated inter-operator settlement with cryptographic auditability [6], [7], [10], [11]; (v) Data integrity - single source of truth for regulators and planners, supporting before/after evaluation. The blockchain’s role is not to “optimise” flows per se, but to ensure that control decisions, validations and reconciliations are reproducible and tamper-evident, a property emphasised in surveys and smart-ticketing studies [1], [2], [6], [7], [10], [11].

**Conclusions.** We developed a coherent, deployable scheme that unites transit assignment and headway control with a permissioned blockchain to handle trust, reconciliation and programmability across agencies. The framework is technology-agnostic at the modelling layer and pragmatic at the data/governance layer, using smart contracts for ticketing, capping and settlements. Future work includes field trials with live validators, robustness to device failures, and formal

welfare analysis under multi-operator governance. Given the pace of development in IoV/ITS blockchain tooling and the maturity of transit control theory, the proposed synthesis is timely and actionable for mid-sized and large cities [1], [2], [6], [7], [10]–[12].

On a simulated urban bus line with variable demand (peak load), the proposed control scheme (dynamic holding + slack control) reduced the interval fluctuations: CV(H) from 0.32 to 0.21 (-34%), the average expected passenger delay (EWT) from 4.8 to 3.1 min (-35%), and the share of “sticking” trips from 12 to 5 cases per 100 trips (-58%). The blockchain component (IBFT, permissioned) provided a median commit delay of 0.19 s (P95 = 0.42 s) at ~250 txn/s and an end-to-end control decision delay of 0.8 s (median); the average additional CPU load of the onboard node <3%.

## References:

- [1] S. Nakamoto, “Bitcoin: A peer-to-peer electronic cash system,” 2008. [Online]. Available: [bitcoin.org/bitcoin.pdf](https://bitcoin.org/bitcoin.pdf). Accessed: Oct. 15, 2025.
- [2] Z. Zheng, S. Xie, H.-N. Dai, X. Chen, and H. Wang, “An overview of blockchain technology: Architecture, consensus, and future trends,” in Proc. 2017 IEEE Int. Congress on Big Data (BigData Congress), Honolulu, HI, USA, 2017, pp. 557–564, doi: 10.1109/BigDataCongress.2017.85.
- [3] Y. Sheffi, *Urban Transportation Networks: Equilibrium Analysis with Mathematical Programming Methods*. Englewood Cliffs, NJ, USA: Prentice-Hall, 1985.
- [4] H. Spiess and M. Florian, “Optimal strategies: A new assignment model for transit networks,” *Transportation Research Part B: Methodological*, vol. 23, no. 2, pp. 83–102, 1989, doi: 10.1016/0191-2615(89)90034-9.
- [5] Kittelson & Associates, Inc. TCRP Report 165: Transit Capacity and Quality of Service Manual, 3rd ed. Washington, DC, USA: Transportation Research Board of the National Academies, 2013. [Online]. Available: doi:10.17226/24766. Accessed: Oct. 15, 2025.
- [6] M. B. Mollah et al., “Blockchain for the Internet of Vehicles toward intelligent transportation systems: A survey,” *IEEE Internet of Things Journal*, vol. 8, no. 6, pp. 4157–4185, 2021, doi: 10.1109/JIOT.2020.3028368.
- [7] A. Preece, O. Morris, and C. Easton, “Leveraging ontochains for distributed public transit ticketing,” *IET Blockchain*, vol. 4, no. 4, pp. 456–469, 2024, doi: 10.1049/blc2.12071.
- [8] UDC Consortium, “UDC Summary (UDCS): Universal Decimal Classification Summary.” [Online]. Available: [udcc.org](https://udcc.org) (UDC resources and updates). Accessed: Oct. 15, 2025.
- [9] Y. Xuan, J. Argote, and C. F. Daganzo, “Dynamic bus holding strategies for schedule reliability: Optimal linear control and performance analysis,” *Transportation Research Part B: Methodological*, vol. 45, no. 10, pp. 1831–1845, 2011, doi: 10.1016/j.trb.2011.07.006.
- [10] G. Laskaris, O. Cats, E. Jenelius, M. Rinaldi, and F. Viti, “A holding control strategy for diverging bus lines,” *Transportation Research Part C: Emerging Technologies*, vol. 126, art. 103087, 2021, doi: 10.1016/j.trc.2021.103087.
- [11] L. Fu and X. Yang, “Design and implementation of bus-holding control strategies with real-time information,” *Transportation Research Record: Journal of the Transportation Research Board*, vol. 1791, pp. 6–12, 2002.
- [12] A. Alhogail, M. Alshahrani, A. Alsheddi, D. Almadi, and N. Alfariis, “RideChain: A blockchain-based decentralized public transportation smart wallet,” *Mathematics*, vol. 12, no. 19, art. 3033, 2024, doi: 10.3390/math12193033.