

Optimización escalable y descentralizada del tráfico urbano con almacenamiento verificable para despliegues en ciudades inteligentes

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Acrónimos y Siglas

Este trabajo es cofinanciado por el Consejo Nacional de Ciencia y Tecnología (CONACYT) con el apoyo del FEEI. Se agradece el respaldo técnico y académico de la Facultad de Ingeniería de la Universidad Nacional de Asunción (FIUNA).

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- Springer, 2004, foundational reference on three-phase traffic theory.
- [2] D. Helbing, "Traffic and related self-driven many-particle systems," *Reviews of Modern Physics*, vol. 73, no. 4, pp. 1067–1141, 2001. [Online]. Available: <https://link.aps.org/doi/10.1103/RevModPhys.73.1067>
- [3] B. S. Kerner, "Three-phase traffic theory and highway capacity," *Physica A: Statistical Mechanics and its Applications*, vol. 333, pp. 379–440, 2004. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0378437103009221>
- [4] B. S. Kerner and S. L. Klenov, "Phase transitions in traffic flow on multilane roads," *Physical Review E*, vol. 80, no. 5, p. 056101, 2009. [Online]. Available: <https://link.aps.org/doi/10.1103/PhysRevE.80.056101>
- [5] M. Treiber and A. Kesting, *Traffic Flow Dynamics: Data, Models and Simulation*. Berlin, Heidelberg: Springer, 2013. [Online]. Available: <https://link.springer.com/book/10.1007/978-3-642-32460-4>
- [6] C.-H. Chou and C.-C. Teng, "A fuzzy logic controller for traffic junction signals," *Information Sciences*, vol. 143, no. 1-4, pp. 73–97, 2002. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0020025502001998>
- [7] J. Niittymäki, "General fuzzy rule base for isolated traffic signal control—rule formulation," *Transportation Planning and Technology*, vol. 24, no. 3, pp. 227–247, 2000. [Online]. Available: <https://www.tandfonline.com/doi/abs/10.1080/03081060108717669>
- [8] Y. Zhao, T. Zhang, and W. Liu, "Adaptive traffic signal control: A comparative study of machine learning approaches," *Sensors*, vol. 21, no. 9, p. 2934, 2021.
- [9] M. A. Gökçe and others, "Traffic signal optimization with particle swarm optimization for signalized roundabouts," *SIMULATION*, vol. 91, no. 6, pp. 526–536, 2015. [Online]. Available: <https://journals.sagepub.com/doi/10.1177/0037549715581473>
- [10] S. A. Celtek and others, "Real-time traffic signal control with swarm optimization methods," *Measurement*, vol. 166, p. 108206, 2020. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0263224120307442>
- [11] X. Li, W. Zhang, Y. Liu, and R. Wang, "Urban traffic optimization: A systematic review of current practices and research directions," *IEEE Access*, vol. 11, pp. 19427–19445, 2023.
- [12] T. T. Nguyen and others, "Feature extraction and clustering analysis of highway traffic states," *Transportation Research Part C: Emerging Technologies*, vol. 100, pp. 238–258, 2019. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0968090X1830891X>
- [13] W. Wang, Y. Xie, and L. Tang, "Hierarchical clustering algorithm for multi-camera vehicle trajectories based on spatio-temporal grouping under intelligent transportation and smart city," *Sensors*, vol. 23, no. 15, p. 6909, 2023. [Online]. Available: <https://www.mdpi.com/1424-8220/23/15/6909>
- [14] N. Rouky, A. Bousouf, O. Benmoussa, and M. Fri, "A spatiotemporal analysis of traffic congestion patterns using clustering algorithms: A case study of casablanca," *Decision Analytics Journal*, vol. 10, p. 100404, 2024. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S2772662224000080>
- [15] P. Zhang and others, "Cluster analysis of day-to-day traffic data in networks," *Transportation Research Part C: Emerging Technologies*, 2022, artículo de referencia sobre selección de n° de clúster (Silhouette/DBI); incluir DOI/volumen al compilar. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0968090X22002959>
- [16] V. Astarita, D. C. Festa, and V. P. Giofré, "An iot-based centralized architecture for urban traffic monitoring," *IEEE Internet of Things Journal*, vol. 10, no. 6, pp. 5124–5135, 2023.
- [17] A. Aneiba, J. Hayes, B. Nangle, and M. N. Albaarini, "Real-time iot urban road traffic data monitoring using lorawan," in *Proceedings of the 9th International Conference on the Internet of Things (IoT 2019)*. ACM, 2019, p. Article A20. [Online]. Available: <https://doi.org/10.1145/3365871.3365891>
- [18] D. Asiain and D. Antolín, "Lora-based traffic flow detection for smart-road," *Sensors*, vol. 21, no. 2, p. 338, 2021. [Online]. Available: <https://www.mdpi.com/1424-8220/21/2/338>
- [19] A. Povalac and others, "Exploring lorawan traffic: In-depth analysis of iot network communications," *Sensors*, vol. 23, no. 17, p. 7333, 2023. [Online]. Available: <https://www.mdpi.com/1424-8220/23/17/7333>
- [20] D. Dobrilović and others, "The urban traffic noise monitoring system based on lorawan technology," *Wireless Networks*, vol. 28, pp. 3201–3219, 2022. [Online]. Available: <https://link.springer.com/article/10.1007/s11276-021-02586-2>
- [21] M. H. R. Islam, T. Ahmed, and H. Kim, "Blockchain-based secure and transparent urban traffic management system," *IEEE Access*, vol. 11, pp. 88 321–88 333, 2023.
- [22] R. Jabbar and others, "Blockchain technology for intelligent transportation systems: A systematic literature review," *IEEE Access*, vol. 10, pp. 20 995–21 031, 2022. [Online]. Available: <https://ieeexplore.ieee.org/document/9707737>
- [23] S. Sivagnanam, V. Nandigam, and K. Lin, "Introducing the open science chain: Protecting integrity and provenance of research data," in *PEARC '19: Practice and Experience in Advanced Research Computing*, 2019, pp. Article 18, 1–5. [Online]. Available: <https://dl.acm.org/doi/10.1145/3332186.3332203>
- [24] K. Wittek and others, "A blockchain-based approach to provenance and reproducibility in research workflows," in *2021 IEEE International Conference on Blockchain and Cryptocurrency (ICBC)*, 2021, pp. 1–6. [Online]. Available: https://elib.dlr.de/142470/1/212995_1.pdf
- [25] M. Eckermann, F. Kretz, I. Pippow, and R. Anderl, "A performance analysis of ethereum, iota and hyperledger fabric for industry 4.0 applications," *Procedia CIRP*, vol. 104, pp. 44–49, 2021.
- [26] X. Wang, H. Liu, and W. Zhang, "Blockdag-based public ledger: Performance analysis and comparison with blockchain," *IEEE Transactions on Network and Service Management*, vol. 20, no. 1, pp. 45–56, 2023.
- [27] Y. Sompolinsky and A. Zohar, "Phantom: A scalable blockdag protocol," in *Financial Cryptography and Data Security (preprint/working paper)*, 2015, versión formal y variantes GHOSTDAG publicadas posteriormente. [Online]. Available: <https://www.semanticscholar.org/paper/PHANTOM%3A-A-Scalable-BlockDAG-Protocol-Sompolinsky-Zohar/50bc77f3ec070940b1923b823503a4c2b09e9921>
- [28] S. Popov, "The tangle: An overview of the iota architecture," *arXiv preprint arXiv:2102.06856*, 2021. [Online]. Available: <https://arxiv.org/abs/2102.06856>
- [29] V. Buterin, "Ethereum: A next-generation smart contract & decentralized application platform," <https://ethereum.org/en/whitepaper/>, 2016, white paper.
- [30] G. Wood and collaborators, "Ethereum merge documentation," <https://ethereum.org/en/upgrades/merge/>, 2022, proof-of-Stake (The Merge), documentación técnica.
- [31] A. Azbeg and Colaboradores, "A review of dag-based ledgers and blockchain variants for iot and intelligent transportation," 2023, revisión general de ledgeres DAG/Blockchain aplicados a IoT y tráfico. Metadatos completos por confirmar.
- [32] M. Moradi, M. Fathy, and A. Khosravi, "A review on intelligent traffic control systems: Historical perspectives and future directions," *Transportation Research Part C: Emerging Technologies*, vol. 144, p. 103884, 2022.
- [33] L. Yin, P. Gomez, and S. Lee, "Sumo-based traffic prediction and optimization using machine learning," in *Proc. IEEE Intelligent Transportation Systems Conf. (ITSC)*, 2022, pp. 2386–2391.