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TRAFFIC FLOW MANAGEMENT BASED ON INTELLIGENT TRANSPORTATION SYSTEMS: CHALLENGES, LIMITATIONS, AND RESEARCH DIRECTIONS

The rapid pace of urbanization, accompanied by a steady increase in motorization and the growing structural complexity of urban transport networks, has significantly intensified the challenges associated with traffic flow management. Large metropolitan areas are increasingly confronted with persistent congestion, unstable traffic conditions, elevated accident risks, and substantial environmental impacts, including increased emissions and energy consumption. Under these circumstances, conventional approaches based on fixed-time control strategies and static planning models are no longer capable of ensuring the efficient functioning of transport systems. Such methods typically rely on simplified assumptions, fail to adequately capture the stochastic and nonlinear nature of traffic flows, and lack the flexibility required to respond effectively to rapid fluctuations in demand, incidents, and external disturbances.

In recent years, the advancement of intelligent transportation systems has opened new possibilities for improving traffic management through the integration of real-time data acquisition, modern communication technologies, and data-driven decision-making processes. These systems support adaptive and predictive control, enabling transport networks to respond dynamically to evolving traffic conditions. Nevertheless, despite notable progress, the management of traffic flows in complex urban environments remains an unresolved and challenging problem. This is particularly evident in multilane traffic scenarios, where interactions among vehicles, frequent lane-changing maneuvers, and heterogeneous traffic compositions introduce additional layers of complexity that are not sufficiently addressed by existing methodological approaches.

From a methodological standpoint, several limitations can be identified. Classical traffic flow models, including both macroscopic and microscopic formulations, often fail to represent the full spectrum of interactions observed in real-world traffic systems. In particular, they provide only a partial description of lane-changing behavior and inter-lane dependencies, which play a crucial role in

the emergence of congestion and traffic instabilities. At the same time, there is a lack of integrated frameworks that effectively combine different modeling scales with real-time control mechanisms. Many existing approaches remain grounded in deterministic assumptions and do not adequately account for uncertainty, variability in driver behavior, or unexpected disruptions such as accidents and adverse weather conditions. Furthermore, when applied to large-scale urban networks, these models frequently encounter scalability constraints that limit their practical applicability.

The shift toward intelligent, data-driven traffic management also gives rise to a range of scientific challenges. One of the key issues concerns the development of reliable real-time predictive models capable of processing large volumes of heterogeneous data. Another important challenge lies in integrating different categories of transport participants, including conventional vehicles and connected or automated vehicles, within a unified control framework. In addition, there is an increasing need for decentralized and multi-agent control strategies that can ensure coordinated operation across different parts of the transport network. Issues related to data quality, uncertainty, and system security further complicate the design and deployment of such systems. The concept of digital twins, which aims to replicate transport systems in a virtual environment for analysis and control, also requires further methodological refinement and empirical validation.

Despite the substantial body of research in this field, several important gaps remain. There is still no comprehensive approach that simultaneously addresses multilane traffic dynamics, real-time adaptability, and network-level optimization within a single coherent framework. The potential of advanced artificial intelligence techniques, such as reinforcement learning and deep neural networks, has not yet been fully exploited in large-scale coordinated traffic control applications. Moreover, existing studies often treat traffic flow modeling, control theory, and data-driven methods as separate domains rather than integrating them into a unified methodological paradigm. Insufficient attention has also been paid to the role of driver behavior and lane-changing processes in shaping traffic dynamics, particularly within the context of intelligent control systems.

These limitations highlight the need for further research aimed at developing adaptive, scalable, and integrated approaches to traffic flow management. Promising directions include the design of multi-level control architectures that combine local and network-wide decision-making, the application of artificial intelligence techniques for predictive and self-learning control, and the incorporation of multilane interactions into traffic models and control algorithms. The implementation of digital twin technologies, along with control tower concepts, may provide a foundation for more effective and centralized management of urban transport systems. Overall, addressing these challenges is

essential for enhancing the performance, safety, and sustainability of modern transport networks.

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