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The Congestion Control Method System for Urban Mixed Traffic Flow under Intelligent Transportation Systems

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Abstract. With the continuous advancement of Intelligent Transportation Systems (ITS) in China, the originally open urban regional traffic network is progressively evolving into a virtually controlled and closed system, wherein traffic states can be monitored, measured, and regulated. However, traditional theories on urban traffic supply-demand equilibrium and associated congestion control methods, which are rooted in open-system assumptions, are increasingly inadequate for contemporary applications. Under the ITS environment, it is crucial to redefine the equilibrium principles of urban traffic networks and establish corresponding congestion control theories and methodologies. This paper reviews the developmental status of intelligent transportation management and control systems in Chinese major cities and introduces a theoretical framework for regional congestion control in urban road networks accommodating mixed traffic flows (comprising conventional and new-energy vehicles). By constructing a spatio-temporal virtual closed system through a "data boundary" defined by discrete regional detection points of mixed traffic inflow and outflow within a controlled network area, and integrating Macroscopic Fundamental Diagram model under regional perimeter control strategies, this study proposes a hybrid active-pinning control approach based on regional network controllability. Furthermore, a technical pathway and methodological system are designed to further analyze this theoretical framework.

Keywords: mixed traffic flow, urban road network, congestion control, Intelligent Transportation Systems

1. Introduction

The rapid increase in vehicle ownership, including the growing share of new-energy vehicles, has outpaced the expansion of urban road networks, making traffic congestion a critical barrier to sustainable urban development in China. With advancements in technology and the economy, the deployment of ITS—such as secure-access systems, electronic-monitoring systems, various traffic monitoring and control systems—has achieved near-complete coverage of information collection points on major roads and intersections in most modern Chinese cities [1]. However, a significant challenge remains: the current application of ITS in urban traffic management and control relies heavily on computer science and information technology, while traffic engineering theories and

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methods often play a secondary role, partly due to the mismatch between deterministic traffic models and the uncertain conditions of real-world traffic networks.

With the ITS technologies advance and applied in urban transport systems, modern road network is progressively becoming a controllable developed system. Congestion control is consequently shifting from an uncertain challenge to a more deterministic one. This paper discussed the development of ITS and classified related control systems in Chinese main cities. Based on the analysis of regional mixed traffic flow characteristics and corresponding application of ITS technologies, a spatio-temporal system which is virtual closed and bounded by a "data boundary" formed by discrete vehicle detection points is proposed. By leveraging regional traffic controllability, a holistic framework for network supply-demand equilibrium and intelligent congestion control is established, incorporating a kind of mixed active pinning control in conjunction with MFD model and the perimeter control method. The corresponding methodology and technical route are also elaborated in the later part.

2. Urban ITS system development

Intelligent Transportation System represents an innovative integration of information technology and traditional transportation engineering, serving as a key direction for modern transport system development. Since its introduction in the 1980s, China has achieved significant progress in this domain. There are more than 400 cities have established control centers and corresponding traffic operation that integrate traffic information collection, traffic flow control, and emergency processing, enabling regional signal coordination and fostering an increasingly intelligent and digital urban traffic network. The volume of traffic data has also exhibited typical "Big Data" characteristics.

2.1. Investment in ITS and traffic management systems

Traffic investment in the intelligent transportation sector has grown substantially. As illustrated in Figure 1, by 2022 (after covid-19), the amount of urban ITS projects reached 1,087 in China, with over 19.000 billion yuan market scale.

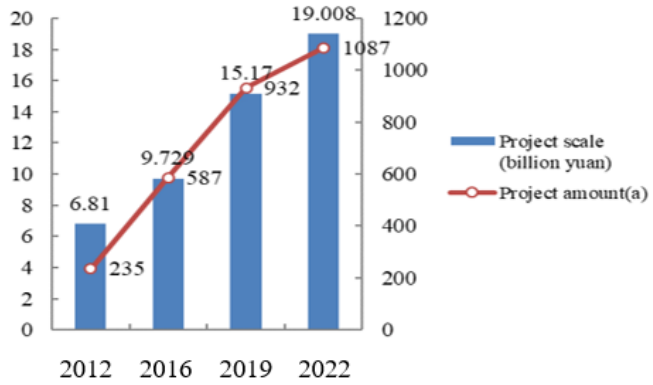


Figure 1. Scale and amount of ITS projects

2.2. Collaborative infrastructure system for vehicle networks

Utilizing developed detective technologies and wireless communication, the urban collaborative infrastructure system enables the acquisition and sharing of vehicle and road information through

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both vehicle-infrastructure and vehicle-vehicle communication [2]. This facilitates intelligent coordination, optimizing resource utilization, enhancing road safety, and mitigating transport congestion [3]. Besides, the vehicular networking industry is poised for continued expansion with ongoing technological progress, becoming an integral component of the future urban transport pattern.

2.3. Electronic monitoring system

The electronic-monitoring equipments have been widely deployed and applied in the urban ITS. As shown in Figure 2, the number of relative electronic-police devices has been increasing annually in major cities. Beijing and Shanghai demonstrate the highest growth rate. By 2022, even the lowest city (Chongqing) possessed nearly 1,500 sets. Furthermore, the functionality of electronic police equipment has advanced significantly, leading to the recognition of complex and specific traffic behaviors, while performing facial recognition at the same time. The trend is toward integrated, multi-functional, high-definition intelligent equipment and integrated into an advanced system.

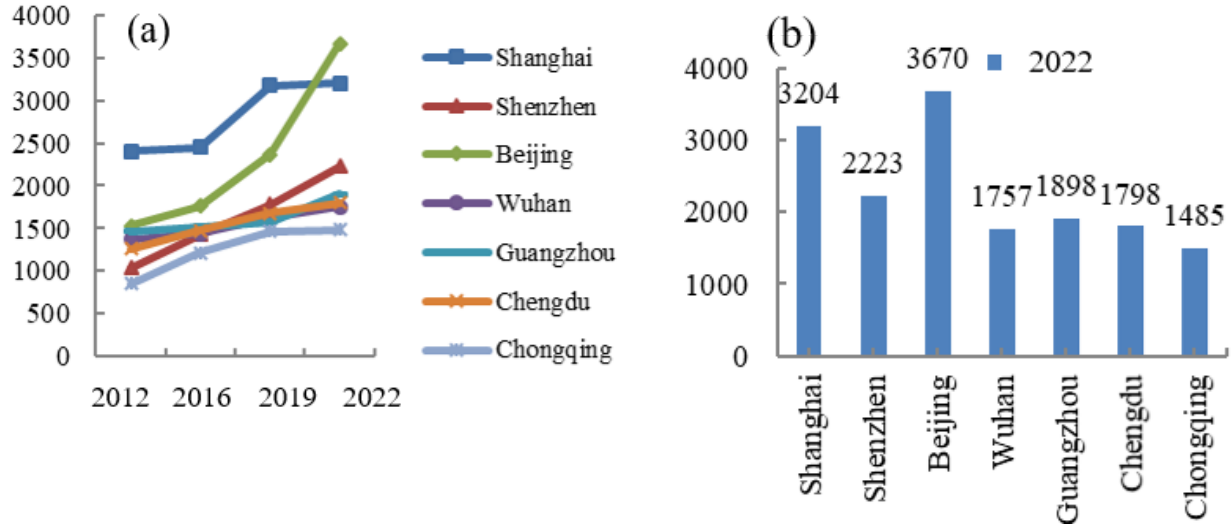


Figure 2. Graph of electronic-monitoring device in Chinese main cities (a)line chart by years; (b)bar chart by cities

2.4. The collection and application for traffic information

With the continuous development of big data, traffic information collection has evolved from the traditional fixed-point methods to dynamic, communication network-based approaches that increasingly involve public participation. Intelligent data processing is expected to continuously enhance the control and management level of regional traffic signal system.

2.5. Autonomous driving

Automatic vehicles utilize sensing technologies to perceive the driving environment and control speed and direction accordingly, ensuring safe and stable operation [4]. The SAE J3016 standard defines six levels of driving automation. Currently, most mass-produced vehicles globally are at L1 (assisted driving) or L2 (partial automation) levels. In China, although research started later,

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development has been rapid. By August 2022, nine cities had opened roads for autonomous vehicle testing. In July 2018, Baidu launched the "Apollo 3.0," an L4 (high automation) driverless bus.

3. Characteristics and evolution of the regional intelligent road network

There are a numbers of related concepts including smart city, smart transportation, intelligent vehicles, and "Internet + Transportation" are continually emerging. The deployment of electronic-monitoring, security assurance systems, various single and multi-control methods, along with the implementation of vehicular networking and autonomous driving technologies, are making the current urban regional traffic network more "closed," and its facilities and flows more "available" and "controllable." Consequently, the regional road network is switching into an intelligent regional transport system which can be controlled effectively, with its controllability expected to become more refined and enhanced with the application of ongoing technological upgrades.

3.1. The intelligent regional road network

The integration of data communication technologies and big data information in ITS has reshaped the analysis of traffic flow monitoring and control methods within network platforms [5,6]. The traditional regional road network is evolving into an intelligent road network system where processes and states are measurable and controllable. Unlike conventional traffic information detection or monitoring systems that focus on local phenomena, the intelligent road network emphasizes coordinated control strategies that manage traffic flow at a holistic network level.

3.2. Characteristics of the intelligent road network

3.2.1. Closure

Although urban road networks are inherently open, empirical studies indicate they exhibit modular structures similar to complex networks, with tightly connected internal components and sparser inter-module connections. This structure allows for the extraction of congested areas from the network [7]. By controlling external traffic inflows, local congestion can be mitigated [8,9]. Perimeter control theory treats the open urban network as a set of corresponding homogeneous, closed sub-regions, maintaining optimal states in each to maximize overall network flow [10].

3.2.2. Observability

Intelligent technologies offer diverse means for information collection. The widespread installation of developed detectors and sensors on urban roads ensures comprehensive coverage, especially in critical regional networks, enabling real-time acquisition of complete traffic information. Integrated with big data and cloud computing, traffic control systems are transitioning from manual monitoring to adaptive control modes capable of proactive statistical analysis and signal timing adjustments. This observability supports quantitative or qualitative descriptions of traffic states, aiding management departments in accurately assessing network performance.

3.2.3. Controllability

Intelligent technologies significantly enhance network controllability. On one hand, multi-source traffic data and rapid processing capabilities allow managers to regulate traffic flow via signaling

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and guidance systems, balancing distribution and reducing overall network delay. On the other hand, travelers can plan routes based on real-time information to minimize travel cost. Intelligent traffic technology enables diverse traffic flow distributions under different control objectives, making network traffic increasingly manageable.

3.3. Characteristics and challenges of mixed traffic flow

The urban road network is increasingly becoming a heterogeneous environment characterized by mixed traffic flow, which comprises conventional internal combustion engine vehicles (ICEVs), electric vehicles (EVs), hybrid electric vehicles (HEVs), and connected and automated vehicles (CAVs). This mixture introduces new dimensions of complexity to traffic dynamics, necessitating a refinement of traditional control theories. Among these, the behavioral differences of new-energy vehicles, primarily EVs, present both challenges and opportunities for congestion control under ITS.

3.3.1. Distinctive driving behaviors

EV drivers often exhibit driving patterns distinct from those of ICEV drivers, primarily influenced by range anxiety and energy regeneration systems. Studies have shown that EV drivers tend to adopt smoother acceleration and deceleration profiles to conserve battery power, a phenomenon known as "eco-driving" [11]. While this can reduce stop-and-go waves in certain scenarios, it may also lead to undesired platoon instability and reduced intersection throughput when mixed with more aggressive ICEVs. Furthermore, the high instantaneous torque of electric motors allows for rapid acceleration, which can be beneficial for merging maneuvers but may also contribute to increased rear-end collision risks if not managed properly. These paradoxical behaviors—ranging from hyper-cautious to performance-oriented—underscore the non-uniform driver response within a mixed flow, challenging the homogeneity assumptions often embedded in macroscopic traffic models.

3.3.2. Route choice and charging behavior

The driving range limitation and the spatial-temporal distribution of charging infrastructure significantly influence the route choices of EV users. Unlike ICEV drivers who primarily optimize for travel time or distance, EV drivers often engage in path planning that incorporates the availability and waiting times at charging stations [12]. This can lead to concentrated congestion around charging hubs, particularly during peak hours, creating new localized bottlenecks that perimeter control must account for. Moreover, the decision to recharge introduces additional trip chains and vehicle stops, altering the traditional origin-destination matrices and dynamic traffic assignment patterns. Consequently, the "virtual closed area" must consider not only the inflow and outflow of vehicles but also the internal generation and attraction of trips directed towards charging facilities.

3.3.3. Vehicle-to-Grid (V2G) and static congestion

The emergence of V2G technology, while promising for energy grid stability, introduces a novel form of static congestion. EVs engaged in V2G services remain parked for extended periods at designated spots, effectively reducing available curb space and potentially blocking traffic lanes if charging infrastructure is poorly located [13]. This static occupancy directly conflicts with the dynamic flow of traffic. From a control perspective, these EVs are not merely absent from the traffic stream; they become temporary, spatially fixed obstacles that alter the network's effective capacity

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and topology. Integrating this static-demand interaction into the MFD-based perimeter control framework is a critical, yet under-explored, challenge.

3.3.4. Implications for control system design

The integration of CAVs into the mixed flow further compounds these complexities. A mixed flow of human-driven vehicles, EVs, and CAVs creates a multi-agent system with varying levels of rationality, connectivity, and automation. CAVs can serve as "mobile actuators" to dampen oscillations and improve network throughput. However, their interaction with human-driven EVs, which may have atypical acceleration and car-following behaviors, requires robust control strategies to prevent unforeseen emergent phenomena [14]. The proposed active mixed pinning control must, therefore, be adaptive enough to not only identify key geographical nodes (intersections) but also key vehicle types (influential CAVs or clusters of EVs) for applying control signals, thereby stabilizing the entire heterogeneous system.

4. Intelligent regional traffic control theory in virtual closed areas

The advancement of ITS enables effective monitoring of key segments and intersections, reducing uncertainties in network cognition. By selectively correlating ITS information collection points, a virtual closed boundary—geographically discontinuous but functionally comprehensive—can be formed around a controlled area, encapsulating its inflow-outflow and generation-attraction relationships. This switch the congested network section to a relatively closed regional system that can be controlled. Coordinating control methods with internal perimeter control can optimize network efficiency.

4.1. Traffic equilibrium principle under regional "data boundary"

The traffic supply-demand equilibrium in regional road networks pertains to the balanced mixed traffic flow distribution. Traditional theories like Wardrop equilibrium, while generally valid, often overlook the controllability and closure of networks under Intelligent Transportation Systems. Studying supply-demand equilibrium models for controlled regional intelligent road networks based on various vehicles with 'closed' and 'controllable' attributes is a current research trend.

The core idea involves selectively connecting information collection sections corresponding to regional network states, measuring inflow-outflow rates at access sections to form a regional closed data boundary. This boundary, though geographically discontinuous, fully captures the traffic flow within the controlled section, creating a virtual closed control area. Subsequently, the internal traffic flow was compared with the carrying capacity of the region to assess the balance between supply and demand.

4.2. Aggregate balance control with MFD model and perimeter control

Geroliminis discovered a Macroscopic Fundamental Diagram model relating network flow to vehicle accumulation in Yokohama, Japan [15]. As shown in Figure 3, the MFD depicts the relationship between vehicle accumulation and network-weighted flow, with a critical point indicating maximum outflow. Accumulation beyond this point leads to rapid congestion formation. Maintaining accumulation below the critical point helps alleviate the congestion in key sections. Perimeter control complements this by managing inflow-outflow rates of relatively crowded areas to maintain acceptable traffic states.

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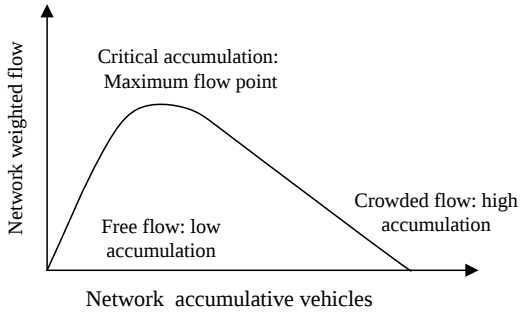


Figure 3. MFD model

According to the MFD model, the maximum flow point brings the largest vehicle outflow rate, which represents a "critical accumulation". When accumulated vehicles in the network exceed the critical accumulation, it will lead to a rapid intensification of regional congestion. Therefore, by keeping the cumulative number of vehicles traveling within the controlled area below the critical limit, it is possible to effectively alleviate the traffic congestion in key sections [16]. As summarized above, the traffic control method under MFD model provides a macroscopic and effective means for traffic flow control in congested sections.

4.3. Internal network optimization control

Due to uneven traffic distribution within areas, merely controlling inflow-outflow may not prevent local congestion. Pinning control—applying control to a small subset of key network nodes—can ensure desired network behavior. In virtual closed traffic networks, pinning control method can alleviate regional congestion cost-effectively and enhance overall control efficacy.

4.4. Method system and technical route

According to the proposed virtual closed areas and corresponding control methods summarized above, the method system and technical route for the intelligent regional network control application is illustrated in Figure 4.

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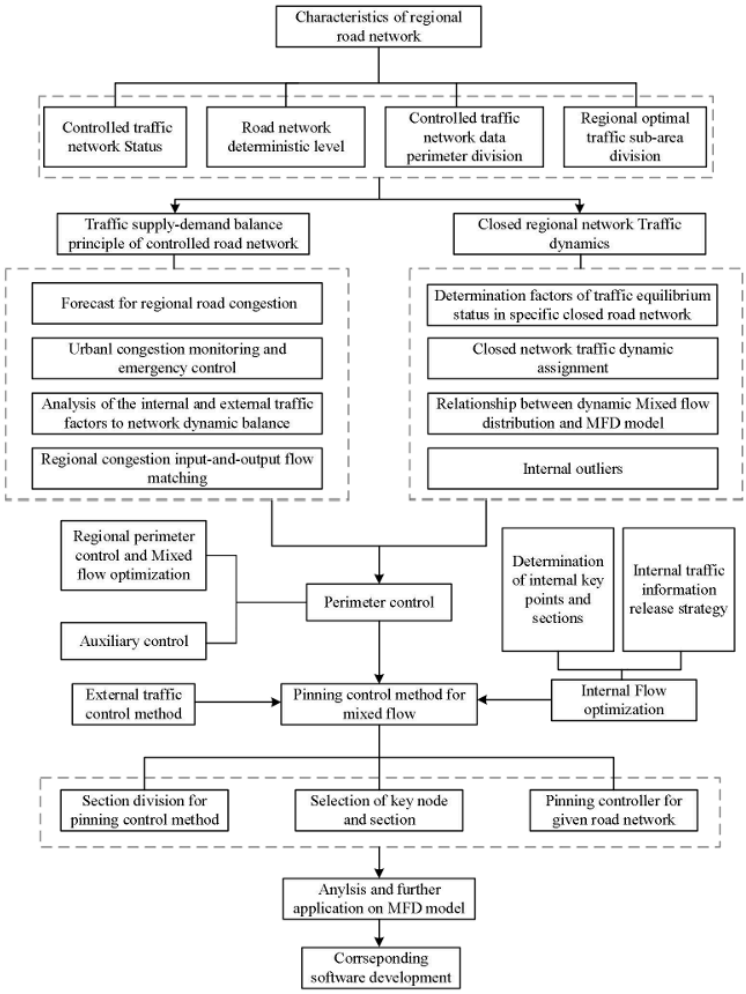


Figure 4. Method system and technical route

5. Key technologies

Key issues to address include:

(1) All conditions for providing intelligent traffic information in a controlled specific network have been met. This involves analyzing relationships among network structure, information point layout, spatiotemporal traffic parameters, road capacity, and traffic processes to establish an accurate representation model of network operation.

(2) Dynamic traffic assignment and equilibrium conditions under closed data boundaries. Exploring the match between dynamic traffic flow distribution on intelligent roads and node-edge mixed dynamic models from complex network cascading failure theory, to develop a dynamic traffic assignment model and study its convergence under various conditions.

(3) Establish relationship between mixed regional flow and state transition processes via spatiotemporal association analysis. Addressing the traffic state transitions under ITS, inflow-outflow rates and their coupling with spatiotemporal capacity, as well as the congestion management based on regional in-out flow matching.

(4) Integrated dynamic mixed model under pinning control. Treating the traffic road system as a determined regional network that can be well controlled and applying pinning control with

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intelligent features for early monitoring and guidance, integrating active control and perimeter control to address both boundary and internal flow management.

6. Conclusion

Reflecting the development trends of ITS and the "controlled system" characteristics of intelligent networks in China, this research explored the principle of traffic equilibrium based on a virtual enclosed area which is defined as a "data boundary". Thereby constructing a complex virtual enclosed time-space system that incorporates mixed traffic flows. An intelligent road network control theory integrating active mixed pinning control with MFD model and specific perimeter control method is established.

The ongoing development of ITS is switching urban road networks to relatively "controllable" and "closed" intelligent transportation systems. The proposed method system not only advances urban traffic equilibrium and traditional control theories for mixed flows, but effectively bridges the gap between ITS technologies and foundational traffic engineering principles.

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