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## Views &amp; Comments

## A Discussion on the Complexity and Transit Mechanisms of Urban Traffic Systems

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Urban traffic is a complex system composed of users, drivers, vehicles, roads, the environment, and information and management strategies, characterized by dynamics, randomness, openness, and complexity. Traditional traffic science and engineering research usually focuses on specific traffic subsystems [1,2], such as drivers (i.e., driving behavior), vehicles (i.e., traffic flow), or traffic control (i.e., signal systems), and significant progress has been achieved in these areas. However, varying levels of traffic congestion in cities worldwide highlight the limitations of traditional methods such as traffic planning, management, and control. Systems science, which is the study of complex systems, emphasizes the relationships between structure, environment, and function, as well as the general principles of evolution and regulation. A systems approach enables us to examine the interactions among the diverse components of urban traffic systems, revealing correlations between individual behaviors, local characteristics, and emergent patterns [3], and thereby providing innovative solutions to urban traffic challenges.

This paper explores the key challenges in studying future urban traffic systems using a systems science approach. Firstly, systems science offers an important methodological innovation for understanding complex phenomena. Reconstructing the research framework for urban traffic systems using systems science principles is a crucial step toward effectively addressing urban traffic challenges [4]. However, there is a notable lack of comprehensive theoretical research and practical validation in this area. Key issues in urban traffic system research include emergence<sup>†</sup>, evolution<sup>‡</sup>, and control<sup>§</sup>. This perspective represents a significant innovation in the tra-

ditional research framework and methodology of traffic theory, which remains in the early stages of development [5]. Moreover, the forthcoming scientific and technological revolution will profoundly reshape the research paradigm of future urban traffic, while simultaneously introducing numerous new challenges in understanding the complexity of urban traffic systems [4]. In particular, the transit process plays a crucial role in the mechanisms underlying the emergence of complex traffic systems. Due to the randomness, dynamics, and complexity of urban traffic systems, transportation challenges inevitably pose systemic scientific and engineering problems.

### 1. It is crucial to reconstruct the research framework of urban traffic systems utilizing systems science principles

The use of reductionist and other methodologies facilitated humanity's significant scientific advancements during the 20th century [6]. The reductionist approach attributes phenomena to the fundamental constituents of matter and the basic laws governing their behavior. All physical phenomena—from microscopic to macroscopic scales—can be explained and deduced by employing these basic laws once they have been established. However, the Nobel-Prize-winning physicist Philip W. Anderson emphasized that: although matter is composed of elementary particles, the properties of systems comprising atoms and molecules cannot be fully determined by the characteristics or motion of these particles alone [7,8]. In fact, as modern science has evolved into the 21st century, the development and evolution of modern science have elicited a series of conclusions, including the theory of relativity and the chaos theory of quantum mechanics, that significantly impact the dominant paradigms of modern science, such as reductionism and determinacy. These developments demonstrate that the real world is not dominated by the traditional scientific paradigm of simplicity [6]. Consequently, a new independent discipline known as systems science has emerged to address these complexities.

As mentioned earlier, systems science is a methodology used to study complex systems. Although there is currently no precise definition of a complex system, researchers generally agree on several common characteristics: A complex system consists of numerous constituent elements with intricate relationships, exhibits limited

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<sup>†</sup> Here, *emergence* refers to the phenomenon in which global system behaviors arise from interactions among local components, or macroscopic effects are precipitated by microscopic dynamics. For example, the aggregate microscopic car-following behaviors of a multitude of vehicles on a road can culminate in macroscopic traffic conditions such as free-flowing or congested states.

<sup>‡</sup> *Evolution* refers to the changes over time in a system's structure, state, properties, behavior, and functions. An example of this is the process of the generation, propagation, and dissipation of traffic congestion within an urban road network.

<sup>§</sup> *Control* refers to the actions implemented within a process in order to achieve a predetermined goal. A quintessential example is the signal control at intersections within urban transportation systems.

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controllability and predictability, lacks orderliness and measurability, involves a large parameter scale, and displays pronounced dynamics and randomness.

The study of complex systems originated with the development of complexity science [9], which initially emerged in the 20th century. In the 1980s, several American Nobel laureates in physics and economics, including Murray Gell-Mann and Philip W. Anderson, acknowledged the importance of complex systems. They established the renowned Santa Fe Institute and denoted the study of complex systems as “complexity science.” Chinese scholar QIAN Xuesen also began to concentrate on complexity science research during this time, pioneering Chinese complexity research based on the theory of open complex giant systems (OCGS) [10]. By the 21st century, research on complex systems had gained significant attention in Europe and America. In 2006, the European Society for Complex Systems published the “Living Roadmap for Complex Systems Science 2007–2013” [11], declaring complex systems science to be a foundational science of the 21st century. Since 2003, numerous research papers on complex systems have been published in the annual US Summit Forum and its associated anthology, *Frontiers of Engineering Science*. In particular, a series of articles on complex systems engineering were published in 2005. Incomplete statistics show that, from 2000 to 2024, a total of 5349 papers on the topics of “complex systems,” “complex networks,” and “complexity” were published in journals such as *Nature*, *Science*, and *PNAS*. Moreover, the number of related publications remains relatively high on an annual basis.

The history of complex systems is fairly short, and its development is not mature, lacking a unified research paradigm. However, complex systems are destined to become an important research direction for future scientific inquiry. Stephen Hawking believed that “the next century will be the century of complexity”. QIAN Xuesen pointed out that “the establishment of systematology is a scientific revolution, and its importance is no less than that of relativity or quantum mechanics” [10]. The 2021 Nobel Prize in Physics, awarded to Syukuro Manabe, Klaus Hasselmann, and Giorgio Parisi for their pioneering contributions to the understanding of complex physical systems, confirms the significant value of complexity research.

Systems science focuses on complex systems as research objects. It decomposes complex systems and subsequently adopts the overall research methodology of the system to conduct comprehensive integration studies, ultimately achieving a holistic emergence of systems functions. The methodology of systems science employs the research approach of *systems decomposition–systems integration–systems emergence*. This approach achieves the dialectical unity of reductionist and holistic methods, bridging the gap between the microscopic and macroscopic levels.

Urban traffic systems are typical examples of OCGS. A traditional research framework based on the reductionism methodology presents numerous challenges in addressing issues such as urban traffic congestion. Systems science principles are indeed essential for reconstructing the research framework of urban traffic systems. From the perspective of systems science, it is possible to uncover the emergence mechanisms and evolution dynamics of macroscopic traffic phenomena under complex conditions. This involves understanding and accurately modeling the complex travel choice behaviors of vast numbers of individual travelers. Moreover, systems science can facilitate a thorough analysis of the interaction and coupling relationships between multi-level traffic supply and demand, allow a deep exploration of the evolution and regulation of urban traffic system structure and function, and enable the development of a planning and management theory that matches the complex urban traffic system. Reconstructing the research framework of urban traffic systems using systems science principles not only provides new theories and methods for collab-

orative planning, design, and regulation but also holds practical significance. It enhances the overall efficiency of the system, promotes sustainable development, and supports national strategies such as building a robust transportation network.

## 2. Emergence, evolution, and control are core aspects in the study of urban traffic systems

Urban traffic systems involve a vast number of travelers (millions or even tens of millions) making travel decisions and dynamic movements within a large-scale, integrated transportation network, representing a classical OCGS. These systems comprise several typical subsystems, including carrying subsystems (e.g., road, urban rail transit), traffic flow subsystems (participants), and management and control subsystems. In urban traffic systems, the participants exhibit typical heterogeneity, with supply and demand restricting each other. There are numerous influencing factors (i.e., variables) with complex and intertwined relationships. In Fig. 1 [12], the subsystems that comprise an urban traffic system are denoted by distinct colors, encompassing transport facilities, vehicles, pricing systems, emergency support, information services, land use, equipment maintenance, policy and regulation, urban population, economic development, and roads. The extent of the interrelationships among these various factors is qualitatively depicted through the width of the connecting lines. It is observable that the urban traffic system is composed of numbers of diverse elements, with direct and indirect interactions of varying intensities among these elements. Under the combined influence of these factors, urban traffic systems exhibit typical phenomena and characteristics, including non-linearity, non-stationarity (time-variant), and non-Markovian chain processes (relevance) [13,14].

The behavior of travelers—which is one of the primary contributors to complexity in urban traffic systems—stands out as the most distinctive characteristic that sets traffic systems apart from natural systems [15]. In traffic scenarios, individuals tend to exhibit the characteristics of autonomy and rationality. Autonomy stems from the fact that each participant in a traffic system acts as an independent decision-making entity, determining her or his own departure time, travel mode, and path selection. Rationality is demonstrated by the fact that the decision-making of each participant is oriented toward maximizing his or her own benefits, such as minimizing the travel time from the origin to the destination. Drivers and carriers constitute the primary components of the urban traffic system; they possess the ability to effectively respond to alterations in the traffic environment while exhibiting intelligent agent functionalities such as self-organization, self-adaptation, and self-driving.

Another important source of complexity in urban traffic systems is the complex coupling relationships that exist among these systems' components. These components are highly interconnected and interdependent; therefore, changes in one or more subsystems can have widespread repercussions on others. Here, traffic participants exhibit the most complex interactions and relationships with other components. The travel behavior of participants not only affects the participants themselves but also exerts influence on various parts of the entire system. There are intensive non-linear interactions among moving drivers, vehicles, and environments in a traffic network. A change in any individual component will lead to unpredictable outcomes, such as phantom traffic jams, congestion diffusion, traffic oscillation, hysteresis, phase transition, and other complex traffic phenomena observed in road traffic [14,16]. Local emergencies or traffic jams can trigger long-term traffic congestion or blockage in the large-scale surrounding urban road network.



supply and demand of urban traffic systems caused by the surge in travel demand remains evident. In addition, urban traffic demands have uneven periodic characteristics, with peaks and valleys. That is, even though there is an overall equilibrium in supply and demand, specific regions and periods will inevitably experience pronounced disequilibrium. Within a certain period, **avoiding** the generation and existence of urban traffic issues is inevitable. Notably, the rapid surge in motor vehicles during China's urbanization process is unparalleled in other countries and regions, resulting in more complex and numerous problems than those faced by developed countries. At present, China's urban traffic system is undergoing a great transformation from focusing on *infrastructure construction* to prioritizing *traffic efficiency improvement*. It is urgent to understand the generation mechanisms and evolution laws of travel demands.

- (2) **The challenge of modeling.** It is necessary to establish a new research paradigm that combines traditional research methods with artificial intelligence driven by new technologies. The ongoing sci-tech revolution—represented by emerging technologies such as mobile Internet, fifth generation (5G) communication, big data, and artificial intelligence—has significantly reformed mobility patterns and, to a certain extent, reshaped both the micro-choice behaviors of traffic participants and the macro-level spatiotemporal distribution laws of traffic demands. It is difficult to adapt traditional extensive urban traffic management theories and methods to the development of intelligent transportation. The combination of traditional research methods and artificial intelligence driven by new technologies can realize complementary advantages. Traditional methods ensure the preciseness of research, while artificial intelligence provides efficient data-processing capabilities, law-mining capabilities, and modeling capabilities for complex scenarios. However, the logical differences between traditional methods and artificial intelligence may lead to difficulties in model coupling, necessitating the establishment of an effective integration strategy. In addition, issues such as data quality may pose challenges to the new research paradigm.
- (3) **The challenge of complexity.** It is necessary to design fast and efficient algorithms for devising traffic problems on a large scale and intelligent Internet scenarios. An urban traffic system involves numerous elements, diverse functions, and complex relationships while occurring on a large scale, exhibiting the features of complexity, dynamicity, and randomness. Moreover, in future urban traffic, connected autonomous vehicles will join human-driven vehicles, resulting in a heterogeneous traffic flow. The aforementioned characteristics will further increase the complexity of the management of urban traffic systems in China. In a highly advanced computing environment for artificial intelligence, ALPHA GO can function with a state space of  $10^{171}$ , while ALPHA STAR operates within a state space of  $10^{1000}$ . However, the traffic state of a typical city is on a scale of 10 to the billionth power. Coupled with the continuous space issues, the difficulty of modeling and solving such a state space is enormous. In intelligent decision-making for urban traffic management, characteristics such as complexity, openness, a large scale, incomplete information, and dynamic games are prominent. Consequently, there is an even greater need for open, dynamic, and adaptive intelligent decision-making methods.
- (4) **The challenge of application.** It is necessary to develop a parallel system and an intelligent decision-support platform for urban traffic operations in the contexts of large-scale sce-

narios and the Internet of intelligence. The rapid development of new-generation information technologies—such as big data, artificial intelligence, and digital twins—has prompted profound reforms in the organization and service modes of traditional urban traffic systems. Simultaneously, it has posed challenges in terms of massive multi-source data fusion, the learning of complex travel behaviors, and the intelligent optimization and extrapolation of ultra-large-scale traffic networks. Furthermore, managing vast amounts of multi-source heterogeneous traffic data requires robust algorithms and substantial computing power to ensure the accuracy and real-time features of the data.

While emerging technologies introduce complexities to urban traffic systems, they also provide powerful tools, facilitating transformative research paradigms. Big data provides extensive and diverse multi-dimensional heterogeneous data for urban traffic system research [19]. For example, vehicle operation data, passenger demand data, road monitoring data, and so forth obtained via vehicle terminals and various types of fixed detectors can comprehensively reflect the operating status and laws of urban traffic systems. Large models provide powerful tools for complex data analysis and data-driven modeling [20]. For example, deep learning models can automatically extract intricate features and patterns from massive amounts of data, enabling accurate predictions and precise management of traffic flow. Powerful computing capability is the underlying support of big data processing and large model computations, as it enables the rapid processing of large amounts of data and the efficient training of complex models, providing real-time dynamic decision support for traffic planning, management, and regulation. In a word, the integration of big data, large models, and powerful computer capability is driving the emergence of a new paradigm for urban traffic systems. In terms of content, this paradigm emphasizes the transformation from partial to systemic in traffic system research; in terms of methodology, it highlights the comprehensive integration of computation, theory, and experimentation; and, in terms of scope, it shifts from traditional disciplinary approaches to interdisciplinary study.

Advancements in research methods and paradigms can help us to better discover and understand the operating states and development laws of complex urban traffic systems. They can also facilitate the analysis and resolution of realistic traffic control problems, significantly enhancing precision and intelligence control. Moreover, they are beneficial for exploring, uncovering, and predicting the evolving trend of urban traffic, as well as scientifically addressing the great challenges posed by future urban traffic control. In conclusion, the new research paradigm brings both opportunities and challenges to the study of urban traffic systems. By integrating advanced technologies and methodologies, it holds the promise of steering urban traffic toward a more intelligent, efficient, and sustainable development pathway.

#### 4. The transit process is a vital element of the emergence mechanisms of urban traffic systems

Examining complex systems from a global perspective reveals various emergence phenomena that cannot be understood solely by aggregating the functions of individual components. This challenge is a core problem in complex system research for which a consensus viewpoint has yet to be established. Upon closer examination, the key lies in the diverse interactions that exist among individuals. *Transit* encompasses the movement of substances, energy, and information through space, from one location to another. It is a critical mechanism for interactions and linkages

among the individuals within a system and between different systems. Without it, systems as we know them would cease to exist.

In the earth system, the earth receives energy from the sun. As a result, a variety of species are generated by entropy decreases, which in turn change the climate. In an ecosystem, the conversion of both energy and matter exists among different species. Plants capture energy from the sun through photosynthesis and convert luminous energy into biological energy. Herbivores utilize the bioenergy and nutrients from plants to build their bodies. Carbon element transport and energy transit occurs between predators and prey. In the human body system, the digestive system, which acts analogously to plants in an ecosystem, acquires energy and the necessary materials for body construction from the external environment. The blood circulation system transports energy and nutrients throughout the body to ensure the normal functioning of all body parts. The primary functions of the lymphatic system encompass immunity, nutrient transport, and tissue healing. The vascular network in the human brain supplies essential nutrients to neurons via blood circulation. A variety of complex cognitive and decision-making functions are realized via the transmission of electrical signals among neurons. In human social systems, the flow and conversion of funds and capital take place between different departments and institutions, and human resources flow between various companies and institutions. Additionally, raw materials and semi-finished products are transported among different manufacturers. Economic and financial systems serve as carriers for the transport of capital and funds. The banking system gathers funds from depositors for investment and feeds them back to depositors in the form of interest payments. The stock market, which is a funds-gathering place that differs from banks, facilitates the redistribution of assets. Online shopping and e-commerce involve not only the transfer of funds but also the transportation processes within logistics networks. Given the importance of transit mechanisms in complex systems, the China Association for Science and Technology (CAST) released the top 10 frontier scientific questions on July 2, 2024, which included “The Transit Mechanism of Multi-Scale Non-Equilibrium Flow” as the fifth question [21].

The transit process is the fundamental mechanism driving various systems. It enables self-organizing behaviors in a system, undertakes various functions of the system, and facilitates the exchange of energy and materials among individuals in the system. The transit process shapes the natural ecosystem; it is a universal characteristic of complex life forms and leads to a widespread dynamic balance phenomena. From a theoretical perspective, the transit process is the conversion bond between different states of the system; it is also the bridge for the system to evolve toward a steady or dynamic balance state. The transit process plays an irreplaceable role as the basis for system evolution. Therefore, research on the transit process is essential in order to gain a deeper understanding of the structure, function, and essential features of complex systems. Such research will further provide valuable insights for advancing theoretical and applied studies on traffic systems.

In urban traffic systems, the transit process of traffic participants via carriers on the traffic network serves as the fundamental driver of complex phenomena. The primary function of transit systems is the transportation of persons and commodities. The transit mechanisms involve transport ways, pathways, and times. Unlike other systems, the prominent characteristic of the transit process in urban traffic systems is the complex dynamic decision-making behaviors of traffic participants. In order to maximize the utilization of existing transportation resources while alleviating and preventing traffic congestion, modern traffic science observes traffic phenomena, explores traffic data, analyzes travel choice behaviors, discovers group regularity and complexity, and then regulates the spatiotemporal distribution of vehicles and pedestrians as a whole

[22,23]. Based on this, Gao et al. [24] and Long et al. [25] conducted exploratory research on the generation, propagation, and dissipation of traffic congestion in urban road traffic networks. They developed a congestion propagation model using a combination of micro and macro approaches. They then further explored the propagation laws of traffic congestion caused by emergencies, identified bottlenecks resulting from increased traffic demands, and proposed several dynamic control strategies for congestion dissipation. It was found that the generation of bottlenecks is the inevitable result of the continuous increase in travel demand. The scale of bottlenecks in urban road networks is positively correlated with the level of travel demand. However, the growth of travel demand has diverse impacts on the traffic states of individual road sections. Regional control strategies were found to be the most effective approach for congestion dissipation.

When studying the transit process in urban traffic systems, the primary task should be to investigate the generation process of traffic demands according to various spatiotemporal characteristics within the system. This includes how diverse categories of travelers determine their departure times and travel modes; how they select interchange locations, tools, and paths; and what kind of network traffic distributions these selection behaviors will lead to. In essence, this task will explore how macro-level network aggregation phenomena arise from a huge amount of micro-level individual decision-making. Simultaneously, it is vital to study how network traffic flows, which result from multi-level and multi-category travel decision-making behaviors, are influenced by the system’s internal mechanisms and external conditions. In real urban traffic systems, traffic flows are the macroscopic aggregation of various complex travel decision-making behaviors within limited times and spaces. The decision-making of travelers generally includes five steps: generating travel demands, gathering information, evaluating and selecting, traveling, and feedback. This process encompasses extremely complex behavior mechanisms and contains numerous basic scientific questions. It is necessary to use the cross-integration of multidisciplinary knowledge in this task, including management science, traffic engineering, systems science, behavioral science, computer science, information science, and statistics. To achieve this task, we can comprehensively depict the complex travel decision-making behaviors of urban residents, discover the spatiotemporal distribution characteristics of multi-level traffic demands, analyze the interaction and coupling mechanisms between multi-mode traffic supply and demand, and reveal the evolution laws of network traffic flows under complex conditions (i.e., the transit process).

Despite the robust support provided by new-generation information technologies for acquiring abundant traffic data, challenges remain in obtaining high-precision data for specific scenarios, such as the long-distance trajectory data of all vehicles required for studying microscopic car-following and lane-changing behaviors. At present, a critical question emerges: Under conditions of observational limitations and difficulties in obtaining high-quality data, how can we infer the internal characteristics of complex traffic systems through data reconstruction and then identify and regulate the key control factor sets of the transit process?

## 5. Conclusions and future works

The modern urban comprehensive traffic network is a dynamic and complex giant system comprising drivers, vehicles, roads, the environment, and control. These components are intricately coupled, exhibiting the typical characteristics of dynamicity, complexity, and randomness. In-depth research into the complexity theory of urban traffic systems is essential in order to develop new theories and methodologies for coordinated planning, design, and regulation.

Such efforts are critical in elevating the comprehensive efficiency of the urban traffic system, promoting sustainable development, and serving national strategies such as the construction of a robust transportation network. To this end, this paper discussed urban traffic systems and their complexity characteristics, explored the issues and challenges in regulation, and presented the research field of complexity analysis and regulation in urban traffic systems.

Currently, system engineering lacks a theoretical and methodological framework for studying integrated transportation networks. This gap limits our ability to provide essential support for the top-level design of comprehensive transportation development strategies and institutional mechanisms. At the same time, due to the complexity of urban traffic systems, this field is an important research direction that requires long-term perseverance. Research on urban traffic systems should focus on the development and application of new technologies. In particular, new-generation information technologies such as artificial intelligence are driving transformative changes in urban transport business formats, management modes, and control methods. These advancements also present new directions and challenges for complexity research and the intelligent regulation of urban traffic systems.

This paper discussed the complexity and the transit mechanisms of urban traffic systems from the perspective of systems science. It is important to clarify that the primary aim of this paper was to introduce novel perspectives rather than to delve into an in-depth analysis of a specific theory or practical issue. Consequently, some viewpoints presented herein remain to be sufficiently validated. In the future, we intend to employ systems science methodologies to conduct further investigations on urban traffic systems.

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## Compliance with ethics guidelines

Ziyou Gao, Bin Jia, Dongfan Xie, Wenxu Wang, and Jianjun Wu declare that they have no conflict of interest or financial conflicts to disclose.

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