Blockchain-Based Traffic Bottleneck Management System

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Contributor: Senlai Zhu, Hantao Yu, Congjun Fan

To alleviate traffic congestion, it is necessary to effectively manage traffic bottlenecks. In existing research, travel demand prediction for traffic bottlenecks is based on travel behavior assumptions, and prediction accuracy is low in practice. Thus, the effect of traffic bottleneck management strategies cannot be guaranteed. Management strategies are often mandatory, leading to problems such as unfairness and low social acceptance. To address such issues, this paper proposes managing traffic bottlenecks based on shared travel plans. To solve the information security and privacy problems caused by travel plan sharing and achieve information transparency, travel plans are shared and regulated by blockchain technology. To optimize the operation level of traffic bottlenecks, travel plan regulation models under scenarios where all/some travelers share travel plans are proposed and formulated as linear programming models, and these models are integrated into the blockchain with smart contract technology. Furthermore, travel plan regulation models are tested and verified using traffic flow data from the Su-Tong Yangtze River Highway Bridge, China. The results indicate that the proposed travel plan regulation models are effective for alleviating traffic congestion. The vehicle transfer rate and total delay rate increase as the degree of total demand increases; the vehicle transfer rate increases as the length of the time interval decreases; and the vehicle transfer rate and total delay rate increase as the number of vehicles not sharing their travel plans increases. By using the model and method proposed in this paper, the sustainability of urban economy, society, and environment can be promoted.

Keywords: traffic bottleneck ; congestion management ; blockchain

1. Introduction

Traffic congestion has become an important global problem that restricts the sustainability of urban economy and society. Vehicle exhaust emissions caused by traffic congestion also restrict the achievement of environment sustainability. Thus, to promote the sustainability of urban economy, society, and environment, it is important to alleviate traffic congestion. Due to factors such as the nature of land use and residents' daily commuting habits, locations that are prone to traffic congestion during daily and holiday periods are generally fixed and concentrated, namely, traffic bottlenecks. Therefore, to alleviate or solve traffic congestion problems, the effective management of traffic bottlenecks is necessary.

The premise for the effective management of traffic bottlenecks is to accurately analyze the behavior of travelers and predict travel demand at bottlenecks. The first traffic bottleneck model for analyzing travel behavior was proposed by Vickrey [1]. In this model, it is assumed that there is a road connecting residential and work areas, with a bottleneck with limited capacity on the road (such as a bridge, a tunnel, a ramp, or another feature). Except for the bottleneck, the capacity of other road segments is sufficient. When the arrival rate at the bottleneck exceeds the bottleneck capacity, a queue is formed. Furthermore, many researchers have extended and improved this model by considering features such as user heterogeneity, multiple travel modes, and travel chains [2][3][4]. Although the bottleneck model is constantly improving, it is still difficult to match real conditions, and there are significant errors in the analysis and prediction of travel behavior based on the bottleneck model.

Based on the analysis of travel behavior at traffic bottlenecks, many researchers have conducted research on control measures for traffic bottlenecks. The most studied topic is congestion pricing for traffic bottlenecks [5][6][7]. Many researchers have also studied management strategies from other perspectives, such as optimizing parking fees, parking capacity, working hours, speed limits, and other management measures [8][9][10][11]. The above traffic bottleneck management strategies are often mandatory measures, and due to differences in the nature of work and income levels of travelers, problems such as unfairness and low social acceptance persist. Additionally, many travelers believe that traffic managers do not develop corresponding strategies to address traffic problems but rather consider other interests, such as increasing the fiscal revenue of government departments. Therefore, they are often resistant to these regulatory strategies, leading to a lack of trust in traffic managers. In addition, traffic bottleneck management strategies are often based on the prediction of travel behavior, and the accuracy of this approach is low in practice. Therefore, the expected effect cannot be achieved through the implementation of management strategies.

In summary, the existing research on traffic bottlenecks has the following shortcomings: (a) travel demand is predicted by a bottleneck model constructed based on travel behavior assumptions, resulting in low prediction accuracy in practical applications; (b) the implementation effect of current traffic bottleneck management strategies is often based on the prediction of travelers' behaviors; thus, neither the prediction accuracy nor the model implementation effect can be guaranteed; and (c) the current traffic bottleneck management strategies are often mandatory measures, with a certain degree of unfairness. Travelers normally distrust managers, and social acceptance is not very high.

2. Traffic Bottleneck Model

The first traffic bottleneck model for analyzing travel behavior at traffic bottlenecks was proposed by Vickrey [1]. Based on Vickrey's traffic bottleneck model, many researchers have conducted extensive research on travel behavior at traffic bottlenecks. Guo et al. [12] studied the daily departure time choice behaviors of commuters with a congestion model, accounting for the bounded rationality of travelers. Chen et al. [13] studied an early peak commuting problem with bottleneck settings, where the bottleneck capacity varied with queue length. Li and Huang [14] explored the user equilibrium state of single-entry transportation corridors and proposed a new mathematical model considering travelers' preferences for specific departure times. Frascaria et al. [15] studied the emergence of super-congestion in Vickrey bottleneck networks, and the departure time of travelers was determined by the second price auction mechanism. They analyzed the conditions for the occurrence of super-congestion and discussed possible policy interventions to prevent congestion. Chen et al. [16] proposed a new modeling framework that combines Vickrey theory with macroscopic data to analyze traffic dynamics in a transportation network from the outskirts of the city to the city center. In the above models, it is assumed that the time value cost and ideal time to reach the work area (or ideal time to pass through a bottleneck) are the same for all travelers.

To make the bottleneck model more realistic, many researchers have improved and extended the classic bottleneck model by considering heterogeneous travelers (i.e., different travelers have different time value costs and ideal times to pass through a bottleneck). Liu et al. [2] proposed a semi-analytical method to solve bottleneck models with general user heterogeneity. They used a dichotomy method to decompose the problem into multiple linear subproblems and then used matrix decomposition techniques to solve these subproblems, ultimately obtaining a closed analytical expression. Lamotte and Geroliminis [17] considered the problem of morning peak congestion for travelers with different travel distances in urban areas. They proposed a new mixed flow model to describe this heterogeneity, where travel time and residence time are set based on different travel distances and destinations, respectively. Qian and Zhang [18] regarded user heterogeneity as a parameter with a continuous distribution and incorporated it into the general equilibrium theory framework. They proposed a solution method that expresses the equilibrium conditions as a set of nonlinear integral equations based on optimal decision making and solved them using an iterative algorithm. Akamatsu et al. [19] recently proposed a new departure time selection equilibrium model that considers user heterogeneity and incomplete information.

Some researchers have constructed corresponding bottleneck models considering random demand, while others have constructed corresponding theoretical models for Y-type bottlenecks, capacity decline, and other situations [20][21][22]. The classic bottleneck model only considers activities from residential to work areas, and some researchers have extended the classic model by considering the travel chain [23][24]. With the development of autonomous vehicles, some researchers have proposed corresponding bottleneck models for autonomous vehicles. Zhao, Y. et al. [25] investigated the impact of autonomous vehicles on commute ridesharing, particularly considering uncertain work end times.

3. Traffic Bottleneck Management

In terms of traffic bottleneck management, the most studied area is congestion pricing for traffic bottlenecks. The development of congestion pricing models is closely related to the development of traffic bottleneck models. The initial congestion pricing models for commuting corridors were based on bottleneck models that considered homogeneous travelers, such as Vickrey's [26] application of queuing theory to consider the effect of time-varying fees on bottleneck travel efficiency. Based on Vickrey's research, many researchers have conducted extended research on congestion pricing strategies for bottlenecks. Xiao et al. [27] studied the effect of implementing affordable pricing and strategic waiting schemes for toll roads during morning peak commuting.

With the development of bottleneck models considering heterogeneous travelers, many researchers have studied static (fixed fees) and dynamic (different charging standards for different time intervals) pricing strategies based on the consideration of heterogeneous travelers [28][29]. A small number of researchers have studied bottleneck pricing strategies considering random demand [30][31][32], while others have studied corresponding pricing strategies by considering travel chains and constructing bottleneck models based on activities [33][34]. In addition, many researchers have conducted extended research on and explored applications involving congestion pricing, such as bottleneck control strategies based on road tickets and charging strategies for travel mode adjustment [35][36][37][38].

Although congestion charging has attracted the most attention from researchers, it cannot be effectively implemented in many countries and regions due to its unfairness and low acceptance among travelers. Therefore, many researchers have studied traffic bottleneck control strategies from other perspectives, such as carpooling behavior and parking restrictions. Xiao, L. et al. [39] delved into the dynamics of carpooling behavior within the morning commute problem, particularly when facing constraints on parking space. Their focus is on optimizing commuting solutions in scenarios with limited parking availability. Xiao, L. et al. [40] examined the temporal and spatial allocation of bottleneck capacity in the context of managing the morning commute with carpooling. Their aim was to improve overall efficiency through a strategic allocation approach. Fu, Y. et al. [41] addressed the issue of parking management during the morning commute, specifically in the context of ridesharing. They explored how effective parking resource management can enhance the entire morning commute experience. Zhong, L. et al. [42] investigated dynamic carpooling during the morning commute, shedding light on the significance of high-occupancy-vehicle (HOV) and high-occupancy-toll (HOT) lanes. They analyzed the impact of these elements on shaping carpooling behaviors. Liu and Li [43] contributed to the discourse by exploring the design of pricing schemes for ridesharing programs addressing the morning commute problem. Their focus was on devising pricing strategies that establish a fair and effective system. Wang, J. et al. [44] introduced a dynamic ridesharing scheme, proposing a variable-ratio charging–compensation approach for the morning commute. Their contribution lies in aiming to enhance the appeal of ridesharing through the implementation of flexible pricing mechanisms. Ma and Zhang [45] delved into the morning commute problem, considering both ridesharing and dynamic parking charges. Their contribution involves exploring the dynamic adjustment of ridesharing and parking charges to optimize the overall commuting experience. In addition, some researchers studied control strategies considering parking charges and parking capacity restrictions [46], the optimization of working hours [10], travel chains [47][48], speed limits [11], and other measures. A small number of researchers have also studied the effect of incentive strategies on traffic bottleneck management [49].

4. Blockchain Applications

Blockchain technology was invented by Satoshi Nakamoto in 2008 as a public ledger [50] for Bitcoin transactions. In an environment that is not completely trusted, it can be used to verify and store data by building a peer-to-peer network using a chained data structure. The blockchain structure is determined by a distributed consensus mechanism to ensure the security of data transmission and access through cryptography. Data can be uploaded and accessed by using a smart contract composed of automated script code. Thus, this technology is based on a brand-new distributed infrastructure and computing paradigm. Its inherent characteristics of transparency, trustworthiness, tamper resistance, traceability, and high reliability give it unique advantages in data authentication, storage, privacy protection, and tokenization. Additionally, blockchain technology is not a single information technology. It can reconfigure and develop existing technologies to create new application functionalities. The many advantages and characteristics of this technology indicate that it can theoretically meet the requirements of interconnectivity, safety, and efficiency in the sharing and management of transportation and travel information.

At present, blockchain technology has received research attention from many researchers and enterprises in the fields of supply chains, public management, logistics, and transportation. Sensen et al. [51] proposed a solution for an organic agriculture supply chain framework based on blockchain and edge computing technology, aiming to solve the trust crisis. Yu et al. [52] proposed a solution for the quality control system of a green composite wind turbine blade supply chain based on blockchain technology. Zhang et al. [53] studied the effect of digital transformation based on blockchain technology on the cold supply chain of third-party logistics service providers. Zhong et al. [54] explored the effect of product information traceability in a dual-channel supply chain based on blockchain technology under government subsidies. Dong et al. [55] considered the phenomenon of green washing and the effect of blockchain technology on logistics outsourcing. Wang et al. [56] studied the effect of blockchain technology on port logistics capabilities, focusing on two different application methods: exclusivity and sharing. Li et al. [57] considered the application of blockchain technology in sustainable supply chains, with a focus on fairness and green investment.

Research on the application of blockchain technology in traffic congestion management is still lacking, often only consisting of a framework description [58][59] and lacking application analyses to solve specific problems.

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