A Review of the Self-Adaptive Traffic Signal Control System Based on Future Traffic Environment

The self-adaptive traffic signal control system serves as an effective measure for relieving urban traffic congestion. The system is capable of adjusting the signal timing parameters in real time according to the seasonal changes and short-term fluctuation of traffic demand, resulting in improvement of the efficiency of traffic operation on urban road networks. The development of information technologies on computing science, autonomous driving, vehicle-to-vehicle, and mobile Internet has created a sufficient abundance of acquisition means for traffic data. Great improvements for data acquisition include the increase of available amount of holographic data, available data types, and accuracy. The article investigates the development of commonly used self-adaptive signal control systems in the world, their technical characteristics, the current research status of self-adaptive control methods, and the signal control methods for heterogeneous traffic flow composed of connected vehicles and autonomous vehicles. Finally, the article concluded that signal control based on multiagent reinforcement learning is a kind of closed-loop feedback adaptive control method, which outperforms many counterparts in terms of real-time characteristic, accuracy, and self-learning and therefore will be an important research focus of control method in future due to the property of "model-free" and "self-learning" that well accommodates the abundance of traffic information data. Besides, it will also provide an entry point and technical support for the development of Vehicle-to-X systems, Internet of vehicles, and autonomous driving industries. Therefore, the related achievements of the adaptive control system for the future traffic environment have extremely broad application prospects.

1. Introduction

The amount of motor vehicles and correspondent travel demand are continuously increasing with economic and social development. The frequent occurrence of traffic congestion in urban road network has negative impacts on economy and environment. Due to the limited land resources of large cities and restrictions to transportation infrastructure construction from socioeconomic factors, to apply traffic management and control measures in a reasonable and effective way, improve the efficiency of existing transportation facilities, and accommodate the growing traffic demand in big cities have become significant research contents for counteracting urban traffic congestion.

Traffic control is one of the most important technical means to regulate traffic flow, improve the congestion, and even reduce emissions. Its progress and development has always been accompanied by the development of information technology, computer technology, and system science. The self-adaptive control system can adjust the signal timing parameters in real time according to the control target of the manager (such as the minimum delay of the intersection) and the arrival characteristics of the traffic flow at the intersection. Compared with timing control and actuated control, the self-adaptive control system can make better use of the overall traffic capacity of the road network and effectively improve the efficiency of road network traffic.

The traffic data collected by the current traffic control system using induction loop detector and other existing sensors is limited. With the advancement of the wireless communication technologies and the development of the vehicle-to-vehicle (V2V) and vehicle to infrastructure (V2I) systems, called Connected Vehicle or V2X, there is an opportunity to optimize the operation of urban traffic network by cooperation between traffic signal control and driving behaviors. This dissertation proposed a series of cooperative optimization methods for urban streets traffic control and driving assistant under the V2X concept. In addition to the existing induction loop detector technology, the video, infrared, radar, floating cars, and other acquisition technologies and equipment provide urban traffic control system with a network of dynamic acquisition traffic flow status data and controller state data, which greatly enriched the information environment and provides more possibilities for the informationalized and intelligent application research. Urban traffic control is entering the data-rich period of multisource holographic network traffic data from the period with only data of cross-section traffic flow.

Recent advances in traffic control methods have led to flexible control strategies for use in an adaptive traffic control system [1]. Metropolitan road traffic digitized and informationalized infrastructure and related system construction has been developed rapidly in the past decade. At the same time, the emergence of intelligent connected vehicles and automated vehicle jointly build a future traffic travel environment, whose abilities of individual information access and perception as well as the performance of response time and interactive behavior are significantly different from conventional artificial driving vehicles. However, the current self-adaptive traffic signal control system cannot effectively utilize these abundant real-time traffic data, and its theory, methods, and techniques have clearly lagged far behind the progress of its key basic technologies [2]. Therefore, the research of data-driven feedback self-adaptive coordination control in data-rich environment is proposed and actively explored by researchers [3].

Moreover, with the continuous improvement of the theory and technology of intelligent control and nonmodel control, the concept of traffic control is changing under the new traffic data environment shown as Figure 1. The researchers hope that the model of the control system is based on the data model identification rather than the existing mechanism model [4]. Besides, they hope that the system is based on real-time monitoring data rather than the traffic forecast data [5] and the control system can automatically adjust the control strategy instead of the manual intervention [6].

The first-generation self-adaptive control system adopts the multi-time timing control of fine division of period, or completely isolated self-adaptive control, to realize the simple regulation of traffic flow. Take the multi-period timing control system as an example, which divides the traffic flow arriving within a day into multiple periods (such as peak, nonpeak), taking into account changes in daily traffic demand to optimize the signal timing scheme in different periods of time each day, using the comprehensive performance index method or green wave band timing method to optimize and generate a signal timing scheme library [10]. According to the number of weeks and control period, traffic controller can directly select the appropriate offline scheme from the scheme library.

The second-generation traffic signal control system dynamically adjusts the parameters of the signal timing scheme (signal period, green signal ratio, and phase difference). Compared with the timing and induction coordination control system, the second-generation system greatly improved the flexibility and adaptive adjustment ability of the control system. Typical second-generation control systems include SCATS [11] and SCOOT [12].

The third-generation control system uses the similar idea as the second generation to dynamically adjust the signal timing parameter in response to the fluctuation of the time-varying traffic flow at the intersection. Typical third-generation control systems include OPAC [13] and RHODES [14]. Kosmatopoulos et al. chose three traffic networks with quite different traffic and control infrastructure characteristics: Chania, Greece (23 junctions); Southampton, UK (53 junctions); and Munich, Germany (25 junctions), where it has been compared to the respective resident real-time signal control strategies TASS, SCOOT, and BALANCE. The main conclusion drawn from this high-effort inter-European undertaking is that traffic-responsive urban control is an easy-to-implement, interoperable, low-cost real-time signal control strategy whose performance, after very limited fine-tuning, proved to be better or, at least, similar to the ones achieved by long-standing strategies that were in most cases very well fine-tuned over the years in the specific networks [15].

The fourth-generation self-adaptive traffic signal control system is an integrated traffic management and control system, which can realize the integrated management of network traffic and maximize the technical and performance advantages of multiple subsystems [16]. It integrates self-adaptive traffic signal control system and other ITS traffic management systems with system hardware and software integration technology, like dynamic process models of combined traffic assignment and control with different signal updating strategies [17]. It is committed to building an efficient urban traffic control integrated management system to achieve the integration of mobile network management so that it can provide better decision support for local government decision-making [18].

The fifth-generation self-adaptive traffic signal control system is based on the abilities of self-learning and high efficiency calculation in automated vehicles and regular vehicles environment [19]. Based on the empirical information and real-time traffic condition, the fifth-generation adaptive traffic signal control system learns the traffic control knowledge independently and reduces the computational burden of decision optimization intelligently. As of June 2014, InSync system has been applied in 1350 intersections in more than 100 cities across the United States and has become the fastest growing self-adaptive traffic control in the United States, which is also recommended by the FWHA currently [20]. Manolis et al. have developed and evaluated, both by means of theoretical analysis and extensive simulation experiments, a new methodology which fully automatically takes over the manual tuning and calibration procedure. Most importantly, this new methodology, called adaptive fine-tuning (AFT), achieved to improve the performance of the system and compensate the effect of the continuous changes of its behavior that may be due to either internal or external factors. The results from AFT real-life application demonstrated that it was capable of significantly improving the performance of the system in a safe and robust manner. Moreover, the real-life results exhibited the capability of AFT to efficiently adapt and compensated in cases of changes in the system behavior, even if these changes were significant [21].

2.2. The Deficiency and Expectation of the Existing Traffic Self-Adaptive Control System

Each generation system not only inherited the excellent characteristics of the previous generation traffic system, but also moves forward continuously to promote the evolution of traffic control technology under the support of the key basic technology and the guide of the new traffic control strategy. However, there are some shortcomings of the existing self-adaptive traffic control theory, method, and technology with fixed period, as follows:(1)The existing model of static traffic prediction and timing scheme does not have learning ability. Therefore, the relevant departments will recalibrate the model parameters only when the network traffic patterns have significantly changed.(2)With the expansion of the traffic network, large-scale regional road network using centralized control is difficult to guarantee the quality of data transmission.(3)The existing system is only suitable for regional traffic with significant corridor effect (due to fixed phase sequence, it can only achieve one-way green wave), and the control capacity of the typical network traffic flow in the vast majority of cities is limited.(4)Regional road network lacks timely response of the actual traffic fluctuation so that it is difficult to achieve real-time control.(5)The existing traffic control methods mostly simplify the control constraints to establish the precise mathematical model, but these methods are different from the actual traffic flow conditions and the control effect is poor.(6)The system requires a lot of human intervention, and the professional and technical personnel are needed to optimize and maintain the system due to the problem of localized migration process.

Many of the existing self-adaptive traffic control systems use the traffic model to predict the evolution of the network traffic flow under the condition of limited traffic flow data and then use the comprehensive index method to optimize the signal timing parameters. Therefore, volume prediction is an essential part. Associated with the prediction are two aspects: resolution and accuracy. It is imperative to study the relationship and tradeoff between the control strategy, prediction resolution, and its associated error, which are crucial to the development of self-adaptive traffic control systems. In a word, it is the inevitable option to study the theory and method of urban road traffic adaptive control in the future traffic data-rich environment.

3. Research on Traffic Signal Control System Based on Future Traffic Environment

3.1. The Overview of Future Traffic Environment Composition and Development

The composition of the regular vehicle (RV) traffic flow is also changed by the emergence and mixing of the Connected Vehicle (CV) and the autonomous vehicle (AV). It is foreseeable that the car traffic flow will consist of conventional vehicle, CV, and AV in the next few decades. In the "China-made 2025" national strategic plan, it is clearly put forward that China should master the overall driving technology and the key technologies to basically complete the transformation and upgrading of the automobile industry in 2025. The National Highway Traffic Safety Administration (NHTSA) in 2014 enforces that new US vehicles must have networking capabilities [22]. Nowadays, connected vehicles with highly self-driving functions (such as Google's driverless vehicles, Tesla autopilot) and networked communications functions (such as the generic Cadillac CTS 2016) have completed several different driving conditions experiment or have been put into the market, and a variety of domestic and foreign auto companies and institutions have also entered the field of research. The United States establishes seven test sites to promote the intelligent connected vehicles testing and large-scale demonstration. Now, Nevada, Michigan, and so forth have allowed driverless vehicles to enter public road for testing.

The concept of intelligent connected vehicle was formed in the 1990s, known as cooperative infrastructure vehicle in the beginning. The United States began organizing the Intelligent Vehicle (IVI) Program, the Cooperative Automatic Highway System (CVHAS), and the Vehicle Infrastructure Integration (VII) [23] in 1998. In 2007, the US Department of Transportation renamed VII to IntelliDrive. Michigan, California, and other states gradually established connected vehicle test platform from 2012. In 2004 to 2010, Europe has developed PreVENT, SAFESPOT, CVIS (Cooperative Vehicle Infrastructure Systems) [24], COOPERS, and other projects to develop key technologies of connected vehicle system. Japan began to build VICS in 1991 and developed Smartway [25] project from 2004 so far. These systems and projects have entered the stage of large-scale system applications and related technology policy development. In recent years, under the support of the National Natural Science Foundation of China (NSFC) and the National High Technology Development Program (863 Project), Tongji University, Tsinghua University, Beihang University, and National University of Defense Technology and other academic and industrial institutions have developed several connected vehicle prototypes and test systems based on short-range communication [26]. With the continuous development of related fields such as mobile Internet and Internet of Things, cooperative infrastructure vehicle system and its application have become the new trend of the intelligent transportation system. Besides, the necessity of carrying out research on relevant theories, technologies, standards, policies, and regulations has become a broad consensus. Vehicle-road/vehicle-vehicle communication and traffic safety technology based on cooperative infrastructure vehicle system has become a research focus at this stage.

The earliest research on autonomous vehicles began in the 1980s, represented by the Navlab Self-Driving Vehicle [27] of Carnegie Mellon University and the ALV (Autonomous Land Vehicle) project of the US Defense Advanced Research Projects Agency (DAPRA) [28]. In 1995, Carnegie Mellon University developed the autonomous vehicle Navlab-5, completing a self-driving experiment of nearly 5,000 kilometers across the US, of which 98.2% was completed by the automatic driving system [29]. In 2008, Stanford University developed the driverless vehicle Junior, which can independently plan the path and realize its precise positioning, perceive other social vehicles and interact, and can achieve driving behaviors such as lane changing, U-turn, and parking [30]. In 2010, the ARGO autonomous vehicle, which was developed by Professor Alberto Broggi of the University of Parma, Italy, equipped with laser radar, camera, global positioning equipment, and so on, was exhibited at the Shanghai World Expo after more than 80 days' travel from the Italian Palma to Shanghai [31]. The red flag HQ3 autonomous vehicle, which is developed by National Defense University of Science and Technology, completed the 286 km self-driving experiment from Changsha to Wuhan, with less than 1% manual intervention mileage of the total mileage [32]. Besides, Google, Nissan, Tesla, GM, Ford, and other companies are also involved in the study of autonomous vehicle, but the technical details of the study are usually not disclosed [33]. In the theoretical study, Levinson et al. [34] optimized the existing automatic driving system, which enabled the vehicle adapted to a variety of lighting, weather, and traffic conditions, to a certain extent, overcoming the challenges of narrow roads, crosswalks, and signal intersections.

3.2. Research Status of Traffic Signal Control System Based on Future Traffic Environment

Following the methods of earliest fixed signal timing and offline delay calculation proposed by Webster [35], the traffic signal control system has evolved from offline to online control, from point to network control, from fixed-time to self-adaptive control. With the development of intelligent transportation system, the research of a new generation of traffic control technology based on multisource heterogeneous data has been gradually started [36]. In recent years, the research on signal control based on cooperative infrastructure vehicle system has become the frontier field of domestic and foreign traffic control theory and application [37]. Professor Yang's team at Tongji University launched the project "Research on the Next Generation of Traffic Control Technology at Intersection Based on CVIS" in 2010 to 2012 under the support of the National Natural Science Foundation, which analyzed multitarget control mechanism, vehicle-road/vehicle-vehicle communication method, and the prototype of signal control integrated platform with a single intersection as the object. The research of intelligent connected vehicle was mainly focused on the optimization methods of traffic safety, such as collision warning [38] and lane changing assistance [39]. With the concept of active safety and traffic signal control problems being put forward, driving optimization strategy for efficiency and emission reduction, such as the speed guidance strategy considering the signal light state [40], eco driving strategy [41], and so on, has been widely studied. Besides, to meet the special needs like emergency rescue vehicles and bus priority, the multimode signal priority control system considering the real-time status of special vehicles has also been put forward and achieved initial implementation [42]. Automatic driving research mainly focuses on the data collection and forecasting problem of mixed traffic flow [43] and the local optimization method based on the rolling optimization strategy [44]. Most of the optimization targets adopt efficiency-related indicators such as the least delay, the least number of stops, or the shortest across time [45]. About the control effect evaluation, most of the research output optimization control effect based on the secondary developed traditional simulation software [46]. Researches show that the traffic control which considers the mixed traffic flow of the connected vehicle and autonomous vehicle can effectively improve the traffic efficiency of the intersection, compared to the conventional traffic flow control [43].

4. Development Status of Urban Traffic Signal Self-Adaptive Control Method

Traffic congestion in urban road and freeway networks leads to a strong degradation of the network infrastructure and accordingly reduced throughput, which can be countered via suitable control measures and strategies. The traffic signal control method is evolved along with the combination of modern control theory, artificial intelligence theory, traffic information technology, and traffic engineering technology. Because the modern control theory is based on the basic assumption that the mathematical or nominal model of the controlled object is precisely known, the method is collectively referred to as Model Based Control (MBC) theory and method [47]. In the last 20 years, Artificial Intelligence (AI) theory and methods, which were represented by agents, neural networks, fuzzy logic, and group intelligence, were gradually mature. Diakaki et al. presented the design approach, the objectives, the development, the advantages, and some application results of the traffic-responsive urban control (TUC) strategy. Based on a store-and-forward modeling of the urban network traffic and using the linear-quadratic regulator theory, the design of TUC led to a multivariable regulator for traffic-responsive coordinated network-wide signal control that is particularly suitable also for saturated traffic conditions [48].

4.1. Traffic Self-Adaptive Control Method Based on Mathematical Model

According to the status and function of the traffic forecasting module in the traffic control model, the typical traffic signal MBC control method includes Travel-Time Responsive (CTR) traffic signal control algorithm [49], Predictive Model Control [50], Arrival–Discharge Process, and Storage-Forward Response Control. Arrival–Discharge Process signal control algorithm is based on dynamic programming and the optimization of signal policy is performed using a certain performance measure involving delays, queue lengths, and queue storage ratios [51]. Storage-Forward Response Control using a real-time monitoring data of arrival and leaving traffic flow to simulate the movement of the vehicle platoon and realize the predictive control [52].

According to the different control targets, the traffic signal MBC control method can be divided into a coordinated control method based on comprehensive performance index and a coordinated control method based on green wave band. The comprehensive index method, represented by TRANSYT [53], considers the delay, the number of stops, and the length of queues to obtain the best overall efficiency of the network. The green wave band method is designed to maximize the number of nonstop platoons of the main line, and the typical arterial coordinated control method based on green wave band includes the maximum green wave band method MAXBAND and the multi-green wave band with variable band width method MULTIBAND [54].

4.2. Traffic Self-Adaptive Control Method Based on Intelligent Computing

Some researchers think that optimization of traffic lights in a congested network is formulated as a linear programming problem [55]. However, considering the complexity of the internal structure of the urban regional traffic system and the external operation environment, it is impossible to establish the precise mathematical model. There are many challenges in effectively integrating signal timing tools with dynamic traffic assignment software systems, such as data availability, exchange format, and system coupling [56]. However, little effort has been put in developing control frameworks that are aimed not only at improving the average performance of the system, but also at improving the system robustness and reliability. In the past 10 years, artificial intelligence computing technology simulates human reasoning and learning process and controls the optimal control strategy in the process of interaction between traffic controller and road environment. Fuzzy logic, group intelligence algorithms, and neural network control dominate the many traffic control methods based on intelligent computing

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2. The Development History and Deficiency of the Existing Traffic Self-Adaptive Control System

2.1. The Development History of the Existing Traffic Self-Adaptive Control System

According to NCHRP, more than 20 self-adaptive traffic control systems have been developed by transportation research institutes and enterprises worldwide, but less than half systems have been put into use [7]. According to the system’s ability to adapt to the environment and the level of intelligent decision-making, Gartner et al. proposed the evolution of urban transport control system development level in 1995 [8], as shown in Figure 2.