Research Article

Signal Control Adaptive Model Based on Microtransformation of Urban Street Space

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Received 28 June 2022; Revised 11 August 2022; Accepted 16 August 2022; Published 1 September 2022

Academic Editor: Lianhui Li

Cities need to develop, people’s lives need to be improved, and the living environment needs to be enhanced. With the strengthening of the national policy of paying attention to people’s livelihood, the speed of development, the increase of the number of cars, and the major demolition and construction of streets are in full swing everywhere. However, traffic congestion has become a serious social problem, which greatly affects economic development and people’s daily life. Therefore, the study of signal coordination control of urban traffic arteries has become an urgent problem for all countries. In this paper, after a brief introduction of the basic concepts and related technologies of traffic control systems, we focus on the arterial coordinated control system. The adaptive control model studied in this paper reveals the vehicle arrival dynamics from a microscopic perspective, which helps to improve the adaptive control effect and alleviate urban intersection congestion. The use of traffic information acquisition and control systems can promote the application of vehicle networking technology, while moreover helping to provide important model simulations for future street simulation renovation.

1. Introduction

It is urgent to analyze and propose solutions to the current shortcomings and problems of urban street space design and the current situation of urban streets in China. We should use system theory as an analytical tool and philosophical theory support, from the cultural, human, ecological, ethical perspective to analyze the design of urban street space in China and the current situation of the street problems. Street space is not a long and narrow independent space, closed space, but widely permeated to other types of space, and benign interaction. Street space condenses and carries a large amount of information, involving economic, political, and cultural and social factors and reflects not only value orientation but also social ethics. The transformation process of historical districts often involves different social groups, and one social group often influences another group in order to realize its own spatial practice [1]. Street space renovation design must not unilaterally pursue the expansion of traffic flow while ignoring the reduction of pedestrian space; unilaterally pursue individual or local economic or commercial interests while ignoring long-term social and overall interests; unilaterally pursue so-called biased visual aesthetics, personal preferences, and a certain style while ignoring the real life and inner feelings of citizens; unilaterally pursue formal novelty and objective prosperity while ignoring the regulation of microclimate. The unilateral pursuit of formal novelty, objective prosperity, while ignoring microclimate regulation and humane care; the unilateral pursuit of verbal ecological green environmental protection and ignore the true meaning of ecological cycle, the true meaning of the green environment, simply because of the so-called international style, while ignoring the unique flavor of the regional personality with a deaf ear. A good street is not only durable but also useable, pleasant, livable, ecological, harmonious, and humane. It is a dynamic open system with all the characteristics of a system that needs to be constantly improved and evolved to meet the needs of the times and to adapt to the development of people. Street space is the window of the city, recording the history of the citizens, and...
every detail gives the space a personalized charm, reflecting the comprehensive quality and public spirit of the citizens. The transformation design of street space needs to be preceded by systematic analysis methods and forward-looking theories, and the transformation plan should be made according to local conditions after careful investigation and research of basic information, meticulous and thorough analysis, feedback and evaluation, and many other procedures of combing and borrowing relevant theoretical research results and comprehensive research.

One of the most important points is that urban traffic congestion has become a serious social problem, and how to regulate and manage urban traffic flow in a rational and scientific way is the focus of attention of the global traffic engineering and theoretical communities. Urban residents are increasingly vulnerable to the problems brought by high urbanization, such as traffic congestion, air pollution, and housing tension. Among them, urban congestion is a common problem in major cities around the world, and it seriously affects the quality of life of residents and the operational efficiency of various services. To solve urban traffic congestion, on the one hand, the layout and proportion of residential land and commercial land should be reasonably arranged from the interactive relationship between land use and traffic, so as to solve traffic congestion from planning; on the other hand, the traffic efficiency of roads and road networks should be improved to reduce the probability of congestion. Urban traffic control signal control intersection, as a key node of the road network, is the most likely location to generate traffic congestion, and if its queue of vehicles spreads without limit, it will seriously affect the traffic efficiency of adjacent intersections. Therefore, the signal control strategy of intersections, as an effective method to alleviate their congestion level, is an important research direction for urban road reconstruction in recent years. According to the traffic flow characteristics of urban arterial roads, it has become one of the important research topics of current intelligent traffic control to design advanced adaptive coordinated control systems for urban traffic arteries by using advanced information technology, communication technology, and control technology to improve the operational efficiency of arterial traffic networks. In addition, with the implementation of the concept of bus priority in major cities, the proportion of buses in the road network has increased significantly. In order to improve the efficiency of bus travel, more and more urban intersections are equipped with bus priority signals. However, existing studies and practices show that vehicle-specific signal priority strategies will inevitably lead to increased delays in normal traffic flows. Especially in the case of a general mix of buses and cars, attention needs to be paid to the signal right-of-way allocation for traffic in different directions. Therefore, a reasonable signal control strategy is particularly important to reduce passenger delays. Conversely, if the signal timing scheme does not correctly reflect the characteristics of real-time traffic flow, it may lead to wasted green time, too short cycles, or underestimated turn times, generating unnecessary waiting time. Studies have shown that up to 40% of excess fuel consumption can be generated due to improper traffic signal timing [2]. It is of practical importance to study and design coordinated signal control systems for urban traffic arteries to solve urban congestion and ensure smooth road flow to promote economic development.

In this paper, after a brief introduction of the basic concepts and related technologies of traffic control systems, we focus on the arterial coordinated control system. With the help of numerical models of arterial traffic delays, we established a set of our own real-time optimization algorithms for arterial coordinated control systems with reference to the current previous control systems. We have collected various literature and technical reports to grasp the current status and development direction of theoretical research in the field of adaptive signal control. In the process of studying the literature, we focused on microscopic simulation-based optimization and control models and organized and summarized the research methods from the perspectives of data collection and traffic flow arrival characteristics. In addition, since developed countries in Europe and the United States started earlier in this field and accumulated rich theoretical foundation and practical experience, this paper pays special attention to the effectiveness of new signal control and optimization methods in comparison with traditional methods based on collecting and organizing relevant data. The phase structure adopted by the signal controller specifies the combination of traffic flow directions for simultaneous release, which will have a certain impact on the final optimization effect. Previous adaptive signal control methods tend to use a four-phase signal structure with simultaneous release of opposing traffic flows, which can only accommodate control requirements where opposing traffic flows are approximately the same. However, in reality, due to the possible deviation of the opposite traffic flow during the peak of the tidal phenomenon, a signal phase structure with higher flexibility in the North American NEMA (National Electrical Manufacturers Association) standard is needed. We then perform adaptive signal optimization and control using a modified dynamic programming (DP) algorithm that is divided into forward recursion and backward recursion. The forward recursive process is combined with the North American NEMA phase structure to invoke a vehicle arrival time prediction model for short-term traffic flow prediction, on the one hand, to estimate the intersection vehicle delay, queue length, and throughput based on the different phase characteristics of vehicles passing through the intersection on the other hand, and finally to determine the optimal green time length and its phase combination for each phase. The optimal phase sequence and duration can be determined through the reverse recursive process, thus completing the optimization of the timing scheme in one go.

The technical route of the research in this paper is shown in Figure 1. The core of the research is an adaptive signal control optimization method for urban intersections based on microscopic simulation. Based on the summary of the current research status, the key issues such as vehicle arrival prediction under microscopic perspective, improvement of traditional dynamic planning algorithm, signal optimization model under the conditions of vehicular network, and
distributed signal cooperative optimization are focused on. An improved adaptive signal control model based on random vehicle arrival under different vehicle arrival mode conditions is proposed. Finally, based on the secondary developed VISSIM simulation, the proposed model is verified and analyzed using two real intersection cases, respectively, and finally, the research conclusions are drawn.

In order to verify the feasibility of the method proposed in this paper, a secondary development platform is constructed for signal optimization and collaboration using the simulation software VISSIM, a microscopic traffic simulation software developed by PTV, Germany, which can effectively simulate and analyze the operation of vehicles, pedestrians, and rail traffic under various traffic conditions. In the simulation of road network intersections, the general practice is to input the timing scheme in advance and keep the timing scheme fixed during the simulation process. This practice not only cannot realize the information interaction between VISSIM and the optimization model but also is not conducive to the development and validation of new traffic control models. Therefore, it is necessary to link the VISSIM simulation platform with external programs using the COM interface to achieve signal collaboration and optimization. Real-time interaction between external programs and simulation software can be realized through the VISSIM COM server interface technology. The principle of interaction between VISSIM simulation software and programming is briefly described in Figure 2.

2. Adaptive Control Method Based on Traffic Flow Model

Model adaptation (MA for short) has now become a research hotspot in several fields. Its goal is to maximize the performance of the target task using both source training data and target data. As shown in Figure 3, we train a good original model on rich source/training data and adapt the model with additional task-related data in the application phase to get an adapted model (adapted model) to better fit the target task/target data. Model adaptation can be seen as a way of migration learning.

In addition to the signal control methods that have been applied in existing systems, scholars around the world have developed various adaptive signal control and optimization theories based on different characteristics and applicability conditions for adaptive models in road modification signal control. The existing studies generally need to rely on specific traffic flow models and mathematical optimization methods, which can be classified into the single intersection, arterial, and regional cooperative adaptive signal control methods according to their applicability.

In this paper, we introduce many methods and generalize and unify them. Since the introduced and organized articles span a wide range of concepts in terms of time and geography, we have unified the concepts in this article and tried to show our unified concepts in the form of diagrams or formulas.
There are a large number of level intersections in urban roads, which become the convergence and diversion points of traffic flow. In order to make the traffic flow safely into and out of the intersection, some control method must be used to reasonably allocate the right-of-way so that conflicting traffic flows are separated in time and space, thus ensuring the safe passage of vehicles and pedestrians. Planar intersections can generally be divided into cross-shaped, X-shaped, T-shaped, Y-shaped, and multiway intersection shapes. Due to the complicated traffic organization of multiway intersection, it should be avoided as much as possible.

The signal used to direct traffic always changes step by step in a cycle, and a cycle consists of a finite number of steps. The sum of the step lengths of each step in a cycle is called the signal period, or cycle for short, and is denoted by $C$. If a cycle has $n$ steps, the step lengths are $t_1$, $t_2$, ..., $t_n$, then the period formula can be shown by the following formula:

$$ C = t_1 + t_2 + \cdots + t_n. \quad (1) $$

In traffic control, in order to avoid conflicts between traffic flow in all directions on the plane intersection,
usually use the method of time-sharing, that is, in a cycle of a certain period of time, the intersection on a certain traffic flow or several traffic flow has the right of way (i.e., the direction of the signal is green or green arrow), and the conflict with the other traffic flow cannot pass (i.e., the signal in the direction of red). In a cycle, the right-of-way obtained by one or more traffic streams on the level intersection is called the signal phase. A cycle of several signal phases, the signal system is said to be a several phase system. The phase can be represented by a directional line segment, the direction of the arrow direction, and the direction of vehicle movement. If a light-controlled intersection is a four-phase system, the first phase of east-west traffic flows straight ahead, the second phase of east-west traffic flows left, the third phase of north-south traffic flows straight ahead, and the fourth phase of north-south traffic flows left, while all right-turning traffic flows are not controlled. The above phase system is generally known as a four-phase signal and can be represented by Figure 4.

Sometimes, in order to improve intersection utilization, the right-of-way of one traffic flow in one phase can be maintained until the next phase, most often for left-turn traffic flows, as shown in Figure 5. Since the left-turn traffic flow of the second and fourth phases is a continuation of the first and third phases, respectively, the step length can be shorter, for example, a few seconds. Therefore, some people call them “half-phases.” However, the concept of steps and step lengths is quite simple to describe that the above example is actually four steps in a cycle.

The phase difference is an important concept in the coordinated control system of traffic arteries. The phase difference is divided into absolute phase difference and relative phase difference. In the traffic arterial coordinated control system, all intersections on the arterial have the same signal period, and each intersection designates a certain phase to participate in the coordination, called the coordinated phase. With an intersection on the traffic arterial as the reference intersection, the minimum time difference between the start time of the coordinated phase of other intersections lagging behind the start time of the coordinated phase of the reference intersection is called the absolute phase difference; the minimum time difference between the start time of the coordinated phase of any adjacent intersection along the direction of vehicle travel is called the relative phase difference.

Single intersection signal control is the basis for implementing traffic arterials, regional signal control, and distributed control strategies. Regardless of the adaptive signal control strategy, vehicle arrival prediction based on a single intersection is required. Fang and Elefteriadou [3] proposed a vehicle arrival-dissipation prediction model considering intersection queues, which can solve the problem that the conventional PREDICT algorithm [4] cannot accurately predict the intersection approach lane queue length. However, since the model only microscopically simulates the queue arrival under red light conditions, its vehicle arrival dynamics under green light conditions remain to be investigated. Sun and Zhang [5] developed a single-intersection vehicle arrival prediction model under triggered signal control conditions, which is not only applicable to NEMA phase structures but can also be extended to multiintersection cooperative control.

The first single-junction-based adaptive signal control strategy was proposed by Miller [6] in 1963, and since then various adaptive signal control strategies have emerged, such as optimization policies for adaptive control (OPAC) [7], PRODYN [8], UTOPIA [9], and controlled optimization of phases (COP) [10]. The aforementioned signal control strategies use dynamic planning algorithms to adjust the green time in real time based on vehicle arrival predictions, among which the COP algorithm is considered to be the best single intersection adaptive signal control algorithm to date because it is not limited by cycle length and phase sequence. The optimization process of the COP algorithm is divided into two main parts: first, a forward recursive step to calculate the vehicle delay time under each alternative scheme and a backward recursive [11] provide a detailed comparison of the performance of various dynamic planning algorithms. Porche and Lafortune [12] proposed the ALLONS-D adaptive signal control theory in 1999, which uses branch constraint method to calculate the optimal timing scheme, while proposing an “implicit coordination” mechanism, that is, optimizes the signal timing schemes of individual intersections sequentially with the predicted upstream traffic arrivals to achieve cooperative control. This approach requires a shorter prediction time (5–15 s), the detector can be placed in the middle of the road, and takes into account the influence of upstream intersection signal control on the prediction results, but the shorter time step places higher

![Figure 4: 4-phase signal diagram. (a) Phase 1. (b) Phase 2. (c) Phase 3. (d) Phase 4.](image)

![Figure 5: Half-phase signal diagram. (a) Phase 1. (b) Phase 2. (c) Phase 3. (d) Phase 4.](image)

From this, it can be found that adaptive signal timing at individual intersections under the framework of a distributed “implicit coordination” control strategy is still necessary for research, first to further improve the short-term vehicle arrival prediction model at the microlevel, while how to improve the algorithmic optimization effect under NEMA phase conditions is still a frontier issue in the field of traffic control. After all, improving the capacity of individual intersections is still the key to achieving smooth traffic flow.

The earliest traffic arterial signal control systems in the world can be traced back to the six-intersection manual signal control system in Salt Lake City, USA in 1917, followed by the development of a 12-intersection cooperative signal control system based on automatic machine timers by the City of Houston in 1922. In contrast, researchers at this stage generally start by maximizing the green wave bandwidth to achieve cooperative control of arterials. The first computational model for bandwidth optimization was proposed by Morgan and Little [15] in 1964, which was able to optimize a fixed signal timing scheme for two-way arterials to maximize the green wave bandwidth. Subsequently, Little [16] proposed a more advanced mathematical planning model to determine the optimal signal cycle length and the recommended travel speed for a given range. Based on this, Little et al. [17] developed the classical MAXBAND model by combining left-turn traffic and queue lengths. The MULTIBAND model was proposed by Gartner et al. [18] in 1995, which can set different bandwidths for traffic arterials to meet specific traffic flow characteristics.

However, the above studies are based on offline methods, and in order to dynamically adjust the signal timing scheme at arterial intersections, Dell’Olmo and Mirchandani [19] proposed the REALBAND optimization model, which uses a decision tree approach to minimize the number of stops and total delays of arriving convoys as the study object, which has been applied through the RHODES [20] system. The real-time, hierarchical, optimized, distributed, and effective system (RHODES) is a distributed adaptive traffic signal optimization system developed by the University of Arizona, USA, using a hierarchical control structure, that is, a network load distribution layer, a network flow control layer, and an intersection control layer. Its traffic flow prediction algorithm obtains vehicle arrival information through detection coils buried in front of the stop line at upstream intersections, and the model system allows for longer prediction times due to possible phase delays.

However, the common drawback of the above models is that they cannot effectively handle the arterial signal coordination problem under saturated traffic conditions. To address the capacity loss caused by vehicle overflow, Lieberman et al. [21] proposed a real-time cooperative optimal control strategy for oversaturated traffic flow on traffic arterials, which mainly uses Lighthill and Whitham [22], and the traffic flow fluctuation theory proposed by Richards [23] to calculate the fleet depletion time and rate. Hu et al. [24] used the hybrid genetic-simulated annealing algorithm of Li and Schonfeld [25] to optimize the signal timing scheme of traffic arteries under oversaturated traffic flow, including phase sequence, cycle length, and green time, and the results showed that a reasonable phase sequence is crucial to improve the optimization effect.

Given the complexity of the actual system, semiautomatic control has been widely used in the field of cooperative signal control at arterial intersections due to its low installation and usage costs. This signal control strategy is mainly based on triggered control logic that dynamically adjusts the phase difference parameters of key phases at upstream and downstream intersections to achieve cooperative control, and part of the adjustment mechanism is implemented based on offline computation. For example, Jovanis and Gregor [26] improved the traditional optimization method of maximizing the green band by moving the reference point of the phase difference to the end of the straight ahead phase to achieve semitriggered cooperative control. Shoup and Bullock [27] used the travel time of the first vehicle in the passing convoy to dynamically adjust the phase difference parameters. Yin et al. [28], on the basis of a large number of basis, Zhang and Yin [29] proposed a robust optimization model to adjust the cycle time and phase difference, which can effectively deal with the effect of uncertainty in the coordinated phase start time in semitriggered signal control. For the uncertainty of traffic flow, Zhang and Lou [30] proposed an optimization model for semitriggered signal control based on integer programming, which can obtain significant optimization results under lower traffic conditions.

In summary, the research of traffic arterial signal synergy and optimization models generally focuses on the modeling of the phase difference adjustment mechanism based on the traffic flow model, because the signal control parameters set can effectively improve the intersection capacity only when the traffic flow changes are reasonably predicted. However, some of these control models are mainly based on off-line calculations, which cannot well match the real-time fluctuation characteristics of traffic flow. If the traffic flow in different directions can be coordinated, this type of signal control model will be extended to the road network level to achieve larger scale traffic coordination and control.

3. Adaptive Control Model for Random Vehicle Arrival in Urban Roads

The signal period of each intersection in the line control system should be the same so as to ensure the stability of the arterial phase difference. Therefore, the period as the timing parameter of the line control system should refer to the common period of the signals at each intersection in the control model. There are usually two methods to determine the common period: one is to directly take the best period of
the most important intersection in the traffic status of the arterial as the common period; the other method is to calculate the best period of each intersection according to the traffic condition of each intersection and then take the largest value as the common period to avoid the bottleneck effect. This chapter introduces the vehicle arrival model and adaptive signal control optimization method based on a microscopic perspective. The method is mainly applied to traffic signal control in the case of random vehicle arrivals. In order to improve the adaptive signal control algorithm, the NEMA traffic signal phase structure, which is common in North America, is introduced into the original dynamic planning algorithm. In addition, the objective functions of vehicle delay, queue length, and vehicle throughput are established in this chapter. Finally, the implementation framework based on the secondary development of the COM component of the VISSIM simulation software is introduced.

In adaptive signal control, vehicle arrival and dissipation information is an important input variable for the signal optimization algorithm, while the signal timing scheme will conversely affect the changes in traffic dynamics near the intersection. In general, traditional adaptive signal control methods collect vehicle arrival information mainly through upstream detection coils or cameras. If a queued vehicle has not completely left the stop line, whether it starts moving or not, the subsequently detected vehicle travel distance is primarily the distance from the upstream detection coil location to the end of the queue. Therefore, the intersection maximum queue length (distance from the stop line to the end of the queueing convoy) [31] is crucial for estimating the vehicle stopping time. In this section, the trajectory and maximum queue length variation of vehicles arriving at the end of the queue until they leave the stop line are studied from a microscopic perspective to model the vehicle arrival-dispersion process. The proposed model is able to predict the vehicle arrival time at the end of the queue fleet under red light and green light conditions.

3.1. Red Light Arrival. Assume that the distance from the upstream detection coil to the intersection stop line is \( D \). The vehicle passes the detection coil and proceeds at the free-flow speed, \( v_f \), and reaches the end of the queue in different lanes according to a certain steering ratio. For simplicity, the deceleration process when the vehicle enters the queue is ignored. The travel time, \( t_{tk} \), and arrival time, \( t_{ak} \), of vehicle \( k \) at this distance can be expressed by the following formulas:

\[
\begin{align*}
  t_{tk} &= \frac{(D - q_{k-1}^{\text{max}})}{v_f}, \\
  t_{ak} &= t_{k}^{\text{a}} + t_{tk},
\end{align*}
\]

where \( q_{k-1}^{\text{max}} \) is the maximum queue length after the vehicle \( k - 1 \) enters the queueing convoy; \( t_{k}^{\text{a}} \) is the time for the vehicle to pass the upstream detection coil. The initial maximum queue length can be expressed as \( q_{0}^{\text{max}} = n_{0} \cdot S \), where \( n_{0} \) is the number of queued vehicles in the lane and \( S \) is the length of the space occupied by the queue.

In Algorithm 1, \( T_{st} \) and \( T_{end} \) are the start and end times of the red or green light in the phase, which can be used as the range of vehicle arrival times. The set of the vehicle arrival times at the detection coil is also used as one of the inputs to the algorithm, and \( K \) represents the number of detected vehicles. If the calculated vehicle arrival time is within the red light time range \([T_{st}, T_{end}]\), it is recorded and used in the subsequent optimization algorithm. Also, the maximum queue length value is updated after the vehicle arrives. If the vehicle arrival time is greater than the predefined time range or if no vehicle arrives, Algorithm 1 ends. The algorithm will end.

3.2. Green Light Arrival. After the start of the green time, as the traffic dissipation wave [22] passes, the queued vehicles start one by one and at the following speed \( v_q (v_q < v_f) \) through the stop line. Depending on whether the end-of-fleet vehicle starts or not, the vehicle arrivals can be divided into two categories: Scenario 1, the arriving vehicle arrives and stops before the dissipation wave passes to the end of the queue and then restarts to cross the intersection. Scenario 2, the arriving vehicle catches up with the started vehicle at the end of the queue at free-flow speed \( v_f \) and passes the intersection stop line at the following speed \( v_q \). The details of the two scenarios are shown as follows.

In Scenario 1, similar to the arrival case during the red light period, vehicles join the stationary queueing convoy, and the maximum queue length continues to increase. According to the traffic flow theory, the start time of the vehicles at the end of the queue corresponds to the time when the dissipation wave ends its propagation [32]. Assuming that the speed of propagation of the dissipation wave of the traffic flow after the start of the green light is \( v_s \), therefore, the start time of the vehicle at the end of the queue after the start of the green light can be determined by the following formula:

\[
t_s = T_{st} + \frac{q_{k}^{\text{max}}}{v_s}, \tag{4}
\]

If the vehicle arrives before the start time, \( t_s \), at the end of the queue, the duration that the vehicle spent in the end of the queue increases accordingly due to the increase in queue length \( \Delta t_s \), which is calculated as follows:

\[
\Delta t_s = \frac{\Delta q_s}{v_s}, \tag{5}
\]

In Scenario 2, the end of the line starts moving before the arriving vehicle joins the convoy, so the arriving vehicle first moves forward at free-flow speed \( v_f \) and then joins the convoy at the following speed \( v_q \) to pass the stop line. For arriving vehicle \( k + 1 \), its arrival process is similar to that of the previous vehicle, the only difference being that the preceding vehicle \( k \) has already started at the \( t_{k}^{\text{a}} \) time. In this case, the final value of the arrival moment is calculated as follows:

\[
\Delta t_{k}^{\text{a}} = \frac{v_q \cdot \left[ t_{k}^{\text{a}, 0} - \max(t_{k-1}^{\text{a}, 0}, t_s) \right]}{(v_f - v_q)}, \tag{6}
\]

\[
t_{k}^{\text{a}} = t_{k}^{\text{a}, 0} + \Delta t_{k}^{\text{a}}, \tag{7}
\]
where $\Delta t^a_k$ represents the additional travel time required for arriving vehicle $k$ to catch up with the end of the moving queue. The numerator in (6) represents the length of the vehicle $k - 1$ traveling forward from the time $t^a_{k-1}$, and the denominator represents the speed difference. Due to the speed difference between the free-flowing vehicle speed and the following vehicle speed, it is assumed that the arriving vehicle $k$ will catch up and join the convoy at moment $t^a_k$. The flow of the arrival time and maximum queue length estimation is shown in Algorithm 2.

In Algorithm 2, first initialize the vehicle start time $t$, at the end of the queue, the initial value of vehicle travel time $tt$, and the initial value of vehicle arrival time $tt^a$. Vehicle arrivals can be divided into two categories according to the relationship between the magnitude of $tt^a$ and $tt$: (Step 3): in scenario 1, the maximum queue length continues to increase; in scenario 2, it is necessary to detect whether the arriving vehicle $k$ can catch up with the convoy before the stop line and pass with the following speed $v_q$. If not, subsequent arrivals will continue and the above process will continue until all arrivals have passed the checkpoint. It can be seen that the maximum queue length and the state of the vehicles at the end of the queue are the keys to estimate the vehicle arrival time in this model.

### 3.3. Real-Time Signal Control Algorithm

The DP algorithm mainly consists of forward and backward recursive algorithms. The forward recursion is mainly used to calculate the optimal green light time and its corresponding objective function value under different control variables. Backward recursion is mainly used to calculate the optimal signal. Backward recursion is mainly used to calculate the optimal signal timing scheme. The details of the forward and backward recursive algorithms are described as follows.

The forward recursive algorithm in the DP algorithm mainly assigns the phase time length and the alternative traffic direction combinations to each phase group. If a phase in the DP corresponds to two alternative traffic direction combinations, the phase group can be omitted assuming that the minimum control variable, $x^m_j$, which means that the minimum green time is zero; otherwise, the minimum green time is a certain determined value (e.g., 10 s). Under the minimum green light time constraint, the state variable corresponding to phase $j$ can be calculated by the following equations:

$$
\begin{align*}
    s^m_j &= \begin{cases} 
        s^m_j + h(x^m_j), & j > 1, \\
        \max\{x^m_j - x_v, 0\}, & j = 0,
    \end{cases} \\
    h(x) &= \begin{cases} 
        x + R, & x > 0, \\
        0, & x \leq 0,
    \end{cases}
\end{align*}
$$

where $s^m_j$ is the smallest state variable in stage $j$ in the DP algorithm, $x_v$ indicates the length of the green time in the end phase of the previous rolling time domain, and $R$ is phase interval, which is the time when there are all yellow or full red light.

In order to simplify the DP algorithm, the maximum green time limit is omitted as it is not often reached in practice. The upper limit of the state variable is $T$, and the rolling time domain is not bounded by the cycle time. The set of feasible control variables, $X_j(s_j)$, for a given state variable, $s_j$, can be expressed by the following formula:

$$
X_j(s_j) = \begin{cases} 
    x^m_j, \ldots, s_j - x^m_j, & \text{if } s^m_j < s_j < T, \\
    0, \ldots, T - s^m_j, & \text{if } s^m_j = T.
\end{cases}
$$

Using (10), it can be found that each phase in the DP algorithm may correspond to the end phase group of the rolling time domain. If the state variable is equal to the rolling time domain duration, the current phase group may be omitted, and the previous phase group may become the end phase of the current rolling time domain. With supporting variables, $c_j$, which is the phase group assigned to $DP$ phase $j$, which contains two nonconflicting traffic directions; $C_{ij}$ is alternative sets that can be assigned to the two traffic directions in the $i$ phase group. $f_{ji(x)}$ is the objective function value when the state variable is $s_j$, the control variable is $x_j$, and the phase group is $c_j$. $v_j(s_j)$ is the cumulative value of the objective function from $DP$ stage 1 to stage $j$. We can then summarize Algorithm 3 as the forward recursive algorithm in the DP algorithm:

The forward recursion algorithm first initializes the cumulative state values. In each stage, the DP algorithm calculates the optimal control variables and the green light phases for each condition. The objective function value can be obtained by the model calculation in the next section. The stopping condition of the proposed algorithm differs from the conventional COP algorithm, that is, the algorithm ends when the minimum value of the state variable is greater than the rolling time domain duration $T$ (step 3) and when the objective function value is no longer varies as the phase group increases.

In the backward recursive algorithm, when the optimal function values of all control variables under each phase of the DP algorithm are known, the optimal phase combinations and green light duration in each $DP$ phase can be obtained by the backward recursive algorithm. When the state variable is $T$, the $DP$ algorithm can be started from the end phase, to phase $J$ where $x^*_J(T) \neq 0$, in order to obtain the optimal control variables, $x^*_J(T)$.

The reasons why the optimal green light duration can be recursively extended through phase $J$ are as follows: first, the stopping condition in Algorithm 3 ensures that no other phase groups can be added at the end of the rolling time domain. Second, for any phase that $j > J$, its corresponding green time length is 0, which can no longer improve the optimization result of the signal timing scheme. At this point, the backward algorithm can be expressed by Algorithm 4 as follows.

With the four algorithms illustrated before, we can then calculate the objective functions or target variables.

For adaptive signal control algorithms, different objective functions often lead to different control effects. Under specific traffic flow or rolling time domain duration
conditions, some objective functions tend to obtain better signal control optimization results. In this text, \( f_j(x_i, x_j) \) represents the objective function corresponding to different measurement indicators, including delay, vehicle queue length, and throughput. The objective function and related variables are calculated as follows:

Objective function 1.

\[
\min \sum_{t=s_j+1}^{s_j} \sum_{p=1}^{8} n_l^d(t). \tag{11}
\]

Objective function 2.

\[
\min \sum_{p=1}^{8} n_l^d(s_j). \tag{12}
\]

Objective function 3.

\[
\min \sum_{t=s_j+1}^{s_j} \sum_{p=1}^{8} n_l^d(t). \tag{13}
\]

Objective function 1 denotes minimizing the sum of queue lengths for all lanes from state moment \( s_{j-1} \) to \( s_j \) for each time step, which is the length of time experienced by all vehicles from the start of the queueing state until they leave the stop line.

Objective function 2 is calculating the minimized queue length, which is the sum of the queue lengths for each lane at the end of each phase group.

Objective function 3 represents the number of vehicles maximized through the intersection, which is the total number of vehicles leaving in each phase. The unit time interval in the above objective function is 1s.

Where \( l \) represents certain lane, and \( L_p \) is the lane set in phase \( p \), and the relative variables are calculated as follows:

\[
n_l^d(t) = n_l^d(t-1) - n_l^d(t) + n_l^d(t), \tag{14}
\]

\[
n_l^d(t) = \min \{v, n_l^d(t-1) + n_l^d(t)\} \forall l \in L_p, p \in c_j \cap c_{j-1}, \tag{15}
\]

\[
n_l^d(t) = \begin{cases} 
\min \{v, n_l^d(t-1) + n_l^d(t)\}, & s_{j-1} + R < t \leq s_j, \\
0, & s_{j-1} < t \leq s_{j-1} + R, \forall l \in L_p, p \in c_j, \\
1, & s_{j-1} < t \leq s_{j-1} + R, \forall l \in L_p, p \notin c_j, \\
A(l, t). & \end{cases} \tag{16}
\]

In equation (14), the number of vehicles in queue at time \( t \) is determined by the number of vehicles in queue, arriving, and departing vehicles at time \( t-1 \) while departing vehicles could be illustrated by equations (15)-(17). Where \( v \) represents vehicle dissipation rate at saturation headway. And \( A(l, t) \) in equation (18) denotes the number of vehicles entering the queuing fleet at moment \( t \), obtained mainly based on the vehicle arrival prediction information described in the previous section.

3.4. Implementation Framework and Methodology. This study uses the C++ programming language and Visual Studio 2012 for secondary development of VISSIM simulation software, VISSIM supports C++, JAVA, and VB for secondary development, and compared with other programming languages, using C++ is more convenient to implement various data structures and improve programming efficiency. The following briefly describes the principle of the COM interface of VISSIM simulation software and its application in this study.

Figure 6 shows the development framework for implementing the algorithmic model in this section.

In Figure 6, the left side shows the simulation function and interface of the VISSIM simulation platform, and the right side shows the C++ console program of the urban intersection adaptive model built in this paper, which is called by the VISSIM simulation kernel through the COM interface, including the prediction model and dynamic planning algorithm. In VISSIM version 4.3, the simulation engine contains several simulation categories, among which the Net category contains signal-controlled intersections and traffic elements in the road network, including the SignalControllers category, Links category, and Vehicles category. The SignalControllers category is used to control the signal controllers at all intersections in the network, and for each signal intersection, there is a corresponding SignalController category. The adaptive signal control program built in this paper mainly obtains the vehicle arrival trigger information through the detector category, then collects the implemented timing schemes through the SignalGroup category, and finally returns the optimized signal phases and durations to the SignalGroup category to achieve real-time signal timing control.

4. Signal Control Model Based on Random Vehicle Arrival

First, in order to validate the adaptive signal control optimization method based on vehicle microarrivals, the intersection of Jianchuan Road and Humin Road is used as an
empirical case and analysis. This intersection is located in Minhang District, Shanghai, and is an intersection with high traffic flow in the region, and the traffic congestion phenomenon is more obvious in the morning and evening peaks, and there is still room for optimization and improvement of its traffic signal timing. Due to the distance from the upstream signal-controlled intersection, the arrival traffic is less affected by the upstream signal timing; at the same time, there are several nonsignal-controlled intersections in the road section, and the vehicle arrival is more random, so this paper uses the random arrival-based adaptive signal control strategy for signal timing optimization. Figure 7 shows the intersection canalization and its corresponding NEMA phase number, where the intersection left-turn lane length is about 150 m, which may generate an overflow phenomenon under oversaturated flow conditions. In order to implement adaptive signal control, it is assumed that a detection coil is buried 500 m upstream to obtain the vehicle passing time and speed for vehicle arrival time prediction.

In this paper, the average stopping distance, the minimum headway, and the desired speed are selected as calibration parameters when establishing the simulation network in VISSIM. Based on the reasonable prediction, the above parameters are set to 3 m, 2 s, and 35 km/h. The C++ console program is written using VISSIM as the COM interface of the simulation platform. The console program contains a prediction module and an optimization module. The prediction module estimates the vehicle arrival time based on the vehicle information collected from the upstream coil at fixed intervals and passes it to the optimization module for calculation, thus realizing real-time control and optimization of the adaptive signal.

Table 1 shows the traffic flow magnitudes for three different congestion levels with intersection saturation levels measured by intersection capacity utilization (ICU) in the traffic signal timing optimization function where the unit is vehicle per hour (vph). The three categories of traffic flow based on different time periods used in this paper cover the low-moderate-high intersection congestion levels, and their traffic saturation rates gradually increase from 58% to 95%. In VISSIM, the vehicle arrival rate obeys a random distribution by ignoring the effect of upstream intersections on the arrival traffic.

The average vehicle delay (s/veh) output from VISSIM is used to evaluate the control effect of the proposed NEMA phase-based DP algorithm, and the optimal fixed signal timing scheme is calculated and compared with the
To investigate the variation of the optimal performance of the DP algorithm at different rolling time domain durations, a sensitivity analysis was performed for this case, that is, three DP algorithms with different objective functions were compared under high traffic conditions with rolling times ranging from 20 s to 60 s. As shown in Table 4, the optimization effect of DP-D gradually improves when the vehicle arrival prediction cycle length increases. This is due to the fact that in the longer rolling time domain, the optimization algorithm can effectively evaluate the impact of the signal timing scheme on traffic flow, especially the magnitude of cumulative delay. However, for calculating queue length and throughput, a longer rolling time domain does not lead to improved optimization results. For example, DP-Q mainly uses the queue length at a particular moment as an optimization metric, which requires frequent traffic state updates to obtain better optimization results. dp-t is also insensitive to changes in the rolling time domain, and the data show that it obtains the best signal control results when the rolling time domain duration is close to the travel time of vehicles from the upstream coil to the stop line.

Based on the simulation experiments and data analysis results, the following conclusions can be drawn: first, the DP algorithm proposed in this paper outperforms the optimal signal timing scheme derived from the traditional 4-phase calculation under different traffic conditions; second, the DP algorithm under NEMA phase outperforms the traditional algorithm when the traffic flow is relatively high, and there is an imbalance in the opposite direction. For the three objective functions, the DP algorithms under the principles of minimizing delay and maximizing throughput have similar control effects, while the DP-Q has relatively obvious advantages mainly under saturation traffic. In addition, DP-Q needs to update vehicle arrival data frequently to ensure the optimization results, so it can obtain a better delay control effect under rolling time domain conditions of short time length, so it should be applied in the road sections with adjacent closer upstream and downstream intersections.

5. Conclusion

Leading urban street transformation is conducive to protecting and improving people’s livelihood, and providing practical experience for the modeling of street transformation. However, we also find that if road traffic conditions are to be improved. It is necessary to rely on more advanced means of traffic information collection and signal control
Step 1 Let $k = 1$, Initialize $t_s, t_t, t_a, t_s^0, t_t^0$, and $t_a^0$.
Step 2 If $T_s^k \leq t_a^k \leq T_{end}$, while $k \leq K$, then move into step 3. Otherwise, Stop algorithm 2.
Step 3 If $t_s^k \leq t_a^k$, then update $t_s^k \rightarrow t_a^k$, and record the time that the vehicle arriving time $t_a^k$, update the longest queue distance $q_{max}^k \rightarrow q_{max}^k + S$, $t_s = t_s + \Delta t_s$. (Scenario 1) Enter Step 5. Otherwise, use equations (6) and (7) to calculate the time that the vehicle arriving time $t_a^k$, update the longest queue distance $q_{max}^k \rightarrow q_{max}^k - \Delta t_{a}^k \Delta x_{a} + S$. (Scenario 2) Enter Step 4.
Step 4 If $q_{max}^k \leq 0$ or $t_a^k > T_{end}$. Stop Algorithm 2. Otherwise, Record the time that the vehicle arriving time $t_a^k$, and enter step 5.
Step 5 Update that $k = k + 1$, use equations (2) and (3) to calculate the arriving time of vehicle, $t_s^{k+1}$, and move back to step 2.

Algorithm 2: Define travel time while green light.

Step 1 Let $j = 1$, Initialize $v_i(0) = 0$, $s^{min}_{ij} = \min [x_{i}^{min} - x_i, 0]$. Step 2 For $s_j = s^{min}_{ij}, \ldots, T$. When the objective function is minimizing the delay as well as the queue length: $v_j(s_j) = \min_{x \in X_j} \{f_j(s_j, x_j, c_j) + v_{j-1}(s_{j-1})| x \in X_j, c_j \in C_j(i) \}$. When the objective function is to maximize vehicle throughput: $v_j(s_j) = \max_{x \in X_j} \{f_j(s_j, x_j, c_j) + v_{j-1}(s_{j-1})| x \in X_j, c_j \in C_j(i) \}$. Record $x_j^* (s_j)$ and $c_j^* (s_j)$ as the best signal timing solution.
Step 3 If $s^{min}_{ij} < T$, then $j = j + 1, i = i + 1$. And return to Step 2. Otherwise stop Algorithm 3.

Algorithm 3: Define state variables.

Step 1 Let $s_j^* = T$.
Step 2 For any $j = J, J - 1, \ldots, 2$, $s_{j-1}^* = s_j^* - h(x_j^*(s_j))$.

Algorithm 4: Backward algorithm.

Table 1: Traffic demand and intersection capacity utility (ICU).

<table>
<thead>
<tr>
<th>Traffic level</th>
<th>West/eastward (vph)</th>
<th>North/southward (vph)</th>
<th>Saturation rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>600/500</td>
<td>600/500</td>
<td>58</td>
</tr>
<tr>
<td>Medium</td>
<td>900/800</td>
<td>800/700</td>
<td>78</td>
</tr>
<tr>
<td>High</td>
<td>1200/1100</td>
<td>1100/1000</td>
<td>95</td>
</tr>
</tbody>
</table>

Table 2: Control performance under different optimization methods (seconds).

<table>
<thead>
<tr>
<th>Control strategy</th>
<th>Phase structure</th>
<th>Traffic level</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>DP-D</td>
<td>NEMA</td>
<td>Low</td>
<td>19.2</td>
<td>25.7</td>
<td>52</td>
</tr>
<tr>
<td></td>
<td>4-phase</td>
<td></td>
<td>18.6</td>
<td>28.1</td>
<td>55.1</td>
</tr>
<tr>
<td>DP-Q</td>
<td>NEMA</td>
<td>Medium</td>
<td>27.4</td>
<td>30.6</td>
<td>50.8</td>
</tr>
<tr>
<td></td>
<td>4-phase</td>
<td></td>
<td>28.4</td>
<td>32.5</td>
<td>53.5</td>
</tr>
<tr>
<td>DP-T</td>
<td>NEMA</td>
<td>High</td>
<td>18.1</td>
<td>25.8</td>
<td>51.8</td>
</tr>
<tr>
<td></td>
<td>4-phase</td>
<td></td>
<td>18.2</td>
<td>27.2</td>
<td>54.5</td>
</tr>
</tbody>
</table>

Table 3: Vehicular delay under different optimization methods (seconds).

<table>
<thead>
<tr>
<th>No.</th>
<th>Low flow rate</th>
<th>Medium flow rate</th>
<th>High flow rate</th>
<th>Mean difference</th>
<th>Significant?</th>
<th>Mean difference</th>
<th>Significant?</th>
<th>Mean difference</th>
<th>Significant?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.4</td>
<td>No</td>
<td>-2.4</td>
<td>Yes</td>
<td>-3.1</td>
<td>Yes</td>
<td>-2.7</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>-1.0</td>
<td>No</td>
<td>-1.9</td>
<td>Yes</td>
<td>-2.7</td>
<td>Yes</td>
<td>-1.3</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>-0.1</td>
<td>No</td>
<td>-1.3</td>
<td>Yes</td>
<td>-2.2</td>
<td>Yes</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
strategies. Therefore, adaptive traffic signal control methods based on different vehicle arrival characteristics information and collection means remain an important research problem in the field of traffic management and control. Although formed traffic signal control systems are commonly installed in large and medium-sized cities in China, the effect of relieving traffic congestion is still limited, and the control effect of predicting vehicle arrival time from the microlevel to improve the signal timing scheme is not good enough. This paper focuses on how to improve the optimization effect of the control model based on the existing adaptive signal control scheme by using new technologies and concepts. On this basis, this paper draws on the latest foreign research results and establishes a vehicle arrival prediction model and an adaptive signal control method according to different information collection methods and vehicle arrival characteristics, and its main research results are as follows.

Starting from the generation and development of adaptive signal control theory, this paper introduces the latest research progress and challenges of its control models and algorithms. This paper argues that it is an important research direction in the future to make reasonable use of the emerging traffic information collection technology, improve the existing signal control methods, realize the linkage and cooperation of different signal controllers under the condition of reasonable computational complexity, and gradually expand the scope of traffic control and cooperation. For individual intersections with strong randomness of traffic arrival distribution, this paper proposes to collect upstream vehicle arrival data by using a loop coil to establish a microlevel vehicle arrival model to predict the vehicle arrival time under different queueing states. The vehicle arrival time estimation models under red and green conditions are developed separately according to the signal states, and their output vehicle arrival times and numbers are the main input variables of the signal optimization algorithm. Subsequently, the classical algorithm is improved by introducing the North American signal control structure NEMA on the framework of the existing COP algorithm. In addition to the traditional delay metrics, a control model with queue length and vehicle throughput as objective functions is developed in this paper. In order to verify the effectiveness of the model, an adaptive signal real-time control program is constructed in this paper based on the principle of the VISSIM simulation COM component, and simulation tests are conducted using the intersection of Jianchuan Road and Humin Road in Shanghai.

Compared with the existing adaptive signal optimization models, the main innovations of this paper are as follows:

1. The vehicle arrival model describes the dynamic process of vehicles arriving at the end of the queue under red light and green light conditions. Combined with the traffic flow fluctuation theory, the arrival time of vehicles entering the queue is quantitatively calculated, which helps to predict the queue length and estimate the delay time.

2. The dynamic planning algorithm is improved by combining the characteristics of the NEMA phase structure. The improved optimization algorithm can determine the optimal phase while assigning the green light duration and improve the flexibility of signal control. Meanwhile, based on the objective functions of vehicle delay and queue length, the optimization objective of maximizing the vehicle throughput is proposed, and a better control effect is obtained.

3. Based on the arrival-dissipation dynamic characteristics of the convoy at the control line, the corresponding delay estimation constraints are established, which simplify the model construction methods in previous literature. An implicit cooperative-based regulation mechanism is proposed to achieve distributed control at multiple intersections.

The properties of street space are very complex and show different functional properties in different spatial and temporal environments, which is also a key to study and interpret the city. However, with the intensification of the "car-oriented" street space design, the original outdoor platform for interaction, entertainment, rest, and chatting is gradually deprived, which is a mockery of modern civilization. The study of street space design can be more effective in mastering other spatial design skills. Street space involves social, economic, cultural, ecological, psychological, human, political and other factors, which must be systematically thought, using forward-looking theories, and formulating corresponding countermeasures according to the time and place. There is no one panacea for all streets, and all streets must be considered in a comprehensive manner by investigating regional culture, citizen’s lifestyle, street texture, and streetscape characteristics. Second, street space is also the window of the city, most easily remembered and most reflective of the humanistic qualities of the citizens. The transformation of street space is also of practical significance for changing the value orientation, promoting the moral spirit of health and frugality, and maintaining sustainable social development.

The starting point of this paper is to establish a new street traffic adaptive model to provide model simulation support for future urban street renovation. However, since the model proposed in this paper is only implemented in the VISSIM simulation platform, whether it can effectively alleviate traffic congestion in the actual road network needs further verification, including calibration and verification of the simulation model. If it can be implemented in the control system, it can also be evaluated by means of hardware-in-the-loop to improve the reliability of the model method.

### Table 4: Vehicular delay under different lengths of rolling horizon (seconds).

<table>
<thead>
<tr>
<th>Rolling time domain duration (s)</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
</tr>
</thead>
<tbody>
<tr>
<td>DP-D</td>
<td>55.1</td>
<td>52.6</td>
<td>52.0</td>
<td>51.9</td>
<td>50.5</td>
</tr>
<tr>
<td>DP-Q</td>
<td>47.9</td>
<td>49.9</td>
<td>50.8</td>
<td>51.4</td>
<td>54.7</td>
</tr>
<tr>
<td>DP-T</td>
<td>53.9</td>
<td>53.5</td>
<td>51.8</td>
<td>50.5</td>
<td>52.9</td>
</tr>
</tbody>
</table>
Data Availability

The dataset can be accessed upon request.

Conflicts of Interest

The author declares that there are no conflicts of interest.

Acknowledgments

The authors thank the Ministry of Education of Humanities and Social Science Project, Research on Dynamic Evaluation of Purchase Intention and Satisfaction of Internet Shopping (no. 18YJC760141) and Guangdong Provincial Social Science Planning Office Project, A Comparative Study of Modern Shophouse Architecture and Culture in the Pearl River Delta and Malaysia Based on Genetic Digitisation Technology (no. GD20CYS15).

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