The Control of Over-saturation at the Critical Intersection Based on the Improved SEFP Method

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Abstract: We have proposed the SEFP (Same Entrance Full-Pass) method in our previous research work in order to avoid the congestion at the key spot in the regional road network. The SEFP method, which can make all vehicles going to the critical intersection pass the stop-line with no stop during each release phase, reducing the vehicle delays and stops greatly. While the green time is underused in this method and the vehicle throughput at the critical intersection can be further increased. On this basis, we propose the improved SEFP method, which can formulate signal offsets control schemes at the upstream intersections by means of traffic wave theory, guaranteeing all the vehicles leave the critical intersection at saturated flow speed. In the meantime, the closure control is adopted at upstream intersections timely in light of the queuing length on the critical intersection lanes, avoiding the spill-outs effectively. This new method can improve the traffic throughput of the critical intersection while decrease the vehicle delays and stops, preventing the critical intersection from traffic over-saturation effectively. The simulation results of an actual critical intersection in Mianyang city demonstrate the validity and feasibility of the improved SEFP method.

1. Introduction

Nowadays, traffic congestion has attracted much attentions with the growing number of vehicles. The critical intersection, which is widely recognized as the key node in urban traffic network, often becomes the bottleneck in traffic control \[1\]. The accurate signal control policies adopted at intersections can effectively alleviate traffic pressure, reduce or even eliminate the negative impacts of bottleneck, and improve road capacity and service level \[2\]. Consequently, many scholars aiming at relieving traffic congestion have been dedicating to researching the signal optimization control plans and have achieved many gratifying results.

In documented literature, Gazis \[3\] is the pioneer of the over-saturated traffic research. He employed the semi-graph method to obtain the optimal solution of signal control scheme and
proved the optimization of his method on the premise of the known OD (origination-destination) flow. Upon the basis of Gazis’ research, some scholars [4-7] optimized the signal control schemes of the over-saturated intersection deeply in light of their work, and their research results provide valuable references for the following study. However, all their researches need the given OD data which are difficult to predict in advance accurately. Accordingly, the practical applications of the above methods are limited seriously due to this inadequacy.

Through fixed number theory, Hong-Xing Z, et al. [8] analyzed change rate of the queue length, and presented the perniciousness of traffic congestion from the point of energy consumption. Eriskin et al. [9] designed an elimination matching model for the traffic signal timing of the over-saturated intersection, introducing a new method for traffic signal solution. Jovanovic et al. [2] analyzed traffic over-saturated state of the isolated intersection, took aim at minimizing the average delay of all vehicles arriving at the intersection over a given time, and got the traffic signal timing plan by the aid of Bee Colony Optimization (BCO) method. Tan et al. [10] adopted Genetic Algorithm to handle the traffic signal timing problem and optimized traffic signal control system fully under over-saturated conditions. Sun et al. [11] presented a quasi-optimal feedback control strategy based upon the vehicle queue length for over-saturated intersections. It is able to approximate the off-line optimal solution well. Yan L I et al. [12] reviewed and evaluated various supersaturation control strategies, and made corresponding optimization principles for traffic signal control according to the characteristics of over-saturated traffic flow, providing significative references for other scholars.

In order to alleviate the traffic pressure at over-saturated intersections comprehensively, both the optimal signal timing plans and the lane function optimization should be considered so as to make full use of time resources and space resources.

Early in the 20th century, scholars began to conduct a series research of Reversible Lanes (RL). Wolshon et al. [13,14] investigated and studied the implementation of RL in the United States and made a detailed description of RL in the National Highway Cooperative Research Program. However, after studying the operation effect of RL in Arizona, USA, Golub [15] pointed out that the implementation of RL might bring difficulties to traffic organization of the surrounding roads due to its special traffic regulations.

Except for RL method, some unconventional traffic management measures and organizing patterns for relieving traffic pressure at intersections are also developed, such as the left-turn restriction [16], Continuous Flow Intersection (CFI) [17], the unconventional left-turn alternatives [18], and the tandem intersections [19]. Nevertheless, they all have drawbacks in some respects due to their non-traditional organization and unconventional traffic regulations [20,21], and need to take some time for drivers to understand and conform to the new traffic rules, which are distinct from the traditional traffic regulations that they observed before. Papageorgiou et al. [22] have proved that the traffic signal control plan with advanced control methods is a feasible and cheap way to prevent and alleviate traffic congestion. Consequently, we commit to researching the traffic signal optimal control method in this paper to smooth the traffic running at the critical intersection [23].

At present, most studies of over-saturated intersections based upon traditional 2-phase or 4-phase release mode, which will bring collision issues to the conflict vehicle streams at the intersection and unfair queuing problem to the vehicles lining up on the different lanes of the same entrance. However, the SEFP method [24] can avoid shortcomings of the traditional release mode and has obtained satisfying results. In the following section, we will first give a brief introduction of the SEFP method, then present the concrete illustration of the improved SEFP
method and the derivations of the related models in the third Section. The experiment results obtained from the traffic simulation software VISSIM and the corresponding analysis will be presented in Section IV, and the conclusions will be made in Section V.

2. The Brief Introduction of the SEFP Method

The SEFP method is primarily aimed at making all vehicles flowing to the critical intersections in each cycle leave it directly, avoiding unnecessary vehicles stops and vehicle delays [25]. Figure 1 displays the signal phase designed in the SEFP method. Since the right-turn traffic flows are not controlled by the signal light and released all the time, they are not marked in the signal phase diagram. By applying the SEFP release mode to the critical intersection, vehicles coming from the different entrances are discharged separately and alternately, so the conflicting vehicle streams and unfair queuing can be avoid effectively. Besides, the vehicles from the upstream intersections need to be discharged and stopped on demand, so we also designed a new signal phase mode for upstream intersection, as shown in figure 2.

![Figure 1. The signal phase of the SEFP method.](image1)

![Figure 2. The signal phases at the upstream intersections.](image2)

If there are \( N \) vehicles in the moving motorcade, the speed of this motorcade is \( v \), and the average space headway of vehicles in it is \( \rho_1 \), then the release time (the green time) for this motorcade required to pass the stop-line is

\[
T_i = \frac{N \times \rho_1}{v}
\]  

(1)

In general, the average distance between the normal running vehicles in a moving motorcade, represented by \( \rho_1 \), is longer than that in a standing queue. If the average distance between vehicles in a standing queue is \( \rho_2 \), then \( \rho_1 > \rho_2 \). The contrast between the space headway in the moving motorcade and standing queue is shown in figure 3(a) and Figure 3(b) (from VISSIM screenshot).
Figure 3. The contrast of the space headway in the moving motorcade and in the standing queue.

As shown in Figure 3, the average space headway of vehicles in a moving motorcade is larger than that in a standing queue. When the moving motorcade passes the stop-line without stopping (realized in SEFP method), the time interval between two adjacent vehicles is longer than the time headway of traffic over-saturation. As a result, it is unattainable for these vehicles to leave the intersection with saturation flow speed, and the green time is underused. Under the over-saturated traffic environment, how to maximize the vehicle throughput of the intersection is the main objective of the traffic control policy, so we pay more attention to improve the utilization of green times and propose the improved SEFP method accordingly, which can take full advantage of the green time, improve the traffic capacity of the critical intersection, and prevent the traffic over-saturation at the same time.

3. The Improved SEFP Method

3.1. The Release Method of “Line Up First, Then Leave”

The primary objective of the improved SEFP method is to make vehicles leave the critical intersection at saturated flow speed and take full advantage of green times. Only when the continuous vehicles exist behind the stop-line during the green time can they leave with the saturated flow speed. Therefore, the vehicles entering the critical intersection entrance lanes should queue up first, shortening the distance between vehicles, then leave. As a result, more vehicles can leave within the same time. In this way, we make the most of the green time for each release phase, raise the total traffic volume of the critical intersection, and prevent the over-saturation effectively.

If the in-coming motorcade (consists of \( N \) vehicles) arrives at the stop-line during the red light duration, the vehicles in this motorcade need to slow down, stop and line up in a queue. When the traffic light turns green, the first few vehicles in this standing queue start to move with a relatively fixed start-up delay \( T_s \) (the total delay of the first few vehicles), then pass the stop-line quickly. Other vehicles will pass the stop-line with the saturation flow speed, \( S \), (veh/s). With this “line up first, then leave” release method, the release time for the queuing vehicles to pass the stop-line is
As mentioned in Section II, a moving motorcade consists of \( N \) vehicles needs \( T_1 \) seconds to leave completely. If the release time of the “line up first, then leave” method is shorter than that in SEFP method, inequality (3) should be satisfied.

\[
T_1 > T_2
\]

Inequality (3) implies the release method of “line up first, then leave” can make more vehicles leave within the same period. During rush hours, the essential task is to get more vehicles “flowing” to maximizing the traffic volume of the critical intersection, relieving or avoiding the traffic congestion.

According to the simulation experiments results and relevant literature, the parameter values are set as follows: \( \rho_1 = 27 \text{ m/veh}, \rho_2 = 6.8 \text{ m/veh}, S = 0.67 \text{ veh/s}, v = 15 \text{ m/s}, T_s = 4 \text{ s} \). The range of \( N \) derived from inequality (3) is \( N > 13 \), it means the “line up first, then leave” method can realize its advantage only when the number of vehicles waiting in the standing queue is more than thirteen.

One thing should be note that the release method of “line up first, then leave” will increase the vehicle delays, stops, as well as queue length inevitably. Actually, The traffic volume of the critical intersection can be increased at the expense of other traffic indexes. During the traffic over-saturation period, it is impossible to optimize all the traffic indexes at the same time. In order to prevent and alleviate congestion effectively, we have to guarantee the increase of the traffic volume at the critical intersection first while ignore some traffic indicators properly.

### 3.2. The Release Method of “Releasing While Lining Up”

According to Traffic Wave Theory, in the course of incoming vehicles stopping and lining up behind the stop-line, the stop wave created by the stoppage of these vehicles moves upstream with speed \( v_2 \). When the last incoming vehicle stops at the end of the standing queue, the stop wave also reaches there. When the traffic signal turns green, the vehicles in the standing queue begin to discharge, and the discharge wave also moves upstream, but at speed \( v_1 \), \( v_1 > v_2 \). The last vehicle in the standing queue starts at the time when the discharge wave spreads to the end of the queue. In order to reduce vehicle delay and stops and guarantee the vehicles leave at the saturated flow speed, we take “releasing while lining up” method, which allows the front vehicles of the standing queue start to be released while the subsequent incoming vehicles still in lining up. In addition, it should satisfy the condition: when the last incoming vehicle arrives at the end of the standing queue, i.e., the stop wave transmits to the end of the standing queue, the discharge wave also arrives there, thus the last vehicle does not need to stop and heads for the downstream intersection (the critical intersection) directly. In theory, the above situation can be realized by providing an appropriate signal timing scheme for the critical intersection and its upstream intersections.

It is crucial to set a suitable cycle length for the formulation of the traffic signal timing scheme. In the research of traffic signal timing, some scholars have pointed out that the optimal value of the signal cycle length for over-saturated intersections is 160 s, and the maximum value should not exceed 180 s [26]. For each signal cycle, there always be start-up delays at the initial stage of vehicle release period. Within the same over-saturation period, the longer signal cycle will lead to the fewer number of signal cycles and the shorter total start-up delays, which are conducive to the full use of the green time and the increase of the vehicle throughput for the critical intersections. However, the longer the signal cycle is, the longer the green time allocated for each phase will be, so will the waiting time of red phases. Under over-saturated conditions, the long waiting time will cause the vehicles accumulation, queue growth, and even spill-back, thereby increasing the risk of
congestion deterioration and propagation. When traffic over-saturation occurs, the most important thing is to make vehicles “flowing” instead of stagnating on the road. Consequently, it is not desirable to pursue a long signal cycle to reduce the total start-up delays, which is a part of the total vehicle delays at the intersections.

In addition to the relatively larger start-up delays for the front queuing vehicles, there are also start-up delays exist in other queuing vehicles due to the operating characteristics of automobile engines. However, since the start-up delays of the rear vehicles are relatively small, they are often ignored or included in the total start-up delay $T_b$. If the signal cycle were long, more vehicles would wait to be released and the total vehicle delays would increase. Accordingly, we take the fourteen vehicles satisfying inequality (3) as the target value and release these vehicles as soon as they complete lining up in a standing queue. The green time $g_i (i=1,2,3,4)$ for each phase can be obtained by equation (2), and $g_i = T_2$, then the signal timing plan at the critical intersection can be obtained.

3.3. The Signal Offsets Control of the Released Three-turn Vehicle Streams

There is still a key problem needs to be solved when implementing the “releasing while lining up” method, that is how to control the number of the vehicles entering the critical intersection entrance coming from the adjacent intersections strictly and uniformly. In order to ensure that there is fourteen (the average value) vehicles flowing into each entrance lane within each signal cycle, we carry out coordinated control and used a new phase mode (also adopted in SEFP method) at upstream intersections. Figure 2 shows the new phase control mode. Three streams of vehicles driving to the same downstream intersection are grouped together, and they are controlled by the same signal. These three-turn vehicle streams going to the critical intersection are defined as “the related three-turn vehicle streams”.

We take the one of the upstream intersections for illustration, as shown in figure 4. At the west intersection, the related three-turn vehicle streams contain: the left-turn vehicles at the north entrance (the number of left-turn lane is $n_1$), the straight vehicles at the west entrance (the number of straight-lane is $n_2$), and the right-turn vehicles at the south entrance (the number of right-turn lane is $n_3$).

Figure 4. The related three-turn vehicle streams at the west intersection.

During peak hours, vehicles in the related three-turn vehicle streams will pass the stop-lines with the saturated flow speed $S$ (veh/s), then flow into the critical intersection. If the number of vehicles on each lane is fourteen, the green time of the related three-turn vehicle streams is $g_i$, then
The release time of the related three-turn vehicle streams at other upstream intersections can be gotten by the same way.

After the related three-turn vehicle streams entering the downstream section, they will group a new motorcade on each lane and drive to the critical intersection. According to “the releasing while queuing” method proposed above, the leading vehicle of each motorcade will arrive at the stop-line during the red light and line up. The later-coming vehicles still queuing when the traffic light turns green. If we want to make the last incoming vehicle arrive at the end of the standing queue when the discharge wave arrives there, the signal offset $t_1$ between the critical intersection and the west intersection should satisfy equation (5).

$$14 = \frac{(n1+n2+n3) \times g_1 \times S}{N1}$$  \hspace{1cm} (4)

where $t_1$ denotes the start-up delay of the first vehicle in the queue, and $t_1 = 1$ s [26]. $L_1$ is the road length, $q$ is the queue length comprising fourteen vehicles, $v$ is the average speed of vehicles, $v_1$ is the speed of the discharge wave, $v_2$ is the speed of the stop wave. For the related three-turn vehicle streams at the west intersection, the leading vehicle will arrive at the critical intersection ($t_s + \frac{L_1}{v}$) seconds later after leaving the west intersection, and the following vehicles arrive in turn and line up. During the process of vehicles queuing, the vehicles waiting in the front of the queue start to be released, and the discharge wave reaches the end of the standing queue after ($\frac{q}{v_2} - \frac{q}{v_1}$) seconds. In the ideal case, the last incoming vehicle will pass through the critical intersection without any stops.

The signal timing plans at the adjacent intersections can be obtained refer to equation (4), and the signal offsets can be calculated by using equation (5), so the coordinated control problem at the upstream intersections is resolved. The coordinated control will help the “releasing while queuing” method to play its role better at the critical intersection, not only taking full advantage of the green time, but also avoiding long waiting periods and the second stop.

3.4. The Closure Control at the Upstream Intersection

Before leaving the critical intersection, vehicles in the related three-turn vehicle streams will line up on different lanes according to their destinations. Actually, the number of vehicles on each lane is not always equal to fourteen, and fourteen is just the average value of the vehicles in each standing queue. If the number of vehicles in the standing queue is greater than fourteen, the vehicles at the rear of the queue cannot leave the critical intersection within the green time $g_i (i = 1,2,3,4)$ calculated just for fourteen vehicles, and they have to take up the green phase of the next cycle to leave. In this case, more vehicles will accumulate behind the stop-line as time goes on, leading to the increase of the vehicle queues length and the occurrence of spill-out. Consequently, it is necessary to control the vehicle queue length for practical application in the real traffic conditions.

In recent years, the development of image processing and video technology [27] has provided new means for urban traffic management. As a high-efficient but low-cost detector, ground sense coils are widely used in traffic management. In this research, we employ the ground-sense coil to detect the actual queuing length on each entrance lane and take the closure control of the related three-turn vehicle streams at the west intersection when the queue length reaches a certain value, stopping redundant vehicles entering the critical intersection in time. As shown in figure 5, $h_i$
denotes the distance between the stop-line and the ground sense coil set on the entrance lane, and \( l_i \) should be larger than the standard queuing length \( q \) (the standing queue consists of fourteen vehicles), i.e. \( l_i > q \). The red rectangle represents the ground sense coil, and the position of the ground sense coil will determine the maximum length of the vehicle queuing that is allowed.

![Figure 5. The sketch of the queuing length control.](image)

When the actual queuing length reaches and exceeds \( l_i \), the excess vehicles of the standard length \( q \) need the extra time to be released completely. This extra time \( G_i \) can be obtained by the following equation.

\[
G_i = T_S + \frac{l_i - q}{\rho_2 \times S} \tag{6}
\]

In order to avoid the further growth of the existing queuing length, the related three-turn vehicle streams should be stopped for \( G_i \) seconds in the next green phase, i.e. the closure time is \( G_i \), and \( G_i < g_i \).

To quantitative describe the relationship between \( G_i \) and \( g_i \), we introduce the concept of the closure coefficient, and

\[
g_i = k \times g_i, \quad (0 < k < 1) \tag{7}
\]

\( k \) is the closure coefficient and it reflects the proportion of the closure time \( G_i \) in the green time \( g_i \). When the length of the existing queuing length is close to \( l_i \), the value of \( k \) will be close to 1, i.e., the closure time \( G_i \) of the related three-turn vehicle streams is nearly equal to \( g_i \). During the rush hours, the vehicles’ arrival rate at each entrance of the upstream intersection will increase, if \( G_i \) were large, the release time for the related three-turn vehicle streams would be shortened, causing the serious phenomenon of queuing and even the spill-out. Therefore, the value of \( k \) should not be set too large. According to equation (6), the value of \( G_i \) depends on the actual queuing length that is allowed, so the value of \( l_i \), which depends on the position of the ground sense coil, should be set appropriately to avoid traffic congestion at the upstream intersection when taking the closure control there.

4. Experimental Results and Analysis
In order to verify the validation and the practicality of the improved SEFP method, we choose five intersections in the central area of Mianyang city as our study objects, and employ the
professional traffic simulation software VISSIM to complete the simulations. Figure 6(a) shows the map of these five intersections. The critical intersection is marked by a red circle and the adjacent intersections are marked by yellow circles. Figure 6(b) shows the lane distribution and number on each section. \( L_1, L_2, L_3 \) and \( L_4 \) represent the section lengths, and \( L_1 = 630 \text{ m}, L_2 = 450 \text{ m}, L_3 = 410 \text{ m}, L_4 = 480 \text{ m} \).

![Figure 6](image.png)

**Figure 6.** The map of the intersections and The sketch of lanes distribution.

According to the computing methods proposed in the previous section, the green time of each critical intersection entrance can be calculated, and \( g_1 = g_2 = g_3 = g_4 = 25 \text{ s} \). The signal offsets are \( t_1 = 46 \text{ s}, t_2 = 36 \text{ s}, t_3 = 34 \text{ s}, \text{ and } t_4 = 31 \text{ s} \). The simulation time is set to one hour, and \( v_1 = 5.8 \text{ m/s}, v_2 = 5 \text{ m/s}, k = 0.5 \). After many one-hour simulations (all begin and end with over-saturated traffic volumes) of the the three method, i.e., the SEFP method, the “line up first, then leave” method and the “releasing while lining up” method, we record the simulation results, calculate the average values of the traffic indexes for each method and list them in table 1. \( Q \) is the traffic volume of the critical intersection, \( l \) is the average queuing length on each entrance lane, \( D \) is the average vehicle delays, and \( P \) is the stops.

|                          | The SEFP method | The “line up first, then leave” method | The “releasing while lining up” method |
|--------------------------|-----------------|---------------------------------------|--------------------------------------|
| \( Q \)                  | 10458 veh       | 10789 veh                              | 10820 veh                            |
| \( l \)                  | 0.22 m          | 14.31 m                                | 0.42 m                               |
| \( D \)                  | 1.62 s          | 12.26 s                                | 2.03 s                               |
| \( P \)                  | 0               | 0.55                                   | 0.01                                 |
For clear comparison, a bar graph is used to display the simulation results of each method, as shown in figure 7. In each comparison group, there are three bars with different colors to denote the experiment results of different methods, and the higher the value is, the longer the bar will be.

![Figure 7. The comparisons of the experiments results.](Image)

The simulation results of each method in table 1 reveal that when the SEFP method is adopted, nearly all the vehicles flowing to the critical intersection can be discharged within the green time, so the vehicle stops \( P = 0 \). The average queuing length is only 0.22 m (shorter than one vehicle), and the average vehicle delay is 1.62 s, which is far below the utmost of drivers’ patience. All these traffic indexes reach satisfactory results, but the traffic volume \( Q \) can be improved further.

By contrast, the simulation results of the “line up first, then leave” method are inferior. The traffic indexes \( I, D \), and \( P \) are all worse than the SEFP method except for the vehicle throughput \( Q \). In the “line up first, then leave” method, all the vehicles entering the critical intersection need to line up first for leaving with the saturation flow speed, therefore, the traffic throughput of the critical intersection is more than that in the SEFP method. The traffic volume at the critical intersection increases from 10,458 veh to 10,789 veh during the same simulation time, which is contributed to relieving the traffic pressure in traffic peaks.

According to the simulation results, we find that the “releasing while lining up” method can achieve the optimal of all traffic indexes. Only some vehicles in the motorcades need to stop first and then leave, so the values of \( I, D \), and \( P \) are all improved relative to the “line up first, then leave” method. Although the values of \( I, D \), and \( P \) are not as perfect as them in the SEFP method, they are all within the acceptable ranges. The average queuing length is 0.42 m (also shorter than one vehicle), almost achieving the goal that no vehicle is stopped after each green phase. The average vehicle delay is 2.03 s, slightly higher than that in the SEFP method (1.62 s), but is far lower than that in the “line up first, then leave” method (12.26 s). The vehicle stops is only 0.1 and this is also an acceptable result. Most of all, the traffic volume is 10,820 veh, which is the highest value among these three methods. Consequently, the improved SEFP method — the “releasing while lining up” method is beneficial to make more vehicles “flowing” in peak periods and avoid the traffic over-saturation at the critical intersection effectively.

5. Conclusions
In this paper, we propose the improved SEFP method (the “releasing while lining up” method) according to our previous study. It can raise the throughput of the key spot in the road network obviously and is more applicable for over-saturated traffic conditions.

The main advantages of the improved SEFP methods are:

1) The fix-time control policy and the SEFP release mode used in this paper greatly simplify the process of traffic control, and are more readily to implement and apply in the actual traffic system.

2) The “releasing while lining up” method can make the vehicles leave the critical intersection with the saturated flow speed, take full advantage of time resources, and maximize the traffic volume of the critical intersection during the rush hours, preventing the critical intersection from over-saturation effectively.

3) In order to address the deviation existing between the theoretical analysis and the practical application, we employ the ground sense coils to monitor the actual queuing length on entrance lanes, then take the closure control at the upstream intersections if necessary, reducing the risk of spill-out caused by the growth of queuing length.

The efficient operation for the critical intersections contributes to the smooth traffic for the regional road network. The future research work is to study the optimal control for road network on the basis of the improved SEFP method.

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