Optimal Control Scheme for Signalized Intersection Based on Phase Stream Combination in Autonomous Driving Environment

Zhihua Yu [1,*,†], Can Zhou [1,†] and Wenbin Xiao [2,†]

[1] *CCCC Second HighwayConsultants Co.Ltd.Wuhan 430056, China*
[2] *Fuzhou Municipal State owned Assets Investment Holding Group Co.,Ltd. Fuzhou 344000, China.*

Abstract

The form of phase stream combination directly affects the control effectiveness of signalized intersections. With the introduction and improvement of autonomous driving technology, the current phase combinations at signalized intersections cannot meet the requirements of phase stream combination in the autonomous driving environment. Based on the existing optimal signal control algorithm for streamline overlap and the existing timing models, this study calculates signal phase timing and average vehicle delay. By comparing the average vehicle delay, it is found that the new algorithm includes a more comprehensive and universal range of phase combination schemes. The control scheme corresponding to the minimum delay is selected as the optimal control scheme for the intersection, providing a reference for the generation of phase combination schemes at signalized intersections in the autonomous driving environment.

Keywords

traffic engineering, signal intersection, movement overlap, phase combination scheme, automated vehicles

1. Introduction

According to statistics from the Ministry of Public Security, as of September 2023, the total number of motor vehicles in China has reached 430 million, including 330 million conventional cars and 18.21 million new energy vehicles. Urban traffic congestion has become a daily occurrence, with congestion at intersections being particularly severe, and its impact far exceeds that of regular road sections. Researching the traffic conditions at intersections and optimizing signal intersection control schemes is one of the effective means to alleviate intersection congestion [1].

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* Corresponding author.
† These authors contributed equally.
46461558@qq.com (Z. Yu); 2423425917@qq.com (C. Zhou); traffic_xwb1910@whut.edu.cn (W. Xiao)
0000-0003-3412-1639 (Z. Yu); 0000-0002-9496-2395 (C. Zhou); 0000-0001-5476-8670 (W. Xiao)

As smart transportation and the proliferation of new energy vehicles continue to develop, some functions of autonomous driving have gradually been implemented on new energy vehicles. Vehicles in the autonomous driving environment can safely drive based on predefined lane trajectories using electromechanical technology [2]. The existing phase stream combination method of the Ring Barrier System (RBS) for reducing phase green light losses does not meet the requirements of the autonomous driving environment as it fails to consider the relationships between different inlet streamlines flowing into the same outlet [3]. Currently, research on intersection control in the autonomous driving environment focuses on vehicle-to-vehicle information transmission and real-time optimization of intersection control timing schemes by accurately collecting inbound traffic flow parameters using advanced autonomous driving technology [4, 5], but does not consider the compatibility of refined streamlines.

Therefore, our research team has developed a more comprehensive algorithm for determining signalized intersection phase stream combinations, taking into account the compatibility between cross-flow, diversion flow, and merging flow [6]. To validate the effectiveness and compatibility of the new algorithm, this paper compares the new scheme with the RBS phase combination scheme, divergence phase combination scheme, and combination phase combination scheme using existing timing models. The feasibility of the new scheme is verified, and the optimal intersection control scheme is further derived.

2. Intersection Streamline Overlay Algorithm

The research team has comprehensively studied a more comprehensive algorithm for determining the phase stream combination at signalized intersections. The algorithm takes into account the compatibility of conflicting, diverging, and merging relationships among the flow streams, specifically refining the merging relationships previously identified as conflicts into compatible relationships in the context of automated driving environments.

Next, all stream combinations are evaluated based on the requirement that phase stream combinations must be compatible, and considerations such as lane-sharing conditions for stream lane settings, in order to identify all feasible phase stream combinations.

Subsequently, the phase combination control scheme, which includes all intersection streams and the continuity of successive movements within the cycle, is used as a filtering condition to derive viable phase stream combination schemes.

Once the feasible phase combinations are determined, they are synthesized with the intersection signal timing model to calculate the phase stream timing. Only when the resulting control scheme is complete and compatible with the intersection control can it be considered finalized.

At the current stage, numerous signal timing models are available for determining phase combinations, with the HCM2010 timing model being one of the more conventional options. Therefore, the paper employs the HCM2010 timing model to calculate the timing for the feasible phase combination schemes determined by the algorithm. During the signal timing process, input parameters such as stream arrival patterns, stream saturation flow rates, and yellow phase timing are required. By inputting these parameters, the timing model can compute the green phase timing for the respective stream, thus determining the signal timing for the intersection phases. For a detailed understanding of the timing process, reference can be made to HCM2010 [7].

Upon determining the signal timing for all feasible phase combinations, the average vehicle delay for different schemes is calculated, and the control scheme with the least average delay is chosen as the preferred signal intersection control scheme. This approach aims to further reduce intersection vehicle delay and improve the intersection control scheme.

3. Algorithm Validation and Analysis Example

To validate the effectiveness of the paper's algorithm, a verification analysis is conducted using a specific example. In the context of complex urban road networks with numerous intersections and random arrival patterns for vehicles at various entry points, diverse lane configurations exist at urban road intersections. The algorithm in the paper is designed for signalized intersections with different lane configurations, and to further demonstrate the feasibility and effectiveness of the algorithm, verification analysis is carried out on a selected urban signalized intersection with a predetermined lane configuration. Assuming that at the intersection, right-turn lanes are all equipped with exclusive right-turn lanes using channelization islands, the right-turn streams are not controlled by signals. The specific lane configuration and corresponding symbols for the streams are represented as shown in figure 1.

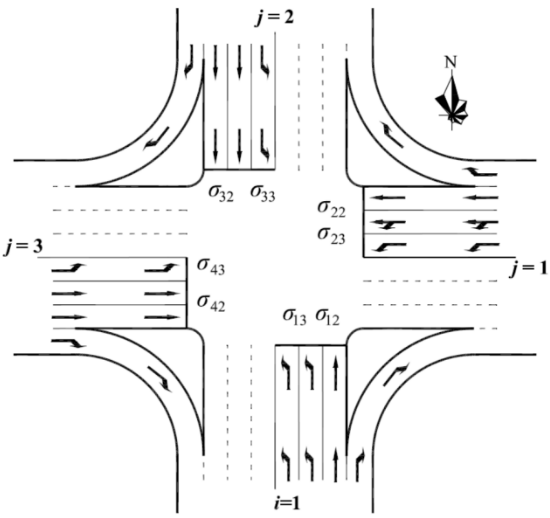

Figure 1: Lane Movement Layout of Experiment Intersection

According to the thesis algorithm the relevant parameters are determined sequentially as follows: the set of all streamlines at the intersection $\boldsymbol{\Psi} = \{\sigma_{12}, \sigma_{13}, \sigma_{22}, \sigma_{23}, \sigma_{32}, \sigma_{33}, \sigma_{42}, \sigma_{43}\}$,The total number of flow lines is 8, namely $|\boldsymbol{\Psi}| = 8$ .Streamlines are paired to form sets $\boldsymbol{\Theta}$,set $\boldsymbol{\Theta}$ have altogether $C_8^2 = 28$ group element, that is, it contains 28 sets $\boldsymbol{\Theta}_\xi$, $\xi = 1, 2, \cdots, 28$. Based on the two-flow line compatibility relationship, compatible flow line pairs can be determined, where the set of diverging compatible flow line pairs are respectively $\{\sigma_{12}, \sigma_{13}\}, \{\sigma_{22}, \sigma_{23}\}, \{\sigma_{32}, \sigma_{33}\}, \{\sigma_{42}, \sigma_{43}\}$;the set of pairs of opposite-compatible flow lines is respectively $\{\sigma_{12}, \sigma_{32}\}, \{\sigma_{13}, \sigma_{33}\}, \{\sigma_{22}, \sigma_{42}\}, \{\sigma_{23}, \sigma_{43}\}$;the set of merging compatible flow line pairs are respectively $\{\sigma_{12}, \sigma_{43}\}, \{\sigma_{33}, \sigma_{42}\}$ .From this it is possible to determine the set of streamline compatible pairs $\boldsymbol{X} = \{\{\sigma_{12}, \sigma_{13}\}, \{\sigma_{22}, \sigma_{23}\}, \{\sigma_{32}, \sigma_{33}\}, \{\sigma_{42}, \sigma_{43}\}, \{\sigma_{12}, \sigma_{32}\}, \{\sigma_{13}, \sigma_{33}\}, \{\sigma_{22}, \sigma_{42}\}, \{\sigma_{23}, \sigma_{43}\}, \{\sigma_{12}, \sigma_{43}\}, \{\sigma_{33}, \sigma_{42}\}\}$,a total of 10 groups are assembled $\boldsymbol{X}_\delta$, assume $\delta = 1, 2, \cdots, 10$ .Then the set of non-compatible streamline pairs $\overline{\boldsymbol{X}}$ total 18 groups,not listed.Collection of all shared lane flow lines $\boldsymbol{\Phi} = \{\sigma_{22}, \sigma_{23}\}$,Only one set of shared lane flow groups, the $\boldsymbol{\Psi}_1 = \{\sigma_{22}, \sigma_{23}\}$,so the set $\boldsymbol{\Psi} = \{\{\sigma_{22}, \sigma_{23}\}\}$ .From this it can be determined that the set $\boldsymbol{\Omega}$, Total elements 1023 groups of elements,the number is large so it is not listed. According to the method of determining phase flow line combinations, all sets of phase flow line combinations can be calculated $\boldsymbol{\Lambda} = \{\{\sigma_{12}, \sigma_{13}\}, \{\sigma_{22}, \sigma_{23}\}, \{\sigma_{32}, \sigma_{33}\}, \{\sigma_{42}, \sigma_{43}\}, \{\sigma_{12}, \sigma_{32}\}, \{\sigma_{13}, \sigma_{33}\}, \{\sigma_{12}, \sigma_{43}\}, \{\sigma_{33}, \sigma_{42}\}\}$,there are a total of 8 sets of phase flow line combinations.

Once the phase streamline combinations are determined, the phase combination scheme needs to be determined $\boldsymbol{P}_\upsilon$,Through the calculation, it can be seen that there are 109,200 sets of all phase combination programs. Not all the phase combination scheme can be used as the intersection control phase scheme, it is necessary to carry out condition judgment on the scheme, and the scheme that meets the setting conditions can be used as the feasible phase combination scheme. Because of the number of calculations of the intersection is large, so the Python software is used to program the judgment. Through the programming judgment to get to meet the conditions of the feasible phase combination scheme group has a total of 400 groups, including four-phase 48 groups, five-phase combination scheme 264 groups, six-phase combination scheme 88 groups, see Table 1.

According to Table 1, the algorithm proposed in the paper not only includes traditional phase combination schemes, but also all phase combination schemes that can be obtained by the RBS, thereby verifying the generality of the algorithm in determining intersection phase combination schemes. After determining all feasible phase combination schemes, the effectiveness of the algorithm is analyzed by combining actual traffic flow analysis. The traffic flow at the intersection reaches a random nature, and in the autonomous driving environment, the traffic flow of each lane at the intersection can be directly obtained through wireless communication technology, thus assuming a set of random traffic flows for each lane at the intersection as shown in Table 2.

Table 1
FPC Schemes

w	m_w	$\boldsymbol{F}_w$	Phase Number
1	4	$\{\sigma_{12},\sigma_{13}\},\{\sigma_{22},\sigma_{23}\},\{\sigma_{32},\sigma_{33}\},\{\sigma_{42},\sigma_{43}\}$	4
2	4	$\{\sigma_{12},\sigma_{13}\},\{\sigma_{22},\sigma_{23}\},\{\sigma_{42},\sigma_{43}\},\{\sigma_{32},\sigma_{33}\}$	
3	4	$\{\sigma_{12},\sigma_{13}\},\{\sigma_{32},\sigma_{33}\},\{\sigma_{22},\sigma_{23}\},\{\sigma_{42},\sigma_{43}\}$	
4	4	$\{\sigma_{12},\sigma_{13}\},\{\sigma_{32},\sigma_{33}\},\{\sigma_{42},\sigma_{43}\},\{\sigma_{22},\sigma_{23}\}$	
⋮	⋮	⋮	
49	5	$\{\sigma_{22},\sigma_{23}\},\{\sigma_{32},\sigma_{33}\},\{\sigma_{42},\sigma_{43}\},\{\sigma_{12},\sigma_{43}\},\{\sigma_{12},\sigma_{13}\}$	5
50	5	$\{\sigma_{22},\sigma_{23}\},\{\sigma_{32},\sigma_{33}\},\{\sigma_{12},\sigma_{13}\},\{\sigma_{12},\sigma_{43}\},\{\sigma_{42},\sigma_{43}\}$	
51	5	$\{\sigma_{22},\sigma_{23}\},\{\sigma_{32},\sigma_{33}\},\{\sigma_{13},\sigma_{33}\},\{\sigma_{42},\sigma_{43}\},\{\sigma_{12},\sigma_{43}\}$	
52	5	$\{\sigma_{22},\sigma_{23}\},\{\sigma_{32},\sigma_{33}\},\{\sigma_{13},\sigma_{33}\},\{\sigma_{12},\sigma_{13}\},\{\sigma_{42},\sigma_{43}\}$	
⋮	⋮	⋮	
313	6	$\{\sigma_{22},\sigma_{23}\},\{\sigma_{32},\sigma_{33}\},\{\sigma_{13},\sigma_{33}\},\{\sigma_{12},\sigma_{13}\},\{\sigma_{12},\sigma_{43}\},\{\sigma_{42},\sigma_{43}\}$	6
314	6	$\{\sigma_{22},\sigma_{23}\},\{\sigma_{32},\sigma_{33}\},\{\sigma_{13},\sigma_{33}\},\{\sigma_{33},\sigma_{42}\},\{\sigma_{42},\sigma_{43}\},\{\sigma_{12},\sigma_{43}\}$	
315	6	$\{\sigma_{22},\sigma_{23}\},\{\sigma_{32},\sigma_{33}\},\{\sigma_{12},\sigma_{32}\},\{\sigma_{12},\sigma_{13}\},\{\sigma_{12},\sigma_{43}\},\{\sigma_{42},\sigma_{43}\}$	
316	6	$\{\sigma_{22},\sigma_{23}\},\{\sigma_{32},\sigma_{33}\},\{\sigma_{33},\sigma_{42}\},\{\sigma_{42},\sigma_{43}\},\{\sigma_{12},\sigma_{43}\},\{\sigma_{12},\sigma_{13}\}$	
⋮	⋮	⋮	
399	6	$\{\sigma_{12},\sigma_{43}\},\{\sigma_{12},\sigma_{32}\},\{\sigma_{32},\sigma_{33}\},\{\sigma_{33},\sigma_{42}\},\{\sigma_{13},\sigma_{33}\},\{\sigma_{22},\sigma_{23}\}$	
400	6	$\{\sigma_{12},\sigma_{43}\},\{\sigma_{12},\sigma_{32}\},\{\sigma_{12},\sigma_{13}\},\{\sigma_{13},\sigma_{33}\},\{\sigma_{33},\sigma_{42}\},\{\sigma_{22},\sigma_{23}\}$	

Table 2
Traffic Volume of the Movements

Streamline	Traffic Flow(pcu/h)	Streamline	Traffic Flow(pcu/h)
σ_{12}	550	σ_{32}	550
σ_{13}	750	σ_{33}	350
σ_{22}	550	σ_{42}	800
σ_{23}	500	σ_{43}	450

For all feasible phase combination schemes obtained based on the above, the traffic signal timings were determined and the average vehicle delay was calculated. The study focuses on researching phase streamlining combinations at signalized intersections in the context of autonomous driving. Throughout the timing calculation process, the base timing model remains unchanged, with input parameters such as a vehicle start-up delay of 1.8

seconds (3 seconds for conventional driving), a saturation flow rate of 2000 pcu/h/lane (1650 pcu/h/lane for conventional driving)[8], and a yellow light duration of 3 seconds. The calculated average vehicle delay for all feasible phase combination schemes is shown in Figure 2.

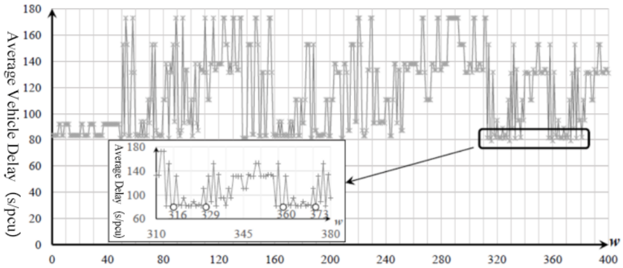

Figure 2: Average Delay of FPC Schemes

From Figure 2, it is evident that different phase combination schemes at signalized intersections have a significant impact on intersection control effectiveness. The minimum average delay per vehicle for a specific stream is 79.3 seconds/pcu, while the maximum value is 173.03 seconds/pcu, representing a difference of more than 2 times. This indicates that phase combination schemes have a substantial influence on intersection control effectiveness, emphasizing the importance of selecting an appropriate phase combination scheme.

Further, the calculation reveals that there are four sets of phase combination schemes, numbered 316, 329, 360 and 373, corresponding to the minimum average vehicle delay: ; ; ; ,the 4 groups of phase combination program has the same phase flow line combination with different phase sequence. The four groups of phase combination scheme has phase streamline combination of the same phase sequence is different, thus also verified that when the streamline vehicle reaches a fixed situation, the same phase streamline combination scheme with different phase sequences, the control effect on the intersection is the same. In the choice of intersection signal phase combination scheme, can choose any one phase combination scheme as the actual use of the program.A protected phase setup is used for the left-turn flowline of the intersection, and since there are shared lanes in the east inlet flowline of the intersection, there is no opposite-side control scheme (OS) for the arithmetic example intersection. Conventional signal control schemes are only DS, CS and RBS.By adopting the phase combination scheme corresponding to number 316 as the best control scheme for the example intersection, it is compared and analyzed with the conventional phase combination scheme, and the results of the analysis are shown in Table 3.

The algorithm proposed in the paper was compared with the conventional control scheme, and it was found that the average vehicle delay was reduced by 3.77 seconds per passenger car unit (pcu), 4.19 seconds per pcu, and 12.68 seconds per pcu, respectively. This indicates that the algorithm proposed in the paper can further reduce vehicle delays at intersections and improve intersection control efficiency.

Table 3
Movements' Timing and Average Delay of the Control Schemes

Scheme	w	Phase flow combination program	Streamline green time/s								Non-English or Math	Non-English or Math
			σ_{12}	σ_{13}	σ_{22}	σ_{23}	σ_{32}	σ_{33}	σ_{42}	σ_{43}		
PM	316	$\{\sigma_{22},\sigma_{23}\},\{\sigma_{32},\sigma_{33}\},\{\sigma_{33},\sigma_{42}\}$ $\{\sigma_{42},\sigma_{43}\},\{\sigma_{12},\sigma_{43}\},\{\sigma_{12},\sigma_{13}\}$	31	25	22	22	18	22	26	28	109	79.3
RBS	65	$\{\sigma_{22},\sigma_{23}\},\{\sigma_{42},\sigma_{43}\},\{\sigma_{13},\sigma_{33}\},$ $\{\sigma_{12},\sigma_{13}\},\{\sigma_{12},\sigma_{32}\}$	29	27	22	22	20	18	26	26	107	83.07
DS	1	$\{\sigma_{12},\sigma_{13}\},\{\sigma_{22},\sigma_{23}\},$ $\{\sigma_{32},\sigma_{33}\},\{\sigma_{42},\sigma_{43}\}$	28	28	22	22	19	19	26	26	107	83.49
CS	5	$\{\sigma_{22},\sigma_{23}\},\{\sigma_{42},\sigma_{43}\},$ $\{\sigma_{13},\sigma_{33}\},\{\sigma_{12},\sigma_{32}\}$	27	24	23	23	27	24	27	27	113	91.98

To further validate the feasibility and effectiveness of the proposed method in the paper, VISSIM was used for verification. The timing schemes corresponding to the conventional signal control scheme and the PM (propose method) scheme obtained from calculations were input into the simulation software. By setting up detectors in the simulation, different phase combination control schemes corresponded to simulation indicators, such as average delay, traffic flow, average queue length, and average number of stops. Specific simulation comparison results are shown in Figure 3.

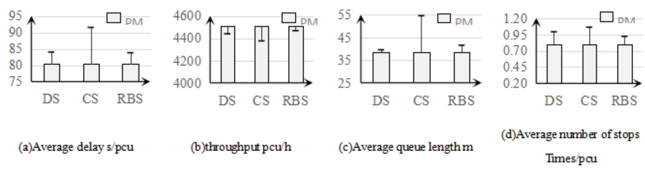

Figure 3: Comparison of Simulation Results

The simulation results found that the phase combination scheme obtained by the thesis algorithm improves the simulation indexes to different degrees compared with the other schemes, which shows that the thesis algorithm can further improve the intersection signal control, and further verifies the feasibility and effectiveness of the thesis method.

4. Conclusion

By combining the existing timing models, the optimal control scheme for the intersection in the true sense is calculated. Through the calculation examples and simulation analysis, it is found that the algorithm can further reduce the average delay of vehicles in the intersection flow lines and improve the intersection control efficiency. However, the thesis research only considers the compatibility relationship between motor vehicle flow lines, and the compatibility relationship between the flow lines of multiple transportation modes will be considered comprehensively to study the intersection control scheme. Meanwhile, with the development and upgrading of automatic driving technology, the unsignalized processing of intersections under the automatic driving environment is studied, and how the streamline vehicles can realize non-stopping passage in the case of unsignalized control of intersections is analyzed.

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