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# Dynamic Crosswalk Signal Timing Optimization Model Considering Vehicle and Pedestrian Delays and Fuel Consumption Cost

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**Abstract:** Due to the development of video perception technology, obtaining the volume of pedestrians and vehicles at a crosswalk has become much easier. Based on this development, this paper proposes a dynamic crosswalk signal timing optimization model and then analyzes the effects for three different signal timing strategies. First, we propose the dynamic signal timing optimization model by involving the delays of pedestrians and vehicles, as well as the fuel consumption cost, simultaneously. In the model, we design a dynamic signal timing strategy, using the volume of past cycles to predict the present volume, and then calculate the optimal signal timing by minimizing the total cost of the system. Second, the model is applied to a crosswalk in Beijing, China, as an example, and we compare and analyze the results of three timing strategies: Dynamic signal timing, optimal fixed timing, and current fixed timing. The results show that the dynamic signal timing is more efficient during the morning peak hour in terms of decreasing the total cost. Compared to the current fixed timing result, the vehicle delay and the fuel consumption decrease, while the pedestrian delay increases in both morning peak hour and flat hour for the other two signal timing strategies.

**Keywords:** optimization; dynamic signal timing; delay; fuel consumption; vehicle; pedestrian

## 1. Introduction

Nowadays, traffic congestion has become increasingly serious as more and more people pay attention to the safety and convenience of the traffic system. As an important way to enhance the efficiency of urban traffic operation, the urban traffic signal timing system needs to be improved.

Signal control and non-signal control are two types of control strategy at the pedestrian crosswalk. Based on whether the pedestrian can be perceived, the crosswalk signal control is classified into two types—fixed signal timing and actuated signal timing with push buttons.

Fixed signal timing is the most common signal control method. Many scholars have carried out research on this aspect. Chen et al. [1] considered the coordination between road utilization rate, traveler time efficiency, and environmental benefits. They established a multi-objective optimization model of intersection signal timing with the goal of maximizing the capacity and minimizing the vehicle parking rate and average traveler delay. Xiong et al. [2] took the four-phase single intersection as the research object, aiming to reduce the total delay of people and the emission in the intersection area. They set up the optimization model by changing the green time of each phase and keeping the signal period unchanged. Zhang et al. [3] focused on coordinated traffic signals along arterials to minimize traffic delay and the risk associated with human exposure to traffic emission. Ma et al. [4]

considered both safety and efficiency in the evaluation framework, selecting the pedestrian phase and optimizing the signal timings simultaneously. Roshandeh et al. [5] adjusted green splits of a.m. peak, p.m. peak, and rest-of-the-day timing plans for each signalized intersection in the urban street network to minimize total vehicle and pedestrian delays per cycle, for which existing cycle length and signal coordination are invariable. Yu et al. [6] built a signal timing framework, aiming to optimize the signals for both pedestrian and vehicles. In the passage, different types of crosswalks were identified. Hunsanon et al. [7] proposed a fuzzy logic control strategy to analyze the optimal traffic signal timing setting for pedestrian crossing signals along an urban corridor. Liu and Wei [8] established a multi-objective signal timing optimization model. The per capita delay and $CO_2$ emissions at intersections were optimization indexes, and the effective green time of each phase was the independent variable. However, fixed timing is not always very effective when traffic demand changes greatly.

In addition to fixed signal timing, pedestrian-actuated signal timing with a push button is also common at pedestrian crosswalks in China. Every time a pedestrian presses the button, the signal light adjusts according to established procedures based on the state of vehicles at the crosswalks. Xie et al. [9] presented a cellular automation model to depict the traffic flow at a crosswalk with a push button. The result showed that the statured flux increased rapidly when green time for vehicle flow after the button was pushed by a pedestrian was smaller than the critical value. Zhang et al. [10] built the signal control model based on the law of traffic flow. In order to reduce the interference between the pedestrian and traffic flow, when the pedestrian pressed the button, the authors assigned the green light in the pedestrian direction to fall in the interval of no traffic flow as much as possible. Kutela and Teng [11] evaluated push-button-utilization-signalized midblock crosswalks. They found that gender, age, and performing secondary activities, among others, hindered utilization.

With the continuous development of science and technology, it has become possible to use video technology to perceive the accurate flow of pedestrians. Therefore, we propose a dynamic signal timing optimization model considering the actual traffic environment to improve control efficiency, which has important theoretical significance and application value.

The main contributions of this paper are: (a) We consider the delays of the pedestrians and vehicles and the fuel consumption cost simultaneously; (b) we develop a dynamic signal timing optimization model.

The remainder of the paper is as follows: Section 2 introduces a signal optimization model. In Section 3, the model is applied to a crosswalk in Beijing, China, as a case study. Section 4 makes the conclusions and provides a plan for future analysis.

## 2. Methodology

With the development of video perception technology, the arrival rate of pedestrians and vehicles is easier to be perceived. Based on that, we proposed a dynamic crosswalk signal timing optimization model, which comprehensively considers the pedestrians and vehicles in the signal timing system. The goal of the model was to minimize the economic loss caused by the overall delay of the system and vehicle fuel consumption. According to Figure 1, minimizing the total cost was the objective. Total Cost is separated into two parts: Time Cost (Section 2.1) and Fuel Consumption Cost (Section 2.2). As for the calculation of the time cost, we not only considered the vehicle delay (Section 2.1.1), but also the pedestrian delay (Section 2.1.2). The optimization procedure of the dynamic signal timing and the optimal fixed timing is discussed in Section 2.3.

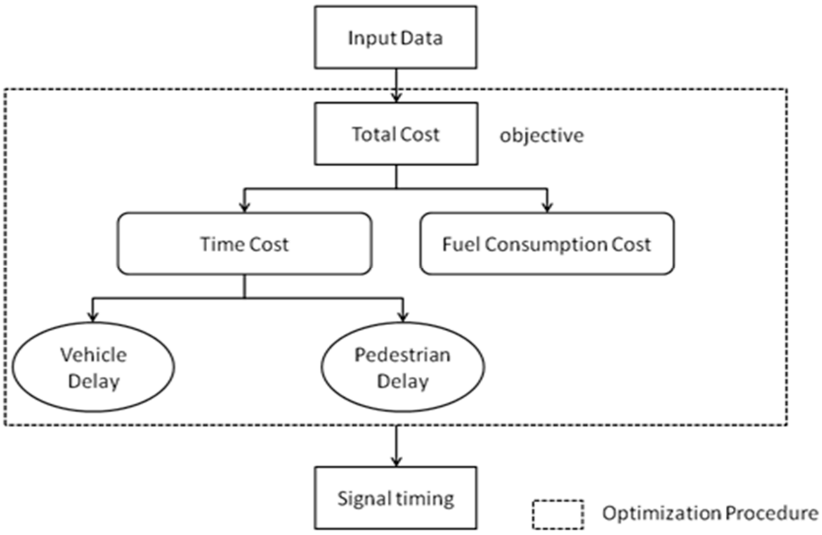


**Figure 1.** Framework of the dynamic signal timing optimization model.

The total cost can be calculated as Equation (1):

$$\boldsymbol{PI} = \boldsymbol{min}(\boldsymbol{PI_1} + \boldsymbol{PI_2}) \tag{1}$$

where $PI$ is the total cost of the intersection in Chinese Yuan (CNY); $PI_1$ is the time cost in CNY; and $PI_2$ is the fuel consumption cost of the intersection in CNY.

### 2.1. Calculation of Time Cost

There are different numbers of people in a bus and car, so we multiply the delay of social vehicles and buses by the average number of passengers per bus and per car, respectively. Then, we multiply the total delay by the value of time (VoT). The system time cost is calculated in Equation (2):

$$\boldsymbol{PI_1} = (\boldsymbol{\alpha d_c} + \boldsymbol{\beta d_b} + \boldsymbol{d_p})\boldsymbol{C_p} \tag{2}$$

where $\boldsymbol{\alpha}$ is the average number of passengers per car; $\boldsymbol{d_c}$ is the total car delay in s; $\boldsymbol{\beta}$ is the average number of passengers per bus; $\boldsymbol{d_b}$ is the total bus delay in s; $\boldsymbol{d_p}$ is the total pedestrian delay in s; and $\boldsymbol{C_p}$ is the time value in CNY/s.

#### 2.1.1. Vehicle Delay Model

Vehicle delay calculation [12] is based on traffic flow theory, assuming that vehicle arrival obeys Poisson distribution (Figure 2). The shaded portion of Figure 2 shows the delay of queuing vehicles before the stop line. The propagation velocity of a traffic wave during vehicle queuing is the slope of line OA (Figure 2), as shown in Equation (3):

$$\boldsymbol{c_{12}} = \frac{-\boldsymbol{q_v}}{\boldsymbol{\rho_{max}} - \boldsymbol{q_v}/\boldsymbol{v_0}} \tag{3}$$

where $\boldsymbol{c_{12}}$ is the propagation speed of vehicle queuing wave surface in m/s; $\boldsymbol{q_v}$ is the vehicle's average arrival rate in passenger car unit/s (pcu/s); and $\boldsymbol{\rho_{max}}$ is the maximum density of road (0.12 pcu/m).

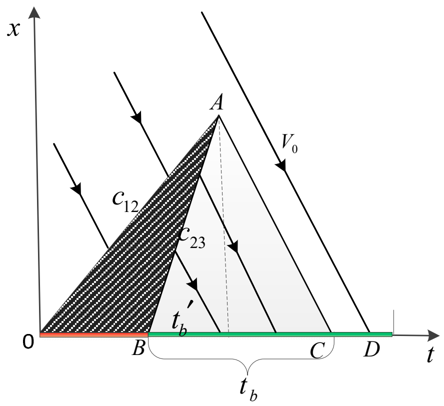


**Figure 2.** Traffic wave propagation.

When the green light is on, at point B, the line of vehicles starts to move away from the stop line. At this time, the traffic wave in the dissipation process is generated, and it propagates backward successively. The propagation velocity of the traffic wave is the slope of line segment BA, as shown in Equation (4):

$$C_{23} = \frac{q_{max} - 0}{\rho_0 - \rho_{max}} = \frac{V_0\rho_0}{\rho_0 - \rho_{max}} = \frac{-1}{\rho_{max}T_0} \tag{4}$$

where $C_{23}$ is the propagation speed of vehicle dissipating wave surface in m/s; $q_{max}$ is the maximum road volume, which corresponds to the density, $\rho_0$; $V_0$ is the free flow velocity, which is set to be 13.89 m/s; and $T_0$ is the time headway under the ideal state, which is set to be 1.2 s [13].

The shaded area in Figure 2 represents the total value of vehicle delays caused by the interference of signal lights in this cycle, which can be calculated in Equation (5):

$$d_v = \frac{1}{2} r q_v \left(\frac{c_{12} r}{c_{23} - c_{12}} + r\right) \tag{5}$$

where $d_v$ is the vehicle delay caused by the signal light in s; $r$ is the red time of the vehicle in s; and $q_v$ is the vehicle arrival rate in pcu/s.

Because the numbers of people in cars and buses are different when calculating the time cost, we divided the delay of cars and buses proportionally, as shown in Equation (6):

$$d_c = d_v \times \frac{q_c}{q_v};\ d_b = d_v \times \frac{q_b}{q_v} \tag{6}$$

where $d_c$ and $d_b$ are the passenger car delay and the bus delay caused by the influence of the signal light, respectively, in s; and $q_c$ and $q_b$ are the arrival rates of the passenger car and bus, respectively, in vehicle/s.

### 2.1.2. Pedestrians Delay Model

In the case of a single crossing, the total delay value of pedestrians under signal timing is calculated according to the formula in the Highway Capacity Manual (HCM), as shown in Equation (7).

$$d_p = \frac{(T - r)^2}{2} q_p \tag{7}$$

where $d_p$ is the pedestrian delay caused by the signal light in s; $q_p$ is the pedestrian arrival rate in ped/s; and $T$ is the cycle length in s.

*2.2. Calculation of Fuel Consumption Cost*

As for the fuel consumption cost of vehicles in the intersection, we mainly considered the idling consumption of vehicles in the system. The average parking delay time is the average idle consumption time of vehicles.

Parking delay time is calculated by a linear equation with delay caused by the signal light, as shown in Equation (8):

$$d_{ci} = 0.959d_c - 19.3;\ d_{bi} = 0.959d_b - 19.3 \quad (8)$$

where $d_{ci}$ and $d_{bi}$ are the average parking delay of the passenger car and bus, respectively, in s.

Therefore, the consumption $E$ is calculated as Equation (9) [2].

$$E = ER_b \times q_b \times d_{bi} + ER_c \times q_c \times d_{ci} \quad (9)$$

where $E$ is the total consumption at the intersection in g; and $ER_b$ and $ER_c$ are the idling fuel consumption rates of the bus and the car unit, respectively, in g/s.

In this way, the fuel consumption cost $PI_2$ can be calculated as Equation (10).

$$PI_2 = E \times C_E \quad (10)$$

where $C_E$ is the unit fuel consumption cost under consumption $E$ in CNY/g.

*2.3. Dynamic Signal Timing and Fixed Signal Timing Strategies*

Aiming to adjust the signal timing to minimize the total cost of the crosswalk, we designed a dynamic signal timing strategy. Dynamic signal timing uses the data of the previous several cycles to predict the flow data of the current cycle, and the signal cycle length and green time of the current cycle are estimated based on the predicted flow data. Firstly, we selected a period of time before the current cycle as the data collection interval (Figure 3). Then, the system state of the next cycle was predicted to be equal to the average vehicle and pedestrian arrival rates in the data collection interval. The total cost of the system can be minimized by changing the signal cycle time and green signal ratio. Therefore, the dynamic signal timing has different cycle lengths and green signal ratio for each cycle, according to real-time traffic conditions. In the procedure, the searching step is 1 s. We exhausted all the timings in the range and found the optimal solution.

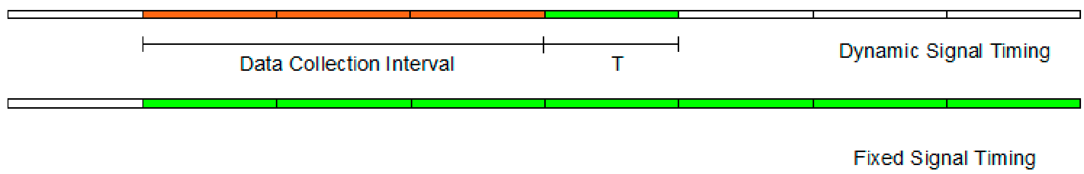


**Figure 3.** Schematic diagram of signal timing strategies.

In order to ensure the safety of vehicles and pedestrians, two constraints were added to the model: (a) The change cycle length does not exceed the maximum cycle length; (b) the pedestrian green time is not less than the minimum pedestrian crossing time. Considering that the change of traffic flow was continuous in the actual situation, and the cycle length and green time had fixed constraints, there would not have been huge changes in adjacent cycles.

We also compared dynamic signal timing, optimal fixed timing, and current fixed timing to illustrate the applicable time period and the optimization effect of the dynamic signal timing. Cycle length and green signal ratio of fixed signal timing remained unchanged comparing with the dynamic signal timing in every cycle. In order to make the research more complete, we optimized the fixed signal timing. We took the minimum total cost of all cycles as the optimization target. Firstly, we added up the cost of each cycle and found the total cost. Then, we changed the signal timing 1 s at a time and calculated the total cost of the changing signal timing. After calculating all possible timing schemes, we found the optimal fixed signal timing.

## 3. Case Study

This paper takes a pedestrian crosswalk in Beijing as an example, which is a two-lane road with a 5 m width and a 14 m length, as shown in Figure 4. The current signal timing control strategy of this crosswalk is fixed timing control, which is divided into vehicle phase and pedestrian phase. The signal cycle length is 90 s, in which the vehicle green time is 60 s, the yellow time is 3 s, the pedestrian green time is 27 s, and the full red time is 2 s.

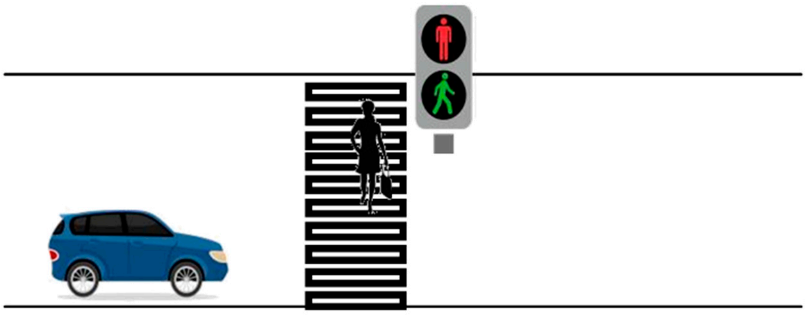

**Figure 4.** Crosswalk diagram with signal timing.

The time value of pedestrians can be calculated by the annual salary in Beijing, as shown in Equation (11).

$$VoT = C_y/(T \times 8 \times 3600) \tag{11}$$

where $VoT$ is the time value of pedestrians calculated by the annual salary in Beijing (CNY/s); $C_y$ is the annual salary of Beijing employees (CNY/year); and $T$ is the working time per year (day/year).

According to public data from the Beijing Municipal Bureau of Statistics and Social Security Bureau, the average annual salary of Beijing employees in 2018 was 128,544 CNY and the working time was 250 days. Based on the salary and the working time, we calculated the time value of pedestrians as 0.0178 CNY/s.

Setting parameters of the dynamic signal timing model are listed in the Table 1.

**Table 1.** Set parameters.

| Shortest Green Time for Pedestrians | Minimum Cycle Length | VoT | 92# Fuel Cost in Beijing |
|---|---|---|---|
| 30 s | 60 s | 0.0178 CNY/S | 0.00785 CNY/g |
| **Idling Fuel Consumption Rate of the Passenger Cars ($ER_c$)** | **Idling Fuel Consumption Rate of the Buses ($ER_b$)** | **Average Number of Passengers Per Car ($\alpha$)** | **Average Number of Passengers Per Bus ($\beta$)** |
| 0.2875 g/s [14] | 0.7150 g/s | 2 | 20 |

The initial data were obtained by a video recording device from 7:10 a.m. to 10:30 a.m. on Friday, 4 January 2019. Then, the research data were acquired by manual counting and divided into the number of east–west pedestrians and the numbers of both north–south cars and buses based on the initial data.

### 3.1. The Influence of Data Collection Interval on Dynamic Signal Timing

In order to explore the best cycle number of the data collection interval for dynamic signal timing, we analyzed the influence of the cycle number in dynamic signal timing.

As can be seen from Table 2, it performed well in terms of the total cost when the data collection interval was two or five cycles. The standard deviation of two cycles is 14.7, and of five cycles is 10.8. Because the five-cycle interval uses more cycles to predict the volume of pedestrians and vehicles, it is more stable to capture the characteristics of the volume. As a result, we chose the data with five-cycle interval for further study.

**Table 2.** Results of different dynamic signal timing plans.

| Data Collection Interval (Cycle) | Total Cost (CNY) | Total Vehicle Delay (s) | Total Pedestrian Delay (s) | Total Fuel Consumption (g) |
|---|---|---|---|---|
| 2 | 2017.5 | 14,164.1 | 38,648.7 | 7747.1 |
| 3 | 2061.1 | 14,196.1 | 40,493.0 | 7756.8 |
| 4 | 2039.8 | 13,981.3 | 40,329.6 | 7622.0 |
| 5 | 2017.2 | 13,829.9 | 39,894.2 | 7548.8 |

### *3.2. The Influence of Data Collection Interval on Dynamic Signal Timing*

We compared dynamic signal timing, optimal fixed timing, and current fixed timing strategy in morning peak hour (7:10 a.m. to 8:40 a.m.) and flat hour (9:00 a.m. to 10:30 a.m.). The comparison results are shown in Table 3.

**Table 3.** Calculation results of three strategies (7:10 a.m. to 8:40 a.m.).

| Strategy | Total Cost (CNY) | Total Vehicle Delay (s) | Total Pedestrian Delay (s) | Total Fuel Consumption (g) |
|---|---|---|---|---|
| Dynamic Signal Timing | 2017.2 | 13,829.9 | 39,894.2 | 7548.8 |
| Optimal Fixed Timing | 2142.3 | 13,192.9 | 49,950.0 | 7245.7 |
| Current Fixed Timing | 2344.8 | 18,505.0 | 29,760.0 | 10,150.1 |

As can be seen from Table 3, in the morning peak hour, the total cost of the dynamic signal timing strategy decreased 13.97% below that of the current fixed timing, and the optimal fixed timing showed an 8.64% decrease from the total cost. The dynamic signal timing and optimal fixed timing both sacrificed more pedestrian time to save the vehicle time. However, the total pedestrian delay of the optimal fixed timing was 10,000 s longer than dynamic signal timing. As a result, dynamic signal timing was more efficient than optimal fixed timing in peak hour.

As can be seen from Table 4, in the flat hour, the total cost of the dynamic signal timing strategy decreased 3.79% below that of the current fixed timing, and the optimal fixed timing showed a 7.07% decrease from the total cost. The optimization effect in the flat period was not as significant as in the peak period.

**Table 4.** Calculation results of three strategies (9:00 a.m. to 10:30 a.m.).

| Strategy | Total Cost (CNY) | Total Vehicle Delay (s) | Total Pedestrian Delay (s) | Total Fuel Consumption (g) |
|---|---|---|---|---|
| Dynamic Signal Timing | 1419.8 | 9027.1 | 27,843.9 | 4496.1 |
| Optimal Fixed Timing | 1371.3 | 8352.1 | 31,027.4 | 4192.1 |
| Current Fixed Timing | 1475.7 | 11,229.9 | 19,400.0 | 5661.3 |

It should be noted that although the total cost of optimal fixed timing was less than that of dynamic signal timing, it does not mean that the former strategy is better than the latter. The reason is that we optimized the signal timing with today's data. In fact, it is impossible to obtain data a day in advance. We can only use historical data as input data for calculation. Consequently, the optimal fixed timing may not perform as well as it performed in our case study.

All in all, dynamic signal timing and optimal fixed timing reduced both vehicle delay and fuel consumption compared with the current fixed timing, while the pedestrian delay increased a lot. The optimal fixed timing sacrificed more time of the pedestrians than dynamic signal timing.

## 4. Conclusions

This paper demonstrated a dynamic crosswalk signal timing strategy considering the consumption cost of the vehicle and the time cost of both pedestrians and vehicles. We compared the efficiency of dynamic signal timing and fixed signal timing. Taking a crosswalk on a road in Beijing as an example to optimize signal timing, the proposed model was tested. The total cost of dynamic signal timing is more efficient during peak hour, and the total cost of the dynamic signal timing strategy decreased by about 14% compared to the current fixed timing. The vehicle delay and the fuel consumption decreased, while the pedestrian delay increased, compared to the current fixed timing result in both the morning peak hour and the flat hour.

To sum up, the model proposed in this paper can effectively reduce the total delay of vehicles and pedestrians as well as fuel consumption cost, and provides a new solution for crosswalk signal control. Future studies can involve variables considering traffic safety and environment. Moreover, we will use less assumptions and simplifications to calculate the total cost more accurately.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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