Dynamic signal control strategy for intersection near a highway-railway at-grade crossing

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Abstract. To decrease the influence of train passage on the efficiency of the intersection near a highway-railway at-grade crossing, this paper proposes a signal control strategy that dynamically applies two fixed signal timings and a priority phase based on the different scenarios, including two rules for judging different scenarios and two signal timings. The rule for judging whether a train is crossing a highway-railway at-grade crossing or not is established by using detected information. The rule for judging whether the influence of train passage is eliminated is designed according to train passage time and signal cycle length with the influence of train passage. Signal timing parameters for traffic flow, with and without the influence of train passage are respectively optimized by the ARRB method. The simulation results indicated that the performance of the dynamic strategy is superior to the performance of the two fixed signal schemes.

1. Introduction
Highway-railway at-grade crossings exist in several regions, such as Beijing, Shanghai, Texas, Illinois, and California [1-3]. With the increase in urban mobility, it is difficult to manage their traffic [2, 3]. A number of researches have been done into the safety of traffic control devices used at highway-railway at-grade crossings [1-6]. Because the absolute priority of train passage leads to an intensive increase in vehicle delays of the intersections near highway-railway at-grade crossings, it is important to improve its efficiency. To achieve this goal, this paper proposes a dynamic control strategy that dynamically applies two fixed signal schemes and a priority phase based on different scenarios.

The remainder of the paper is organized as follows. Section 2 presents an overview of the dynamic control strategy. Section 3 explains the installed locations of detectors and the rule for judging whether the train is crossing the highway-railway at-grade crossing or not. Section 4 discusses how to optimize signal timing parameters using the ARRB method for the traffic flow with or without the influence of train passage. The role used to judge whether the influence of train passage is eliminated or not is stated in section 5. Section 6 presents the simulation experiments and results. The conclusion and future research direction are discussed in section 7.

2. Control Logic
Trains passing through a highway-railway at-grade crossing have absolute priority, therefore, any
traffic movements at the intersection near the highway-railway at-grade crossing that conflict with passing trains must be prohibited. As the train passage time is relatively long, a large number of vehicles will gather at the conflicting approaches of the intersection. In order to improve the efficiency of the intersection, conflicting traffic movements should be allocated more time to cross through the intersection after the train passed through. A dynamic control strategy for this purpose is proposed here, as shown in figure 1. The dynamic control strategy includes two rules and two signal timings. The two rules are designed respectively to judge whether the train is crossing the crossing or not and whether the influence of train passage is eliminated or not. Signal timings for traffic flow with or without the influence of train passage are optimized by the ARRB method.

![Figure 1. Control Logic.](image1)

![Figure 2. Detector Layout.](image2)

The control logic shown in figure 1 is described as follows:

Step 1: Detecting train;
Step 2: Judging whether the train is crossing the crossing or not. If yes, go to step 3; otherwise, go to step 4;
Step 3: Running the priority phase. Then go to step 1;
Step 4: Judging whether the influence of train passage is eliminated. If yes, go to step 5; otherwise, go to step 6;
Step 5: Running the signal timing without the influence of train passage. Then go to step 1;
Step 6: Running the signal timing with the influence of train passage. Then go to step 1.

3. Rule for Judging Whether the Train is Crossing the Crossing

3.1 Detector Layout

In order to judge whether the train is crossing the highway-railway at-grade crossing or not, it is necessary to install four detectors on each railway track, as shown in figure 2.

The four detectors are arranged in two pairs. One of each pair detects the arrival of the train (the arrival detector), such as AR1, while the other is used to detect the departure of the train (the leaving detector), such as DR1. The installation locations of arrival detectors and leaving detectors are calculated as formula 1 and formula 2, respectively.

\[
\begin{align*}
  d_a &= t_{\text{max}} + V_{\text{max}} + d_u \quad (1) \\
  d_l &= d_u 
\end{align*}
\]

where \(d_a\) is the distance between a train-arrival detector and its nearer edge of the intersected road (m); \(t_{\text{max}}\) is the longest time a vehicle among conflicting movements takes to cross the crossing from the stop lines (s); \(V_{\text{max}}\) is the maximum speed of the train (m/s); \(d_u\) is the minimum gap between the train front (rear) and the vehicle rear (front) (m); and \(d_l\) is the distance between a train-leaving detector and its nearer edge of the intersected road (m).
3.2 Rule
When a road intersects with two railway tracks at grade, the rule for judging whether the train is crossing the crossing or not is designed as formula 3. For more or fewer than two railway tracks, the rule only requires to modify the number of variables.

\[
TN(j) \begin{cases} 
  \leq 0, & j = 1, 2, 3, 4 \quad \text{the train is crossing} \\
  \text{otherwise}, & \text{no train is crossing}
\end{cases}
\]

where \(TN(j), j = 1, 2, 3, 4\) are variables.

Each variable \(TN(j)\) records the information detected by a pair of detectors. The value is updated based on three scenarios:

Scenario 1: Initialization \(TN(j) = 0, j = 1, 2, 3, 4\);

Scenario 2: When the arrival detector of detector group \(j\) is activated by the train front,
\(TN(j) = TN(j) + 1, j = 1, 2, 3, 4\);

Scenario 3: When the leaving detector of detector group \(j\) is activated by the train rear,
\(TN(j) = TN(j) - 1, j = 1, 2, 3, 4\).

Next, the principle of the rule is explained. For a railway track intersecting with a road at grade, if the gaps between two train fronts continuously crossing from one direction is larger than the sum of \(d_l\) and \(d_r\), the width of the intersected road and the length of the former train, the two trains will be respectively regarded as one. Otherwise, trains will be regarded as a group, because their passage times partly overlap. Therefore, trains cross the crossing in two forms: a train or a group of trains. For this reason, variation in the recording variables for different forms will respectively be discussed to state the suitability of the rule. Let us suppose that there exists railway track 1. When a train crosses the crossing from right to left, \(TN(1)\) will be from 0 to 1 and then from 1 to 0 while \(TN(2)\) will be from 0 to -1 and then from -1 to 0. When \(TN(1)\) becomes 1 from 0, it indicates that the train is about to cross the crossing. Then, when it becomes 0 from 1, it indicates that the train has just crossed the crossing. At this time, \(TN(2)\) is always lower than 0 or equal to 0, although \(TN(2) = 1\) or \(TN(2) = 0\) depends on the relation between the train length and \(d_r - d_l\), the width of intersected road. Therefore, if \(TN(1) \leq 0, j = 1, 2\) no train is crossing the crossing; otherwise, a train is crossing the crossing.

For a group of trains crossing from right to left, \(TN(1)\) will firstly be from 0 to 1, then vary above 0 several times, and finally return to 0, such as \(0-1-2-1-2-3-\ldots-1-0\). Among these, the maximum value of \(TN(1)\) depends on \(d_l\), \(d_r\), the width of intersected road, the length of trains, and the minimum front gap between trains. When it becomes 0 again, it similarly indicates that a group of trains has just crossed the crossing. However, \(TN(2)\) will firstly be from 0 to -1, then vary below 0, and finally return to 0, such as \(0-(-1)-(-2)-(-3)-\ldots-(-1)-0\), which is always lower than 0 or equal to 0. Therefore, the former rule is also suitable for the form.

In the case of two railway tracks, no train is crossing the crossing only when no train is crossing the crossing on track 1 and simultaneously no train is crossing the crossing on track 2, which means the terms of judging whether no train is crossing the crossing for every railway track must be unified, that is, \(TN(1) \leq 0, TN(2) \leq 0, TN(3) \leq 0, TN(4) \leq 0\). Therefore, when the value of \(j\) is modified as \(j \in \{1, 2, 3, 4\}\), the rule for one railway track is also applicable for two railway tracks. Accordingly, the rule will be practical for more than two railway tracks after a similar modification.

4. Signal Timing
Signal timings are optimized by the classic ARRB method that is described in section 3 of Chapter 4 on the literature [7]. For traffic flow without the influence of train passage, when the goal of optimization is set to decrease the average vehicle delay, the signal cycle length, effective green times of all movements, and the green time of phases are calculated by formula 4-6, formula 7-9 and formula 10, respectively [7]:
where \( C \) represents signal cycle length (s); \( L \) represents total loss time (s); \( Y \) represents the sum of critical flow ratio of the intersection; \( q_i, S_i, y_i \) represent traffic volume (pcu/h), saturation traffic volume (pcu/h) and flow ratio of critical movement \( i \), respectively; and \( n_{cm} \) represents the number of critical movements.

\[
C = \frac{1.4L + 6}{1 - Y} \tag{4}
\]

\[
Y = \sum_{j=1}^{n_c} y_j \tag{5}
\]

\[
y_j = \frac{q_j}{S_j}, \quad i = 1,\ldots,n_{cm} \tag{6}
\]

where \( t_i \) represents the effective green time of critical movement \( i \) (s); \( u_i \) and \( x_i \) represent green split and the saturation degree of critical movement \( i \), respectively; \( U \) represents the sum of green split of the intersection; and other variables are the same as previously defined.

The effective green time of non-critical movements \( i \in \{n_{cm},\ldots,n\} \) can similarly be calculated as critical movements. Finally, the green time of phase \( p \) can be calculated by formula 9:

\[
G_p = (t + l)_p - I_p, \quad p = 1,2,\ldots,P \tag{10}
\]

where \( G_p \) represents the green time of phase \( p \); \( t + l \) represents the sum of the effective green time and loss time of a traffic movement that belongs to phase \( p \); and \( I_p \) represents the interval time of phase \( p \).

For traffic flow with the influence of train passage, signal timing parameters are re-optimized on the condition that the traffic volume of conflicting movements is multiplied by a constant \( m \) that is more than 1. During the period that the influence of train passage is not eliminated (abbreviated influence period), the arrival amount of the conflicting movements that need to be given right of way to cross the intersection equals to the sum of the traffic volume and train passage period. This can be regarded as the increase in the traffic volume of the conflicting movements during the influence period. As the result of the change to the input variable of formula 6 (traffic volume), signal timing parameters should be re-optimized. Considering that the increased percentage of the traffic volume of the conflicting movements during the influence period varies with the length of the train passage period and the influence period, and in order to prevent oversaturation of the intersection because of releasing the arrival amount of the conflicting movements in a signal cycle, it is proposed that a fixed multiple \( m \) of the average arrival amount of the conflicting movements is given right of way in each signal cycle, but \( m \) musts make signal cycle length lower than 120s [8].

Moreover, the saturation degree of conflicting movements \( x_i \) belongs to the set \( n \), can be set as a relatively higher value but lower than 0.95, \( x_i \leq 0.95, i \) belongs to the set \( n \) [7], owing to the reduction of the randomness of conflicting movements during the influence period because of vehicle accumulation during the train passage period.

5. Rule for Judging Whether the Influence of Train Passage is Eliminated

When signal timing for traffic flow with the influence of train passage is re-optimized, the average traffic volume of the conflicting movements is multiplied by a constant \( m \) that is more than 1. Hence, the number of vehicles of conflicting movements that can be released during a signal cycle with the influence of train passage (abbreviated influence signal cycle) is \( m \) times the arrival number of those
movements. The signal cycles necessary to let all the accumulated vehicles in a train passage period cross is as formula 11:

\[ M = \frac{T \cdot q_i}{(m-1) \cdot q_i \cdot C} = \frac{T}{(m-1) \cdot C_{IT}}, i \text{ belongs to the set } n. \]  

(11)

where \( M \) represents the number of signal cycles with the influence of train passage needed; \( T \) represents the length of a train passage period(s); and \( C_{IT} \) represents the signal cycle length with the influence of train passage(s).

However, because of the randomness of train arrival, the next group of trains or a train is probably about to cross the crossing before all the accumulated vehicles have been given permission. Therefore, formula 11 should be modified to formula 12:

\[ M = M + \frac{T}{(m-1) \cdot C_{IT}} \]  

(12)

Based on the above, the rule for judging whether the influence of train passage is eliminated or not is designed as formula 13:

\[
\begin{align*}
M &= 0 \quad \text{the influence of train passage is eliminated} \\
M &\neq 0 \quad \text{the influence of train passage is not eliminated}
\end{align*}
\]  

(13)

\( M \) is updated based on four scenarios in the following:

Scenario 1: Initialization: \( M = 0 \);

Scenario 2: After a group of trains or a train crosses the crossing, \( M = M + \frac{T}{(m-1) \cdot C_{IT}} \);

Scenario 3: After a signal cycle with the influence of train passage is completely displayed, \( M = M - 1 \);

Scenario 4: If \( M < 0 \), then \( M = 0 \). That is because \( M \) of scenario 2 is not always a positive integer.

6. Case Study

The simulation model of the intersection of Jingang Road, Yingang Road, and Chuangye No.1 Road in Dalian City, Liaoning Province, China, which is near a highway-railway at-grade crossing and was selected as an experimental intersection, is established by VISSIM 4.3, a professional micro-traffic simulation software that can be used to simulate and evaluate urban traffic[8-10]. The dynamic control strategy proposed is achieved by the VAP[8].

6.1 Test Case

The geometric characteristics, signal phases, and phase sequence of the experimental intersection are displayed in figure 3.

Figure 3. Geometric Characteristics and Signal Phases of the Experiment Intersection.
The saturation traffic volume of all movements is 1468 pcu/h. The start-up lost time and the compensation time after green time are set as 2.4s and 0s, respectively. The conversion coefficients of a small vehicle are set according to the composition of traffic volume: if the proportion of large vehicles is higher than 85%, the conversion coefficient is 1.35; if the proportion is higher than 35% and lower than or equal to 85%, the conversion coefficient is 1.15; otherwise, the conversion coefficient is 1. The conversion coefficient of a container truck is set as 2.34[7].

The priority phase used in the train passage period is shown in figure 3. As a result of simulation experiments only being run for peak hour, the signal timings at peak hour without the influence of train passage and with the influence of train passage are optimized and displayed in table 1. In practical applications, the signal timing at any hour can be designed using the same methodology so that an intersection near a highway-railway at-grade crossing can be efficiently controlled all day.

### Table 1. Signal Timing.

| Signal Phase | Green Interval Time (s) | Green Time (s) | Green End | Signal Phase | Green Interval Time (s) | Green Time (s) | Green End |
|--------------|-------------------------|----------------|-----------|--------------|-------------------------|----------------|-----------|
| 1            | 5(3+2)                  | 17             | 22        | 1            | 5(3+2)                  | 33             | 38        |
| 2            | 4(3+1)                  | 10             | 36        | 2            | 4(3+1)                  | 18             | 60        |
| 3            | 4(3+1)                  | 8              | 48        | 3            | 4(3+1)                  | 8              | 72        |

a)saturation degree of all movements is set as 0.8, \(x_i=0.8\), \(i=1,2,\ldots,9\).

b)saturation degree of conflicting movements is set as 0.9 and the other is the same as the former, that is, \(x_i=0.9\), \(i=1,2,3,4,5,6\); \(x_i=0.8\), \(i=7,8,9\); traffic volume of conflicting movements is multiplied by 2, \(m=2\).

Two fixed signal timings used in the dynamic control strategy are used as comparative cases, respectively. When the fixed signal schemes are used, a signal controller is added to give priority to the train.

### 6.2 Analysis of Results

Average vehicle delay times given different train traffic volumes are shown in table 2 and table 3.

### Table 2. Average Vehicle Delay (Train Traffic Volume is 6 trains/h).

| Random        | Average Vehicle Delay Time (s/per vehicle) | Percentage of Difference (\(\frac{\text{②}-\text{min}(\text{①,③})}{\text{Min (①,③)}}\) | Average Percentage of Difference |
|---------------|-------------------------------------------|-------------------------------------------------|---------------------------------|
|               | ① fixed signal scheme (m=1)               | ② dynamic signal strategy (m=2)                 | ③ fixed signal scheme (m=2)     |                                 |
| 1             | 19.7                                      | 19.1                                            | 20.2                            | \(-3\%\)                       |
| 2             | 12.5                                      | 9.7                                             | 13.4                            | \(-22\%\)                      |
| 3             | 9.5                                       | 7                                               | 8.7                             | \(-20\%\)                      |
| 4             | 10.5                                      | 8.4                                             | 9.8                             | \(-14\%\)                      |
| 5             | 11                                        | 9.1                                             | 11.4                            | \(-17\%\)                      |
| Average       |                                            |                                                 |                                 | \(-15\%\)                      |

As shown in table 2, the performance of the dynamic control strategy is superior to the better performance of fixed signal schemes on the condition of different traffic arrival modes. This is because the dynamic control strategy can catch the variability of the influence of the train passage caused by train arrival randomness, train length and the variation of train speed and accordingly adjust the signal timing and the number of signal cycles to let the accumulated vehicles go, whereas both the fixed signal schemes cannot. When the train traffic volume increases, the same results can be found from table 3, which further validates the proposed dynamic control strategy has good performance.
Table 3. Average Vehicle Delay (Train Traffic Volume is 9 trains/h).

| Random | Average Vehicle Delay Time (s/per vehicle) | Percentage of Difference |
|--------|------------------------------------------|--------------------------|
|        | Fixed signal scheme (m=1) | Dynamic signal strategy (m=2) | Fixed signal scheme (m=2) |
| 1      | 29 | 27.5 | 33.4 | -5% |
| 2      | 10.5 | 8.7 | 10.7 | -17% |
| 3      | 17.3 | 14 | 15.6 | -10% |
| 4      | 17.2 | 12.8 | 15.8 | -19% |
| 5      | 21.7 | 19.1 | 20.7 | -8% |
| Average Percentage of Difference | -12% |

7. Conclusion and Discussion
On the condition of non-saturation of the intersections near a highway-railway at-grade crossing, the quick release of the vehicles that accumulate during the train passage period and the reduction of the average vehicle delay time are able to be achieved by increasing the average traffic volume of traffic movements conflicting with the train passage to re-optimize the signal timing and deciding its running times according to the length of the train passage period and the signal cycle length with the influence of train passage.

Future research will focus on designing an adaptive control scheme for the intersection near a highway-railway at-grade crossing to further improve its effectiveness.

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