Safety Prediction and Conflict Prevention for High-speed Train Operations in the Railway Network

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Abstract. The architecture of safety prediction and conflict prevention is proposed for high-speed train operations in the railway network. Train movement prediction models are employed to predict the potential conflicts based on the interval numbers. The dependent parameters such as accelerations and decelerations are attained through off-line statistics of historical data and on-line feedback adjustments of the weights of multiple models. The predictive movement authorities are formulated in the moving prediction horizons to guarantee the train operation safety, different from the current reactive movement authorities. The energy-saving planning is performed for the scheduled trains. The measure of safety level is proposed using various braking distances. The evidence theory is utilized to deal with the inconsistent information flow and assign the belief degrees of prediction models and operation conditions. The discernment of inconsistent information flow and equipment failure is implemented centering on the main clue of train movements.

Introduction

The high-speed railway lines in China are developing towards networked operation. When subject to the disturbances such as signal equipment failure and bad weather, high-speed trains cannot run according to the planned timetables. In this case, operation conflicts will occur at the nodes of the railway network. This paper attempts to establish the architecture of safety prediction and conflict prevention for the safety and rescheduling optimization of high-speed train operations in the railway network under the framework of model predictive control.

Potential conflict prediction requires the train movement model [1, 2]. The possible minimum and maximum train positions are predicted using interval numbers. Off-line classified statistics of train movement historical data provides reference models. And the on-line information feedback is utilized to further adjust the prediction models based on the idea of multiple model adaptive control with second level adaptation [3]. Trains run according to specific operation conditions. If train operational conditions are illogical or control equipment is out of order, train operation safety will be endangered. Evidence theory [4] is incorporated to diagnose illogical processes and inconsistent information flow driven by train movement reference models. The architecture proposed in this paper is appropriate for the normal and abnormal train operation states. The concept of predictive movement authority is proposed, which is engendered in the
moving prediction horizon and integrated with energy-saving planning. The inconsistent information flow is perceived, which endangers train movement safety, such as illogical relationships between signal codes of track circuits and train positions.

**Architecture of Safety Prediction and Conflict Prevention**

Fig. 1 demonstrates the architecture of safety prediction and conflict prevention. The history data of train movements and operation conditions is processed to engender model pool of train movements for on-line utilization. According to the real-time feedback information, one or more train movement prediction models are generated corresponding to the possible operation control modes, and the train operation conditions such as signals can also be inferred. Combining the evidence theory, the belief degrees are updated of the prediction results of various prediction models. The safeties are predicted to dynamically reflect the possibilities of train collisions. So, the appropriate prediction models and operation conditions are gradually sifted out. The potential conflicts are perceived in advance, and the movement authorities (MAs) and scheduling commands (SCs) are formulated and their safeties are evaluated. Train dispatchers should pay much attention to the prediction results having high belief degrees but low safeties. If the train positions with sufficient belief degrees are sampled, the prediction horizons move forward and the new prediction processes are initiated. The movement authority formed in the prediction horizon is called predictive movement authority, different from the current reactive movement authority engendered through just considering the current train positions.

![Figure 1. Architecture of safety prediction and conflict prevention for high-speed train networked operations.](image)

**Safety Prediction and Conflict Prevention in the Normal State**

**Mode Prediction**

Train movement models have been proposed in [1, 2], which are rationally justified. Fig. 2 demonstrates the predictive result (red line) and 18-day practical data of train D5051 utilizing the model in [1, 2], which indicates the high prediction accuracy. Train movement model can employ the statistical data of accelerations and decelerations and be adjusted on line. Suppose there exist $N$ groups of accelerations and decelerations. One way is the switching approach to select the group with the smallest prediction error. And the other way is the weighting approach. Assume the weights of $N$ groups are $\alpha_1, \alpha_2, \ldots, \alpha_N$, respectively. The weights can be iteratively attained as follows:

$$\tilde{\alpha}(t) = -M^T(t)M(t)\tilde{\alpha}(t) + M^T(t)\ell(t)$$

where $\tilde{\alpha} = [\alpha_1 \alpha_2 \cdots \alpha_{N-1}]^T$, thus $\alpha_N = 1 - \sum_{i=1}^{N-1} \alpha_i$. $M(t) = [e_1(t) - e_N(t), e_2(t) - e_N(t), \ldots, e_{N-1}(t) - e_N(t)]$, $\ell(t) = -e_N(t)$, and $e_1, e_2, \ldots, e_N$ are the prediction errors using $N$ groups of accelerations and decelerations.
Confliction Identification

At instant $k$ (i.e. $kT$, $T$ is the unit time or simulation period), the upper and lower position estimations of train $i$ in the prediction horizon $N_p$ (i.e. $N_pT$ time interval) can be calculated as follows:

$$x_{i,k+p}^{up} = x_{i,k} + \sum_{p'=0}^{p-1} \alpha_{i,k+p'}^{up}$$  \hspace{1cm} (2)

$$x_{i,k+p}^{low} = x_{i,k} + \sum_{p'=0}^{p-1} \alpha_{i,k+p'}^{low}$$  \hspace{1cm} (3)

where $x_{i,k}$ is the real position of train $i$ at instant $k$; $\alpha_{i,k+p'}^{up}$ and $\alpha_{i,k+p'}^{low}$ in the unit time of $T$ are the upper and lower limits of accelerations and decelerations ($p=1, \ldots, N_p$).

If trains $i$ and $i'$ run in the same direction, and if $\text{Prj}_{i,j} \neq \emptyset$, then the conflict exists, where $\text{Prj}_{i,j}$ is the position projection from the coordinate of train $i$ to that of train $i'$. If trains $i$ and $i'$ run towards the same junction node, and if $\text{Prj}_{i,j} \neq \emptyset$, then the conflict exists, where $\text{Prj}_{i,j}$ denotes the upper and lower positions of the block section of the junction in the respective railway line coordinates.

Safety Prediction

Suppose the maximum position prediction of the following train is $d_{j}^{max}$, and the minimum position prediction of the preceding train is $d_{p}^{min}$. The distance prediction between two trains is $dp = d_{p}^{min} - d_{j}^{max}$. Suppose the speed of the following train is $v_f$, and the distance of emergent braking is $d_{min}^{b} = F(v_f)$. Assume the train is only braked through the frictions between wheels and tracks and the air resistances, the corresponding braking distance is $d_{max}^{b} = F(v_f)$. The safety degree of the following train is measured by:

$$SD_f = \frac{(dp - d_{min}^{b})^+ + (dp - d_{max}^{b})^+}{(dp - d_{max}^{b})^+ + (dp - d_{min}^{b})^+}\hspace{1cm} (4)$$

where $(x)^+$ means if $x \geq 0$, $(x)^+ = x$, and $x < 0$, $(x)^+ = 0$. If two trains run towards the junction, the safety degree can be measured in the similar way. The conservative braking distance can replace the braking distance of basic resistances to formulate a new measure of safety degree.
Conflict Prevention

In the prediction horizon, if the conflict has been predicted using train movement models, adopt a scheduling principle, such as first arrival first leave or fast train first leave, to solve the conflict. One train is assigned as a passing-through train, and the other train is as a scheduled one.

Figure 3. Energy-saving planning.

At first, we calculate the time-saving speed-time curve for the passing-through and scheduled trains. If the time that the scheduled train arrives at the junction $T_s$ is less than that the pass-through train arrives at the junction, the energy-saving movement is feasible for the scheduled train. Try to select one time $T_1<T_2$ as the coast instant in the Fig. 3(a). In Fig. 3(b), find the point $X_1$ corresponding to $T_1$ as the coast position, and the cross point of the coast curve and braking one. Calculate the coast time $T_c$ and braking one $T_b$ as shown in Fig. 3(c). If $T_1+T_c+T_b<T_p$, move point $T_1$ to the left until $T_1+T_c+T_b$ approaches $T_p$. In this way, the movement trajectory is planned for the scheduled train, which can be issued through predictive movement authority or scheduling command.

Information Flow Consistency

In the train control system, there exists the redundant information flow. If this information flow keeps consistent, it indicates that the train control system performs in the normal state, or in the abnormal state. Establishing the ontology description of the consistency of the information flow in the train control system, as a reference model, benefits discovering the inconsistency of information flow and verifying if the train control system is in failure or not. Train control system is a huge one, the analysis of train movement situation, such as acceleration, speed-holding and deceleration, is an effective way to judge if the train control system performs in the normal or abnormal state.

Safety Prediction and Conflict Prevention in the Abnormal State

Information Flow Inconsistency

The inconsistency of information flow is judged by the reference model of the consistent information flow. If there exists the inconsistent information flow in the train control system, the estimations of train movements should be undertaken in the worst case, that is, the possible maximum and minimum positions. Only in this way can the prediction of safety be reliable. The synthesis of the inconsistent information flow should be oriented towards the operation safety of train movements in the worst case.

Evidence Theory

The purpose of evidence theory in the safety prediction and conflict prevention is to infer which prediction model and operation condition are most applicable to the trains en route. Define the model set $M = \{M_1, M_2, \cdots, M_u\}$, the operation condition set $S = \{S_1, S_2, \cdots, S_v\}$, the block section set $B = \{B_1, B_2, \cdots, B_w\}$, the discern framework set $\Theta = \{\Theta = (M_j, S_j), \quad i = 1, 2, \cdots, u; \quad j = 1, 2, \cdots, v\}$, the operation time interval $T_{i,j,k}$ ($i = 1, \cdots, u$; $j = 1, \cdots, v$; $k = 1, \cdots, w$).
For train \( i \) running in the block section \( k \) under the operation condition \( j \), and the evidence set \( E = \{ E_1, E_2, \ldots, E_x \} \). According to evidence \( E_l (l = 1, \ldots, x) \), the operation time is denoted as \( T_{ij}^k \) for model \( i \) in block section \( k \). The basic possibility assignment (BPA) for model \( i \) under condition \( j \) is denoted as:

\[
m_i(M, S_j, B_k) = \frac{\text{Len}(T_{ij,k} \cap T_{i,k}^E)}{\text{Len}(T_{ij,k})}
\]

(5)

where \( \text{Len}(T_{ij,k} \cap T_{i,k}^E) \) is the length of the intersection between the time intervals \( T_{ij,k} \) and \( T_{i,k}^E \), \( \text{Len}(T_{ij,k}) \) is the length of time interval \( T_{ij,k} \). For the discernment framework \( \Theta \), the BPA is denoted as \( m_i(\theta) = 1 - m_i(M, S_j, B_k) \).

With regard to \( \theta \subseteq \Theta \), \( \theta_k \subseteq \Theta, \ldots, \theta_n \subseteq \Theta \), moreover \( \theta = \theta_1 \cap \theta_2 \cap \cdots \cap \theta_n \), define the \( n \) belief functions \( m_1, m_2, \ldots, m_n \) in \( \Theta \). In order to infer which prediction model and operation condition are the best, the BPA is calculated using Dempster rule as:

\[
(m_1 \oplus m_2 \cdots \oplus m_n)(\theta, B_k) = \frac{1}{K} \sum_{\theta_1 \cap \theta_2 \cap \cdots \cap \theta_n = \emptyset} m_1(\theta_1, B_k) m_2(\theta_2, B_k) \cdots m_n(\theta_n, B_k)
\]

(6)

\[
K = \sum_{\theta_1 \cap \theta_2 \cap \cdots \cap \theta_n = \emptyset} m_1(\theta_1, B_k) m_2(\theta_2, B_k) \cdots m_n(\theta_n, B_k) = 1 - \sum_{\theta_1 \cap \theta_2 \cap \cdots \cap \theta_n = \emptyset} m_1(\theta_1, B_k) m_2(\theta_2, B_k) \cdots m_n(\theta_n, B_k)
\]

(7)

With the movements of trains, the best prediction models and operation conditions are gradually discerned.

**Case Study**

On July 23, 2011, the most catastrophic accident had happened between two high-speed multiple unit trains D3115 and D301 on the Yongwen railway line. There are 13 block sections from Yongjia station to Wenzhou station, orderly numbered as block section 1, block section 2, ..., as shown in Table 1. At 20:21:22, D3115 stopped at the third nearby block section apart from Wenzhou station. Table 1 shows the normal and abnormal signal codes of track circuits. The belief degrees (BPAs) denote the possibilities that D301 run according to the normal codes. However, at block section 6, the possibility becomes into 68.57%, where the emergent braking command should be issued to train D301 to prevent this accident. Fig. 4 shows the trajectories of trains D3115 and D301 in the normal and abnormal states, in blue, green and red lines, respectively.

<table>
<thead>
<tr>
<th>Block section</th>
<th>Normal code</th>
<th>Abnormal code</th>
<th>Belief degree</th>
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</thead>
<tbody>
<tr>
<td>Block section 1</td>
<td>L5</td>
<td>L5</td>
<td>1</td>
</tr>
<tr>
<td>Block section 2</td>
<td>L5</td>
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<td>1</td>
</tr>
<tr>
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<td>L4</td>
<td>L5</td>
<td>1</td>
</tr>
<tr>
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<td>L3</td>
<td>L5</td>
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</tr>
<tr>
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<td>L2</td>
<td>L5</td>
<td>0.916667</td>
</tr>
<tr>
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<td>L</td>
<td>L4</td>
<td>0.68571</td>
</tr>
<tr>
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<td>L3</td>
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<tr>
<td>Block section 9</td>
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<td>L</td>
<td>0</td>
</tr>
<tr>
<td>Third nearby section</td>
<td>Red tape</td>
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</tbody>
</table>
Conclusions

The architecture of safety prediction and conflict prevention has been proposed when high-speed trains run in the networked railway lines. The parameters of train movement prediction models such as accelerations and decelerations can be attained through off-line classified statistics and on-line abstraction and feedback adjustment. In the prediction horizon, the potential conflicts are predicted based on interval numbers, and conflict prevention measures are planned considering energy saving for the scheduled trains. Safety measure is similar to the TOPSIS (technique for order preference by similarity to an ideal solution) approach. Evidence theory is utilized to deal with the inconsistent information flow and assign the belief degrees of prediction models and operational conditions.

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References


