Train Collision Risk Index for Anti-collision Assessment and Early Warning Method Based on Neural Network

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Abstract. Collision Risk Index is used as the criteria for measuring collision occurrence. This paper introduces Collision Risk Index into the field of rail transit after analyzing the rationality and feasibility to analyze the collision problems in the train operation process. By establishing train running position models to analyze the problems of rear-end collision and side impact in the two states. Basing on the truly driving data about train 681 of Beijing Metro Line 5, the relative position distance between the front and rear cars, the running speed of the front and rear cars, the safe distance of the train as the main inputs, the Collision Risk Index is defined as the output with the collision time of 20s. Back Propagation, Elman, Radial Basis Function neural network models are established in MATLAB, for simulation training and compare the performance between these models. The simulation results show that: The fastest training speed of RBF neural network is 4 seconds, and the minimum MSE is 0.0016; therefore, the model established by training can be used to evaluate the train collision risk index and provide early warning information in time, which could provide a reference for the collision avoidance strategy in the field of rail transit.

1. Introduction
Safety has always been a priority in the field of rail transit, and accidents will affect the entire industry [1]. During the actual operation of the train, it will cause a collision accident due to the influence of various factors. As an important safety hazard in driving problems, the collision problem has always been one of the most important issues in the railway industry [2]. In the process of train travel, the train operation control system controls the train running speed so that the train can ensure the safe operation according to the space interval method [3]; Protection for train collision mostly uses train-to-train Communication [4] strategy in urban rail transit. In existing CTCS-2 and CTCS-3 systems of china, it lacks quantitative information on collision although the driver can understand the actual train speed, target speed, distance information, vehicle equipment status and other information through the man-machine interface. In the field of marine traffic engineering, the "1972 International Maritime Collision Avoidance Regulations" (referred to as "Rules"), proposed "RISK OF COLLISION" and "DANGER OF COLLISION" and other related concepts, which in Chinese version of the "Rules" was translated as "Collision risk", but it does not give a clear definition for the degree of collision risk [5]. Cai Cunqiang gave explanation and supplement to the "risk of collision", Professor Imazu of Japan proposed the concept of "collision risk index" [6]. At present, the most commonly used methods for calculating the collision risk index are: fuzzy mathematical calculation method, gray correlation analysis method, etc. The fuzzy mathematics calculation method has high calculation accuracy but with a large calculation
amount; the gray correlation method can mainly realize data correlation analysis and prediction, the advantages of which is that it has a small calculation amount, high speed, and accurate calculation results, but only when multi-target calculation is possible the relative collision risk of each target can be calculated; the calculation error of neural network is small and the self-learning ability is strong, while the probability of calculation failure is greater and it has a strong dependence on the sample. The neural network algorithm can be optimized and improved to achieve the purpose of improving performance for this reason. The paper comprehensively analyzes the rationality and feasibility of introducing the concept of "collision risk index" into the field of rail transit. At the same time, the BP, Elman and RBF models are implemented in MATLAB software, and the actual train operation data is combined to calculate the collision risk index.

2. Collision Risk Index

Collision Risk Index (CRI) is a basic concept in the field of collision. It is used to measure the possibility of collision. As a measure of collision risk, it is also the basis and judgment criterion for collision avoidance decision [7]. Figure 1 is the collision risk curve. The range of CRI value is [0, 1], 0 means no collision risk; 0.5 means there is collision risk, while the driver should be vigilant to run at the specified speed and be ready to stop at any time; if CRI is 1, collisions cannot be avoided no matter what kind of avoidance actions are taken. the CRI choose 0.5 as the benchmark to decide whether to take action. If the CRI exceeds 0.5, collision avoidance measures should be taken in time; when the CRI is less than 0.5, the driver should be vigilant and maintain the specified speed.

![Collision Risk Curve](image)

Figure 1. Curve of collision risk index

2.1. Collision Risk Index of Train

In the actual collision avoidance analysis, there are not only many factors that affect the risk of collision but also the relationship of them is mutual restriction. The main factors generally considered are: Distance to Closest Point of Approach (DCPA), DCPA error, (Time to Closest Point of Approach, TCPA), TCPA error, target train orientation, own vehicle speed and target vehicle speed. Among these factors, DCPA and TCPA are the two most important factors that affect the risk of collision [8]. The smaller the DCPA and TCPA values are, the greater the risk of collision will be. For the analysis of train collision avoidance in the field of rail transit, if only two vehicles are considered, it is denoted as the front vehicle F and the rear vehicle B. The corresponding analyzable factors are: the relative distance R of the train, the running speed of the forward train is recorded as \( v_f \), the running speed of the subsequent train is recorded as \( v_b \) and the minimum safety distance is recorded as \( L \), etc. There is no need to consider the angle for the straight track tracking of the preceding train and the following train. If you analyze collision problems in other scenarios, you should consider other relevant factors.

2.2. Calculation of train relative motion parameters

The straight-line tracking operation diagram of the two cars is shown in Figure 2, where the front car F and the rear car B run in the same direction (Either in the upward direction or in the downward direction), where \( v_b \), \( v_f \) is the speed of follow-up train B and the forward train F respectively, \( L \) is the minimum safety distance, and \( R \) is the relative distance between the two vehicles.
If \( R(t) \) is the relative position between the two cars after time \( t \), then:

\[
R(t) = R - (v_f - v_b) t
\]  

(1)

Therefore, when: \( R(t) > L \), regard as no rear-end accident; when: \( R(t) \leq L \) Treat as a train collision. If \( T \) is defined as the critical collision time, means the maximum safe driving time, then:

\[
T = \frac{R - L}{v_f - v_b}
\]

(2)

at this time: \( R(t) = L \); when \( t < T \), it is considered that there is no rear-end collision; when \( t \geq T \), it is regarded as a train collision.

The non-straight line tracking operation diagram of the two cars is shown in Figure 3, and the speed direction of the forward train \( F \) is selected as the positive direction of the X axis, and the speed direction of the rear car \( B \) has a certain angle with the X axis. and \( v_b, v_f, L, R \) have a same definition as in Figure 2. Let the coordinate of the following car (B car) be \((x_b, y_b)\), \( \theta \) is the angle between the speed direction of train \( B \) and the positive direction of X axis. According to the geometric relationship, the components of car \( B \) on the X axis and Y axis are:

\[
\begin{align*}
    v_{xb} &= v_b \sin \theta \\
    v_{yb} &= v_b \cos \theta
\end{align*}
\]

(3)

Then the relative velocity components of the two vehicles on the X axis and Y axis can be expressed as:

\[
\begin{align*}
    v_{xR} &= v_f - v_b - v_{xb} \\
    v_{yR} &= v_{yf} - v_{yb}
\end{align*}
\]

(4)

The relative speed is expressed as follows:

\[
v_R = \sqrt{v_{xR}^2 + v_{yR}^2}
\]

(5)

The relative speed direction is expressed as follows:

\[
\phi_R = a_0 - \tan^{-1} \frac{v_{yR}}{v_{xR}}
\]

(6)

The distance between the two cars is as follows:

\[
R_t = \sqrt{(x_f - x_b)^2 + (y_f - y_b)^2}
\]

(7)
The closest meeting distance $D$ and the time $T$ to the closest meeting point of the front car $F$ and the back car $B$ are expressed as follows:

$$D = R_f \sin(\varphi_R - \varphi - \pi)$$

$$T = R_f \cos(\varphi_R - \varphi - \pi) / v_R$$

In the formula: $\varphi = a_1 - \tan^{-1} \frac{y_R - y_b}{x_R - x_b}$

For straight-line tracking trains, it is easier to calculate the relative position distance $R(t)$ and the maximum safe travel time $T$, but consider that the train line conditions and the changing specified driving speed during the train travel process. The linear tracking problem of trains is shown in Figure 2, if the speed of the rear car $B$ is less than the speed of the front car $F$ all the time, there will be no rear-end collision; if the speed of the rear car $B$ is greater than the speed of the front car $F$, it will definitely cause a rear-end collision if the rear car $B$ without decelerating. However, the speed of the train is affected by many factors during the driving process. In line with the actual situation, the straight line tracking problem is not a single constant speed straight line tracking; for the non-straight line tracking problem, if there is a turnout in line operation, as shown in Figure 3, considering the influence of different turnouts on the running speed of trains, it is prone to cause the problem of side thrust. The formulas above provides information about train collisions, but it does not take the diversity and complexity of train operation into account, so the collision information provided is not intuitive. Therefore, an analysis method of train collision risk index based on neural network is proposed. Evaluating the collision information of trains with numbers between 0-1 can effectively and intuitively reflect the possibility of collision.

3. Artificial Neural Network

Artificial Neural Network (ANN) is a mathematical model that can carry out distributed parallel information processing on data\[9\]. Using neural network can effectively realize the modeling and simulation analysis of the risk of train collision. The reason is that the risk of collision is affected by many factors, and the neural network can obtain the optimal data model through the training and analysis of effective data to achieve the calculation and prediction of the risk of collision.

3.1. BP Neural Network

The BP neural network has a three-layer structure. The network structure is shown in Figure 4. The idea is the gradient descent method, which is easy to fall into the local optimal solution\[10\]. It can be optimized by changing the learning algorithm or using genetic algorithms. The genetic algorithm can avoid local optimal problem, but the training time is longer. For the BP neural network, although the accuracy of training result can be improved to a certain extent by increasing the number of neurons in the hidden layer, it will also cause lower training speed and longer training time, and it cannot make the training results more accurate when the number of hidden layers in the neural network is too much. Therefore, a reasonable choice of the number of neurons also plays an important role in the training results.

![BP neural network structure](image-url)
3.2. **Elman Neural Network**

The Elman neural network is a typical dynamic recurrent neural network. Its network structure is shown in Figure 5. Compared with the BP network, the Elman neural network adds an additional layer at the hidden layer, so that the system has the ability to adapt to time-varying characteristics. And the global stability of the network were enhanced\[11\].

Due to the increase of the bearing layer, the Elman network has higher data fitting accuracy than the BP network, and it has a better performance in meeting the result requirements in actual simulation. In order to better meet the actual needs of the simulation process in the application process, the Elman neural network can be improved or optimized. There are two main ways to improve the Elman algorithm: the use of heuristic learning algorithms and the use of more effective optimization algorithms.

![Elman neural network structure](image)

3.3. **RBF radial basis function neural network**

The Radial Basis Function is a forward neural network with a two-layer network structure: a hidden layer with radial basis function neurons and an output layer with linear neurons \[12\]. The structure diagram is shown in Figure 6:

![RBF neuron model](image)

Compared with the traditional BP neural network, the advantage of the RBF neural network is that it has a high training speed. On the one hand, there are fewer hidden layers, on the other hand, the local approximation can simplify the calculation amount, and achieve a best effection in approximation to the continuous function \[13\].

4. **Data Analysis**

The input quantity in MATLAB simulation is the relative distance of the train \( R \). The running speed of the forward train is recorded as \( v_f \), The running speed of the subsequent train is recorded as \( v_s \), The minimum safety distance is recorded as \( L \), etc. The input data comes from the actual data of the two vehicles tracking in a straight line in Dengshikou-Songjiazhhuang of Beijing Metro Line 5.

Regarding the output of CRI value, the relationship between the CRI value and the analysis object distance \( \text{DIST} \) was fully illustrated by the collision risk curve shown in Figure1 .Considering the constraints and particularities of the train travel process in actual train collision avoidance problem, it is easy to obtain the functional relationship between the distance of the two trains and the time of collision, so it is reasonable and effective to establish the relationship between the CRI and the time of collision.
Different speeds, weights, line factors, and braking methods should be considered when defining the relationship between the specific risk of collision and the time at which the collision occurs. It is stipulated in current "Technical Regulations for Railway Technology" that "The emergency braking distance of the train is stipulated as 800m no matter on what railway slope. And the railway bureau can appropriately extend the braking distance within the allowable speed range according to the line conditions, but the maximum should not exceed 1100m. Take 250km/h train as an example. At a braking distance of 1100m, a braking time of 31.68s is also required; at present, tracking interval of high-speed railway in China basically reaches a 3min under CTCS2/3 operating conditions\textsuperscript{[14]}, so it is reasonable to define the value of CRI as a time interval of 20s. CRI=1 is taken if a collision occurs within 20s, indicating that, train collision accidents cannot be avoided no matter what braking or collision avoidance measures are taken; CRI=0.9 is taken if a collision occurs within 20s-40s. When CRI=0.5, the driver should be reminded to run at the specified speed, and pay attention to observation; when CRI=0, it means that there is no danger of collision at this time, and it can drive normally. The CRI value in the paper can be calculated according to the above definition of CRI, the map of two-vehicle operating position and the data, but this calculation method is more time-consuming and not intelligent enough. For this reason, the powerful parallel ability of the neural network can be used to calculate CRI, and the requirement of real-time efficient and accurate calculation can be meted.

5. Simulation Results and Analysis

Neural network modeling and simulation such as BP-bfg, BP-cgf, BP-gda, Elman-cgf, Elman-gdx, Elman-rp, RBF, etc. are realized in MATLAB software. The results are shown in Figure 7-9 below. At the same time, the performance of each neural network is compared in terms of training time and simulation accuracy. The less training time, the higher the speed; the smaller the mean square error (MSE) and root mean square error (RMSE), the higher the accuracy is, the performance of neural network is shown in Table 2.

For the simulation results, Figure 7(a), (c), (e) and Figure 8(a), (c), (e) and Figure 9 are simulation diagram of BP-bfg, BP-cgf, BP-gda, Elman-cgf, Elman-gdx, Elman-rp and RBF network in MATLAB, the two curves in the figure represent the actual output and predicted output, the fitting of different networks can be seen intuitively, but lack of data instructions. The degree of respective network it fits can be compared intuitively from the network iteration performance graphs shown in Figure 7 (b), (d), (f) and Figure 8 (b), (d), (f). It can be seen from Figure 7(b), (d), (f) and Figure 8(b), (d), (f) that the best training performance of BP-bfg, BP-cgf, BP-gda, Elman-cgf, Elman-gdx, Elman-rp respectively appeared in the second 0.17235, the third 0.10518, the 73rd 0.1315, the 37th 0.054456, the 25th 0.06386, the 13th 0.066961, and in fact that the RBF network has reached 0.01 at the 20th iteration. So in terms of the best fitting performance, RBF followed by Elman, BP is relatively slow; from the neural network training of Table 1 we can see that the training speed from fast to slow is: RBF, BP-cgf, BP-gda, BP-bfg, Elman-gdx, Elman-rp, Elman-cgf; simulation accuracy from high to low: RBF, Elman-rp, Elman-cgf, Elman-gdx, BP-bfg, BP-cgf, BP-gda.

Therefore, through comparison of training speed and simulation accuracy, it can be considered that RBF neural network is superior to BP and Elman neural network in speed and accuracy, and can better meet the calculation and prediction of train collision risk in this paper.
Figure 7: BP neural network performance chart
a) Elman-cgf simulation diagram

b) Elman-cgf performance diagram

c) Elman-gdx simulation diagram

d) Elman-gdx performance diagram

e) Elman-rp simulation diagram
6. Conclusion
This paper mainly introduces the concept of collision risk into the field of rail transportation, and analyzes the rationality and applicability of the collision risk in the field of train transportation safety. Establish a mathematical model for the rear-end problems existing in the train operation process, and at the same time consider the complexity and diversity of the line during the train operation process, and give the reason why the collision risk degree is also applicable under special conditions; the value range of train collision risk is defined at intervals of 20s based on the time of the collision. Consider the relative position distance between the two trains, the running speed of the preceding car, the running speed of the following car, the maximum safety distance of the train and other factors on the collision. Take the data of Line Songjiazhuang-Dengshikou in Beijing subway as verification data. Model and simulation of BP, ELMAN and RBF neural networks are established in MATLAB software. By comparing the simulation results, conclusion can be obtained that the accuracy and speed of the RBF neural network are better; the model established in this paper can be used to calculate and predict the collision risk of a train at a specific time, and can provide drivers with timely and effective collision avoidance information, so that staff can detect potential safety hazards as soon as possible, and implement corresponding collision avoidance strategies as early as possible. Prevent collision accidents and protect the safe and efficient operation of trains.
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