Configuration design of the trainset of a high-speed train using neural networks

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Abstract

Prediction of the top (service) speeds of high-speed trains and configuration design of trainset of them has been studied using the neural network system. The traction system of high-speed trains is composed of transformers, motor blocks, and traction motors of which locations and number in the trainset formation should be determine in the early stage of train conceptual design. Components of the traction system are the heaviest parts in a train so that it gives strong influence to the top speeds of high-speed trains. Prediction of the top speeds has been performed mainly with data associated with the traction system based on the frequently used neural network system – backpropagation. The neural network has been trained with the data of the high-speed trains such as TGV, ICE, and Shinkansen. Configuration design of the trainset determines the number of trains, motor cars, traction motors, weights and power of trains. Configuration results from the neural network are more accurate if the neural network is trained with data of the same type of trains that will be designed.

Keywords:

High-speed train, Traction system, Configuration design, Train formation, Trainset, Neural network, Backpropagation, Power concentration traction system, Power distribution traction system

Introduction

After the Industrial Revolution, once the major transportation system – train – has been reduced in the role of traffic system because of the rapid development of automobile and airplane. During the recent ten years, the volume of intercity traffic has been increased rapidly and train has been spotlighted because of the safety, punctuality, and low environmental disruption effect.

High-speed train generally means that its top speed (commercially operated) is over 200 km/h, and its service distance is between 300 ~ 600 km. Car is usually used for the transportation for the distance of lower than 300 km, and plane is used for the distance of more than 600km to save time. Considering this, high-speed trains are suitable for the Korean peninsula.

At present, high-speed trains are operated in such countries as Japan, France, German, Italy, and Spain, and more are being constructed in more than ten countries such as Korea, USA, Taiwan, China, and Russia. Especially the high-speed train systems of France, Japan, and Germany, i.e. TGV, Shinkansen, ICE has their own technical characteristics compiled from each country's high technology. For example, the articulated bogie type is uniquely adopted by TGV. The power distributed trainset is the main trainset formation of Shinkansen. ICE minimizes the air friction force by aerodynamic design of trains. It is difficult to compare these high-speed train systems based on a single technical point of view. In recent years ICE3 adopts the power distributed trainset of Shinkansen.

The power to operate a high-speed train is electric force transmitted from the catenary to the pantograph which is attached to the roof of the train. The electric force passes through transformer, motor block (inverter, converter), and is converted into mechanical energy in the traction motor(Fig. 1). This group of components in a high-speed train is called Electric Multiple Unit (EMU) or traction system of which weight is heavies. It is a single part in a train and is considered as the major part in the conceptual design stage of trains[1].

There are various arrangements of traction systems in high-speed trains. The number of transformers, motor blocks, and traction motors is different for different types of trainset – power concentration or power distribution. The power concentration trainset has fewer components for the traction system than the power distributed trainset of which components is distribute all over the trainset. The configuration design of the trainset has strong influence on the overall train. [2][3][4][5].

In this paper, the relationship among the top (service) speed the major parameters of the traction system, and the trainset formation has been investigated using a neural network system with back-propagation.[6][7][8]. The top speed and the configuration design of a trainset are suggested by the neural network. Data of commercially operated high-speed trains such as TGV, ICE, and Shinkansen has been utilized for the training of the neural network.

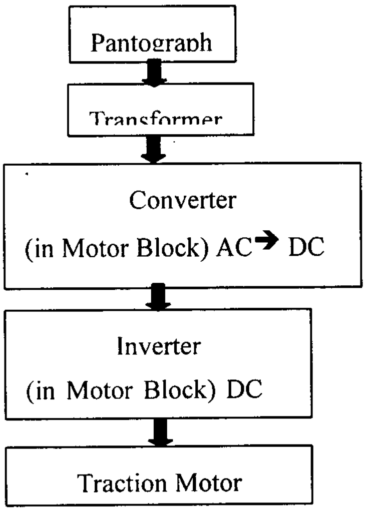


Fig 1 - Power transmission in a high-speed train

Approach and Methods

Dynamic modeling and neural network

One-Axis Train Model

One-axis train model is shown in Fig.2, which simplifies a train moving on the rail. This model is used for an evaluation of train speed[9].

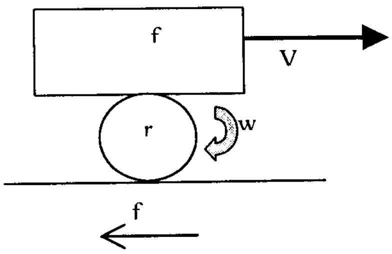


Fig 2 - One-axis train model

Equations (1) ~ (3) show the equations of the motion of wheel, train, and the friction force between wheel and rail shown in Fig. 2.

$$J\frac{dw}{dt} = Te - f \cdot r - b \cdot w \tag{1}$$

$$W\frac{dv}{dt} = f - c \cdot v^2 \tag{2}$$

$$f = \mu \cdot W \cdot g \tag{3}$$

Where,

v velocity of train

w angular velocity of traction motor

f adhesive force

μ friction coefficient

Discription of other variables are shown in Table. 1.

Table 1- Variables of the one-axis train model

J	Te	r	B
Wheel moment	Input torque	Wheel radius	Viscosity resistance
Kg'm	N'm	m	Kg'm/sec
w	c	G	
Train weight	Aerodynamic coefficient	Gravity	
kg	m3/sec	m/sec2	

A slip is occurred between wheel and rail when there is a velocity difference between the angular velocity of wheel and the train as shown in equation (4), (5).

$$slip = w \cdot r - v > 0 \tag{4}$$

$$\mu = \gamma \cdot \exp(-\alpha \cdot slip) - \chi \cdot \exp(-\beta \cdot slip) \tag{5}$$

where, $\alpha, \beta, \gamma, \chi$ are the constant values determined by the surface condition which is again obtained from experiment. Two examples of the constant values are shown in Table 2.

Table 2 - Values of friction coefficient

	α	β	γ	χ
Wet condition	0.54	1.2	0.29	0.29
Dry condition	0.54	1.2	1.0	1.0

The top speed of a train is determined mainly by the driving force of the train, the speed of traction motor, the weight of train, and the slip between wheel and rail expressed in equation (4).

When a high-speed train is in the configuration design stage, it is difficult to get the coefficient values of Table 2 and some of Table 1 because they are experimental data. In this paper, the backpropagation – one of neural network systems– is used to predict the top speed without experiments.

Backpropagation method

Backpropagation is a supervised learning method, which is most widely used in neural network systems[7][8]. Fig. 3 shows the characteristics of the backpropagation in a neural network system.

This method is composed of three layers – input, hidden, output layers – and each layer has nodes, which are connected to other nodes of the same layer or other layer. The connection is multiplied by weights (w_{ij}) (Fig. 4).

Each node sums all input values coming from other nodes and calculates the activation function. The roles of a node and activation functions are shown in Fig. 5(a), Fig. 5(b) respectively.

If a node is not in the output layer, the output value of a node (Fig. 5(a)) is multiplied by the weight of each node, which is accepted as the value input

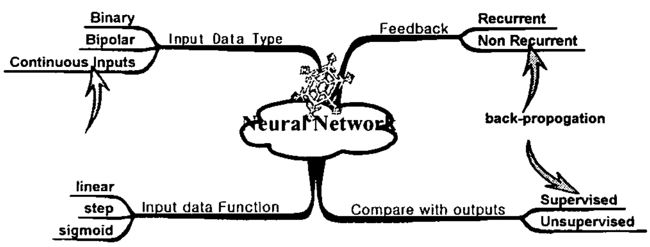


Fig 3 - Backpropagation method

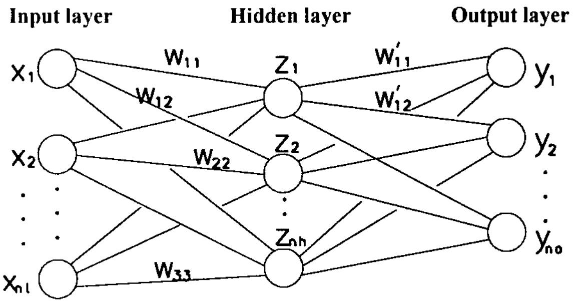
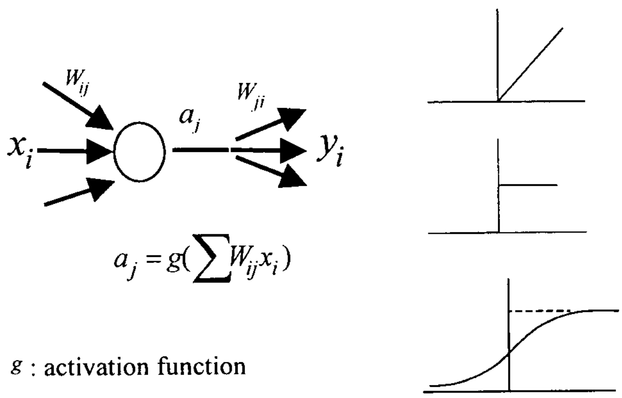


Fig 4 - A neural network



g : activation function

a_j : output value

(a) (b)

Fig 5 - Node and activation functions

To train the neural network the output value y_i of the output layer is compared with the target value t_i that is a predefined value. Weights w_{ij} are controlled to minimize the difference between y_i and t_i repeatedly until the RMS error is smaller than the predefined value ε as expressed in equation (6). When this condition is satisfied, the training of a neural network is finished.

$$E = \frac{1}{2}\sum_j (t_j - y_j)^2 \le \varepsilon \qquad (6)$$

Prediction of top speed with neural net

Data for training of neural network

Data closely related to the speed of a train are used for training the neural network. Input data for a neural network are taken from commercially operated trains. – TGV, ICE, Shinkansen as shown in Table. 3 for Shinkansen, which also show target values(top speeds)of the neural network.

Table 3 - Training data for top speed prediction (Shinkansen)

Shinkansen Type	Weight (ton)	Length (m)	Power (kw)	mass/ seat (ton)	power/ mass (kw)
700	1120	404.7	13200	0.847	11.786
500	1264	404	18240	0.955	14.430
400	575.9	148.66	5040	1.443	8.752
300	1037.4	402.1	12000	0.784	11.567
200	1785	400.3	11040	1.451	6.185
100	1428	402.1	11040	1.083	7.731
Shinkansen type	**Power /seat (kw)**	**No. of motor car /total train**	**No. of trailer /total train**	**No. of traction motor**	**Top speed**
700	9.977	0.75	0.25	48	285
500	13.776	1.00	0.00	64	300
400	12.632	0.86	0.14	24	240
300	9.070	0.63	0.38	40	270
200	8.976	0.88	0.13	48	240
100	8.370	0.75	0.25	48	220

Neural network system

Fig. 6 shows the neural network system, which is used to predict the top speed. It is composed of 9 input nodes, one output node (top speed), and three hidden layers composed of two 18 nodes and one 9 nodes respectively. The input and output nodes have the values as shown in Table 3. The Sigmoid function is used for the activation function and the Qnet --a commercial software for neural net– is used to train the network system.

The parameters for the training of neural networks in Qnet software is shown in Fig. 7 and the reduction curve of RMS error is shown in Fig. 8 where the training iterations are performed 1,000,000 times before the estimation of the top speed.

After training the neural network with data shown in Table.3, The prediction of the top speed is put into practice for the selected railroad train data.

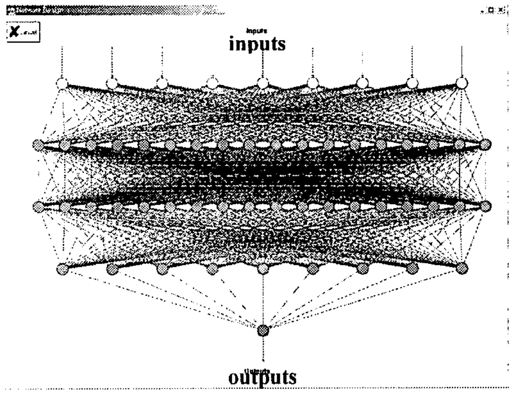


Fig 6 - Structure of the neural network for estimating the top speed

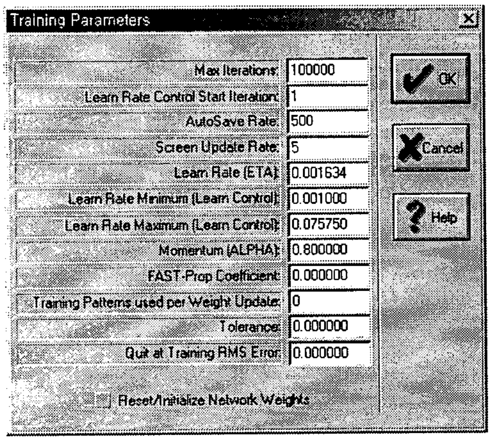


Fig 7 - Variables for neural network training

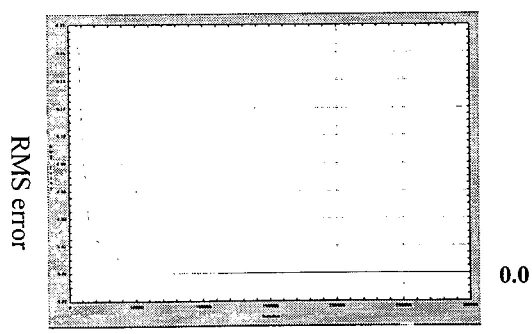


Fig 8 - Reduction curve of RMS error

Configuration design of trainset with neural net

The configuration of a trainset is closely related to the traction system, which means, for example, the number of motor cars, traction motors, power of trains. As the top speed can be predicted with the neural network, the configuration design of a trainset can be performed with the aid of a neural network, which has, in this case, two inputs and six outputs with three hidden layers. Table 4 shows the inputs (training data) and outputs of the neural network for trainset configuration.

Table 4 - Input and output values of the neural network for trainset configuration

Input	Total number of seats		Top speed
output	Weight of trainset	Length of trainset	Total power
	Percentage of motor car to total train.	No. of traction motors in trainset	No. of trains

Results

Prediction of the Top speed

The estimated top speeds of various trains and their actual values are compared in Table.5. Predicted top speeds are from the neural networks which are trained by data of same type, e.g. Shinkansen, TGV, ICE, with the exception of data of the new train. The accuracy is high as shown in Table 5 because the same type train has similar trainset formation and performance of the traction system.

Table 5 - Prediction of top speeds (from neural networks trained with data of same type)

	Estimated	Exact	Accuracy (%)
Shinkan-sen 700 series	274.1	285	96.2%
ICE 3	348.3	330	105.5%
TGV-K	300.0	300	100.0%

Using the neural network trained with data of Shinkansen, the estimated top speeds of ICE, TGV and their actual values are compared in Table.6. The trainset of ICE reduces the air friction efficiently by an aerodynamic design so that the exact top speed shown in Table 6 is larger than the estimated value.

Korea's new high-speed train (KHST) is under development now, and its top speed is predicted with the neural networks trained by data of various trainsets as shown in Table 7. Power concentration trains group means the trainsets of ICE-V, ICE 1, TGV Eurostar, and TGV-K, of which traction systems are concentrated on relatively small number of trains. The configuration of KHST traction system belongs to this category, which predicts the speed of KHST with high accuracy.

Table 6 - Prediction of top speeds of TGV and ICE(using neural network trained with the data of Shinkansen)

	Estimated	Exact	Accuracy (%)
TGV-Atlantique	266.1	300	88.7%
TGV-EuroStar	298.5	300	99.5%
TGV-Thalys	302.7	300	100.9%
TGV-Korea	300.1	300	100.0%
ICE-V	304.1	350	86.9%
ICE 1	286.1	280	102.2%
ICE 2	217.2	280	77.6%
ICE 3	301.6	330	91.4%

Table 7 - Prediction of top speed of KHST (using neural networks trained with data of Shinkansen, ICE, TGV, respectively)

	Estimated	Exact	Accuracy(%)
Shinkansen	303.7	350	86.8%
ICE	311.3	350	88.9%
TGV	300.0	350	85.7%
Power concentration train group	315.8	350	90.2%

Configuration of trainset

The configuration result for Shinkansen 700 are shown in Table 8, which are drawn from the neural network trained by Shinkansen data with the exception of the Shinkansen 700 data itself.

The result predicts more power for the trainset than the actual value, therefore number of traction motors and total weight are larger than the actual value. This means that the actual Shinkansen 700 trainset is more energy efficient than the other trainsets in the past time so that it needs less power and traction motors accordingly.

Table 8 - Trainset configuration result of Shinkansen 700 (using the neural network trained with data of Shinkansen)

	weight	length	power
Trainset configuration result	1136	403.0	15989
Actual trainset configuration	1120	404.7	13200
	motor car/ total train	No. of traction motors	No. of total trains
Trainset configuration result	83 %	55	16
Actual trainset configuration	75 %	48	16

The trainset configuration design of KHST is performed with the neural network trained by the data of Shinkansen and power concentration train group respectively as shown in Table 9. Shinkansen has a distributed traction system so that the configuration design with the neural network trained by the data of Shinkansen has more traction motors and motor cars than the power concentration train group.

Because of the similar trainset formation between power concentration train group and KHST, the trainset configuration result of power concentration train group (shown in Table 9) has a similar configuration with KHST.

Table 9 -Trainset configuration result of KHST train (using the neural network trained with the data of Shinkansen, Power concentration train group)

Trainset configuration result	weight	length	power
Shinkansen	1341.6	407.6	19809.4
Power concentration train group	687.5	385.5	13475.8
Actual trainset configuration	712	394.6	17600
	motor car/ total train	No. of traction motors	No. of total trains
Shinkansen	100%	69	16
Power concentration train group	25%	12	20
Actual trainset configuration	30 %	16	20

Conclusion

A neural network can be a useful tool in the conceptual design stage of trainset. The top speed of a high-speed train is a typical engineering target and an estimation of it with a neural network (without experiment) will be helpful for quick estimation of trainset formation – arranging the traction system and passenger seats.

The top speed from the neural network which is trained by same type of train data – Shinkansen, ICE, or TGV – is more accurate because the same type of trains have common relationships between the top speed and the power of train, weight, and train formation.

The configuration of trainset can be estimated with a neural network, which produce the total number of trains, motor cars, traction motors, etc.

If one estimates the trainset configuration with neural networks, it will be necessary to decide previously which type of traction systems – power concentration or power distribution – is selected because the estimation will be different apparently by the neural network used, as shown in the previous results. With the estimated result of neural network, the location of motor car and traction motor, and the total number of transformer and pantograph in trainset configuration can be determined.

The results from the neural networks in this paper are approximations drawn from the existing trends. This result can not be used directly but it can be conveniently used to estimate the overall trainset configuration based on the data of existing trains, and predict configurations in two different viewpoints – power concentration and power distribution.

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