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What type of electric brake is most reasonable? - friction and heat free braking of moderately powered, moderately distributed traction system

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Abstract

Types of service brake for modern traction vehicles can be classified as friction brake and electrical brake; the latter is either dynamic, eddy current or regenerative brake. Initial and running cost of each type of brake is very different and depends sharply upon installed maximum power especially for regenerative braking system.

Almost all rail vehicles have friction brake in addition to other types of brake. Installed maximum power of electric brake can be reduced substantially if friction brake is used for service brake, with increased maintenance cost of friction brake especially for high-speed operation. To the contrary, a new concept of brake, "pure electric brake", has been successfully developed which eliminates friction brake from service brake. Comparison has been made of life-cycle cost for urban railways and of installed mass for high-speed trainsets, and moderately distributed traction system with regenerative service brake has been found the best system.

1 Introduction

Regenerative brake has been introduced in conjunction with ac motor traction as well as historical use for a retarding brake for a long down gradient. In recent years the so-called pure electric braking of regenerative mode has been gradually introduced for rapid transit with ac motor traction because of better riding comfort and easier for driving. On the other hand, even if all service braking is made in electric mode, friction brake equipment cannot be abandoned for the

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purpose of achieving dual braking system, sufficient braking force at high speed, and as the best means to keep the train at standstill. Among electric brakes, there is still some discussion as to which of rheostatic braking or regenerative braking is better from the viewpoint of reliability, safety and controllability.

Distributed traction system with electric braking has recently been popular because of remarkably less train mass per available floor area and less maximum axle load. This movement has been recognised for European railway operators such as SNCF and DB who had been adhered for concentrated traction. The reason is clear; maintenance work for a big number of ac traction motors is much easier than for even bigger number of braking pads for friction brake.

Life-cycle cost in relation to braking methods should be carefully examined. Train mass, running energy and maintenance cost is strongly related to braking methods. Generally speaking, regenerative braking is the best for all the above three items, but under dc contact system normal rectifiers at substation cannot receive regenerated power, which means regenerative braking itself is sometimes ineffective. If non-receptive condition often takes place, some countermeasure of combined regenerative/rheostatic braking or inverter for substation should be considered.

2 Importance of braking system from the viewpoints of life-cycle cost of urban trains and of light weight construction of high speed trains

In urban transit, station spacing is relatively short and in order to compete with private cars, commercial speed of the train should be kept high requiring frequent and strong brake application from high speed. This means that kinetic energy to be dissipated by brake is big and associated energy cost and maintenance cost of braking system is high. If kinetic energy is absorbed by friction brake, wear of braking pad and wheel tread or braking disc requires high maintenance cost but if braking is by regenerative mode, regenerated energy can reduce energy cost considerably. Rheostatic, or dynamic, brake requires almost no running cost with sacrifice of additional mass and installation .

Small mass is strongly required for trainsets for high-speed railways because ground vibration and track deterioration is caused by axle load, especially by unsprung mass, and relatively high value of power / mass ratio in order to keep high performance requires a high level of light-weight design and construction. If conventional TGV-A design, made of 4 motored bogies and 11 trailer bogies for the maximum speed of 300 km/h, is extended to higher speed region, all bogies should be motored for a maximum speed of around 460 km/h if required power is proportional to the cube of the maximum speed; this means that the whole train should be locomotive and there is no longer passengers' space at all. The similar situation is applicable for the braking system of a high speed trainset. At high speed, braking power is very big even if braking force is moderate and so if braking power is dissipated in the form of heat, additional mass to deal with this dense heat power is substantial. In this respect, regenerative braking is very

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advantageous even if braking is not so frequently applied than in the case for urban trains. Most high-speed railways are ac electrified and there is no risk for non-receptive condition of power system. This is very favorable for regenerative braking.

3 Kinds and characteristics of major braking methods for normal service operation

Comparison will be made among five systems; regenerative brake, rheostatic (dynamic) brake, friction brake, eddy-current disc brake and eddy-current rail brake.

Regenerative brake, when effective, produce no inherent heat. This makes the vehicle lighter and safer than any other braking system. Regenerated energy, used for hotel power of the train, acceleration of other trains or for station, produces profit, or negative cost. In most cases, regenerative brake equipment is lighter than any other brake.

Care should be taken if the train is fed through dc catenary where excess regenerative power makes braking force ineffective. Dynamic brake is also a kind of electric brake with much better controllability than friction brake. Mass of this equipment is determined by the maximum handling power and duration of time of braking. Special care should be taken if the train is used on a line with long down gradient at high speed.

Friction brake requires highest running cost due to wear of braking pad and related maintenance. Actual maintenance cost often increases further through reshaping works of the damaged flat wheel. Wheel skid itself is characterised by inferior friction brake. Friction brake sometimes makes fire, which burns timber sleeper or wayside grass.

Eddy-current disc brake is widely used for trailer cars of Tokaido and Sanyo Shinkansen. Braking characteristics are much better than that of friction brake but disadvantage is big mass, especially big unsprung mass. Another type of eddy-current brake, eddy-current rail brake is a kind of non-adhesive brake, but temperature rise of the running rail will limit this brake to be used for a rural railway with short and infrequent trains.

4 Rough cost estimation of typical three types of braking

Regenerative braking produces electric energy to be absorbed by other trains. This advantage can be estimated in money roughly as follows; regenerated energy at onboard power converter times per unit energy cost at substation input. Rheostatic braking costs almost nothing as far as running cost is concerned.

Friction braking requires exchange of braking pad and additional reshaping of wheel tread; this amount, made of labour cost and material cost, is nearly proportional to absorbed kinetic energy and from Japanese experience price per unit energy is almost identical of regenerative braking with, of course, reverse direction.

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Important factors other than running cost include; safety and maintainability related to heat generation, mass especially unsprung mass, and deterioration of characteristics at loss of regeneration when line is non-receptive.

5 A typical example of optimisation of traction and braking power and of operation for rapid transit

5.1 Pure electric braking with different installed power

Based on the characteristics of the world first trainset series 8900 of Shin Keisei Electric Railway Co., whose regenerative-mode electric break can be applied down to standstill, two cases of comparison of running energy have been made. One example is achieving energy saving and wear free operation of braking pad. Existing formation made of four motor cars (4M) and four trailers (4T) is running typically in 84 seconds for a station spacing of 1200 meters with additional friction brake application at higher speed region due to insufficient regenerative braking capability. If traction power is slightly increased to 4.5M 3.5T, acceleration and deceleration is also increased with no braking pad wear and with reduced energy as shown in table 1.

Another example is comparison between high performance trainsets; 4.5M 3.5T, 5M 3T and 6M 2T of the same performance per motor car. Based on Yamanote Loop line in Tokyo, where there are 29 stations in 34.5 km loop and 2.5 min. (150 sec.) headway trains using 25 formations each way are operated, typical 85 second running time is shortened by 150/29 seconds in order to reduce one formation each way. Running performance of each trainset is shown in Fig.1.

Table 1 Comparison of energy vs. traction power

Formation	4M 4T	4.5M 3.5T
Station spacing	1200 meters	1200 meters
Running time	84 seconds	84 seconds
Acceleration time	37.4 sec.	30.9 sec.
Acceleration energy	95.4 MJ	90.6 MJ
Coasting time	25.3 sec.	33.1 sec.
Braking velocity	69.9 km/h	66.3 km/h
Deceleration time	21.3 sec.	20.0 sec.
Regenerated energy	51.0 MJ	47.3 MJ
Net energy consumed	44.4 MJ	43.3 MJ
Energy by friction brake	0.6 MJ	0 MJ

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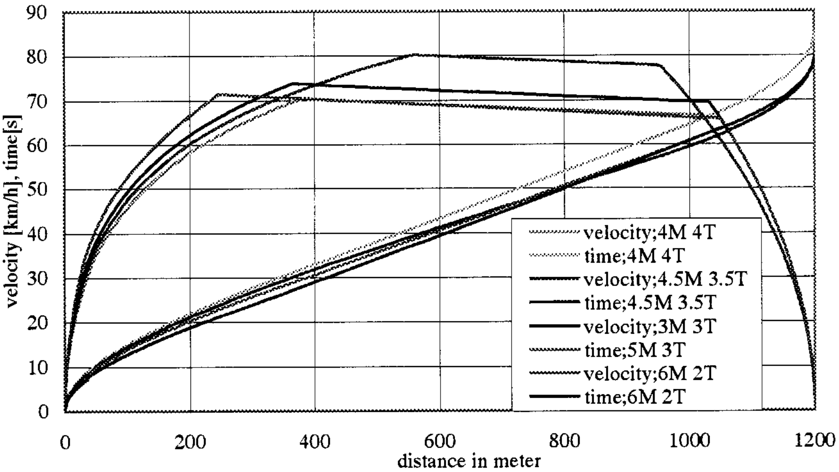

Fig. 1 Running curve for various formation

Net energy required to run average 1200 meter section is shown in Table 2.

Table 2. Energy consumption vs. performance and running time

Formation	4M 4T	4.5M 3.5T	5M 3T	6M 2T
Running time (sec)	85	79.83	79.83	79.83
Net energy consumed (MJ)	35.96	48.68	41.11	37.15

5.2 Optimum life-cycle cost

Based on the previous trainsets, profile and demand of Tokyo's Yamanote Line, as well as the following assumption, life-cycle costs of several trainsets have been compared.

Assumption taken is:

- Investment cost and train mass for improvement of train performance; actual price and mass of average motor cars and non-driving trailers of Series 8900
- Labour cost; two times actual annual payment for employers, driver and conductor.
- Energy cost; actual electric energy price at substation bought from electric power company.
- Total cost for friction brake; as shown in Chapter 4.
- Social benefit obtained by faster running; average labour cost per time multiplied by saved time by all passengers.
- Return rate for train operator of the social benefit; 1.5%. There are no reliable data for the rate in Japan. Estimation has been made through estimated increase of ridership.
- Demand of passengers; based on actual data for Yamanote Line.
- Life of vehicle; 30 years. Intermediate heavy repair cost omitted.
- Interesting rate; 3 percent per year.

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In Table 3, basic running cost per section of 1200 meters station spacing is compared by braking methods. And taking regenerative trainset as the basic case, the obtained results of life cycle cost are shown in accumulated cost increase by faster running with less trainsets for both directions in Table 4.

Table 3. Basic cost comparison of braking system with identical performance

Formation	4M 4T	4M 4T	4M 4T
Braking method	Friction	Dynamic	Regenerative
Acceleration energy	82.02 MJ	82.02 MJ	82.02 MJ
Cost for acceleration	342 JPY	342 JPY	342 JPY
Regenerated energy	0	0	46.06 MJ
Cost for braking	192 JPY	0	- 192 JPY
Running cost	534 JPY	342 JPY	150 JPY

Table 4. Accumulated cost increase in billion JPY by various formations

Formation	Running time	after 1 year	10 years	30 years
4M 4T	85 sec	0	0	0
4.5M3.5T	79.83 sec	- 0.48	- 1.76	- 4.75
5M 3T	79.83 sec	+1.56	- 1.02	- 6.45
6M 2T	79.83 sec	+5.34	+3.16	- 1.67

6 Typical optimum design of braking system for Shinkansen-type high speed trainsets

6.1 Actual mass difference due to braking system

Superiority of distributed traction system over concentrated traction has been widely recognised in recent years especially for high-speed trainsets. One of the most important performance indices for high-speed trainset is mass per floor area for revenue purpose. Since ac motor traction was adopted, superiority for distributed traction has been increased as shown in Table 5.

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Table 5. Comparison of mass / floor area for revenue among various formation

Country	**France**	**Germany**	**Intern'l**	**Japan**	**Japan**	**Japan**	**Japan**
Trainset	TGV-A	ICE-1	Eurostar	200 1]	300	500	700 2]
Year	1989	1991	1994	1982	1992	1997	1999
Formation	L 10T L	L 14T L	L9T·9TL	12M	10M 6T	16M	12M 4T
Brake L/M	D, R	R, D	D, R	D	R	R	R
Brake T	4 discs	4 discs	4discs	2 discs	2e.c.discs	NA	1e.c.disc
Train mass t	473	931	800	703	710	700	704
Floor area m^2	505	1002	913	826	1215	1196	1215
Mass / area	**0.937**	**0.929**	**0.876**	**0.851**	**0.584**	**0.585**	**0.579**

Note: 1; dc motor traction 2; brake of trailer reduced to one third that of motor cars
L; locomotive M; motor car T; trailer D; dynamic brake R; regenerative brake

6.2 Optimum design for Shinkansen-type vehicles

It was revealed that total and unsprung mass of eddy-current braked axle is to be bigger than motored axle during the design stage of Series 300. Series 300 has had no time to redesign braking system and actually trailer car with a main transformer is much heavier than motor car with traction inverters. Series 700, which adopted modified design of Series 300, has also trailer cars but with reduced number of cars, number of eddy-current discs per bogie. Braking effort lost is supplemented by increased braking effort by motor cars. Thanks to this modification, mass of trailer cars of series 700 are almost the same as that of the motor cars and unsprung mass of the trailer axle is slightly less than that of the motored axle.

The author proposes to dismantle eddy current disc brake of Series 700 so that service brake becomes pure electric brake with friction brake intact for emergency purpose. This will be possible only if capability of traction inverter is slightly increased because there are as many as 12 motor cars out of 16 cars.

7 Conclusion

Optimum traction design in terms of minimum life-cycle cost is such that proportion of motored axles and power of each axle are just enough for service brake with regenerative mode. If distribution of power is more than enough, cost and mass of the trainset is bigger than the optimum, and if additional friction brake is necessary for service brake, running cost is more than the optimum due to loss of regeneration and increase of maintenance cost for friction brake equipment.

The optimum proportion and power of motored axle depends on train performance, such as maximum velocity and deceleration, and adhesion performance. Even if very small proportion of motored axle is given from low braking requirement and high adhesion performance, too concentrated traction

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system requiring floor area for traction equipment is generally disadvantageous. But further discussion is thought necessary for a double-decker trainset without enough underfloor space for traction equipment such as the case of TGV-2N.

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