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Evaluation of Current Trends of High Speed Trains Brake System

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under mechanical engineering

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DECLARATION

I, the undersigned, declare that this thesis work is my original work, has not been presented for a degree in this or any other universities, and all sources of materials used for the thesis work have been fully acknowledged.

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Name Signature

Place: Addis Ababa

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Date of submission

This thesis has been submitted for examination with my approval as a university advisor.

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ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIES

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Abstract

The research aims reviewing currently available braking systems on different high speed trains which are found around the world and finally evaluates such systems using one of the Multi-criteria decision making method TOPSIS. To do so various factors useful for evaluation were selected and utilized after examining different literatures. The result show that a significant importance of regenerative brake followed by rheostatic, eddy current E-P and magnetic track brakes. The result can help planners and engineers to conduct preliminary general assessments concerning the suitability of the five brake system, to develop tools for evaluation, to assess different brake system for a given high-speed train, and also helpful for anyone who engaged with train braking. The result obtained is satisfactory and currently 82.35% of high speed trains around the world use regenerative brake system.

Key words: - High speed train, brake system, E-P, regenerative, Rheostatic, Eddy current and magnetic track.

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List of Acronyms

AAIT	Addis Ababa Institute of Technology
GDP	Growth domestic product
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
UIC	International union of railway
IGBT	Isolated gate bipolar transistor
EMU	Electric multiple unit
HST	High speed train
EDS	Energy dispersive x-ray spectroscopy
SEM	Scanning electron microscope
AWPER	Air born wear particle emission rate
MCDM	Multi criteria decision making
ATO	Automatic train operation
E-P	Electro pneumatic
ECP	Electronically controlled pneumatic
PWM	Pulse width modulation
TSI	Technical specification for interoperability
MG	Motor/Generator
DC/AC	Direct current/ Alternate current
FWD	Flywheel diode
ICE	Inter City Express
TCU	Traction control unit
BCU	Friction brake control unite
BEA	Brake effort achieved
WSP	wheel slip/slide protection
TS	Tube stock
AD	Aerodynamic diameter
PM	Particle mass
ECTS	European train control system
PMSM	Permanent Magnet Synchronous Motor

CHAPTER ONE: INTRODUCTION

1.1 Background

A brake is a device by means of which artificial frictional resistance is applied to moving machine member, in order to stop the motion of a machine. In the process of performing this function, the brakes absorb either kinetic energy of the moving member or the potential energy given up by objects being lowered by hoists, elevators etc. The energy absorbed by brakes is dissipated in the form of heat or changed to other usable energy (Association, 2004).

Brakes are most important safety parts in trains. Generally all trains have their own safety devices to stop or maintain a constant speed. Trains that regularly travel long distances at high speeds require braking systems that can keep these forces under control – both safely and economically. As well as lightweight, compact systems that can be used worldwide. In general train braking is a very complex process, specific to rail vehicles and of great importance by the essential contribution on the safety of the traffic. This complexity results from the fact that during braking occur numerous phenomena of different kinds - mechanical, thermal, pneumatic, electrical, etc. The actions of these processes take place in various points of the vehicles and act on different parts of the train, with varying intensities. The major problem is that all must favorably interact for the intended scope, to provide efficient, correct and safe braking actions (Association, 2004).

The purpose of braking action is to perform controlled reduction in velocity of the train, either to reach a certain lower speed or to stop to a fixed point. In general terms, this happens by converting the total energy (kinetic, potential and rotational energy) of the train into some useful energy like by using regenerative brake system or converting it to heat and finally dissipates to the environment (Johnson, 2012).

As a consequence, along the time, for railway vehicles have been developed various brake systems, whose construction, design and operation depend on many factors such as running speed, axle load, type, construction and technical characteristics of vehicles, traffic conditions, etc. Among various principles and constructive solutions that were developed, following the studies and especially the results of numerous tests electro-pneumatic brake system proved the most important advantages. Therefore, it was generalized and remains even nowadays the basic and compulsory brake type (Cruceanu, 2008).

Principles of Brake Systems

There are three main principles of braking a running train.

- Adhesion brakes: Brake performed using the adhesion between wheels and rails, which is the most common.
- Track brakes: which use the friction between the track and brake shoes on the train, track brakes are in principle only used as emergency brakes.
- The eddy current brake that instead of friction uses electromagnetic current to create resistance between the track and the brake shoes (Sjöholm, 2011).

The adhesion brakes can in turn be divided into three sub-principles: thread brakes, disc brakes (which are mechanical brakes) and electrical brakes. Electrical brakes can be regenerative or rheostatic brakes that produce retardation force on the wheel and rail by generating electrical resistance force on the traction motor. Some trains use all of the three, with an additional track brake as emergency brake:

- the tread brakes are used to clean the wheel treads and improve the adhesion
- disc brakes as the main mechanical brake and
- Electrical brakes to perform as much of the braking as possible to save energy and mechanical brake wear.

Each disc brake set consists of two pairs of brake pads which press against both sides of a brake disc. The pads are pressed against the disc by a link mechanism, which normally is controlled by a pneumatic cylinder. The discs can be placed on the wheel axle (usually between the wheels) or on the wheels themselves. The pads are usually made of an organic or sintered material; the latter makes them able to withstand higher temperatures. The discs are usually made of steel, but they can also be made of an aluminum alloy to save weight.

The electrical brake can be either rheostatic or regenerative and produces brake force by using the traction motors as generators. In both cases a braking torque on the wheel axle is produced, which in turn produces a braking force between the wheels and rails. If it's rheostatic the kinetic energy is transformed into heat in resistors. If it’s regenerative the electrical energy can be returned to the catenary and used by other trains or sometimes it is even possible to feed it back to the public grid. A big advantage of regenerative brakes is the possibility to re-use the electrical energy that otherwise would have been transformed into heat when using either rheostatic electrical brakes or mechanical brakes. This benefits both the environment and the economy for the operator. There is also a big advantage as the wear of the mechanical brakes becomes lower which prolongs the maintenance intervals. For safety reason the mechanical brakes must be capable to stop the train running at full speed at a maximum distance. This means that each brake disc must be able to dissipate a large amount of energy in a very short time, in some cases up to 25 MJ (about 7 kWh) per disc in less than two minutes (TGV train braking from 310 km/h) (Desplanques Y., 2007).

The pad material is sometimes depending on whether they are used for a locomotive, motor coach or a trailing car. Locomotives and motor coaches usually have sinter pads which can withstand higher temperatures while trailing cars sometimes are equipped with organic pads, mainly for economic reasons (Lönnermo, 2010).

Definition of High Speed Trains

High Speed Rail System is a relative term, which constitute the "system" i.e. infrastructure, rolling stock and operating conditions.

1. According to UIC "high-speed train" is defined as a train that runs at over 250 km/h on dedicated tracks or over 200 km/h on upgraded conventional tracks.
2. The Council Of The European Union, The rolling stock referred to in this Directive shall comprise trains designed to operate: either at speeds of at least 250 km/h on lines specially built for high speeds, while enabling operation at speeds exceeding 300 km/h in appropriate circumstances, or at speeds of the order of 200 km/h on the lines of upgraded conventional track.
3. In the United States, the term "higher-speed rail", as opposed to "high-speed rail", is used by regional planners in many U.S. states to describe inter-city passenger rail services with top speeds of between 90 mph (145 km/h) and 110 mph (177 km/h). This is the equivalent of the definition of Emerging High-Speed Rail as defined by the Federal Railroad

> Administration. However, the Congressional Research Service defines Higher Speed Rail as rail services with speeds up to 150 mph (241 km/h) and defines rail services on dedicated tracks with speeds over 150 mph (241 km/h) as Very High Speed Rail

For the purpose of this thesis trains runs over 200 km/hr considered as high speed.

List of High Speed Trains

The following is a list of high-speed trains with their respective brake types used (Administration), (Consortium) and (http://en.wikipedia.org/wiki/List_of_high-speed_trains).

Table 1.1: List of High Speed Trains

No	Train type	Design Speed (km/h)	Brake system used
1	Alstom TGV	320	E-P disc and regenerative brake.
2	Alstom AGV	360	Rheostatic, regenerative braking and E-P disc brakes.
3	Alstom Pendolino	220	Regenerative, Rheostatic, E-P Disc brakes
4	Bombardier Acela Express	265	Regenerative and rheostatic braking.
5	Bombardier Zefiro	300	E-P and regenerative brake.
6	Caf ATPRD S/120	250	Regenerative and rheostatic brakes, supplemented with E-P brake
7	Shinkansen 800 Series	260	Regenerative E-P and Aerodynamic resistance braking
8	Shinkansen 200	275	Rheostatic, and E-P disc brake
9	Shinkansen 300	270	Regenerative, E-P disc and Eddy current brake
9	Hitachi A-Train	225	Regenerative braking
10	Siemens Velaro ICE 1 and 2	280	Regenerative, Rheostatic, E-P brake
11	Siemens Velaro ICE 3	330	Regenerative, Eddy current and E-P brake
12	Talgo 350	350	Regenerative and Rheostatic brake
13	CRH3	350	Regenerative and E-P brake

14	Amtrak Acela Express	266	Rheostatic and E-P brake
15	X2	210	Regenerative, magnetic track and E-P brake
16	ETR450	280	Rheostatic and E-P brakes

The following table shows that how high speed trains use combination of brake systems to stop or maintain constant speed of a train.

Table 1.2: Combination of brake systems on high speed trains

Rheostatic and E-P brake	Amtrak Acela Express, ETR450 and Shinkansen 200
Regenerative brake	Hitachi A-Train and Shinkansen800 Series
Regenerative and E-P brake	CRH3, Bombardier Zefiro and Alstom AGV
Regenerative, E-P brake and eddy current brake	Shinkansen 300 and Siemens Velaro ICE 3
Regenerative, Rheostatic and E-P brake	Siemens Velaro ICE 1 and 2 and Caf ATPRD S/120, Alstom Pendolino and Alstom AGV
Regenerative and Rheostatic brake	Talgo 350, Bombardier Zefiro and Amtrak Acela Express
Regenerative, magnetic track and E-P brake	X2 train

Current high speed trains use two or more of the combination of electro-pneumatic brake, dynamic (rheostatic+regenerative) brake, electro-magnetic brake and eddy current brake. Air resistance brake is only used in the Japanese Shinkansen. This thesis work examine and compare the technological options available for the above mentioned brake types, except air resistant brake which is only used by Shinkansen, in the major ground transportations of high speed trains around the world. Each of brake type reviewed based on the following criteria:

- The working principle
- Main components
- Merit and demerit

1.2 Statement of the Problem

The need of transportation demand in Ethiopia is growing, as a product of economic, developmental and population growth. To accelerate the economic, educational and social growth of the country, the Ethiopian government implementing rail transport system in two phases. In the first phase constructing light rail transit in the capital city Addis Ababa and freight and passenger train transport from Addis Ababa to Djibouti. On the second phase a rail transport system that joins main cities of the country will be constructed. According to the World Bank and the national bank of Ethiopia the country's GDP growing in two digits. In the future this GDP will need a better transport system that facilitates the economic growth. Trends of other countries show that after constricting high speed rail system their economic growth increases and their transportation system more facilitated. Such rail system needs a high level of safe brake systems to run at their maximum performance.

This thesis work reviews and evaluates currently available high speed trains brake system around the world based on evaluating criteria. Such work is important in future implementation of high speed train system by removing improper selection of brake system which will lead to inefficient control of the train, economical crises and environmental pollutions.

1.3 Research Objectives

1.3.1 General Objective

The general objective of this research is reviewing the current trends of high speed trains brake system and finally examining each brake systems by preparing evaluation criteria.

1.3.2 Specific Objectives

- Reviewing high speed trains brake type, merit, demerit and working principles.
- preparing evaluating criteria
- Selecting evaluating method
- Evaluating and ranking the braking system by the method TOPSIS.

1.4 Significance of the Research

This research basically reviews and evaluates high speed trains brake systems. Efforts have been made to gain leverage from the ability of TOPSIS to evaluate brake types by preparing evaluation criteria.

This research will give the better braking system for high speed trains based on the evaluation criteria. The insights obtained from this research, will help engineers, planners and workers related with train brakes to know the fundamental usage of each brake system, to prepare evaluation criteria and examine each brake system based on the specified method.

1.5 Limitations

Limitations are constraints to the research which cannot be easily accessible to conduct the research smoothly. There are many constraints for this research and some of them are summarized and listed below:

- Current data for each evaluation criteria is not easily accessible from manufacturers and suppliers and all data are taken from previous researches.
- Data for some criteria were not found interms of number and benefit ratings for such criteria were given based on discussion.

1.6 Research Outline

The topics to be discussed in the next chapters are outlined here as follows. In chapter 2 literature review is performed on the definition of high speed train, evaluation and review of brake systems. In chapter 3 brake systems are reviewed base on their working principle, advantage, disadvantage and main components. In chapter 4 brake systems are examined based on evaluation criteria. Chapter 5 is the last chapter of this research and therefore the result, discussion, conclusions and future works are laid down in this chapter.

CHAPTER TWO: LITERATURE REVIEW

In order to understand the leading edge of high speed trains braking systems, literatures have been studied related to this topic. In this section, some important and useful articles are summarized. This review mainly focused on Research works containing working principle, merits and demerits, components and the evaluation criteria of braking systems which are used in high speed trains.

2.1 Review of Brake Systems

(Sjöholm, 2011), his research is part of research and development program that is preparing for new high-speed trains in Sweden. The purpose of this study was to investigate the effects of regenerative braking and eco driving with regard to energy consumption and wear of the mechanical brakes.

The first part of the study aims at developing a method to calculate wear on train brake pads. This was done by using a reformulated version of Archard's wear equation with a temperature dependent wear coefficient and a temperature model to predict the brake pad temperature during braking. The temperature model is calibrated using trustworthy data from a brake system supplier and full-scale test results.

By performing simulations in the program STEC (Simulation of Train Energy Consumption), energy consumption for different cases of high-speed train operations is procured and significant data for the wear calculations are found. Simulations include both "normal driving techniques" and "eco driving". The driving styles were decided through interviews with train drivers and experts on energy optimized driving systems. In general his research focuses only the benefits of regenerative braking interms of energy saving and reduction of pad and disc materials wear by considering different riding conditions.

(Podol'skii S. K.), in their work the investigation of eddy-current and magnetic rail brake structures are described. They state the working principle of both eddy-current and magnetic rail brakes. Comparisons on experimental and computed operating characteristics of eddy-current and magnetic rail brakes for use on a tram-car, on a railroad vehicle, and on a high-speed train are presented. It is demonstrated that a brake built up from permanent magnet pieces that combines both magnetic rail brake and eddy-current brake permits of the most profitable braking action through the whole range of acceptable speeds – from zero (a parking brake) to 350 km/hr. Their research reviews the working principle and using of permanent magnet instead of conventional magnet for both of eddy current electromagnetic track brake.

(lionginas liudvinavicius, 2009), the paper considers some theoretical and practical problems associated with the use of traction motor as a generator during braking in high speed trains. Mathematical and graphical relationships of electro dynamic braking, taking into account the requirements raised to braking systems in rail transport are presented. The latter include discontinuity of braking process, braking force regulation, depending on the locomotive speed, mass, type of railway and other parameters. Schematic diagrams of the locomotive braking and ways of controlling the braking force by varying electric circuit parameters are presented. The authors suggested contact-free regulation method of braking resistor for controlling braking force in rheostatic braking, and resistor parameters regulate with pulse regulation mode by semiconductor devices, such as new electrical components for rolling stock – IGBT transistors operating in the key mode.

(Alper Kara, 2013), energy saving on urban rail systems has been studied and the major parameters affecting energy consumption are defined as the driving strategy, regenerative braking and energy storage systems. In this study, the factors influencing energy consumption is analyzed and innovative solutions are extensively reviewed. The present paper reports the main results of analysis and giving some suggestions about possible energy saving actions in electric power system. Lastly, the advantages of current energy storage systems are stated.

(Painter, 2004), a study was conducted on the potential recovery of dynamic brake energy from diesel-electric locomotives in North American freight service. He briefly reviews regenerative and rheostatic braking based on the working principles, the advantage and disadvantage and also the main components of the brake system. Also he shows the energy recovered from dynamic braking using computer simulation (Train Energy Model) and locomotive event recorder data.

(Gay, 2005), his dissertation includes an introduction to friction braking, a theory of eddy-current braking, analytical and numerical models of the eddy-current brake, its excitation and power generation, record of experimental validation, investigation and simulation of the integration of the brake in conventional and hybrid vehicles.

Railway systems, technologies and operations across the world (Kongphan, 2007), in this paper technology on railway were reviewed. E-P and EPC brake systems also reviewed in detail based on their function, components, advantage and disadvantages.

2.2 Evaluation of Brake Systems

(Johnson, 2012), the benefit of adopting an 'all-electric brake' system is analyzed. This research establishes the constraints that need addressing to permit this approach ('all-electric brake') and proposes alternative solutions that would need to be adopted to replace the air systems on trains. The research includes evidence gathered from interviews with leading industry stakeholders from train operating companies, train leasing companies and suppliers of vehicles, traction systems and friction braking systems as well as examination of specifications and standards.

The research is divided in to three discrete packages these being; to assess the current dynamic brake capability of trains under all service and emergency braking situations, to consider how the rail industry could exploit an 'all-electric brake' with no pneumatic brake and to discuss the impact of an air free train on the other vehicle systems.

This report describes the dynamic brake capability of trains in the UK and also in a number of other countries including parts of Europe, the USA, Russia and Japan. Other countries have allowed a far greater capacity of dynamic brakes. The Shinkansen Series 800 trains use only dynamic braking during service and emergency braking. Moscow Metro does not have a fully rated friction brake and trains are withdrawn from service should the train be degraded through failure of the dynamic braking systems. The Siemens ICE3 high-speed train uses eddy current track brakes to supplement the dynamic brake. The research also revealed that there have been advances and developments in friction braking systems, most notably the development new friction materials and an electric actuator for friction brakes. This has the added benefit of an integrated parking brake function. According to this research electric braking to zero speed and the implementation of a 'safety brake' is possible by the use of permanent magnet synchronous machines. They also offer significant advantages over induction machines such as an increased power to weight ratio.

The simulations completed for this research are based on designing a dynamic brake capable of achieving a normal service braking of 0.6m/s2 for an electrical multiple unit, EMU, and 0.3m/s2 for the high-speed train. Modeling with this nominal service braking performance has shown that an ‘all-electric brake’ EMU could be achieved with a 75% motored four car unit fitted with eddy current track brakes on six bogies. Similarly, for a high-speed train (HST), an ‘all-electric brake’ HST could be achieved with a 50% motored nine car unit fitted with eddy current track brakes on nine bogies. Both train types will need electrically actuated parking brakes capable of deployment in an emergency. The actual arrangement of eddy current track brakes, motored axles and electrically actuated friction parking brakes will depend on the train performance requirements and the balance required between capital cost and life cycle costs. Other solutions that allow variable rate braking could reduce the required motorization.

There is a significant cost benefit in adopting an ‘all-electric brake’ philosophy over the anticipated 25-year lifetime of the train systems due to the reduced maintenance requirements, reduced use of friction brake consumables and energy savings. An ‘all-electric brake train is likely to be heavier than its pneumatic equivalent and additional track costs will be associated with this increase in mass. Increasing the dynamic brake capability and removing the pneumatic friction braking system may reduce un-sprung mass at the expense of increasing the sprung masses. This will depend on the mix of braking and the eddy current track brake mounting arrangement if fitted. Further work is recommended to validate the anticipated savings in pneumatic system maintenance and reduced usage of friction consumables to validate the costs estimated for this study.

Savings could also be made in electrification systems if regenerative braking is considered and this could be of the order of six to eight million pound for a new 20km line. The rolling stock financial review does not account for these possible savings.

This research concludes that, subject to the constraints mentioned, all electric braking is possible with technology already proven in service today. An all-electrically braked train would probably have a higher percentage of motored axles than current and will likely be fitted with a mix of eddy current track brakes and electrical friction brake actuators. The dynamic brake would need to be active in emergency brake and wheel-slide protection available at all times. The electric friction brake actuators would be part rated and retains a limited ‘failsafe’ emergency brake function. Permanent magnet motors are likely to be a significant feature of future traction systems and these offer the possibility of safety critical braking.

Generally this research reviews available braking systems up to 2012 based on different criteria and making a simulation of braking without air system. Finally he recommends adopting all electric braking systems for new manufactured trains.

(Vinzents P.S. M. P., 2005), this work reviews recent researches on particle emissions from rail vehicles. Both exhaust and non exhaust particle emissions are characterized by size, morphology, composition, and size distribution. Current legislation, knowledge of adverse health effects, and available and proposed solutions for emission reductions are also treated. Emission of airborne particles is a side effect from rail transport.

(Saeed Abbasi), their study investigates the characteristics of particles generated from the wear of braking materials, and provides an applicable index for measuring and comparing wear particle emissions. A pin-on-disc tribometer equipped with particle measurement instruments was used. The number concentration, size, morphology, and mass concentration of generated particles were investigated and reported for particles 10 nm to 32 μm in diameter. The particles were also collected on filters and investigated using EDS and SEM. The effects of wear mechanisms on particle morphology and changes in particle concentration are discussed. A new index, the airborne wear particle emission rate (AWPER), is suggested that could be used in legislation to control non-exhaust emissions from transport modes, particularly rail transport.

(Ziemke, 2010), the study evaluates and compares two high-speed ground transportation systems that have the potential to improve intercity passenger transportation in the United States significantly: the wheel-on-rail high-speed system and the high-speed maglev system. Both high-speed ground transportation systems were evaluated with respect to 58 characteristics organized into 7 categories associated with technology, environmental impacts, economic considerations, user-friendliness, operations, political factors, and safety. Based on the performance of each system in each of the 58 characteristics, benefit values were assigned. In order to weight the relative importance of the different characteristics, a survey was conducted with transportation departments and transportation professionals. The survey produced weighting factors scoring each of the 58 characteristics and the 7 categories. Applying a multi-criteria decision making (MCDM) approach, the overall utility values for either system were calculated based on the benefit values from the systems comparison and the weighting factors from the survey.

CHAPTER THREE: REVIEW AND EVALUATION OF HIGH SPEED TRAINS BRAKE SYSTEMS

3.1 Review of brake systems

3.1.1 Electro-Pneumatic Brake System

3.1.1.1 Background

Originally designed for subways or metros, the electro-pneumatic brake has more recently been used on main line passenger railways and some specialized freight operations. Its main advantage over the air brake is its speed of control and quick on-vehicle reaction times, giving instantaneous control of the whole train to the driver. Its speed of operation makes it ideal for automatic train operation (ATO). E-P braking is not the same as ECP braking. ECP brakes have been introduced recently in an attempt to overcome the drawbacks of the air brake system on long freight trains.

Even the most modern, purely air brake systems rely on the transmission of an air signal along the brake pipe. This is initiated from the front of the train and has to be sent to all vehicles along the train to the rear. There will always be a time lapse (called the propagation rate) between the reaction of the leading vehicle and the reaction of one at the rear. This time lapse is a considerable restraint on operation. It causes the braking of vehicles to happen at different times along the train so that while some cars are slowing down; others are still trying to push, unbraked, from the rear. When releasing, the front of the train is pulling the rear, still braking, and causes stress to the couplers. Another drawback is the lack of a graduated release, an elusive goal for many years.

The introduction of electric traction and multiple unit control was the spur which eventually produced electrically controlled air brakes. The rise of rapid transit operations in cities, with their high volume and frequent stops and starts, meant that quick responses to brake commands and accurate stopping at stations was an essential ingredient in getting more efficiency. E-P brakes first appeared in the US. They were tried on the New York Subway in 1909 and then on London Underground in 1916 (Kongphan, 2007).

3.1.1.2 General Working Principles of the E-P Brake

There are many types of e-p brake systems in use today and most of them were developed as an "add-on" to the original air brake system. Working system of air brake is; Compressed air is generated and processed (dried and filtered) and stored in a reservoir. This reservoir feeds air to the automatic air-brake pipe that is connected to all vehicles. On each vehicle, the automatic air-brake pipe supplies air to a distributor designed to maintain the auxiliary reservoir at a fixed pressure. During braking, air is fed to a brake cylinder that applies a braking force to the brake pads and disc system in the calliper. The brake cylinder pressure is varied, according to the driver’s demand and brake blending, to control the retardation of the train

A basic e-p brake system as applied to a multiple unit train comprises an electrically operated "holding valve" and "application valve" on each car together with control wires running the length of the train. The main reservoir is also connected to each car on the train by a main reservoir pipe. Often more than one main reservoir is provided. Usually, each car also has an "e-p brake reservoir".

The e-p brake operates independently of the air brake. It uses main reservoir air instead of brake pipe air and the air brake and triple valves are kept in the release position. The e-p brake is controlled from the same driver's brake valve as the air brake but using new positions to apply and release the e-p brake. Electrical connections attached to the driver's brake valve send commands along the train to the holding and application valves on each car.

To apply the brake the driver selects "Application", which causes all holding and application valves to energize. The holding valve closes off the brake cylinder exhaust and the application valve opens to admit main reservoir air into the brake cylinder. Selecting "Release" de-energizes the valves, closing the application valve and cutting off the main reservoir pipe connection and opening the holding valve to allow brake cylinder air to exhaust. E-P brakes should not be confused with ECP (Electronically Controlled Pneumatic) brakes. E-P brakes are used on multiple unit passenger trains whereas ECP brakes have been developed recently for use on freight trains. ECP brakes do not always require a train wire and, if they do, it is usually a single wire. There are two types of e-p brakes:

1. Analogue E-P Brake Control

A form of electro-pneumatic brake, normally restricted to multiple unit trains, which uses a single train wire to control the braking on each vehicle. The brake commands consist of pulses of electricity applied to the wire, a continuous signal denoting brake release and a loss of signal an emergency brake application. The brake control valve on each vehicle detects the length of the pulses and provides air input to the brake cylinders accordingly. The air supply is from the main reservoir pipe. The analogue e-p brake system requires no brake pipe and the brake commands can be generated by a driver's brake controller or an automatic train driving system (ATO). It is also known as PWM (pulse width modulation) control or P-wire for short.

2. Digital E-P Brake Control

A development of electro-pneumatic (e-p) brake control is the digital control system. It is normally only used on multiple unit trains. It incorporates the fail-safe features of the air brake but eliminated the need for a brake pipe. The brake pipe is replaced by a "round the train wire" which is permanently energized. As long as it remains energized, the brake remains released. If it loses current for any reason, an emergency application follows.

3.1.1.3 A Simple E-P Brake System

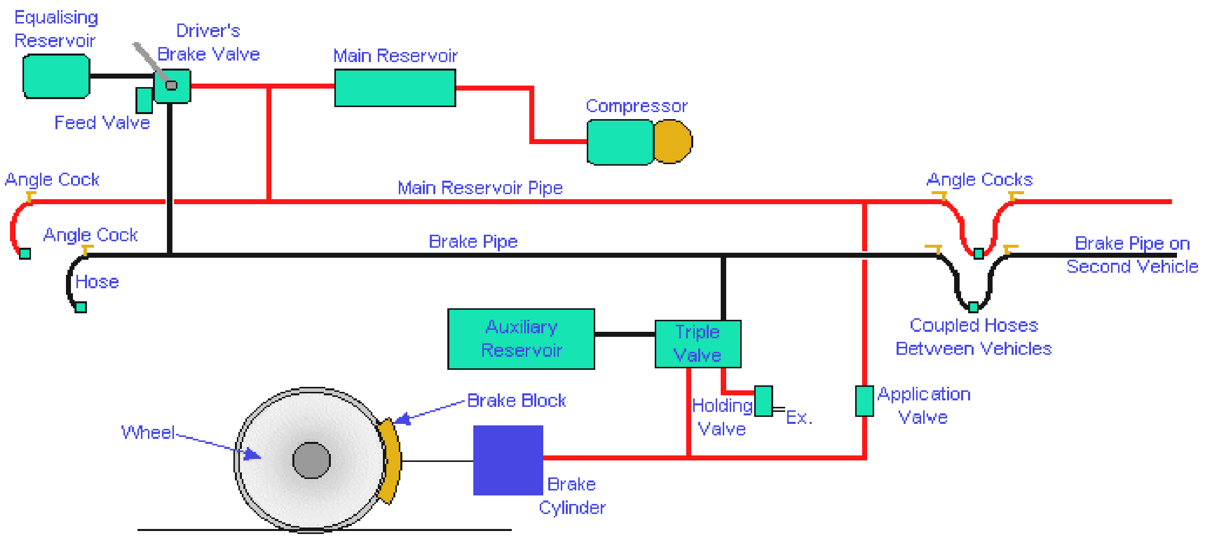

Fig. 3.1: Block diagram of electro-pneumatic brake system (Kongphan, 2007)

The diagram above shows the pneumatic layout of a simple e-p brake system. The special wiring required is shown in the e-p brake electrical diagram.

The standard air brake equipment is provided as the safety system for back-up purposes. A main reservoir pipe is provided along the length of the train so that a constant supply of air is available on all cars. A connection pipe is provided between the main reservoir and the brake cylinders on each car. An "application valve" in this connection pipe will open when required to allow main reservoir air into the brake cylinders. Because the brake pipe is fully charged during an e-p application, the triple valve is in the release position so the brake cylinder is connected to the exhaust. For e-p operation, a "holding valve" is added to the triple valve exhaust. When an e-p application is called for, the holding valve closes and prevents brake cylinder air escaping through the exhaust.

3.1.1.4 E-P Brake Application

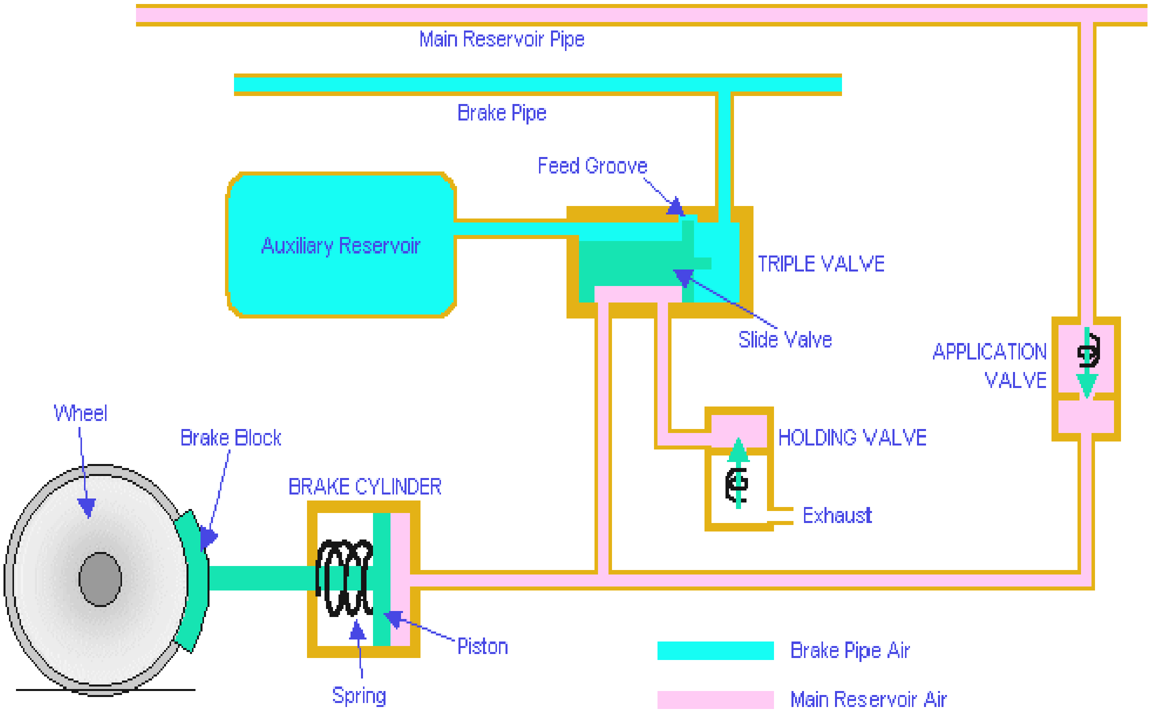

Fig. 3.2: Schematic diagram of electro-pneumatic brake application position (Kongphan, 2007)

This diagram shows the operation of the holding and application valves during an e-p brake application. The application valve is energized and open while the holding valve works the opposite way, being energized and closed. Main reservoir air feeds through the application valve into the brake cylinder to apply the brakes in the usual way.

3.1.1.5 Brake Cylinder Pressure

It is essential to ensure that, during braking, the train wheels do not skid. Skidding reduces the braking capability and it damages wheels and rails. Wheels involved in a skid will often develop "flats", a small flat patch on the tyre which can normally only be removed by re-profiling the wheel in a workshop. To reduce the risk of skidding, brake cylinder pressure must be restricted. In a pure air brake system, a natural restriction is imposed by the maximum allowed brake pipe pressure and in the proportion of volume between the auxiliary reservoir and the brake cylinder. In an e-p equipped train, the main reservoir supply is not restricted, so it would be possible to go on pumping air into the brake cylinder until it burst. Of course, this will not happen because the brake cylinder is fitted with a safety valve (not shown in the diagram) set at the maximum pressure normally obtained in full braking.

3.1.1.6 E-P Brake Release

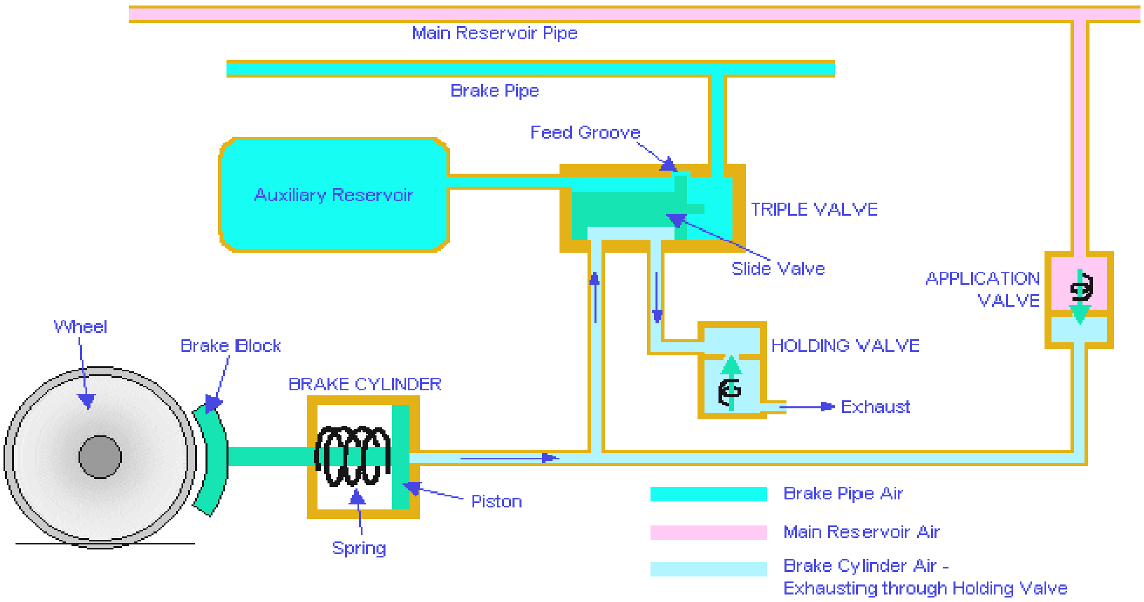

Fig. 3.3: Schematic diagram of electro-pneumatic brake in release position (Kongphan, 2007)

In the "Release" position (diagram above), both electrically operated valves are de-energized, the application valve being closed and the holding valve being open. Once the holding valve is open, brake cylinder air can escape and release the brakes. It is possible to stop the release by energizing the holding valve again. This prevents any more brake cylinder air escaping. By adjusting the applications and releases of the brake during the stop, the driver is able to get a very precise stopping position. In addition, the response of the equipment to his commands is instantaneous on every car. This sort of control is essential for a rapid transit service on a metro line with frequent stops, heavy patronage and short headways.

3.1.1.7 E-P Brake Control

Electro-Pneumatic brakes are controlled by the driver's brake valve handle. It is usually the same handle used to control the air brake. Electrical contacts are provided so that selection of a position will energize the train wires required to operate the e-p valves on each car, as shown below. Current to operate the brake control is supplied from a battery through a control switch, which is closed in the operative cab. In the release position, all contacts are open and the e-p valves on each car are de-energized. In the "Application" position, the holding and application contacts are energized and the holding and application valves will be energized on each car to cause the brakes to apply. Note that the contact for the holding wire is arranged to close first so that no air will escape when the application valve is opened.

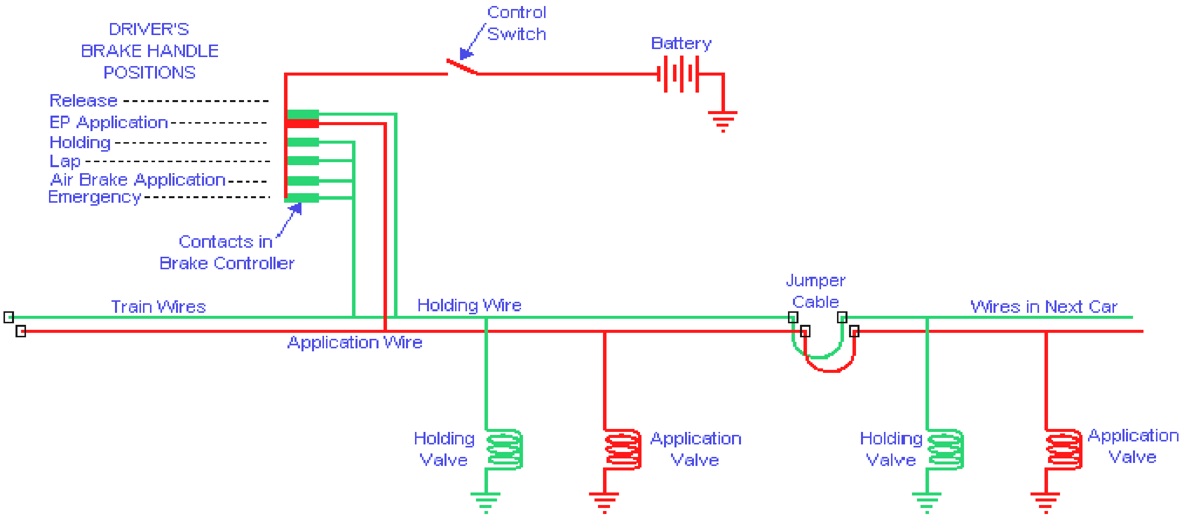

Fig. 3.4: Electrical diagram of electro-pneumatic brake control system (Kongphan, 2007)

In the "Holding" position, only the holding wire is energized. If this position is selected after an application, the brake cylinder pressure remains at the value reached at that time. In effect, the driver can add or subtract air at will and can obtain an infinite variety of braking rates according to the requirements of each stop.

3.1.1.8 E-P Variations

There have been a number of developments of the e-p braking system over the years, including a common addition the "Self Lapping" brake. There have also been "retardation controllers" and, more recently, variable load control and single wire or P-wire control. In all other positions, only the holding wire is energized. In reality, it is not needed to allow the operation of the air brake but it is closed anyway to act as a backup.

3.1.1.9 Self Lapping Brakes

A "self lapping" brake is really a brake controller (brake stand or brake valve, call it what you will) in the driver's cab, where the position of the brake handle between "Release" and Application" corresponds to the brake rate achieved by the equipment in theory at least. This is similar in principle to the self lapping controllers fitted to some air braked locomotives. A number of different systems have been adopted, including one which uses a pressure sensitive valve detecting brake cylinder pressure and comparing it with the position of the brake handle. When the pressure corresponds to the position of the brake handle, the application electrical connection is opened to keep the brake cylinder pressure at that level.

Another version was developed, using mercury filled tube inside the brake controller. The mercury was used to conduct the control current to the application and holding wires. The shape of the tube was oval and it was aligned "forward and aft" so it allowed the mercury to flow forward if the train started braking. When "Application" was called for, the movement of the brake handle towards full application tilted the mercury tube backwards and caused the holding and application valves to be energized. As the train brakes applied, the mercury detected the slowing of the train and it ran forward in the tube. This had the effect of cutting off the application so that the rate of braking conformed to the angle of the tube set by the driver's movement of his brake handle.

3.1.1.10 Retardation Controller

The mercury brake controller was an adoption of a device introduced to London Underground in the mid-1930s called the "mercury retarder" or "retardation controller".

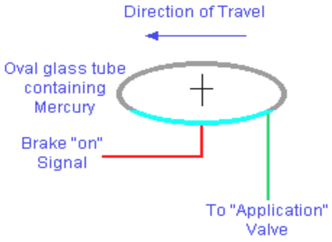

Fig. 3.5: Mercury retarder (Kongphan, 2007)

The mercury retarder is a dynamic switch set into the electro-pneumatic brake application circuit, comprising a glass tube filled with mercury. It is mounted parallel to the motion of the train so that the mercury fluid reacts to the train's braking. The tube is curved so that the electrical contact at the base is always covered with mercury but a second contact, set higher up the rear of the tube, becomes exposed when the mercury runs forward during braking. It has the effect of measuring the deceleration rate. It cuts off application at a pre set level, no matter how much more the driver tries to put into the brake cylinders. Its main purpose was to reduce flatted wheels. It also acted as a crude form of load compensation.

In the London Underground version, two retarders were provided and they were stationary, being fixed in the driving car. They were used to regulate the rate of braking at the full application end of the range, primarily to reduce skidding and the dreaded "flats" on wheels. One retarder limited the application while the second was used to reduce the brake cylinder pressure by releasing some air through a special "blow down" valve.

Retardation controllers were later used to control braking rates on the world's first ATO railway, the Victoria Line. Four were used in all, each being set at a different angle and selected as necessary to give the required braking rate. They were also used by British Rail as self-lapping brake controllers provided on the EMU stocks built in the 1960s and 70s (http://www.railway-technical.com/index.shtml).

3.1.1.11 Variable Load Control

Although the retardation controller is a form of load control - because the braking rate is monitored, a heavier train will require more brake cylinder pressure, so the retarder will not reach its setting until the right rate is reached - it is rather crude. It only monitors the whole train, not individual cars. This means that lightly loaded cars in a generally heavy train are still at risk from a skid or wheel slide, as it is called. The solution is in variable load control. The car weight is monitored, usually by a lever fitted between the car and the bogie, which detects the bogie spring depression as weight increases. The lever is connected to a regulating valve in the brake cylinder feed pipe, so that the brake cylinder pressure is varied in relation to the weight of the car. With the introduction of air suspension, load control is achieved by monitoring the level of air in the suspension system and regulating brake cylinder pressure accordingly. Nowadays, the same load signals are used to vary acceleration and dynamic braking according to car weight.

3.1.1.12 E-P Wire Control

As train control systems grew more complicated, more train wires were required and the traditional 10-wire jumper used by so many railways grew to the 40-wire jumper often seen today. In an attempt to reduce wiring, a novel form of e-p brake control appeared in the 1970s called the P-wire system. The brake rate was controlled by a single wire carrying pulses of different lengths to correspond to different brake rates. The pulse width was modulated to correspond to the brake demand required and it became known as the PWM (Pulse Width Modulation) system or P-wire, for short. The system was "fail-safe" in that no pulse activated the full brake while a continuous pulse kept the brake released.

3.1.1.13 Parking Brakes

Most modern EMUs are fitted with spring applied, air release parking brakes. The spring applies the brake force to the pads and discs directly and air is applied to the cylinder to counteract the spring force to remove the parking brake. The parking brake can be integrated into the brake actuator to provide all braking functions (service, emergency and parking) in one unit. The parking brake function is designed to achieve the requirements of the relevant applicable standard. GM/RT2044 requires that ‘Each multiple unit shall be fitted with a parking brake that is capable of holding the multiple units stationary on a gradient of 1 in 30 in the tare condition’.

The High Speed TSI requires that ‘It shall be possible to keep a train with a normal load stationary for an unlimited period on a 35‰ gradient’ provided that power remains available. If the power fails, then the parking brake must hold the train on this gradient for at least 2 hours.

In order to hold a train of mass M on a gradient of 35‰ then the friction force must be greater than Mx0.035kN. Once the required parking brake force is known, it is a simple matter for the brakes design engineer to determine the number of parking brakes required on a train, taking into account any safety factor.

3.1.1.14 Pneumatic Friction Braking System Developments

New materials are being developed for friction braking systems such as ceramic discs. These can withstand far higher temperatures and can, therefore, store and dissipate more energy. A 20kg ceramic disc being developed by Faiveley replaces two 120kg steel discs. A TGV axle has four steel discs that could be replaced by just two ceramic discs representing a potential saving of approximately 640kg (assuming that each brake actuator is around 100kg) per braked axle. (Johnson, 2012) Provides the following data:

Table 3.1: Energy and Mass of Brake Discs (Johnson, 2012)

Disc	Pad	Capacity (MJ)	Mass
Cast-iron	Organic	12	140
Aluminum	Organic	12	84
Steel	Sintered	35	140
Ceramic coated	Ceramic	50	140
Fiber reinforced ceramic	Ceramic	60+	55

3.1.1.15 E-P Brakes Advantage

- E-P system allows instantaneous reaction on all cars at the same time and it allows small and graduated applications and releases. This gives accurate and rapid stopping, which is particularly important in suburban and rapid transit operations.
- The driver’s brake valve is self-lapping; the position of the valve activates a specific brake pressure in the brake cylinders and therefore a specific braking rate

- The distributors are activated instantly and simultaneously, so that there is no longitudinal surging and the response is consistent irrespective of train length.
- Release of a brake application starts instantly in response to the driver’s brake valve, throughout the train; and partial release and re-application is possible
- The analogue e-p brake system requires no brake pipe and the brake commands can be generated by a driver's brake controller or an automatic train driving system (ATO).

3.1.1.16 E-P Brakes disadvantage

- E-P brakes are not normally used on freight trains because of the diversity of wagons and the cost of conversion. Also, getting an electric signal to transmit at a low voltage down a very long train is difficult.
- Another disadvantage in current railway train design is that the engineer has no access to critical operating data from other vehicles in the train. The computers used in modern E-P braking systems have very little functionality beyond applying the brakes and other brake associated tasks.
- Like other air brake systems its large volume and weight needed considered as a disadvantage.

3.1.1.17 Summary for Friction Brakes

- Pneumatic friction braking is a mature railway technology.
- The cost of ‘consumables’ is significant.
- New, lighter and more efficient braking materials are being developed.
- Electric actuators have been developed to replace pneumatic actuators. These have an integral parking brake function which has a safety critical function.
- Modern rolling stock has a ‘spring applied – air release’ parking brake system.
- It would be possible to replace the pneumatic friction brakes with electrically actuated friction brakes to achieve the goal of an all electrically braked train but this would not improve the efficiency of the train nor reduce the consumables used.

3.1.2 Regenerative Brake

As the basic law of Physics says ‘energy can neither be created nor be destroyed it can only be converted from one form to another’ in conventional brake system during braking huge amount of energy is lost to atmosphere as heat. It will be good if we could store this energy. Regenerative braking is any technology that allows a vehicle to recapture and store some part of the kinetic energy that would ordinarily be lost when braking. It is an energy recovery mechanism which slows a train by converting its kinetic energy into another form, which can be either used immediately or stored until needed. Electric railway vehicles feed the recaptured energy back into the grid, while road vehicles store it for re-acceleration using flywheels, batteries or capacitors. Regenerative braking is a small, yet very important, step toward our eventual independence from fossil fuels.

Regenerative braking is an important control technology of DC metro trains that reduces train speed by converting some of its kinetic energy into current instead of dissipating it as heat as with a conventional brake. The ratio of modern trains with regenerative braking function has been increased in the latest years, and electric railways need new strategies both in electrification and train controls in order to take advantages of braking energy recycling effectively (Gonzalez, 2010).

The two main reasons to employ regenerative brake are energy saving and reduced wear of mechanical brakes. The technique of regenerative braking is most effective in full stop passenger trains and subway (metro) trains, because they stop often enough to make recovery worthwhile. The rate of regenerated energy usage can be increased with synchronizing of departing and arriving trains in a station (Gonzalez, 2010).

In regenerative brake system, the braking controller is the heart of the system because it controls the overall process of the motor. The functions of the brake controller are monitor the speed of the wheel, calculate the torque, rotational force and generated electricity to be fed back into the catenary or energy storage system (Gonzalez, 2010).

Electric railway systems can be either DC or AC powered. It is much easier to implement regenerative breaking for AC powered systems. For DC powered systems, there are two main barriers:

- Most DC powered systems use relatively low voltages and
- Often the generated electricity cannot be fed back into the public electricity grid.

In very dense suburban DC powered networks, however, regenerative breaking can be an effective way to reduce the electricity demand. In all other cases, the effectiveness of regenerative braking is rather low but may be enhanced by technological upgrades of vehicles and/or substations. These upgrades are associated with relatively high investment costs.

Railway systems working with AC power can implement regenerative braking with almost no additional costs. Also the implementation of regenerative braking in diesel powered locomotives poses no obstacle. Virtually all locomotives are diesel-electric, so the capacity to do regenerative braking is available (Sjöholm, 2011).

3.1.2.1 General Working Principle of Regenerative Brake

Concept of this regenerative brake is better understood from bicycle fitted with dynamo. If our bicycle has a dynamo (a small electricity generator) on it for powering the lights, we'll know it's harder to peddle when the dynamo is engaged than when it's switched off. That's because some of our peddling energy is being "stolen" by the dynamo and turned into electrical energy in the lights. If we're going along at speed and we suddenly stop peddling and turn on the dynamo, it'll bring us to a stop more quickly than we would normally, for the same reason: it's stealing our kinetic energy. Now imagine a bicycle with a dynamo that's 100 times bigger and more powerful. In theory, it could bring our bike to a halt relatively quickly by converting our kinetic energy into electricity, which we could store in a battery and use again later. And that's the basic idea behind regenerative brakes!

Electric trains are powered by electric motors connected to AC or DC power supply. When we're driving along, energy flows from the power supply to the motors, turning the wheels and providing us with the kinetic energy we need to move. When we stop and hit the brakes, the whole process goes into reverse: electronic circuits cut the power to the motors. Now, our kinetic energy and momentum makes the wheels turn the motors, so the motors work like generators and start producing electricity instead of consuming it. Power flows back from these motor-generators to the power supply or other storage devices. In practice, regenerative brakes take time to slow things down (J. collah 1996), so most trains that use them also have ordinary (friction) brakes working alongside (that's also a good idea in case the regenerative brakes fail). That's one reason why regenerative brakes don't save 100 percent of our braking energy.

3.1.2.2 Main Components of Regenerative Brake

In general the following components are required:

- Motor/generator

  During acceleration, the Motor/generator unit acts as electric motor drawing electrical energy from the power supply to provide driving force to move the locomotive and during brake the power supply is disconnected by electronic control unit and acts as a generator by using the kinetic energy of the locomotive.
- Batteries: Batteries provide storage in the form of chemical energy. The chemical reactions that occur in a battery require the movement of electrons. This electron flow is regulated so that a path is only available when the terminals of the battery are connected. The chemical reaction then takes place only when the battery is connected to a circuit.
- Electronic control system: During braking electric supply from the power supply is cut off by the electronic system. As the train is still moving forward, the Motor/ Generator unit acts as electric generator converting the train’s kinetic energy into electrical energy and store in the batteries for later use or feed to the catenary system.

3.1.2.3 Regenerative brake Advantage

- The main advantage of regenerative brakes is that they do not use mechanical friction their use does not cause wear on the wheels of the locomotives or cars.
- The advantages of using regenerative brakes on grades are further increased when helper locomotives are used. Helper locomotives are used to help move trains up long grades. The added regenerative braking force that helpers provide on the downgrade means better control of the train is possible and less air braking is required. A train must be able to stop itself through a full service brake application without relying on dynamic brakes or

emergency braking. However, reducing the reliance on air brakes allows for a greater margin of safety by assuring that there is a reserve of available braking force that can be applied if the situation calls for it. In short, use of helper locomotives enables heavy trains to be pulled up long grades more effectively and to be more safely controlled on the way down (Armstrong, 2000).

- Another advantage of regenerative braking is that wheel slides due to excessive braking force cannot occur. Regenerative brakes only produce a retarding force when the wheels are rolling, and this force reduces as the rotational speed approaches zero. The wheel will be providing less and less braking force as its rotation slow and zero braking force when it stops turning all together, effectively eliminating slides due to excess braking force. This system enables maximum braking force to be applied without worrying about damaging rails or wheels due to sliding (Armstrong, 2000).
- They allow for greater control of the braking characteristics of the train. With the single pipe air brake systems, once a brake application is made, gradual release is not possible. Once a brake application has been made, the only reduction that is possible is a complete release. With regenerative brakes, the applied braking force is almost completely variable between no braking and full braking. This substantially increases the amount of control that an engineer has over the train, and this also leads to reduced wear on the draft gear and rail (Association, 2004) and (Hay).
- Unlike air brakes, regenerative brakes are not subject to brake fade, so there is no time limit on their use. As such, they are particularly useful on long downgrades where braking applications may last an hour or more.
- Significant electrical energy will be saved and
- There is no pollutant emission during braking

3.1.2.4 Regenerative Brake Disadvantage

- They are limited to locomotives:
- Their efficiency decreases as speed decreases:
- Energy consumption*:* Dynamic brake operation consumes energy. In order for dynamic brakes to function, there must be current to the electromagnet in the traction motor. The main power supply delivers this energy.

3.1.3 Rheostatic Brake System

Although dynamic brakes have been used since the early days of electric locomotives, their widespread use did not occur in diesel-electrics until recently. The type of dynamic braking used on diesel-electric locomotives is rheostatic braking. Current freight locomotives do not have any means for storing the energy onboard and do not use catenary or third rail required for regenerative braking. Some high speed trains like the Spanish Valero E, the French TGV and the Japanese Shinkansen uses rheostatic brake in combination with other brake systems. The system used for dissipating the energy produced during rheostatic braking is specially designed to handle large amounts of energy. The current produced by the traction motors passes through a series of resistors that convert the electrical energy into heat. The resistance of this resistor grid is low, less than one ohm, so that a situation close to a dead short occurs. This situation allows for the most energy to be dissipated (Runion, 2005).

3.1.3.1 General Working Principle of Rheostatic Brake

The general working principle is the same as regenerative braking; the only difference is the use the electrical current after production. The high amperage and voltage characteristic of dynamic brake resistance grids create a large amount of heat; this heat must be dissipated rapidly enough to not damage the resistor grids. This is accomplished by large fans that force cooling air through the grids, which are designed to maximize heat transfer. If the fans become inoperable or the ducts clog with dirt and debris, the heat buildup and the arcing that occurs within the grids can cause them to explode and throw shrapnel and molten metal yards away (Prevention). The resistor grid fans are powered by the electricity generated by the traction motors during dynamic braking. This is beneficial for two reasons. First, this can be thought of as free power. The electricity produced by dynamic braking has already served its purpose as a force to slow the train. The electricity that the fans use is energy that would not be used for any other purpose. Second, the system is self-regulating. As the power flowing through the resistor grid increases, so does the speed of the fan. This insures that as heat production increases, so does the flow rate of air through the grid (Judy).

Figure 3.6 shows the ductwork and fans in an example dynamic brake resistor grid, and Figure 3.7 shows a typical resistor grid. The grid is designed as a heat transfer device. To accomplish this, its surface area must be maximized while maintaining adequate airflow.

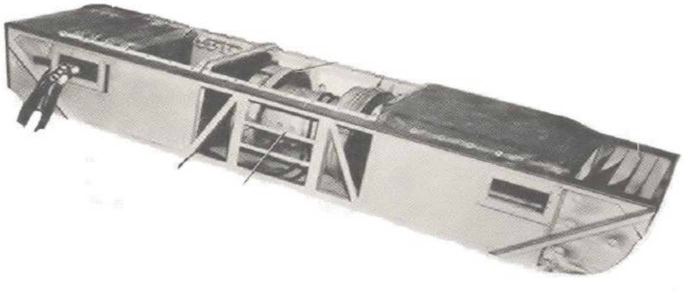

Fig. 3.6: Example of the resistor grid ductwork (Judy)

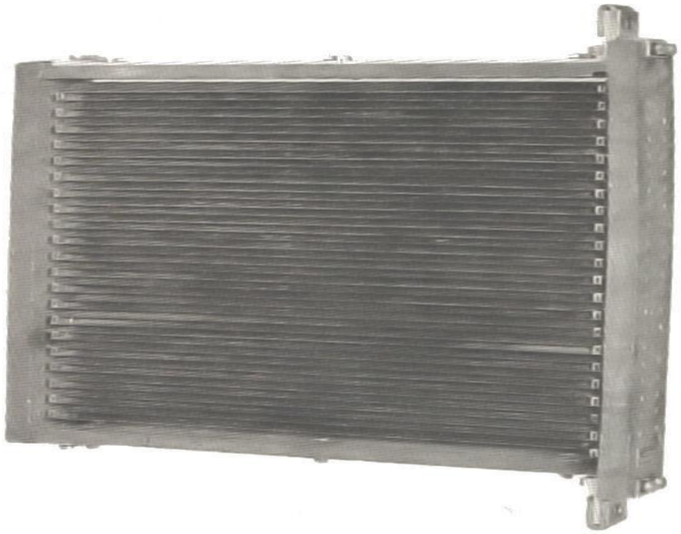

Fig. 3.7: Typical resistor grids (Judy)

The controls on a dynamic brake are simple from the locomotive engineer's point of view. All he or she sees is the position that the dynamic brake lever is in and an ammeter that shows the amount of current being produced by the traction motors. The ammeter is important because high current levels could cause damage to the traction motors, resistor grids, and wiring (Association, 2004). The regulation of this current was once the job of the locomotive engineer, but it is now is regulated by automatic controls within the locomotive. The regulation of dynamic braking current is the most important factor in protecting the electrical system of the locomotive. At high currents, arcing may occur within the traction motors and electrical connections, and the braking grids could overheat and melt. These three failures are avoided by limiting the amount of current produced during braking (Judy).

3.1.3.2 Main Components of Rheostatic Brake

A rheostatic Brake consists of:

I. Chopper:
II. Chopper transistor
III. Chopper transistor voltage control
IV. Freewheel diode
V. Resistor grid
VI. Wires

Chopper is the Dynamic Braking circuitry that senses rising DC bus voltage and shunts the excess energy to the Dynamic Brake Resistor.

Chopper Transistor is an Isolated Gate Bipolar Transistor (IGBT). The Chopper Transistor is either ON or OFF, connecting the Dynamic Brake Resistor to the DC bus and dissipating power, or isolating the resistor from the DC bus. The most important rating is the collector current rating of the Chopper Transistor that helps to determine the minimum resistance value used for the Dynamic Brake Resistor.

Chopper Transistor Voltage Control regulates the voltage of the DC bus during regeneration. Voltage dividers reduce the DC bus voltage to a value that is usable in signal circuit isolation and control. The DC bus feedback voltage from the voltage dividers is compared to a reference voltage to actuate the Chopper Transistor.

Freewheel Diode (FWD), in parallel with the Dynamic Brake Resistor, allows any magnetic energy stored in the parasitic inductance of that circuit to be safely dissipated during turn off of the Chopper Transistor.

Resistor dissipates the regenerated electrical energy in the form of heat.

Fan removes the heat generated on the resistor grid to the atmosphere

3.1.3.3 Rheostatic brake Advantage

- Since they do not use mechanical friction their use does not cause wear on the wheels of the locomotives or cars.

- The advantages of using rheostatic brakes on grades are further increased when helper locomotives are used. Helper locomotives are used to help move trains up long grades. The added regenerative braking force that helpers provide on the downgrade means better control of the train is possible and less air braking is required. A train must be able to stop itself through a full service brake application without relying on dynamic brakes or emergency braking. However, reducing the reliance on air brakes allows for a greater margin of safety by assuring that there is a reserve of available braking force that can be applied if the situation calls for it. In short, use of helper locomotives enables heavy trains to be pulled up long grades more effectively and to be more safely controlled on the way down (Armstrong, 2000).
- Another advantage of rheostatic braking is that wheel slides due to excessive braking force cannot occur. Regenerative brakes only produce a retarding force when the wheels are rolling, and this force reduces as the rotational speed approaches zero. The wheel will be providing less and less braking force as its rotation slow and zero braking force when it stops turning all together, effectively eliminating slides due to excess braking force. This system enables maximum braking force to be applied without worrying about damaging rails or wheels due to sliding (Armstrong, 2000).
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- Unlike air brakes, rheostatic brakes are not subject to brake fade, so there is no time limit on their use. As such, they are particularly useful on long downgrades where braking applications may last an hour or more.
- The heat energy developed on the resistor grid is used to warm up the interior part of the train and
- There is no pollutant emission during braking

3.1.3.4 Rheostatic brake disadvantage

- They are limited to locomotives:
- Their efficiency decreases as speed decreases:
- Energy consumption*:* Dynamic brake operation consumes energy. In order for dynamic brakes to function, there must be current to the electromagnet in the traction motor. The main power supply delivers this energy.
- The resistor grids need repeated maintenance

3.1.4 Electro Magnetic Track/Rail Brakes

3.1.4.1 Working Principle

The electromagnetic rail brake operation is based on developing electromagnetic attractive forces towards the rail [see figure 3.8] which causes a normal application force acting on their contact surfaces that are in relative displacement. This leads to friction forces between the magnetic brakes and rails, opposing the vehicle’s direction of motion, which generate braking forces. The electromagnetic brake is used as additional wheel-rail adhesion independent braking system, generally associated to the brake disc. Electromagnetic track brakes are usually mounted on the bogie frame between the wheels and are aligned above the running rail. When deployed, a current is passed through the electromagnet to create a magnetic force to the running rail. The track brake is clamped to the rail by this magnetic force and the resulting friction provides a retardation force.

Using a rather low excitation power, about 1 kW/magnetic track brake, it is possible to obtain important application forces, about 50...70 kN and accordingly, for a normal vehicle installation (four axles coach), braking force per shoe between 4...10 kN (Cruceanu, 2008).

1. Coil
2. Yoke
3. Rail

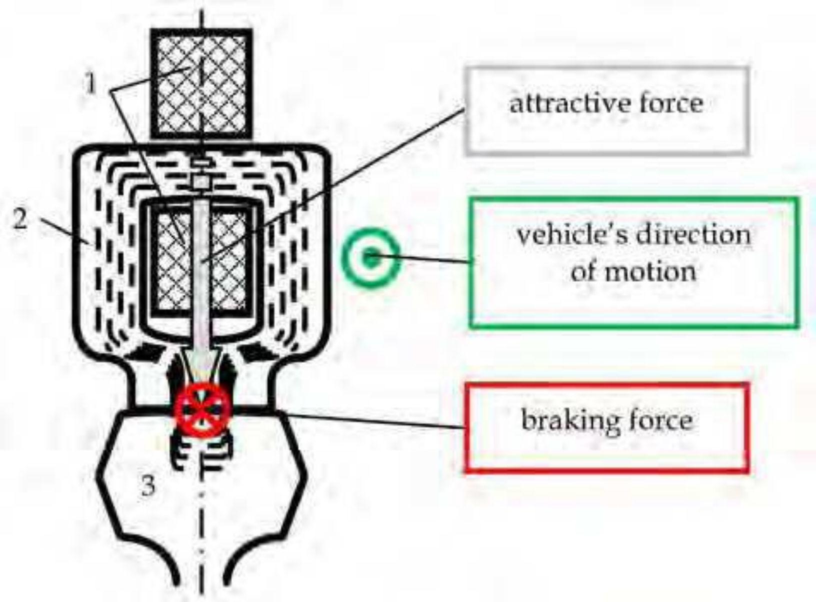


Fig. 3.8: operating principle of magnetic rail brake system (Cruceanu, 2008)

The performance of the magnetic rail brake is governed by the attraction force F_N that is in direct proportion to the induction of the magnetic field *B* at the contact area of the brake and the rail and to this contact area value *S*:

$$F_N = k * B^2 * S \qquad 3.3$$

Where: B is the induction of the magnetic field,
S is the value of the contact area,
k is the proportionality coefficient

Magnetic track brakes are commonly installed on trams [Figure 3.9] but have also been installed on high speed trains - X2000 in Sweden for example.

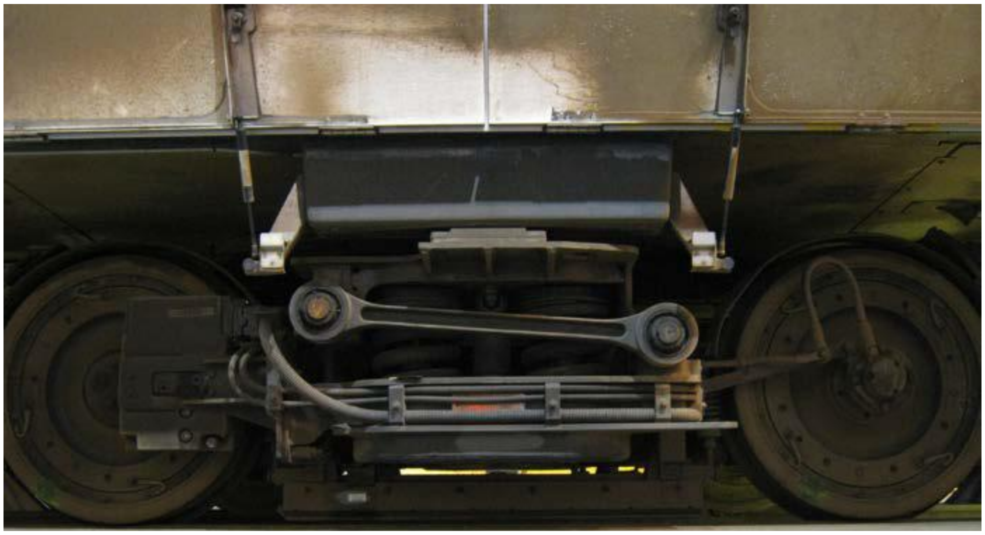


Fig. 3.9: Electromagnetic track brake on a Metrolink Tram (Johnson, 2012)

The braking performance of a magnetic track brake is not uniform making control problematic. It is very dependent on the state of the pole pieces. During its operation, the base of the magnetic track brake in contact with the rail suffers from the generation of “weld-ons”. This is metallic debris that fuses to the pole pieces which has the effect of reducing the magnetic attraction of the brake. To restore the magnetic track brake performance these “weld-ons” need to be physically removed during bogie maintenance. This means that magnetic track brake is not a cheap solution and generally has only been fitted where high emergency deceleration rates are required to meet short signaling distances or when inter-running with pedestrians and cars (such as a tram operation). The mass of a magnetic track brake is approximately 700kg per bogie (Johnson, 2012).

When designing the magnetic rail brake is important to consider also the interaction with the rails and generally with the track. Width and length of the magnetic brake shoe is critical in relation to the safe passage over the unguided area of switches and crossings, check/guard rails and other track design features or permanent way installations. On the other, the length is limited by the bogie wheel base, but the length of the braking surface must be kept equal to or above 1 m (Cruceanu, 2008). Also, if too wide, parts of the frog can be hit outside the normal wheel-rail contact area or, in the extreme, fouling check rails. UIC leaflet no. 541-06 specifies the width of the friction plate to 0.065 – 0.072 m, which is within the railhead width of UIC 46 to UIC 60 rails. The braking surface has to be flared at the ends in order to negotiate discontinuities in the rail head and the end elements of the brake shoes have both the characteristics of crossings with a tangent above or equal to 0.034 and the check rails. The general features of magnetic track brakes applicable to railway vehicles are stated in UIC leaflet no. 541-06.

The operating principle of the magnetic track brake by using a magnetic field may be determine incompatibilities with train detection systems working on magnetic principles. Consequently it is advisable to be equipped with shields to reduce the adverse effects. Also, the friction operating may lead to abrasion of primarily shoe material, conducting to possible bridging of isolated rail joints for track circuits and to the formation of ridges on the shoe surface leading to reduced performance.

Because the magnetic track brake may develop high braking forces, one must not exceed an equivalent total deceleration of 2.5 m/s^2 (Cruceanu, 2008) over the train length, avoiding also excessive longitudinal track forces in track with low longitudinal resistance or prone to rail creep.

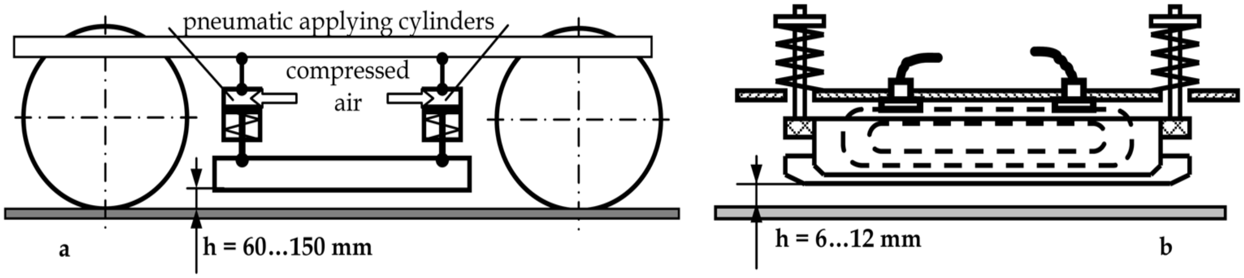


Fig. 3.10: Constructive solutions for magnetic track brake: a – high suspended; b – low suspended (Cruceanu, 2008).

According to the maximum running speed, there are two constructive solutions [see fig.3.10] regarding the release position: high suspended, with a distance between the braking surfaces and rails of 60...150 mm, common for running speeds exceeding 100 km/h and low suspended in the case of vehicles running up to 100 km/h, usually applied to tramways, the distance being 0.006...0.012 m (Cruceanu, 2008).

3.1.4.2 Electro Magnetic Track/Rail Brake Advantages

- The main advantage of the system is that it is wheel/rail adhesion independence, important for the safety of operation by enhancing the braking power of the basic braking system.
- Moreover, the friction between the braking surface and rail can sometimes significantly improve adhesion between wheel and rail due to vigorous cleaning of the tread rails during operation.
- As a result, for the classic braking systems, the wheels slide is usually avoided even in adverse conditions.

3.1.4.3 Electro Magnetic Track/Rail Brakes Disadvantage

- The main disadvantages are determined by the frictional operation of the system that lead to several drawbacks due not only to the relatively rapid wear of the braking surfaces especially for high traffic speed, but also to the increasing dependence of the shoe-track friction coefficient corresponding to the decrease of the running speed. As a consequence, the magnetic rail brake is designated only for emergency braking and is usually automatically released when the running speed is less than 50 km/h (Cruceanu, 2008). This particular operation mode gives the complementary character of this system.
- Difficult to control and require regular maintenance.

3.1.5 Eddy Current Brakes

What Are Eddy Currents?

Before we can understand eddy current brakes, we need to understand eddy currents! They're part of the science of electromagnetism: electricity and magnetism aren't two separate things but two sides of the same "coin"—two different aspects of the same underlying phenomenon. What if the conductor you're moving through the magnetic field isn't a wire that allows the electricity to flow neatly away? You still get electric currents, but instead of flowing off somewhere, they swirl about inside the material. These are called eddy currents. They're electric currents generated inside a conductor by a magnetic field that can't flow away so they swirl around instead, dissipating their energy as heat.

An eddy current brake, like a conventional friction brake, is responsible for slowing an object, such as a train or a roller coaster. However, unlike electro-mechanical brakes, which apply mechanical pressure on two separate objects, eddy current brakes slow an object by creating eddy currents through electromagnetic induction which create resistance.

The braking action of an eddy-current brake is the fact that a conducting body slows down when crossing a region of changing magnetic field. The braking force of an eddy-current brake is divorced from adhesion forces between the railroad vehicle and the rail; it does not depend on the condition of the rail surface. However, it can be changed when the rail is heated or cooled.

Eddy current track brakes can operate in two modes: static and linear motor. In a static mode, the track brake is operated with a constant field whereas in linear motor mode, the magnetic poles are varied using a variable frequency drive. They are more effective in linear motor mode.

Fundamental Physics of Eddy-Current Braking

An eddy-current brake consists of a stationary source of magnetic flux (permanent magnet or electromagnet) in front of which a conductor (metal disc, drum or rail) is moving. Because of the motion, the conductor experiences a time-varying magnetic flux density, which by virtue of Lenz’s law results in an electric field:

$$\nabla X \vec{E} = -\frac{\partial \vec{B}}{\partial t} \qquad \ldots \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; 3.4$$

This electric field results in circulating currents in the conductor by virtue of Ohm's law:

$\vec{J} = \sigma.\vec{E}$ ………………………………………………………………………… 3.5

These currents are called "eddy-currents". The interaction of eddy-currents with the flux density results in a force that opposes the motion:

$\vec{F} = \vec{J}\, X\, \vec{B}$……………………………………………………………………….. 3.6

Fig. 4 illustrates the fundamental physics of eddy-current braking applied to a disc.

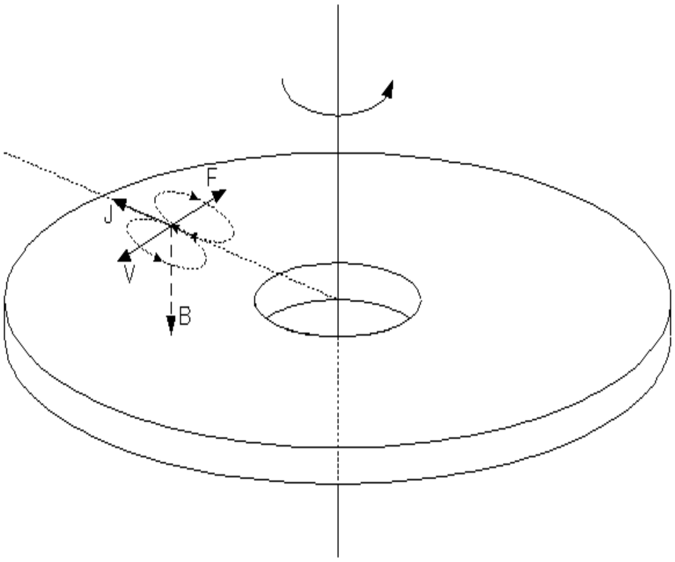


Fig. 3.11: Fundamental physics of eddy-current braking (Gay, 2005)

3.1.5.1 Basic Working Principles of Linear Type Eddy Current Brake

The linear eddy current brake consists of a magnetic yoke with electrical coils positioned along the rail, which are being magnetized alternating as south and north magnetic poles. This magnet does not touch the rail, as with the magnetic track brake, but is held at a constant small distance from the rail (approximately 7 mm) (Gay, 2005). When the magnet is moved along the rail, it generates a non-stationary magnetic field in the head of the rail, which then generates electrical tension (Faraday's induction law), and causes eddy currents. These disturb the magnetic field in such a way that the magnetic force is diverted to the opposite of the direction of the movement, thus creating a horizontal force component, which works against the movement of the magnet.

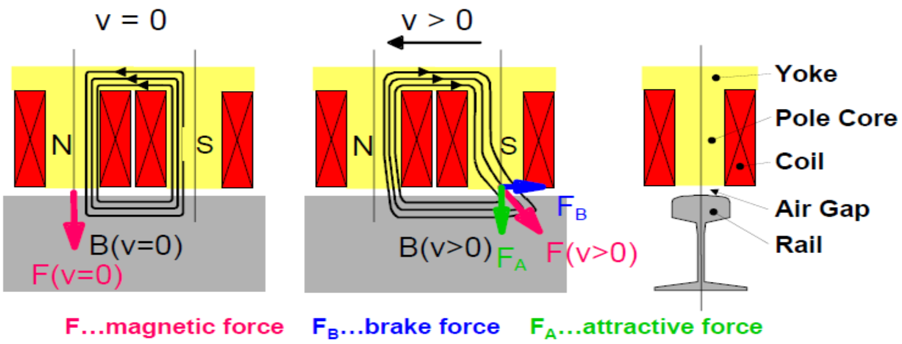


Fig 3.12: Functioning of linear eddy current brakes (Gay, 2005)

The braking energy of the vehicle is converted in eddy current losses which lead to a warming of the rail. The eddy current brake does not have any mechanical contact with the rail, and thus no wear, and creates no noise or odor. The eddy current brake is unusable at low speeds, but can be used at high speeds both for emergency braking and for regular braking. The eddy-current track brakes provide a brake force that is not dependent on the wheel/rail interface or friction and can achieve a constant brake effort at high speed.

Eddy-current brakes require an energy input of around 4kW/kN and this will need to be from a fail-safe source if this type of brake is to be used to provide the emergency brake function. For example the ICE3, the eddy current track brake is powered by a DC chopper supplying up to 95A DC to the coils (Gay, 2005).

The weight of an eddy current brake assembly is significant at around 700kg to 900kg per bogie. For example the ICE3 installation has a mass of 860kg on each bogie but can replace six fully rated disc brakes. The mass of each disc brake installation is estimated to be 200kg so the installation of the eddy current track brake without friction brakes represents a mass reduction (Gay, 2005). The development of ceramic disc and pad friction braking components offers a potential reduction in the number of discs, pads and actuators and the ceramic components are lighter. In this instance, the overall impact on mass is likely to be neutral. Track forces could also be an issue but, if the train braking remains the same as achieved with friction brakes then the forces applied to the track are the same. Figure 3.13 shows an eddy-current track brake manufactured by Knorr-Bremse.

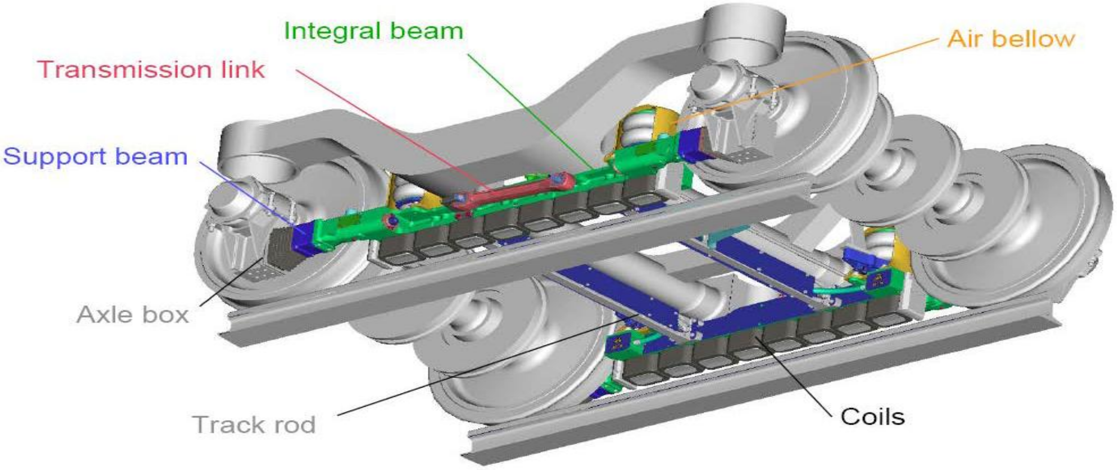


Fig. 3.13: Eddy-Current Track Brake (Johnson, 2012)

The harmonic current induced in the running rail would be dependent on the energization frequency of the coils. The power for the magnets would be derived from the traction equipment when braking dynamically, from the traction supply, or from the locomotive batteries (if it is attached) on failure of the other supplies. The eddy current track brake would be located between the axles of the bogie and, theoretically, the currents should only flow locally under the bogie in the loop formed by the axles and the connecting running rails. However, these may induce a voltage due to rail resistance and reactance which could propagate down to a track circuit or they might cause a loop current to flow through the bogie/axle/wheel/rail loop giving problems with some forms of train detection circuits which use low frequencies (50Hz for example).

Eddy current track brakes are operating in service on the ICE3 train sets in Germany are operational over diverse signaling systems including axle counters (Johnson, 2012).

The eddy current track brake has to be maintained at a fixed distance to the railhead during the time it is deployed and some additional rolling stock maintenance maybe required achieving this as the wheels wear. However, this need not be a significant task.

The bogie design will need to consider the air gap between the railhead and the eddy current track brake under all train loading conditions. In addition, the track geometry will need to be controlled to ensure that rail dips and joints do not adversely affect the air gap but this is likely to be minimal due to bogie designs and their wheelbase.

The Deutsche Bahn experience (Johnson, 2012) confirms that the use of the eddy current track brake is restricted to areas of slab track due to concerns of over track heating. The use of the eddy current track brake in emergencies is permitted on slab track and ballasted track with concrete sleepers. Deutsche Bahn is currently working on removing this restriction to allow a more widespread usage for service braking. Operation on ballasted track with wooden sleepers is not permitted as these do not have sufficient lateral resilience. The ICE-3 trains are allowed to use the eddy current track brakes during service braking in France on ballasted track with concrete sleepers (Gay, 2005).

Heating Effects

Concerns have been raised about the rail heating effects when operating trains equipped with eddy current track brakes. The Deutsche Bahn experience confirms that the use of the eddy current track brake is restricted to areas of slab track due to concerns over track heating. The use of the eddy current track brake in emergencies is permitted on slab track and ballasted track with concrete sleepers.

3.1.5.2 Basic Working Principles of Circular Type Eddy Current Brake

Electromagnetic brakes are similar to electrical motors; non-ferromagnetic metal discs (rotors) are connected to a rotating coil, and a magnetic field between the rotor and the coil creates a resistance used to generate electricity or heat. When electromagnets are used, control of the braking action is made possible by varying the strength of the magnetic field. A braking force is possible when electric current is passed through the electromagnets. The movement of the metal through the magnetic field of the electromagnets creates eddy currents in the discs. These eddy currents generate an opposing magnetic field (Lenz's law), which then resists the rotation of the discs, providing braking force. The net result is to convert the motion of the rotors to heat in the rotors. An eddy current disc brake is energy inefficient as the kinetic energy of the train is lost as heat in the disc. Thus, the only advantage of an eddy current disc brake over a friction brake is that it is frictionless and has no wearing parts. The disadvantage is that it is ineffective at low speeds and cannot be used as a stopping or parking brake.

Fig. 3.14: Eddy-current disc brake on 700 Series Shinkansen (Johnson, 2012)

Eddy-current disc brakes were installed on the 700 series Shinkansen trains but it is understood that they were removed as the train braking requirement could be achieved dynamically (Johnson, 2012). The Shinkansen trains have a high proportion of motored axles and are able to achieve the required brake rate using dynamic brake: there is no requirement for an energy inefficient eddy current brake on these trains.

The braking energy is dissipated in the disc of the eddy current disc brake and in the running rails for the eddy current tract brake. The disc is obviously a lot lighter than the running rails and thus the temperature of the disc must be allowed to attain very high temperatures to dissipate the same energy as the track brake.

3.1.5.3 Main Components of Eddy Brake

- yoke
- pole core
- coils and the braking system includes the following elements:
- Bearings, crowbars for the transmission of braking forces, integral beams, connection bars.

3.1.5.4 Eddy Current Brake Advantage

- Reduced wear of friction pads: the eddy-current brake can provide a large fraction of the braking force, thereby reducing the amount of kinetic energy dissipated at the pads and consequently reducing their wear. The eddy-current brake is contactless and therefore wear-free and no smell.
- Reduced sensitivity to fading: the eddy-current brake can assist the friction brake when the rotor is hot. The combination of two sources of braking torque compensates for their respective loss of effectiveness at high temperature. Furthermore, it is possible to increase the effectiveness of the friction brake by keeping the pads cool. This is achieved by relying as heavily as possible on the eddy-current brake.
- Reduced sensitivity to wheel lock: the eddy-current brake reacts faster to control inputs than a friction brake. Therefore, the brake's control system can prevent wheel-lock more easily than with friction brakes. Furthermore, the friction brake is mostly used at low speeds. The effects of wheel lock are much less severe at low speed than at high speed.
- Faster control dynamics: the eddy-current brake is directly controlled by its excitation magnetic field. The response time of an eddy-current brake is counted in milliseconds, whereas the response time of mechanical systems is counted in tenths of seconds. This is particularly true of power assisted and pneumatic brake systems (Robert Bosch, 2004.)
- Easier integration with vehicle electronic driving aids: Traction control and dynamic stability systems require fast response times for more precise and safer vehicle control. The fast response time of eddy-current brakes makes them more suitable for interfacing with these electronic driving aids.
- Reduced fuel consumption of power assistance: the primary reliance on eddy-current braking reduces the maximum braking force required from friction brakes. The power assistance requirement is consequently decreased, making it effective to replace the hydraulic actuation and vacuum assistance by an electric actuation, which drains power only when actuation is needed.
- They produce no smell or pollution (unlike friction brakes, which can release toxic chemicals into the environment)

3.1.5.5 Eddy Current Brake Disadvantages

The major disadvantage of an eddy-current track brake is:

- Braking force diminishes as speed diminishes
- Not regenerative; means not changing the total energy of the running train to other useful energy during braking.
- The input energy requirement is high
- Heat is dissipated both in the electromagnet and the running rail during braking. If there's a busy section of track where many trains brake in quick succession (something like the approach to a station), the heating and expansion of rails could prove to be an issue, either reducing the effectiveness of the brakes or leading to structural problems in the rails themselves, and
- The main perceived problem with eddy current track brakes is that they could, potentially, interfere with the signals from axle counters and other track circuit systems as they run over them and may cause miscounts or incorrect train detection.

3.1.6 Aerodynamic/Air Resistance Brake

These brakes are used on Japanese (Shinkansen) trains. The efficiency is not known, but they are only effective at high speed (Johnson, 2012).

Aerodynamic brakes must be seen as an additional braking aid, not as the primary braking system. If every coach were fitted with such a system then it will necessary to have some kind of activator/control to deploy them. This will add to the cost and complexity of the overall control. It is possible to estimate the effect of an aerodynamic system by adjusting the aerodynamic coefficients in the Davies equation using an approximation to the effective increase in frontal area of the train. If it is assumed that the effective increase in frontal area is equivalent to a vane of approximately 300mm2 on the periphery of several cars of the cross section of the train then, for a typical EMU this would result in a 10 to 20% increase in drag coefficient (Johnson, 2012).

Fig. 3.15: Aerodynamic brakes (Johnson, 2012)

Even if such an increase is practical (due to gauging constraints) then, it is possible to calculate that, to achieve the same brake effort as exists from the electric brake alone (at that speed) the speed must be in excess of 350 km/h.

3.1.7 Wheel Slide Protection

A wheel slide occurs when the retardation forces exceed the friction forces that can be supported at the wheel/rail interface. To correct a slide, the applied brake effort must be removed from the wheelset: the dynamic brake must be reduced and the friction brakes, if applied, must also be reduced. Thus, to correct a slide, there needs to be a controlled reduction in dynamic brake and friction brake (if applied). Wheel slide detection and correction by the TCU is inherently faster with a modern 3-phase drive than previous traction control. Direct current (DC) drive systems often relied on detecting the changes in motor armature voltages to determine which axle is sliding. It has been reported that, sometimes, the traction control system and friction brakes, having separate slide control systems were not optimally integrated with each other. Reverting to friction brakes overcomes this difficulty (T685).

With the advent of modern traction and braking systems with microprocessor control and reliable speed probes, it has been possible to develop sophisticated algorithms for the control of wheel slide. During the slide, the TCU will output a digital signal to the BCU to effectively hold off the friction brakes to prevent friction applying and exacerbating the slide. The BEA signal can either be ‘frozen’ at the pre-slide value or be allowed to reflect the true BEA developed. If the brakes are blended – that is the brake cylinders are charged and applying brake effort, the friction brake WSP system can command ‘dump valves’ to quickly exhaust the brake cylinders to remove the brake effort. The BCU will time-out the TCU WSP response to prevent the holding off the brakes indefinitely. This time out varies between trains and is four seconds on London Underground 95 Tube Stock (Northern Line 95TS) and was ten seconds on Class 323 as designed and originally operated (Johnson, 2012).

Typically, a modern traction drive will control two (and sometimes four) motors in parallel on a per bogie (or per car) basis and slide control initiated by the traction system will be on a per bogie (or per car) basis. This results in the reduction of brake effort from multiple motors even if only one wheelset experiences a loss in adhesion. A friction based wheel slide protection system operates on an axle basis and will provide an enhanced response compared with a traction system with several motors operated in parallel.

During the slide correction period, from the point at which wheel slide is detected to the end of recovery, dynamic braking is reduced. The duration of reduced dynamic brake will depend on the severity of the slide (depth of slide) and the recovery characteristic. The friction system will normally allow the traction system a fixed time to correct a slide before it declares the traction WSP as faulty and takes over responsibility for correction and braking. This time-out is usually of the order of five seconds: 95TS times out after 4 seconds and Class 323 after 10 seconds (Johnson, 2012). A severe slide may take several attempts at correction until the brake effort matches the available adhesion.

Typically, during emergency brake, responsibility for wheel slide protection reverts to the BCU and the traction system is inhibited. An exception is the Shinkansen 800 Series train set but this has a backup pneumatic brake.

The maximum adhesion usually allowed is 15%. This is the value adopted when calculating train performance and is often specified in train requirement specifications. As WSP algorithms are becoming more sophisticated and faster, control systems are being introduced that do not assume a maximum adhesion level – brake demand is allowed to increase to the threshold of sliding before setting the maximum demand. This allows the actual adhesion conditions to be utilized and this control philosophy is known as ‘floating adhesion’.

3.1.8 Some images from the Main Components of the Brake System

1 E-P Brakes (www.knorr-bremse.com)

Compressor

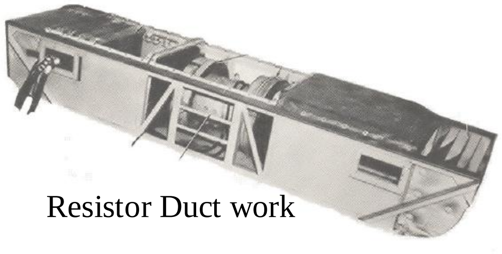
Disc with Caliper

Modular Brake Control

Air Drier

2 Rheostatic (Judy) and (Yoshiyasu Hagiwara)

Resistor Grid



Resistor Duct work

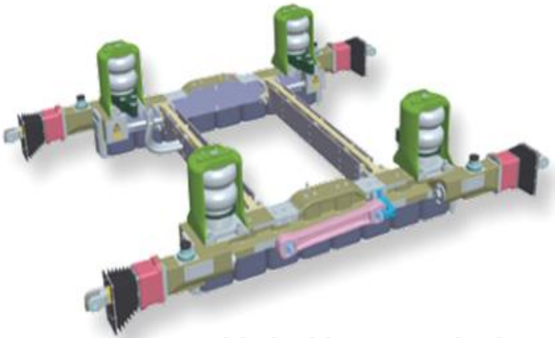
Fan

PMSM Motor

3 Regenerative Brake (Judy) and (Yoshiyasu Hagiwara)

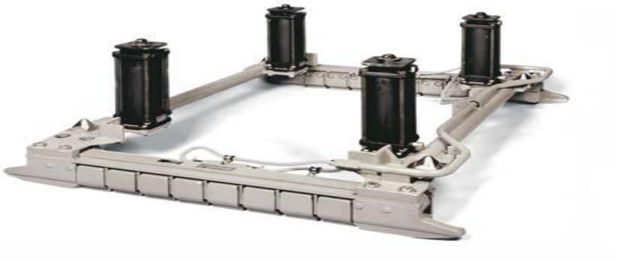
PMSM Motor

4 Eddy current (www.knorr-bremse.com)

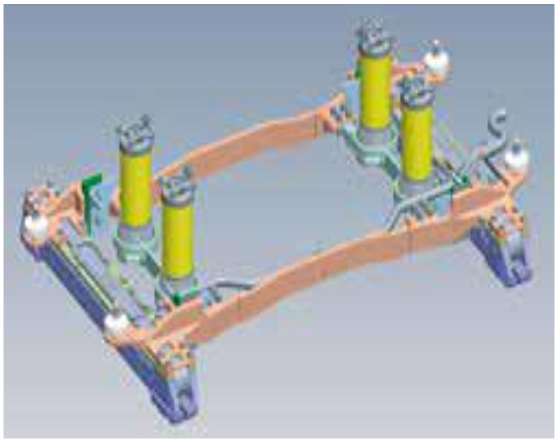


Assembled eddy current brake

4 Magnetic Track Brake (Johnson, 2012) and (www.knorr-bremse.com)



Part of magnetic track brake



Assembled Magnetic track brakes

3.2 Evaluation of Brake Systems

This thesis develops an evaluation methodology for comparing braking systems of high-speed trains. All brake systems are evaluated based on eleven characteristics organized into four categories associated with technical aspects, environmental impacts, economic considerations and operations. For each of the eleven characteristics, benefit values are assigned for each system based on their performance.

These benefit values are the foundation for the analysis part that develops weighting factors for each of the eleven characteristics. The assignment of these weighting factors is based on a survey that has been conducted with Ethiopian Railway Corporation.

Table 4.1: Benefit rating and their description

Benefit rating	5	4	3	2	1
Description	Excellent	Very Good	Good	Fair	Poor

Evaluation Criteria:

Technical aspects

1. Braking Performance
2. brake equipment weight
3. Compactness of brake equipment
4. Wear

Environment impacts

1. Noise Emissions
2. Electromagnetic field interference
3. Pollutant Emissions

Economic considerations

1. Investment/Initial Costs
2. Maintenance Costs
3. Operation Costs

Operation

1. Reliability

3.2.1 Braking Performance

The achievable braking performance is an important factor for the travel time on a given route segment. The higher the achievable braking rate, the longer the train can travel at a higher speed. Furthermore, a higher maximum braking rate increases the level of safety. For the wheel-on-rail high-speed trains, the braking rate is partially dependent on external conditions like temperature and precipitation.

The parameters used to evaluate the braking performance of high speed train braking system for this research is the braking distances and times needed to reach a complete stop from a given travel speed during service braking.

Wheel-on-rail high-speed trains have up to three different braking systems. A dynamic brake converts kinetic energy into electrical energy or heat and thereby slows down the trains and feeds energy back into the power system or dissipate to the atmosphere. A mechanical brake takes effect directly on the wheel-rail interaction and thus slows down the train at the expense of mechanical wear. An eddy-current and electromagnetic track brakes are additionally applied when highest braking rates are necessary. The evaluation parameters (braking distance and time) were taken by assuming the train braking is not blended. For all brake systems latest data are taken by comparing currently available brakes on all high speed trains.

Electromagnetic track brakes are actuated by pairs of air cylinders, overcoming return-spring forces, and are electrically energized to generate a minimum 100 kN, installed on X2 tilting trains weighing 377.66 ton and some trailer cars with less braking forces. At a speed of 200 km/h, the magnetic track brakes alone are estimated to produce an average braking rate of 1.53 km/h/sec (Administration).

To see the effect of E_P disc brakes consider Amtrak Metro liner (USA) weighing 402.98 tons and ICE-Intercity Express (Germany) weighing 863.22 tons having a brake rate of 2.7km/hr/s from 201 km/hr and 3.2km/hr/s from 280km/hr respectively. Their respective braking distance is 1950m and 2020m using only friction brakes installed on all of their axles (Administration). Each axle has four ventilated discs in case of ICE and two ventilated discs per axle in case of

Amtrak. Considering the train weight and the initial velocity at the time of braking, the performance of ICE train is better.

In regenerative brake system the maximum braking power is slightly more or the same as that of motor power output. The Japanese Shinkansen 800 series Intercity Train and the Moscow Metro are the only train using a fully rated regenerative brake system for service braking. Shinkansen 800 series (weighing 286.27 ton on each of the 6 cars) uses the latest PMSM (6600 Kw) motor which is light weight and produces a better frictional torque. During service braking, the brake rating is 0.38 m/s at 260 km/hr and rising to 0.75 m/s at 70 km/hr, the braking distance and time is 3500 m and 90 s respectively from a speed of 260 km/hr (Johnson, 2012).

In rheostatic brake the basic brake principle is similar with regenerative brake and is widely used on Amtrak metro liner, TGV, Inter City 225, Shinkansen 100 and 200 series, Talgo and ETR 450 trains. Its maximum braking power is lower than regenerative brake due to temperature capacity limitation on resistor grids. To see the braking distance and time effect let’s take TGV trains whose large portion braking power is covered by regenerative brake. The TGV trainset weighs 523 tons with a normal passenger load and the dynamic/resistive braking provides a large portion of the braking power using independent systems for each driving bogie on the power cars. The proportion of electric brake effort provided, however, varies with speed and the brake demand. The dynamic/resistive brake has a maximum power level of 405 kW per piece, or about 6480 kW for the trainset at 300km/hr and has braking distance 3200 m at 300 km/hr in combination with friction brake (Administration). Assuming the effect of friction brake on the braking distance is very low (from 30km/hr to zero) and a max deceleration rate of 3.57 km/hr/s, the braking time is 84 s.

As the eddy-current effect requires relative movement between the rail (the reaction link) and the electromagnet, it is only suitable at high speeds and provides no braking effort at low speeds and whilst stationary. Eddy current brake is currently fitted with ICE 3, X2, Shinkansen 100, 200 and 300 series. It is reported that a deceleration of 0.88 m/s can be obtained between 300 and 200km/h with around half of the effort being provided by the eddy-current brake on ICE 3 train. Eddy current brake installed on ICE 3 train weighing 440 ton produces a maximum braking force 170KN per piece. 50% of the bogie is fitted with eddy current brake (four bogie) and having a total maximum braking power of 13MW (Johnson, 2012). If all the bogie of the train is fitted with Eddy current brake, a deceleration of 0.88 m/s can be obtained between 300 and 200km/h. Assuming a uniform deceleration the eddy current brake needs 2184.86 meter braking distance and 15.7 second to decrease the speed from 300km/hr to 200km/hr. if this maximum deceleration is not altered till to stop the braking distance will be 3928 m and braking time is 95 s.

Based on these physical properties, Table 4.1 compares the values of service braking distances and times needed to reach a complete stop.

Table 4.2: Benefit rating for brake performance

	Electro-Pneumatic brake		Regenerative brake		Rheostatic Brake		Eddy current brake		Electromagnetic track brake	
brake performance	Time [S]	Distance [m]	Time [S]	Distance [m]	Time [S]	Distance [m]	Time [S]	Distance [m]	Time [S]	Distance [m]
	87.5	2020	90	3500	>84	>3200	>95	>3928	130.72	3631
Benefit ratings	5		4		4		3		2	

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.2.2 Brake Equipment Weight

In general, a lower brake equipment weight is favorable as it helps to minimize energy consumption, lower the construction cost and ease for maintenance. Weight reduction as a whole (including the brake equipment weight), in addition to reduction of mechanical resistance, it has effect on reduction of gradient resistance and traction force in acceleration and deceleration. Weight reduction is also effective on reduction of kinetic energy, which increases in proportion of mass and square of velocity. When velocity increases from 220km/h to 270km/h, kinetic energy becomes 150% more. However, 30% of weight reduction realized, like the series 300, kinetic energy increases only 5% (Yoshiyasu Hagiwara). Weight reduction also contributes to low energy consumption, low braking energy, and good train performance. Weight reduction also has a great importance during maintenance. A larger weight needs more human power and time during dismantling and assembling.

Eddy current track brake installation has mass of 800-900kg per bogie (including the bogie equipment, DC chopper and associated cabling and supports) (Johnson, 2012). It has been estimated that the friction brake equipment and air generation and preparation equipment accounts for approximately 4.8% of the train motor car mass (Zaidi). A typical mass of a high-speed train motor car is 50t and a trailer car 45t (Johnson, 2012), each disc assembly of high speed train constitutes approximately 600kg. The traction motor which acts as a brake element during braking in case of regenerative and rheostatic braking is not included on the evaluation because its primary function is as a traction element. Weights of additional materials added on both braking systems are considered. Light weight materials like Resistor grids, ducts fans and electronic control unit increases the weight of rheostatic braking where as only electronic control units are added on regenerative brake systems because the generated electric current is feed back to the catenary system. Typical mass of a magnetic track brake is approximately 700kg per bogie (Johnson, 2012).

Table 4.3: Benefit rating for weight of brake equipment

	Electro-Pneumatic brake	Regenerative brake	Rheostatic Brake	Eddy current brake	Electromagnetic track brake
Weight (kg)	600	Small compared with others	More than regenerative brake	900	≈ 700
Benefit ratings	3	5	4	2	3

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.2.3 Compactness of Brake Equipment

The term compactness describes the external measures of brake equipment related to its internal space. A small brake equipment that offers the same usage as big brake equipment can thus be considered more compact. More compact brake equipment is in general superior in aerodynamic performance and more economical in some aspects of infrastructure. The parameter used to evaluate the compactness of brake equipment is its external volume. The benefit ratings are given by analyzing this external volume with the regenerated brake power.

The braking equipment of linear eddy current that produces 170KN at 200 km/hr has a volume of $L*W*H = 2(1540*130*269)*10^{-9}\ m^3$ and total weight of 900 kg (www.knorr-bremse.com). Assuming the regenerated electrical current is fed back to the catenary system the only element added on the regenerative brake is electrical controlling element. In case of rheostatic brake the volume of resistor grid, fan and grid duct work will be added. The volume of friction brake is not comparable with electromagnetic braking systems because it needs a total of large volume from the beginning of air compression up to the end of delivery to the brake cylinder (Johnson, 2012). In general the length of magnetic track brake is limited by the bogie wheel base, but the length of the braking surface is equal to or above 1 m (Cruceanu, 2008). The width of the friction plate is 0.065 – 0.072 m, which is within the railhead width of UIC 46 to UIC 60 rails. The magnetic brake fitted on X2 train has a volume of L*W*H = $2(1000*68*70)*10^{-9}$ m^3. The volume difference between rheostatic and regenerative braking is the additional volume coasted by resistor grid, fan and duct. The right dimension of the fan, resistor grid and duct work were not found, as we can see from their picture they need more spaces compared with regenerative, eddy current and magnetic track brake. The following table compares the external volume the brake equipment.

Table 4.4: Benefit rating for compactness of braking equipment

	Electro-Pneumatic brake	Regenerative brake	Rheostatic Brake	Eddy current brake	Electromagnetic track brake
Compactness (m^3)	Greater than other brake systems	Very low	> electrical brake	0.10770	>0.00952
Benefit ratings	2	5	3	4	4

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.2.4 Wear

During braking wear is formed by the physical contact between braking equipments. Wear can be defined as the loss or displacement of material from a solid surface as a result of mechanical action (friction). The life of a friction material will depend to a great extent upon the wear rate. As the life of the material decreases the maintenance cost will increase. One major advantage of dynamic braking (regenerative and rheostatic) and eddy current brakes are lack of any physical contact between brake equipments during brake operation and which are essentially wear/tear free. The contact between brake equipments in case of Electromagnetic and electro-pneumatic brakes produces a considerable amount of wears.

The life of the brake disc will typically be around 16 times that of the pads, the disc life is usually designed to coincide with the overhaul periodicity of the wheelsets (Cruceanu, 2008). The pad material is sometimes depending on whether they are used for a locomotive, motor coach or a trailing car. Locomotives and motor coaches usually have sinter pads which can withstand higher temperatures while trailing cars sometimes are equipped with organic pads, mainly for economic reasons. During braking more wear comes from the pad and the volume of the removed material can calculated using a reformulated version of Archard's wear equation with a temperature dependent wear coefficient.

$$\dot{w} = k_w pv \quad \text{……} \quad 4.1$$

Where

$\dot{w}$ = wear rate [m/s]

k_w = wear rate coefficient [m^3/Nm]

P = Contact pressure [Pa]

V = Sliding speed [m/s]

Experimental results on three high speed trains (X2, GT-250, and GT-VHST) in Sweden, wear on sintered brake pad show that with the density of 5.120 g/cm3:

Table 4.5: Approximate brake pad wears of the different trains when braking with blended brakes from top speed 250 km/hr to stop (Sjöholm, 2011).

Train Type	Speed (km/hr)	Deceleration (m/s^2)	Brake pad wear/disc (cm^3)	Brake pad wear/disc (grams)	Brake pad wear/train (cm^3)	Brake pad wear/train (gram)
X2	200	0.6	0.064	0.328	3.59	18.39
GT-250	250	0.6	0.043	0.220	2.06	10.46
GT-VHST	320	0.6	0.039	0.201	2.83	14.49

X2 braking from 200 km/h to a full stop using blended brakes at 0.6 m/s^2 generates a wear of 0.064 cm^3 or 0.328 grams per brake disc which adds up to 3.59 cm^3 or 18.39 grams for the whole train.

GT-250 braking from 250 km/h to a full stop with blended braking at 0.6 m/s^2 generates a wear of 0.043 cm^3 or 0.220 grams per brake disc which adds up to 2.06 cm^3 or 10.46 grams for the whole train.

GT-VHST braking from 320 km/h to a full stop with blended braking at 0.6 m/s^2 generates a wear of 0.039 cm^3 or 0.201 grams per brake disc which adds up to 2.83 cm^3 or 14.49 grams for the whole train.

Note that braking several times without letting the brakes cool down would render in a much higher temperature, and consequently higher brake wear. Also the increase in deceleration and the minimize effect of the dynamic and electromagnetic brake will increase the brake wear.

If we analyze the wears of the three high speed trains, it may be under the design consideration. But the concentration of such wear particle on air will have an adverse effect on human and living things. For the benefit ratings the average of the three trains wear rate were taken. The wear rate during metal to metal contact between rail and magnetic track brake per brake application on X2 train (6.25 grams) shows lower compared with pad and disc (Sjöholm, 2011).

Table 4.6: Benefit rating for wear from pads and electromagnetic track during braking from top speed to stop

	Electro-Pneumatic brake	Regenerative brake	Rheostatic Brake	Eddy current brake	Electromagnetic track brake
Wear (grams)	≥14.44	Free	Free	Free	6.25
Benefit ratings	2	5	5	5	3

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.2.5 Noise Emissions

Noise from high speed trains is a sensitive issue, as high speed train lines are built either in densely populated areas, or conversely in zones where the pre existing noise was very low. As soon as the 1990's, high interest was then given to measuring of pass-by noise from high speed trains, and understanding the different sources contributions in order to help reducing global external noise (railway). There are many sources of noise in railway transport systems, the sources of noise in railway transport systems are traditionally classified in three types:

- Aerodynamic source (e.g. train turbulence and ventilation, motor fan)
- Mechanical source (e.g. train wheel-rail squealing noise, motor bearings and gearbox)
- Braking source, for the purpose of this thesis; only noise sources from braking resistance is considered.

The main contributors of noises are (railway):

- At 200 kph, the rolling noise is an important source but the noise radiated by the area located around the first bogie (bogie and windscreen) is of the same order,

- At 300 kph, the area around the first bogie is the main source but the noise radiated by the cooling and the pantograph cannot be neglected,
- At 350 kph, the area located around the first bogie and the pantograph radiates much more.

These data are currently used as input of pass-by noise simulation software like MAT2S and VAMPASS to assess the contribution of each source to global pass-by noise. Audible noise always has an aerodynamic origin, in the sense that it is produced by air vibrations occurring in the audible range (20 Hz, 20 kHz).

Noise emitted during braking is dependent on the speed of a train, friction force and the condition of the friction element. Noise data during braking were not found but researches show that braking noise is not part of the main contributor of noises (railway). In case of dynamic braking and eddy current braking system there is no contact between the moving and fixed part during braking, they are noise free. Whereas e-p brakes and electromagnetic rail brake types due to contact between moving and fixed part during braking produces noise. Friction braking and electromagnetic track braking noise are smaller compared with aerodynamic and wheel/rail contact noise but it has significant difference compared with the non noise braking systems. The noise from metal to metal contact of magnetic track is greater than that of sintered pad with metal contact.

Table 4.7: Benefit rating for noise emission

	Electro-Pneumatic brake	Regenerative brake	Rheostatic Brake	Eddy current brake	Electromagnetic track brake
Benefit ratings	3	5	5	5	2

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.2.6 Pollutant Emissions

Different kinds of emissions and pollutions occur over the lifetime of a braking system. First, emissions are discharged when raw materials for braking are extracted, followed by emissions during the production or construction processes. Also emissions occur when braking are recycled. However, this research focuses on air born wear emissions occur during operation. The main concerns about airborne wear particles are the adverse health effect on humans.

Many researches show that increased sliding velocities or contact pressures coincide with increased particle concentrations. The rate of ultrafine particle emissions from cast iron brake block material was significantly higher than from organic brake block material. The rate of fine and ultrafine particle emissions from sintered brake material was significantly lower than from organic brake pad material. Investigations in the Stockholm, London and Budapest underground systems have shown particle mass concentrations in the range of 300–1000 $\mu g/m^3$ (Saeed Abbasi), much higher than the upper limit for urban traffic in the EU, which is 50 $\mu g/m^3$ per day. The investigation shows the mass concentration of particles sourced from different part of the train. Saeed Abbasi and his colleagues experimentally show that the maximum PM concentration on different pad and disc with different speed is $2.67 mg/m^3$, which is also higher than the limiting value. PM with an aerodynamic diameter (AD) ≤10 mm (PM_{10} size fraction) can penetrate into the human lungs. Particles with an AD≤2.5 mm ($PM_{2.5}$ size fraction) are recognized because of their potentially harmful chemical composition, their larger surface area, and their larger atmospheric residence time.

The following table shows selected data from US and EU outdoor air quality regulations, which limit emissions of PM with an aerodynamic diameter of 10μm (PM_{10}) or 2.5μm ($PM_{2.5}$):

Table 4.8: Comparison of US and EU outdoor air quality regulations (Vinzents P.S. M. P., 2005)

		$PM_{2.5}$ ($\mu g/m^3$)	PM_{10} $\mu g/m^3$
US	Daily (24h)	35	150
	Annually	15	-
EU Directive	Daily (24h)	-	50
	Annually	25	40

According to (Rausch, 2004), during braking the magnetic fields produced in the Trans-rapid vehicles along the route have to be below human health threshold values. This is equally true for the electric and electromagnetic fields. The effects on the health of passengers, staff and third parties have to be minimal.

Extremely low frequency sensory effects caused by movements in a strong static magnetic field are experienced with flux densities above 2 - 3 T. The maximum sensitivity is expected at frequencies around 0.1 Hz. Sometimes these effects last longer than the actual field exposure and can be detrimental to work performance and quality. Pathological effects of blood flow induced electric fields in the tissue causing nerve and muscle excitation in the immediate vicinity of these blood vessels or that may interfere with the autonomous heart action are expected for flux densities exceeding 8 - 10 T (Orner F. B).

Motors and traction equipment of trains and trams are normally located underneath the floors of passenger cars. At floor level, magnetic field intensities may amount to tens of μT in regions of the floor just above the motor. The fields fall off quickly with distance from the floor, and exposure of the upper bodies of passengers is much lower. Permanent Magnet Synchronous Motors (PMSMs), which acts as a generator during braking (case of regenerative and rheostatic), the magnets used in are manufactured from rare earth metals. The magnetic field typically produced by rare-earth magnets can be approximately 1.2-1.4 Tesla (Johnson, 2012), the eddy current brake which is installed on ICE series and TGV high speed trains has a 1.5T (Tesla) magnetic field induction at the pole of the magnet assembly and the magnetic field at the contact area of the brake and rail in case of electromagnetic rail brake is also approximated 1.5 T (Podol'skii S. K.). According to the Directive 2004/40/EC, the exposure limit values for static electric fields are: (Orner F. B)

Table 4.9: Maximum magnetic flux density exposure

	Maximum magnetic flux density (T)
Exposure of head and trunk	2
Exposure of limbs	8

Table 4.10: Benefit rating for pollutant emission

	Electro-Pneumatic brake (μg/mm^3)	Regenerative brake (tesla)	Rheostatic Brake (tesla)	Eddy current brake (tesla)	Electromagnetic track brake (tesla)
Pollutant emission	267	1.2-1.4	1.2-1.4	≈1.5	≈1.5
Benefit ratings	2	4	4	3	3

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.2.7 Electromagnetic Fields (Emfs) Interference during Braking

EMFs are electric and magnetic fields. Electric fields are forces that electric charges exert on other electric charges where as magnetic fields are forces that a magnetic object or moving electric charge exerts on other magnetic materials and electric charges. Electromagnetic field interference occurs when the electromagnetic fields produced by a source adversely affect operation of an electrical, magnetic, or electromagnetic device. Electromagnetic fields are described in terms of their frequency, which is the number of times the electromagnetic field increases and decreases its intensity each second. The strength of magnetic fields often is measured in milligauss (mG), gauss (G), tesla (T), or microtesla (μT).

All vehicles operating on Rail Corporations network shall always be correctly detected by the existing signaling system, including track circuits, axle counters, wheel detectors & presence detection loops. Trains shall generate no energy or electromagnetic interference capable of interfering with Rail Corporations signaling systems for safe and reliable operation of all forms of signaling equipment and specifically train detection systems. A simple example to show field interference is an axle counter, which detect electromagnetic braking devices on high-speed trains as axles by mistake during braking (David Randall, 2013.). Also interference will occur at some distances from the centerline of the high speed train right-of-way, because there will be an equipment which are sensitive to magnetic fields produced by the braking system.

The strength of magnetic field intensity emitted by the braking system will decrease with distance from the source. For unshielded equipment near to the source that is sensitive to magnetic fields in the range of 1 to 1.5 tesla interference is possible and could disrupt the operation of equipment. For example magnetic resonance imaging systems (1-3mG), electron-beam microscopes (0.1-0.3mG) and implanted medical devices (1-12G) (Bakersfield) might be interrupted by emitted magnetic fields based on the closest distances from the centerline of the HST right-of-way.

Table 4.11: Benefit rating for field interference

	Electro-Pneumatic brake	Regenerative brake	Rheostatic Brake	Eddy current brake	Electromagnetic track brake
Magnetic field (tesla)	free	1.2-1.4	1.2-1.4	≈1.5	≈1.5
Benefit ratings	5	4	4	3	3

3.2.8 Investment Costs

Investment costs are construction costs that are required to implement new brake equipment set or changing the whole of defective equipment set by a new one. The cost of a typical friction braking system (including the air generation, preparation and storage) for a high speed train is approximated 46,875 pound per pad (Johnson, 2012). Initial cost of regenerative brake is the cost of electrical controlling element. In case of rheostatic brake the cost will increase due to addition material requirement like resistor grids, fans and ducts compared with regenerative braking. Researches show that the cost of rheostatic brake is 7895 pound (Johnson, 2012). The cost not includes the motor value, which acts as a generator during braking. Definitely the cost of regenerative brake is less than rheostatic brake because cost of resistor grid, duct and fan will not include.

Eddy current track brakes will represent a significant cost, estimated at around 10,000 pound per bogie equipment and 30,000 pound for the additional power equipment. The cost of magnetic track brake reaches up to 20,000 pound (Johnson, 2012).

Table 4.12: Benefit rating for investment cost

	Electro-Pneumatic brake	Regenerative brake	Rheostatic Brake	Eddy current brake	Electromagnetic track brake
Investment cost (pound)	46,875	<<7895	7895	40,000	20,000
Benefit ratings	2	5	4	2	3

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.2.9 Maintenance, Repair, and Rehabilitation Costs

Deterioration of the installations of a high-speed train braking equipments requires performing a series of maintenance operations in order to reach an acceptable level of operability. Maintenance performance serves to restore operational status to defective components or conserve operational components and also includes servicing, inspection and re-conditioning. Maintenance costs arise from costs for preventative maintenance and for re-conditioning (corrective maintenance) with the inclusion of the necessary personnel and material costs. According to a typical high speed vehicle maintenance plan, the jobs include (Johnson, 2012):

- Compressor Valves - Renew

- Safety Valve Freedom of Movement- Check
- Compressor Oil & Filter (Air & Oil)- Renew
- Compressor Oil Level - Check
- Air Dryer & Compressor - Check
- Air Dryer Dessicant Material - Renew
- Air Dryer Filter - Renew
- Filter/Water Separator - Clean/Renew
- Sandboxes - Check & Fill
- Safety Valves - Change
- Reservoir Drain Cocks – Drain
- Slack Adjuster & Parking Brake – Test
- Brake Pads – Gauge & Renew
- Brake Callipers – Check
- Brake Actuators – Lubricate/Breather Clean (MOTOR)
- Brake Actuators – Lubricate/Breather Clean (TRAILER)
- EP Brake Decoder – Test
- Strainer/Check Valve – Clean/Renew
- Brake Test

The majority of these tasks are completed at least twice every month. Some tasks will need to be retained but at a lower frequency to maintain the remaining friction equipment and it is estimated that the redundant jobs would take approximately 16 hours to complete. This represents a cost of 4,320 pound per month (assuming a labor cost of 40 pound per hour). Cost benefits from the use of regenerative breaking stem from reduced energy costs and lower maintenance costs of the mechanical brakes. The full stop commuter services at Birmingham and Manchester in the UK are for example able to use regenerative braking. With regenerative braking being enabled, their disc brake pad life was around 18 months. When the electric braking was switched off, the pad life reduced to 18 days (Johnson, 2012). As a consequence of less needs for replacement, regenerative brake also reduces the down-time of the train.

Maintenance cost data for braking system except e-p brake were not found in figure and for evaluation purpose the values of benefit ratings were given based on the explanation of each brake system working principle. The basic operating principle of regenerative eddy current and rheostatic brake show that they have wear free and needs lower maintenance cost. Rheostatic brakes, unlike regenerative brakes, dissipate the electric energy as heat by passing the current through large banks of variable resistors. This heat can be used to warm the vehicle interior, or dissipated externally by large radiator-like cowls to house the resistor banks. These resistor grids, ducts and fans needs continue assessment and maintenance to prevent them from more damage due to the heat generated on the resistors.

The main disadvantage of regenerative brakes when compared with rheostatic brakes is the need to closely match the generated current with the supply characteristics and increased maintenance cost of the lines. With DC supplies, this requires that the voltage be closely controlled. Only with the development of power electronics has this been possible with AC supplies, where the supply frequency must also be matched (this mainly applies to locomotives where an AC supply is rectified for DC motors).During its operation of magnetic track brake, the base of the magnetic track brake in contact with the rail suffers from the generation of “weld-ons”. This is metallic debris that fuses to the pole pieces which has the effect of reducing the magnetic attraction of the brake. To restore the magnetic track brake performance these “weld-ons” need to be physically removed during bogie maintenance. This means that magnetic track brake is not a cheap solution and generally has only been fitted where high emergency deceleration rates are required.

Table 4.13: Benefit Rating for maintenance cost per month

	Electro-Pneumatic brake	Regenerative brake	Rheostatic Brake	Eddy current brake	Electromagnetic track brake
Maintenance cost (pound)	4,320	Not found in figure	Not found in figure	Not found in figure	Not found in figure
Benefit ratings	2	4	4	4	2

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.2.10 Operation Costs

Operation costs refer to all costs which do not belong to one-time costs. According to some researchers, maintenance costs counted as operation costs, however, they have already been treated in the previous section separately. Hear the essential cost is the energy required to activate the brake equipment. On average the eddy current track brake absorbs 4kW/kN – i.e. instead of energy being returned to the power supply it is absorbed during braking (4kW input power is required for every 1kN of brake effort (Johnson, 2012). Using a rather low excitation power, about 1 kW/magnetic track brake, it is possible to obtain important braking force per shoe between 4...10 kN (Cruceanu, 2008). In case of regenerative and rheostatic brake the energy require to initiate the brake equipment is significant but it is very small compared with the energy recovery during braking. In Rheostatic brake the recovered energy dissipated to the atmosphere in some trains and also it is used to heat the cabin and interior part on other trains. To produce 1KN force on the frictional disc less than 1KW of energy consumed on the compressor (Johnson, 2012).

Table 4.14: Benefit Rating for operation cost (input power/brake forces)

	Electro-Pneumatic brake	Regenerative brake	Rheostatic Brake	Eddy current brake	Electromagnetic track brake
Operation cost	<1kw/1KN	Insignificant	Insignificant	4kw/1KN	1kw/10KN
Benefit ratings	3	5	4	2	3

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.2.11 Reliability

Reliability describes the ability of a system to perform its functions in routine circumstances, as well as hostile or unexpected circumstances, with little variation in performance. Reliability of brake equipments is highly significant for ensuring economic operation.

The braking action of a magnetic rail brake is due to the adhesion force between the brake and the rail, not the wheel and the rail. The adhesion force appears when the brake is attracted to the rail. The magnetostatic attraction force depends on the magnetic field strength and on the contact area of the brake and the rail. The braking force of a magnetic rail brake can be greater than the adhesion force between the wheel and the rail, but it depends crucially on the condition of the rail surface, that is on the weather condition. During its operation, the base of the magnetic track brake in contact with the rail suffers from the generation of “weld-ons”. This is metallic debris that fuses to the pole pieces which has the effect of reducing the magnetic attraction of the brake. To restore the magnetic track brake performance these “weld-ons” need to be physically removed during bogie maintenance. If there is a frequent braking, the brake equipment loses its brake performance due to weld-ons.

The braking action of an eddy-current brake stems from the fact that a conducting body slows down when crossing a region of changing magnetic field. The braking force of an eddy-current brake is divorced from adhesion forces between the railroad vehicle and the rail; it does not depend on the condition of the rail surface. However, it can be changed when the rail is heated or cooled. The heating effect of this brake type will raise rail temperature and resulting in an additional rail tension. Furthermore, in curves and in sections with a bad rail level and position, the increased longitudinal rail forces cause additional transversal forces. The rigid slab track is able to assimilate these additional forces in a much higher amount. Ballast superstructure is less suitable for these additional loads or respectively has to be especially upgraded for this purpose. The braking action restricted on areas of slab track due to the heating effect. The performance of the system decreases as the speed of the train decreases means braking force diminishes as speed decreases. For safety reason the mechanical brakes must be fitted to stop the train.

The friction brake can absorb and convert enormous energy values in some cases up to 25 MJ per disc in less than two minutes (TGV train braking from 310 km/h) (Johnson, 2012). This high energy conversion therefore demands an appropriate rate of heat dissipation if a reasonable temperature and performance stability are to be maintained. Unfortunately, design, construction, and location features all severely limit the heat dissipation function of the friction brake to short and intermittent periods of application. This could lead to a ‘brake fade’ problem (reduction of the coefficient of friction, less friction force generated) due to the high temperature caused by heavy brake demands. More usage of the friction brake and humidity will affect its reliability greatly.

Regenerative brake used in major new high-speed trains, N800 series of the Shinkansen in Japan, which became operational in February 2009, use regenerative braking. However, friction brakes are still needed as backup in the case that the regenerative brakes fail. It is possible to use only regenerative braking on these high speed trains to make the speed zero, because most cars have their own electric motors, this is in contrast to trains in which only the locomotive has electric motors. The fourth generation TGVs in France, the German ICE 3 trains are also fitted with regenerative brake. In this case its reliability will not be affected by the reduction of speed and weather conditions but it is fully dependent on the ability of other trains on the same route to capture the current produced or the capacity of the power storage battery. This is known as receptivity and is affected by a number of variables, including location, traffic density and line.

The main braking principles of Rheostatic brake is the same as regenerative brake, the difference is the work after production of the current. In the case of rheostatic brake the electrical energy is dissipated as a heat on the resistor grid to the atmosphere or used to heat the interior part of the train. The reliability of the system will be affected by the condition and capacity of the resistor grid.

Table 4.15: Benefit rating for reliability

	Electro-Pneumatic brake	Regenerative brake	Rheostatic Brake	Eddy current brake	Electromagnetic track brake
Benefit ratings	3	4	4	3	2

1 = Minimum Benefit Value; 5 = Maximum Benefit Value

3.3 Method

Decision making is the process of arriving at a determination based on consideration of alternatives. It involves making decision based on more than one criterion, usually conflicting criteria. Multi criteria decision making (MCDM) techniques can be defined as the evaluation of the alternatives for the purpose of selection or ranking, using a number of qualitative and/or quantitative criteria that have different measurement units (ISSN). Most used models of multi criteria decision makings are (Pohekar, 2004):

- Linear Goal Programming (LGP),
- Multi-Attribute Utility Theory (MAUT),
- Technique for Order Performance By Similarity to Ideal Solution (TOPSIS),
- Analytic Hierarchy Process (AHP).
- Case-Based Reasoning (CBR)
- Data Envelopment Analysis (DEA)
- Simple Multi-Attribute Rating Technique (SMART)
- ELECTRE
- PROMETHEE
- Simple Additive Weighting (SAW)

The following table shows the advantage, disadvantage and application areas of each of the multi criteria decisive making models;

Table 4.16: Summary of MCDM Methods

Method	**Advantages**	**Disadvantages**	**Areas of Application**
LGP	Capable of handling large-scale problems; can produce infinite alternatives.	It's ability to weight coefficients; typically needs to be used in combination with other MCDM methods to weight coefficients.	Production planning, scheduling, health care, portfolio selection, distribution systems, energy planning, water reservoir management,
MAUT	Takes uncertainty into account; can incorporate preferences.	Needs a lot of input; preferences need to be precise	Economics, finance, actuarial, water management, energy management, agriculture
TOPSIS	Has simple process; easy to use and program; the number of steps remains	Its use of Euclidean Distance does not consider the correlation of attributes;	Supply chain management and logistics, engineering, manufacturing systems, business and marketing,

	same regardless of the number of attributes.	difficult to weight and keep consistency of judgment.	environmental, human resources, and water resources management.
AHP	Easy to use; scalable; hierarchy structure can easily adjust to fit many sized problems; not data intensive.	Problems due to interdependence between criteria and alternatives; can lead to inconsistencies between judgment and ranking criteria;	Performance-type problems, resource management, corporate policy and strategy, public policy, political strategy, and planning.
GBR	Not data intensive; requires little maintenance; can improve over time;	Sensitive to inconsistent data; requires many cases.	Businesses, vehicle insurance, medicine, and engineering design.
DEA	Capable of handling multiple inputs and outputs; efficiency can be analyzed and quantified	Does not deal with imprecise data; assumes that all input and output are exactly known.	Economics, medicine, utilities, road safety, agriculture, retail, and business problems
SMART	Simple; allows for any type of weight assignment technique; less effort by decision makers.	Procedure may not be convenient considering the framework	Environmental, construction, transportation and logistics, military, manufacturing and assembly problems.
ELECTRE	Takes uncertainty and vagueness into account.	Its process and outcome can be difficult to explain in layman's terms; outranking causes the strengths and weaknesses of the alternatives to not be directly identified.	Energy, economics, environmental, water management, and transportation problems.
PROMETHEE	Easy to use; does not require assumption that criteria are proportionate.	Does not provide a clear method by which to assign weights.	Environmental, hydrology, water management, business and finance, chemistry, transportation, energy, manufacturing and agriculture.
SAW	Calculation is simple does not require complex computer programs.	Estimates revealed do not always reflect the real situation	Water management, business, and financial management

TOPSIS (technique for order preference by similarity to ideal solution) is a numerical method among the multi-criteria decision makings and was firstly proposed by Hwang and Yoon (Mohanty). This is a broadly applicable method with a simple mathematical model. Furthermore, relying on computer support, it is very suitable practical method. The method is applied in the last three decades (on the history of TOPSIS, and there are many papers on its applications) (ISSN).

The basic concept of this method is that the chosen alternative (appropriate alternative) should have the shortest distance from the positive ideal solution and the farthest distance from negative ideal solution. Positive ideal solution is a solution that maximizes the benefit criteria and minimizes adverse criteria, whereas the negative ideal solution maximizes the adverse criteria and minimizes the benefit criteria. The steps involved for calculating the TOPSIS values are as follows:

Step 1: This step involves the development of matrix format. The row of this matrix is allocated to one alternative and each column to one attribute. The decision making matrix can be expressed as:

$$\mathbf{D}= \begin{array}{c} A_1 \\ A_2 \\ . \\ A_i \\ . \\ A_m \end{array} \begin{bmatrix} x_{11} & x_{12} & . & x_{1j} & x_{1n} \\ x_{21} & x_{22} & . & x_{2j} & x_{2n} \\ . & . & . & . & . \\ x_{i1} & x_{i2} & . & x_{ij} & . \\ . & . & . & . & . \\ x_{m1} & x_{m2} & . & x_{mj} & x_{mn} \end{bmatrix} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Here, A_i (i =1, 2,.......,m) represents the possible alternatives; x_j (j =1, 2,........,n) represents the attributes relating to alternative performance, j =1, 2,..........,n and x_{ij} is the performance of A_i with respect to attribute X_j.

Where Alternative (A_1) = E-P brake

Alternative (A_2) = Regenerative brake

Alternative (A_3) = Rheostatic brake

Alternative (A_4) = Eddy current brake

Alternative (A_5) = Electromagnetic rail/track brake

Step 2: Obtain the normalized decision matrix r_{ij}. This can be represented as:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

Here, r_{ij} represents the normalized performance of A_i with respect to attribute X_j.

Step 3: obtain the weighted normalized decision matrix, **V** = $[v_{ij}]$ can be found as:

$$V = w_j * r_{ij} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

Here, $\sum w_j = 1$

Step 4: Determine the ideal (best) and negative ideal (worst) solutions in this step. The ideal and negative ideal solution can be expressed as:

a) The ideal solution is

$$A^{+} = \left\{\left(\max v_{ij} \mid j \in J\right)\left(\min v_{ij} \mid j \in J \ where\ i = 1,2,3 \ldots\ldots\ldots\ldots, m\right)\right\} \quad \ldots\ldots\ldots\ldots \quad (4)$$

$$= \left\{v_1^{+}, v_2^{+}, \ldots\ldots\ldots, v_j^{+}, \ldots\ldots, v_n^{+}\right\}$$

b) $$A^{+} = \left\{\left(\min v_{ij} \mid j \in J\right)\left(\max v_{ij} \mid j \in J \ where\ i = 1,2,3 \ldots\ldots\ldots\ldots, m\right)\right\} \quad \ldots\ldots\ldots\ldots \quad (5)$$

$$= \left\{v_1^{-}, v_2^{-}, \ldots\ldots\ldots, v_j^{-}, \ldots\ldots, v_n^{-}\right\}$$

Step 5: Determine the distance measures. The separation of each alternative from the ideal solution is given by n-dimensional Euclidean distance from the following equations:

$$S_i^{+} = \sqrt{\sum_{j=1}^{n}(v_{ij} - v_j^{+})^2} \quad where\ i = 1,2, \ldots\ldots\ldots.. m \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

$$S_i^{-} = \sqrt{\sum_{j=1}^{n}(v_{ij} - v_j^{-})^2} \quad where\ i = 1,2, \ldots\ldots\ldots.. m \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

Step 6: Calculate the relative closeness to the ideal solution:

$$C_i^{+} = \frac{S_i^{-}}{S_i^{+} + S_i^{-}}, i = 1,2, \ldots\ldots\ldots\ldots\ldots, m; 0 \le C_i^{+} \le 1 \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

Step 7: Rank the preference order. The alternative with the largest relative closeness is the best choice. In the present study C_i^{+} for each product has been termed as Multi-Performance Characteristic Index (MPCI) which has been optimized by Taguchi method.

3.4 Analysis of the TOPSIS Method

Step 1: Obtaining the decisive matrix

$$D\begin{bmatrix} 5 & 3 & 2 & 2 & 3 & 2 & 5 & 2 & 2 & 3 & 3 \\ 4 & 5 & 5 & 5 & 5 & 4 & 4 & 5 & 5 & 5 & 4 \\ 4 & 4 & 3 & 5 & 5 & 4 & 4 & 4 & 4 & 4 & 4 \\ 3 & 2 & 4 & 5 & 5 & 3 & 3 & 2 & 4 & 2 & 3 \\ 2 & 3 & 4 & 3 & 2 & 2 & 3 & 3 & 2 & 3 & 2 \end{bmatrix}=$$

Step 2: Obtaining the normalized decisive matrix

$$\begin{bmatrix} 0.597 & 0.378 & 0.2390 & 0.111 & 0.311 & 0.2857 & 0.566 & 0.305 & 0.248 & 0.378 & 0.408 \\ 0.478 & 0.629 & 0.5976 & 0.559 & 0.518 & 0.5714 & 0.453 & 0.762 & 0.620 & 0.630 & 0.544 \\ 0.478 & 0.504 & 0.3586 & 0.559 & 0.518 & 0.5714 & 0.453 & 0.610 & 0.496 & 0.504 & 0.544 \\ 0.358 & 0.252 & 0.4781 & 0.559 & 0.518 & 0.2857 & 0.339 & 0.305 & 0.496 & 0.252 & 0.408 \\ 0.239 & 0.378 & 0.4781 & 0.223 & 0.311 & 0.4285 & 0.339 & 0.457 & 0.248 & 0.378 & 0.272 \end{bmatrix}$$

Step 3: Obtaining the weighted normalized decision matrix, for each of the evaluation criteria the weighted value is as follows:

Table 4.17: Weighted values

Criteria	F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8	F_9	F_{10}	F_{11}
Weighted value	0.15	0.05	0.05	0.1	0.05	0.05	0.1	0.1	0.15	0.1	0.1

Where: F_1 = benefit rating of braking performance

F_2 = benefit rating of brake equipment weight

F_3 = benefit rating of compactness of brake equipment

F_4 = benefit rating of wear and degradation

F_5 = benefit rating of noise emission

F_6 = benefit rating of electromagnetic interference

F_7 = benefit rating of pollutant emission

F_8 = benefit rating of investment cost

F9 = benefit rating of maintenance cost

F_{10} = benefit rating of operation cost

F_{11} = benefit rating of reliability

$$\begin{bmatrix} 0.090 & 0.019 & 0.012 & 0.011 & 0.016 & 0.014 & 0.057 & 0.031 & 0.037 & 0.038 & 0.041 \\ 0.072 & 0.031 & 0.028 & 0.056 & 0.026 & 0.029 & 0.045 & 0.076 & 0.093 & 0.063 & 0.054 \\ 0.072 & 0.025 & 0.023 & 0.056 & 0.026 & 0.029 & 0.045 & 0.061 & 0.074 & 0.050 & 0.054 \\ 0.054 & 0.012 & 0.018 & 0.056 & 0.026 & 0.014 & 0.034 & 0.031 & 0.074 & 0.025 & 0.041 \\ 0.036 & 0.019 & 0.024 & 0.022 & 0.016 & 0.021 & 0.034 & 0.046 & 0.037 & 0.038 & 0.027 \end{bmatrix}$$

Step 4: Determination of the ideal (best) and negative ideal (worst) solutions.

$V_1^+ = 0.090$ $V_1^- = 0.036$

$V_2^+ = 0.031$ $V_2^- = 0.012$

$V_3^+ = 0.028$ $V_3^- = 0.012$

$V_4^+ = 0.056$ $V_4^- = 0.011$

$V_5^+ = 0.026$ $V_5^- = 0.016$

$V_6^+ = 0.029$ $V_6^- = 0.014$

$V_7^+ = 0.057$ $V_7^- = 0.034$

$V_8^+ = 0.076$ $V_8^- = 0.031$

$V_9^+ = 0.093$ $V_9^- = 0.037$

$V_{10}^+ = 0.063$ $V_{10}^- = 0.038$

$V_{11}^+ = 0.054$ $V_{11}^- = 0.027$

Step 5: Determination of the distance measures S^+ and S^-

$S_1^+ = 0.09542$ $S_1^- = 0.06095$

$S_2^+ = 0.02185$ $S_2^- = 0.10842$

$S_3^+ = 0.03620$ $S_3^- = 0.08758$

$S_4^+ = 0.07949$ $S_4^- = 0.06621$

$S_5^+ = 0.12310$ $S_5^- = 0.02762$

Step 6: determination of the relative closeness to the ideal solution.

$C_1^+ = 0.38978$

$C_2^+ = 0.83222$

$C_3^+ = 0.70754$

$C_4^+ = 0.45442$

$C_5^+ = 0.18325$

Step 7: Ranking the preference order.

Regenerative brake (C_2^+) ------------------------------------ 1st

Rheostatic brake (C_3^+) --------------------------------------- 2nd

Eddy current brake (C_4^+) ------------------------------------ 3rd

E-P brake (C_1^+) --- 4th

Electromagnetic rail brake (C_5^+) -------------------------- 5th

CHAPTER FOUR: RESULLT AND DISCUSSION

4.1 Result

Regenerative brake (C_2^+) ……………………………….. 1st
Rheostatic brake (C_3^+) ………………………………….. 2nd
Eddy current brake (C_4^+) ……………………………….. 3rd
E-P brake (C_1^+) ………………………………………….. 4th
Electromagnetic rail brake (C_5^+) ………………………… 5th

4.2 Discussion

Following the systems comparison in this thesis and the weighting of the various comparison characteristics according to the survey, the relative closeness of regenerative brake system shows superior over the other braking systems. Based on the evaluation criteria stated above this brake system is ranked more than the average mark, specially the non contact and energy recovery behavior helps to rank first among the other brake system.

The relative closeness of Rheostatic brake system shows that it is superior over Eddy current and E-P brakes and more superior over Magnetic track and E-P brakes. Many systems of this brake system is similar with regenerative brake system, but the additional materials needed to dissipate the current as a heat on the resistor grid and the non recovery of the whole brake energy behaviors ranked next to regenerative brake system.

Eddy current brake relative closeness shows slightly superior over E-P brakes and inferior over regenerative and rheostatic brake systems. This brake system performance will diminish as the speed of the train decreases and needs the help of other brake system to stop a train. The larger weight, high initial and operation cost of this brake system minimizes its benefit rating values and is ranked at third.

The contact between friction materials during braking increases the wear, pollutant emission, maintenance cost and noise emissions in case of magnetic track and E-P brakes, which has also an adverse effect on human health. Since they are not speed dependent they are more important at low speed and emergency braking. The relative closeness of E-P brakes are superior over magnetic track brakes and ranked fourth and fifth.

CHAPTER FIVE: CONCLUSION AND RECOMENDATION

5.1 Conclusion

- The research outcome as expected. From the results, it can be concluded that regenerative brake system is better than the others based on the selected evaluation criterion.
- According to the result it is better to cover most of the braking power by regenerative or by rheostatic braking.

5.2 Recommendations

- Covering most of the braking distance by regenerative and rheostatic brake is advantageous for speeds greater than 30km/hr.
- Covering the braking distance with E-p followed by magnetic track/rail brakes during speeds lower than 30 km/hr and emergencies is also advantageous.
- To modify the evaluation criteria and weight included in this thesis work, it would be recommendable to conduct surveys with potential customers, potential operators, potential investors and other stakeholders.
- Giving benefit rating for the criteria are the main task for such works and it is better to works in group rather than individually.
- Future work should be conducted to improve the reliability of the research by taking real data for each evaluation criteria from manufacturer/supplier of brake systems and railway corporations.

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