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Use of Linear Motors for Conventional Railroad Applications

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ABSTRACT

This paper discusses the various possible uses of linear electric motors in railroads under particular operating conditions found in the United States. Performance characteristics of some linear motor designs are presented first to provide an illustration of the range of performance that can be expected from these motors. The paper then examines two specific uses of linear motors--a LIM booster-retarder for classification yards and an eddy-current brake for a high speed passenger train. The necessity for new components for these applications, the advantages offered by linear motors, and the possible problem areas, as well as some recommended solutions, are also discussed.

ACKNOWLEDGMENTS

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1.0 INTRODUCTION

The concept and topology of linear electric motors has been known for the past several decades. All types of motors--i.e., dc, induction, synchronous and reluctance motors--are possible with a linear configuration. However, the dc and synchronous motors require double excitation--field and armature--thus making the whole concept quite complex. The reluctance motor, on the other hand, has a poor thrust density because the secondary has no excitation, either external or induced. Hence, the initial attention was focused on linear induction motors. Also, the emphasis was on small power applications where the linear configuration could be advantageously used and where poor efficiency and power factor were relatively unimportant.

The interest in Linear Induction Motors (LIMs) was renewed in the mid 1960's because of a necessity of a suitable contactless propulsion system for high speed tracked vehicles. A significant effort--analytical as well as experimental--has been made both in the United States and abroad to understand clearly the operating characteristics of LIMs as affected by the large air gap, the end effect and the edge effect of the motor. Both single-sided and double-sided configurations have been built and tested. Power conditioners which can supply a variable voltage, variable frequency power for controlling the motor have also been developed. The Federal Railroad Administration (FRA) LIM programs over the past several years in particular haveproduced good motor designs that have performed about as predicted and have proven the feasibility of LIM propulsion for high speed tracked vehicles. Recently, however, FRA LIM programs have been reoriented towards applications in conventional railroad operations. Considering the inherent simplicity of the LIM configuration and the attainable thrust density, linear dc, synchronous and reluctance motors have little or no significance in such applications. This paper, therefore, discusses the various possibilities for LIMs under the particular conditions of U.S. railroading.

2.0 CHARACTERISTICS OF LINEAR MACHINES

Before studying the individual applications in detail, it is necessary to understand the performance limits of linear motors. A linear motor is basically an electromagnetic deveice and its performance characteristics are based on three important design factors--electric loading, magnetic loading and the duty cycle. Table I gives a comparison of the performance characteristics of some linear motor designs. These devices have been selected to include various design possibilities such as water cooling, short duty cycle, etc. This table can provide a fair illustration of the range of performance that can be expected from linear motors. A brief description of each motor is given below.

2.1 LIMRV SLIM(1)

This Single-Sided Linear Induction Motor (SLIM) is taken as half of the double-sided linear induction motor that has been extensively tested on the Linear Induction Motor Research Vehicle (LIMRV). The LIMRV SLIM is a large air-cooled motor having 10 poles and speed capabilitiy in excess of 400 km/h. The power rating at this speed is approximately 1 megawatt. The core width is 25.4 cm and the length is approximately 380 cm.

2.2 TLRV SLIM(2)

The Tracked Levitated Research Vehicle (TLRV) SLIM is similar to the LIMRV SLIM except that it is water cooled, is narrower, and has a longer pole pitch. The core width is 19 cm and the length is approximately 225 cm for 5 poles. This motor is rated approximately 1.5 megawatt at 400 km/h.

2.3 WEDWAY SLIM (3,4)

This long-stator SLIM is part of the Wedway People Mover at Disney World. It is air-cooled, has 6 poles, and operates on an

TABLE I

CHARACTERISTICS OF SOME LINEAR ELECTRIC MACHINES

SLIM QUANTITY		LIMRV SLIM	TLRV SLIM	WEDWAY SLIM	TYPICAL BRAKE	ICTS SLIM
Thrust Density kPa(psi)	Duty Factor					
	1.0	10 (1.5)	22 (3.2)			16.6 (2.4)
	.25			5 (.7)		
	100 sec	23 (3.4)			-103 (-15)	
Airgap mm (in)		6 (.63)	16 (.63)	4 (.15)	7 (.28)	13 (0.51)
Pole Pitch cm (in)		36 (14)	45 (17.75)	5.7 (2.25)	16.5 (6.5)	29.68 (11.3)
Normal Force Density kPa (psi)		14 (2)	35 (5)		310 (45)	10.7 (1.55)
Minimum Power Required/Thrust W/N (W/lb)		13.3 (59)	35 (154)	13.0 (90) 60 Hz excitation	3.3 (15)	
Best PF x EFF (optimum motor operation)		.5	.46	.4 (estimated)		0.38
Weight per Unit Area kPa(psi)		12.4 (1.8)	17.0* (2.4)		.44	1.0
Weight/Thrust		1.2	.76*		.44	1.0

*Water cooled; weight of cooling system is not included intermittent basis. The core of the units, having a 25 percent duty factor, is 17.8 cm wide and 38 cm long. The thrust rating of this machine is 334 N (75 lb). Motor stators having a duty factor of 33 percent have a core width of 25.4 cm.

2.4 Typical Brake(5-11)

The data are based upon examination of designs made in France and Germany. Performance figures are based upon actual experimental results. Typical brakes are excited with dc, have a core width of approximately 8 cm and a length of 150 cm.

2.5 ICTS SLIM(21)

The Intermediate Capacity Transit System (ICTS) SLIM is a 6 pole air-cooled motor. The machine is designed for a top speed of 45 miles per hour (72 km/h). The maximum thrust developed by the motor is 10 kN. The core width is 21.6 cm and the length is 190 cm.

2.6 Comparison of Motors

The data are now discussed starting with thrust density. The densities are in kilopascals (kilonewtons per square meter). 6.894 kPa is equivalent to a pressure of one pound per square inch (psi). The air-cooled LIMRV motor has a continuous thrust density of 10 kPa, where as the water-cooled TLRV-SLIM with a thrust density of 22 kPa represents a design that pushes the state-of-the-art to its limits. The Wedway motor operates with a duty factor of 0.25 and is air-cooled without the use of forced air. Although it operates with a small air-gap, the thrust density (5 kPa) of the Wedway motor is substantially less than that of the LIMRV motor. The magnitude of the thrust density of the brake (103 kPa) is many times that of the motors due to its short duty cycle and its basic mode of operation.

The airgaps of the motors range from 4 to 16 mm. Considering the present condition of U. S. railroad tracks, a practical gap for railroad applications is in the range 10-15 mm. The pole pitch of the motors is usually made as large as possible until the overall LIM weight increases due to the increase in yoke thickness required with increasing pole pitch.

The normal force densities relate to the pulling force on the motor cores. The normal force of a SLIM varies over a wide range--from an attractive force at low slip operation to a repulsive force at higher slip values. The values of normal force density of Table I are for normal operating slip and represent an attractive force. The normal force densities for the brake are substantial--as high as 310 kPa (45 psi) resulting from a higher airgap flux density compared to a SLIM.

All of the motors must be supplied with power at least equal to that required for the vehicle propulsion (thrust X velocity). Additionally, all of the motors must be supplied with power corresponding to winding and reaction rail losses although the brake does not need to supply the rail losses. This power defines the minimum power that must be supplied to the motor. The ratio of the minimum power to thrust is given in Table I for each of the motors. The brake is by far the most efficient structure because of its method of operation (dc excited structure used to produce a drag force).

Besides real power, reactive power must be supplied for the induction motors. Some indication of the penalty that must be paid for poor power factor can be gained from the product of power factor and efficiency. The induction motors have such a product in the order of 0.4-0.5, with their efficiency typically in the range 80-90 percent. In estimating the kVA requirements of a power converter for a propulsion application, the motive power (force X velocity) should be divided by the product of the efficiency and power factor.

The weight of a linear motor is an important consideration for some applications. It can be estimated using the weight/area and weight/thrust ratios given in Table I. The weight/thrust ratio is generally less for water-cooled motors. For example, the air-cooled LIMRV-SLIM has a weight to thrust ratio of 1.2, whereas the water-cooled TLRV-SLIM has this ratio of 0.76. The ratios for water-cooled motors given in Table I do not, however, include the weight of the cooling system.

2.7 Summary of Characteristics

A linear motor, being an electromagnetic device, has the following characteristics:

- It has a fundamental force density limitation imposed on it by the electric and magnetic loading of the design.
- High power is thus possible only at high speeds.
- Better performance (higher kVA/kg) is possible only with better cooling techniques or with short duty cycles.

These operational characteristics are clearly evident from the data of Table I.

These considerations limit many applications of LIMs as efficient propulsion devices in conventional railroading. With a large airgap, a linear motor can never compare favorably with a rotating machine operating with a small airgap on a one-on-one basis. One has to find situations where a rotating machine cannot adequately do the job, limited by other operational considerations such as a necessity for contactless propulsion, a light truck design, etc. Some attractive possibilities under these conditions are:

- A LIM booster-retarder in classification yards,
- A linear eddy-current brake,

- LIM propulsion of urban rail vehicles, and
- LIM-rotary motor systems for propulsion of high speed vehicles on rail.

These possibilities are discussed in later sections.

3.0 USE OF LIMs IN CLASSIFICATION YARDS

3.1 General Background(12)

Railroad operations account for almost 40 percent of the total intercity freight transportation in this country. Almost all rail freight movements involve railroad classification yards. A classification yard is an area where incoming multi-car trains are broken up and new multi-car trains are formed according to the consist demands. There are two basic types of yards--a hump yard and a flat yard.

In a hump yard an individual car or a group of cars is driven on a hump using a humping locomotive. The car then rolls down a slope, with its speed controlled at some locations by retarders, and is directed to a particular consist by means of switches (See Figure 1). Thus a freight car has to leave the last retarder with a speed just sufficient to reach its final destination with a permissible speed. If the speed of the car leaving the retarder is less, then the freight car will stop before reaching its destination, causing an interruption in the yard operations. If, however, the car leaves the retarder with more than necessary speed, the coupling impact can cause severe damage to the lading and/or equipment. It could also lead to a derailment in case of a mismatch coupling. Moreover, every car has different rolling characteristics and has to travel different distances. Thus, every car has to be individually controlled according to its characteristics, and the car control system should have a very high statistical guarantee. The statistical guarantee has extremely important operational implications, e.g., in a yard with a capacity of 4000 cars per day a statistical guarantee of 99 percent means that even so 16 cars per day will halt prematurely. With a guarantee of 99.9 percent one must expect that 1.6 cars per day will come to a halt too soon. It should be mentioned here that if a car is found to be mechanically

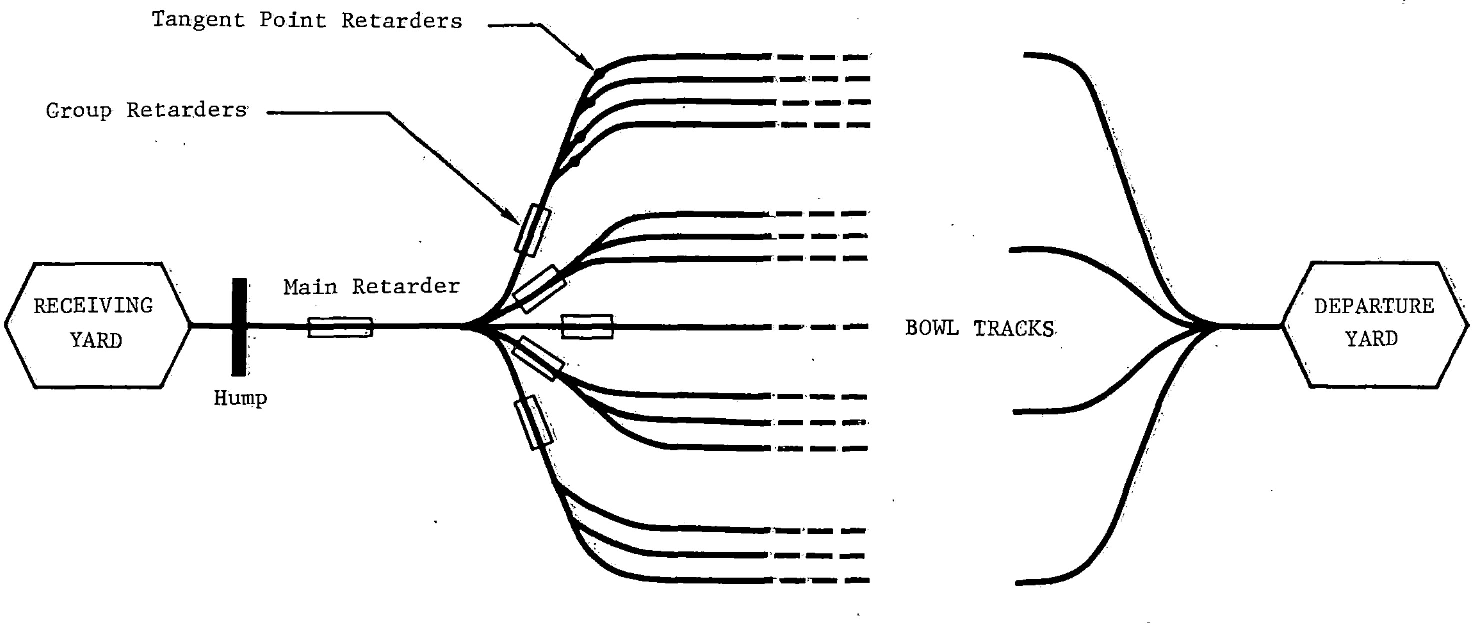


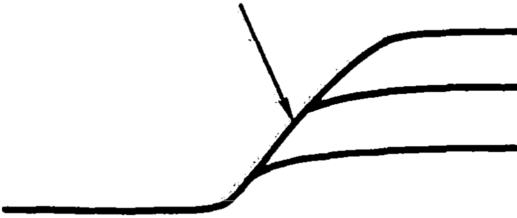
FIGURE 1
LAYOUT OF A HUMP YARD

defective or is carrying hazardous material it is handled on an individual basis without being humped. For a typical modern hump yard, about 0.5-1 percent of the cars are not humped.

A flat yard, on the other hand, usually consists of a series of tracks connected by a ladder track and a switching lead as shown in Figure 2. The classification process begins with a group of cars being pulled out to the switch lead. Here the switch engine accelerates quickly toward the yard and then decelerates. Just prior to deceleration, a car or a group of cars are uncoupled so that they separate from the rest. This procedure is called "kicking the cars." The switch engine continues to kick and separate the cars until reaching the ladder track when it pulls the remaining cars back to resume the process. The cars that have been kicked travel along the lead and the ladder track and are switched onto appropriate track. The switches in flat yards are generally manually controlled and in many small yards a brakeman rides the car to control the speed at coupling.

Most speed control devices in yards used to slow the cars are called "retarders." Others called "booster-retarders" can be used to slow or speed up the cars. Basically, there are two types of such devices--clasp-type and nonclasp-type.

Clasp-type retarders consist of two long steel rails that flank the track rails. As a car rolls down the track, these beams are forced toward each other to compress the lower portion of each wheel. The friction between the contacting surfaces retards the car. Such a device cannot obviously be used to speed up the car. Electropneumatic retarders are by far the most commonly used heavy-duty retarders in hump yards. The actuating mechanism is in part electrically controlled and in part pneumatically controlled. It consists of air cylinders that actuate the long retarder beams, pipes, hoses and the valves of these


LADDER TRACK
SWITCHING LEAD

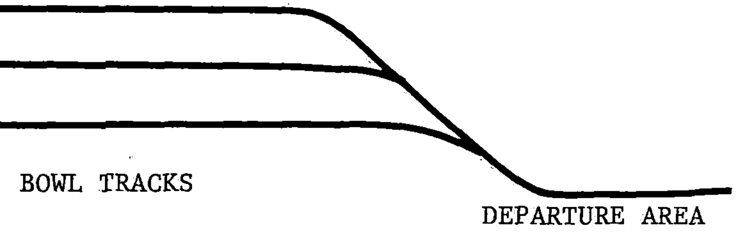


FIGURE 2
A FLAT YARD

cylinders are electrically controlled. The retarding force is controlled by changing the air pressure in the cylinders. Some of these retarders can handle cars weighing as much as 160 tons. Cars heavier than that, if encountered, are manually controlled. These clasp-type devices are equipped with replaceable steel shoes and have a tendency to excite piercing wheel squeals. This problem of noise pollution is discussed in the next section.

There are many other clasp-type retarders, such as a spring loaded retarder, an electric retarder, a weight responsive retarder, etc. Also, there are many non-clasp type retarders such as a Dowty system, a hydraulic retarder, a rubber retarder or an electrodynamic retarder. A few of these can be used as booster units to propel cars but most of these are basically retarders. A detailed discussion of these, however, is beyond the scope of this report.

3.2 Incentives for Improvements

A close look at the present yard operations reveals that labor related costs and damage to lading and/or equipment due to overspeed coupling impacts are two significant problem areas of current yard technology.

Over the last ten years, direct costs of U. S. railroads due to loss and damage (L&D) of freight have been of the order of 240 million dollars per year.(13,14) It is also estimated that the indirect costs for claim investigations, processing, and so on, total at least this amount. Moreover, study of L&D payments indicates that more than a third of these payments are due to damage from end-to-end impacts.(13,14) Thus it could be conservatively estimated that the total loss to the railroads resulting from end impacts exceeds 150 million dollars annually. An unspecified portion of this is the direct result of the coupling impacts in a classification yard.

Figure 3 shows the results of a survey of switchyard impacts.(15) This curve shows the relationship between a given impact speed and the percent of total impacts below that speed. The range of limiting speeds for different TOFC/COFC arrangements based on 40,000 lbs (178 kN) end-wall load are also shown here. This shows that except for CU/Fixed Brackets container system, the limiting speed is below 6 1/2 mph (10.5 km/h) and that there are more than 30 percent impacts above 6 1/2 mph. Even for CU/Fixed Bracket container system there are more than 6 percent impacts above the limiting speed of around 8 1/2 mph (13.7 km/h). Impacts with speeds up to 18 mph (29 km/h) have occasionally occurred in some yards. This clearly shows a need for precise speed control in classification yards.

A close scrutiny of yard expenses shows that about two-thirds of the total operating costs are labor related. In fact, about 65 percent of these labor costs are directly associated with the use of switch engines. It has been estimated that in the period 1980-2000, U. S. railroads will be spending about $35 billion related to the operation of switch engines. In a recent study of yard technology improvements, it has been estimated that use of remote controlled switch engines and better speed control devices could save more than $6.5 billion (1975 dollars) over a period of 1980-2000. This study also estimates that 80-120 hump yards and 75-85 flat yards will be constructed in the U. S. between 1980-2000. Thus there is tremendous potential for saving on yard expenses with new improved booster-retarder technology and especially if the use of switch engines can be drastically reduced or eliminated completely.

Another major problem with the clasp-type retarders is the screeching noise created by retarder action on the cars.(16) The society in general and the labor unions in particular are demanding stringent controls on the noise pollution. Anyone who has ever been

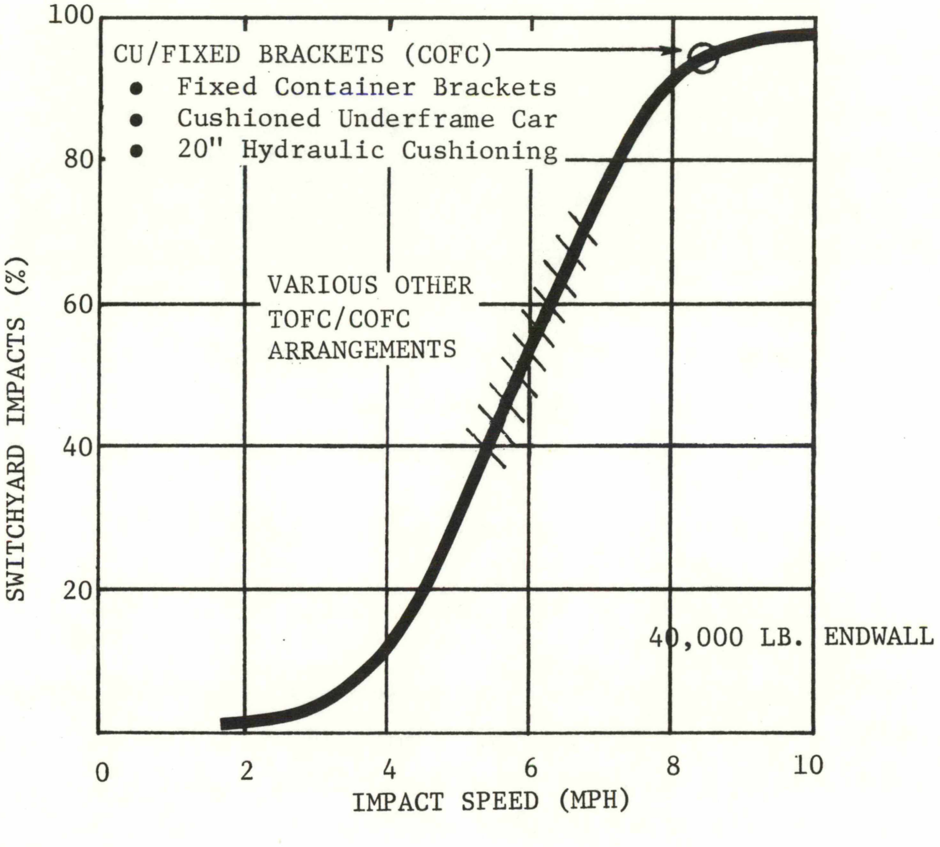


FIGURE 3
SWITCHYARD IMPACTS

close to a retarder in action knows that the sound is deafening and quite painful--100 to 134 db at 15 feet from the retarder. The human ear is most sensitive to frequencies in the range 500-5000 Hz and a retarder creates extremely high sound levels in 2000-4000 Hz range. The screeching of a retarder is, therefore, very annoying to anybody within hearing range. The low frequency rattling or rumbling noises are of less significance away from the retarder since they are not carried far.

Earlier attempts to use soft steel shoes to suppress noise were not very successful as shoe wear was considerably increased without an appreciable reduction in noise. The new designs use ductile iron shoes containing a fair amount of free graphite dispersed throughout the metal. These shoes reduce the screeching incidences by about 30 percent although the wear is increased by 300-400 percent. Several other approaches to noise control include:

1. drilling holes in the face of the shoe and plugging the holes with lead
2. slotting the shoe lengthwise over the entire length and packing it with lubricant
3. applying controlled lubrication to the retarder shoes and car wheels, etc.

Most of these attempts, however, reduce noise at a cost of either increased wear or reduced retarding action. Vertical sound barriers are also occasionally constructed to comply with local noise ordinances.

It can thus be seen that the above economic and environmental considerations provide enough incentive to look for a better system.

3.3 LIM Booster-Retarder

Since 1967, the Japanese have been developing different kinds of booster-retarder systems using linear induction motors. The main component of the system is a low profile carriage which constitutes the primary side of the LIM system. This carriage runs on an aluminum-clad reaction rail. This device is located in each of the bowl tracks between the two running rails. When a humped car goes through the main and group retarders into a particular bowl track it goes over this device. The carriage then engages the wheels of the freight car and either accelerates or decelerates the car to the desired speed. When the car comes close to the consist, the carriage disengages itself from the car and returns to its stand-by position at the hump end of the bowl track, ready to handle another car. If on this return travel, the carriage encounters another car it will, of course, capture it midway and take it to the consist. This process is shown in Figure 4.

Table II gives some technical details of two prototypes of Type L4 booster-retarder currently being used in Japan.(17) Prototype 1 consists of three units--a pusher car to hold the wagon wheels, a control car and a linear motor car. It is 8.28 m long, 1.051 m wide and stands 0.074 m high above rail tread. It weights 1.77 tons. The motor thrust is controlled by a simple on-off control using one or both motors as required. This L4 type retarder was first tested at Toyama freight yard. It was then put into regular use at Shiohama yard in 1974 (see Figures 5 and 6). The same kind of system is also used in a freight yard at Kitagami. Japanese are also planning Suhotonda yard near Hiroshima using L4 type retarder. This yard will not use any clasp-type devices at all.

The system has excellent control characteristics free from external distrubances. In one survey, the coupling speed was controlled with an average of 4.3 km/h and a standard deviation of 1.0 km/h with a head wind of 10 m/s and tail wind of 8 m/s.

One commonly held misconception among the proponents of such a LIM booster-retarder is that it can increase the thru-put of a yard by

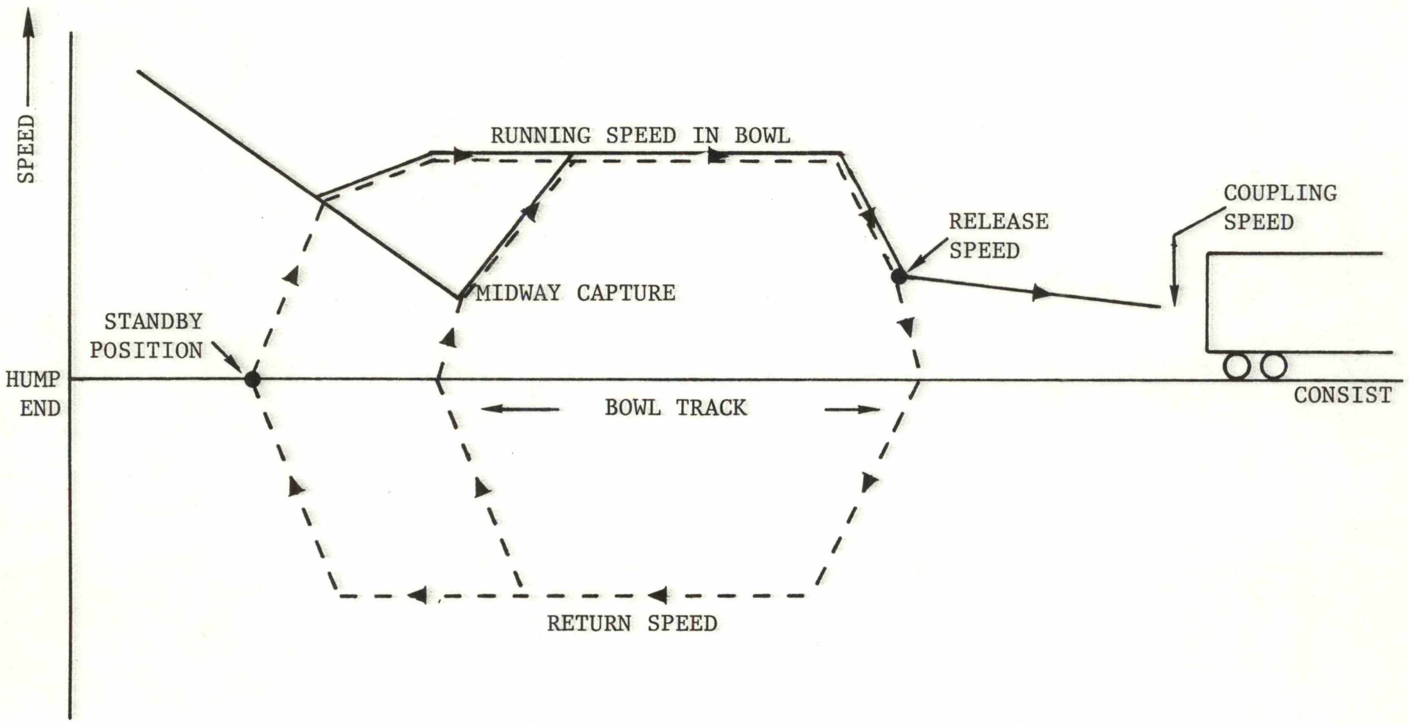


FIGURE 4
OPERATION OF A LIM BOOSTER-RETARDER

TABLE II

SOME TECHNICAL DATA FOR L4 TYPE LIM BOOSTER-RETARDER

	Prototype 1	Prototype 2
Linear Motor	220 V, 3 phase, 50 Hz Syn. Speed 25 km/h Starting Thrust 650 kg/two sets	220 V, 3 phase, 60 Hz Syn. Speed 30 km/h Starting Thrust 650 kg/two sets
Reaction Rail	2 mm aluminum with 16 mm backiron	3 mm aluminum with 16 mm backiron
Power Pickup	3 phase pickup at two L4 rails (between the running rails) and the reaction rail	3 phase pickup at two L4 rails (between the running rails) and the reaction rail
Configuration	LIM Car + Control Car + Pusher Car	Motor & Control Car + Pusher Car

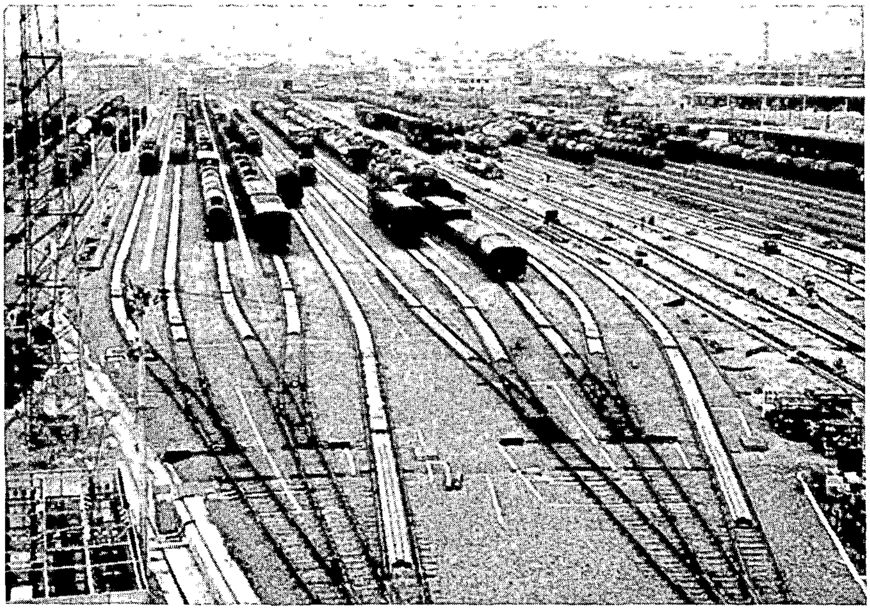


FIGURE 5
GENERAL VIEW OF SHIOHAMA YARD

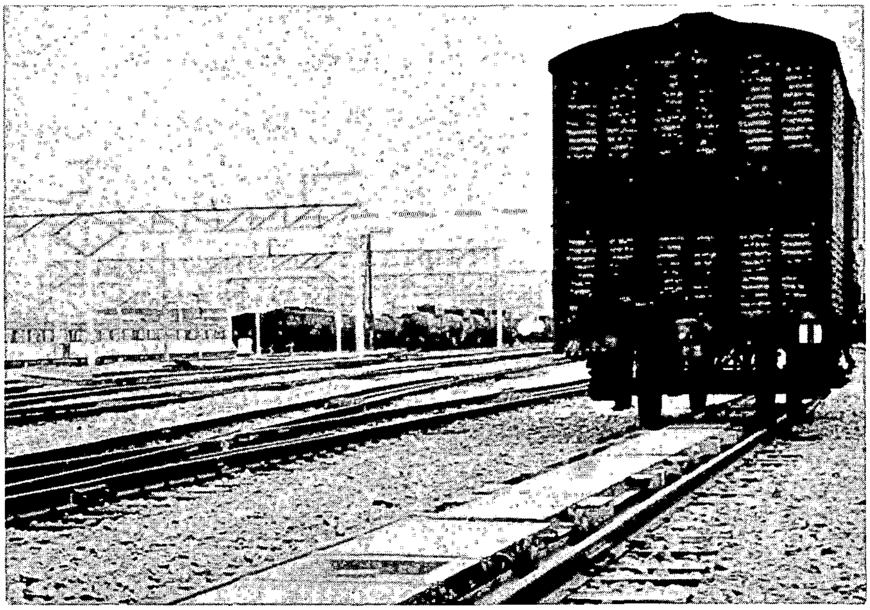


FIGURE 6
A CAR BEING PUSHED BY A LIM BOOSTER-RETARDER

improving the humping rate. The modern yards in the U. S. and abroad can hump cars at a fairly high rate of 6-8 cars per minute. Also, the thru-put of a yard is more limited by the speed with which one can pull the cars out of the bowl on the departure tracks rather than by a limit set by the humping rate. Moreover, most of the yards are operating at less than capacity for lack of business. Thus there is no need to increase the current humping rates and the LIM booster-retarder is not the only way to do it. Better control of coupling speeds and reduction in the noise are the two major advantages of this type of booster-retarder.

The application of LIM systems in U. S. classification yards will depend on its economic justification under suitable operating conditions. It should also be noted that the Japanese rail equipment is much lighter than the U. S. equipment and hence equipment like the L4 booster-retarder cannot directly be applied in freight yards here. The LIM components and the booster-retarder system would have to be designed and developed for application in U. S. yards.

4.0 LINEAR EDDY-CURRENT BRAKES

The demands on the performance of the braking system are becoming increasingly severe for freight and passenger trains. For a freight train this is mainly due to the continuing introduction of heavier and longer trains. And for a passenger train the performance of the braking system is a major factor to consider when an increase of the average speed is contemplated. A consistent and predictable braking distance independent of rail condition or adhesion characteristics is very important to assure the certainty of braking. It also has a significant cost/benefit implication for safety standards and signal system design. Also, the maintenance cost of the braking system is another important index of performance. A new candidate braking system, in order to compare favorably with the existing ones, has to provide a better performance at comparable costs or a comparable performance at lower costs.

4.1 General Background

In assessing a need for a better braking system and suitability of linear eddy-current brakes in particular, one has to first examine the braking requirements of a vehicle and how they are met by the existing equipment. The system requirements and hence the braking equipment used on a passenger train and a freight train are quite different.

The present freight train air brake system consists of a manually connected single pneumatic line and a control valve on each car. A control signal in the form of pressure changes travels down this line and initiates braking action on each car. This system has in the past provided excellent braking performance with sufficient safety margins. But because of the introduction of heavy cars and longer trains on an increasing level, the demands on the braking equipment are becoming more severe. Use of improved control valves, increased air pressures coupled with improved pipe fittings, and dynamic braking on a locomotive are some of the approaches used to meet these severe demands.

For a longer freight train, a time delay is introduced in brake application along the length of the train. This in turn can lead to unacceptable levels of longitudinal in-train coupler forces. This problem is more severe for heavy long trains running on especially difficult terrain. Although the demands on a braking system can be relaxed by simply shortening the train length, longer trains will continue to be run because of other operational and economic considerations.

Thus an ideal braking system for current needs is the one which can provide increased braking levels uniformly along the length of the train without any time delay. Both these characterisitcs would result in shorter, predictable braking distance without increasing the in-train dynamic forces. These would in turn reduce lading and equipment damage and overall maintenance costs.

Any attempt to eliminate the time delay in brake application along the length of the train (of the order of 100 seconds for a 100-car train) necessitates either the use of radio controlled valve equipment or running an electric line along the train length.(18) Radio control on every car is probably prohibitively expensive and running an electric line is impractical unless it is for a unit-train consist or unless a new automatic coupling system is introduced. Considering a total fleet of more than 1.3 million cars with the U. S. railroads, a quick introduction of new revolutionary braking systems can be ruled out and any evolution will probably come quite slowly. Use of linear eddy-current brakes for freight transportation, therefore, has to be examined in this context.

The passenger train braking system requirements are quite different, as can be expected, from the freight train. The average speed of the passenger train is higher and the train is very short. Moreover, the braking system on a passenger train is more complex and sophisticated to a level where the problem of longitudinal coupler forces has been almost eliminated. The braking system requirements on a passenger train are, therefore, limited to providing a guaranteed deceleration at a minimum cost. An ideal system should have the following characteristics:

- effective and predictable operation at all speeds
- low life-cycle costs
- long duty cycle as well as overload capacity
- minimum axle loading
- minimum actuation power
- capable of recovery of braking energy
- ability to work as an independent emergency brake
- not be limited by rail adhesion, or provide a cleaning action to maximize adhesion

It can be seen that no single system can provide all of these features. The available alternative braking systems listed below can be used singly or in combination:

- Tread Brakes--iron or composition pads act on wheel tread
- Disc Brakes--composition pads act on axle-mounted steel disc
- Dynamic Braking--resistor bank driven by traction motor operating as a generator
- Flywheel System--flywheel driven by traction motor or by a separate motor
- Magnetic (Electromagnetic) Track Brake--iron electromagnet clamped to rail
- Eddy-Current Track Brake--magnet system induces eddy currents in rail

Tread brakes are the traditional brakes of railroading and are considered indispensable because of their cleaning action. Disc brakes are beginning to be used with tread brakes for high speed operation. The other brake systems, with the exception of dynamic braking, have thus far had limited application. The magnetic track brake is used in an emergency rather than as a service brake. The eddy-current track brake is promising new technology and is perhaps most developed in France, Germany, and Japan. It uses a magnetic structure having a number of alternating north and south poles. When moved, the magnet structure produces a time-varying magnetic field in the rail. This in turn results in eddy-currents. The energy to keep the eddy currents flowing produces braking (i.e., a reduction in kinetic energy).

Current braking systems on passenger trains depend on the adhesion characteristics of the wheel and the rail. The braking rates, therefore, are directly related to the adhesion limit. For example, if the adhesion coefficient is reduced from 14 percent to 8 percent, the maximum braking rate is reduced from 3 mphps (0.14 g) to less than 1.8 mphps (.08 g). Since the adhesion coefficient decreases with increasing speed--6 to 22 percent at 20 km/h (12.5 mph) down to 5 to 12 percent at 200 km/h (125 mph) depending on the rail conditions--the maximum deceleration rate is 2-3 mphps (0.09 g - 0.14 g) depending on rail condition. Any upgrading of the average speed on existing tracks without changing the signal spacing demands increased deceleration rates.(19) This in turn warrants the use of braking systems which do not depend on rail adhesion characteristics. This is precisely why linear eddy-current brakes have been developed in recent years.

As mentioned earlier, the initial and periodic maintenance costs of the braking system are also an important index of performance. In general, factual information on the maintenance costs is not available but it has been estimated that the brake related life-cycle cost of passenger train equipment is 4-8¢/mile (2.5-5¢/km) depending on the equipment. Passenger trains driven by locomotives have generally lower costs as compared to MU equipment. These costs are, however, expected to increase rapidly with speed. Any new braking systems such as those using linear eddy-current brakes will have to be evaluated and justified on the basis of overall costs.

4.2 Principle of Operation

A linear eddy-current brake consists of an alternating line of north and south poles facing the top of the running rail as shown in Figure 7. The instantaneous distribution of the magnetic field in the airgap is similar to that found in a linear induction motor with respect to the primary at synchronous speed, whereas in a linear brake it is stationary with respect to the primary due to direct current excitation. This airgap field moves with respect to the surface of the rail at a speed equal to the vehicle speed. Eddy currents are, therefore, induced in the solid steel rail and a force is produced that tends to oppose the vehicle motion. The current distribution in the rail surface is also similar to the current distribution in a LIM secondary. Such a distribution is shown in Figure 8, where the currents are shown to flow along the side of the rail. In fact, the behavior of a linear eddy-current brake is analogous to that of a LIM under dc dynamic braking conditions when LIM primary is excited with direct current.

An analytical modeling of linear brake is quite difficult compared to a LIM analysis. This is mainly due to the following reasons:

a. A top layer of the rail carries most of the flux and is magnetically saturated. The thickness of such a layer depends on the pole pitch and the vehicle speed. Any model, therefore, has to consider a basically non-linear phenomenon.

b. Brake operation on a running rail limits the width of the active airgap to 5-8 cm. The edge effects of such a small width are more predominant and hence important. Moreover,

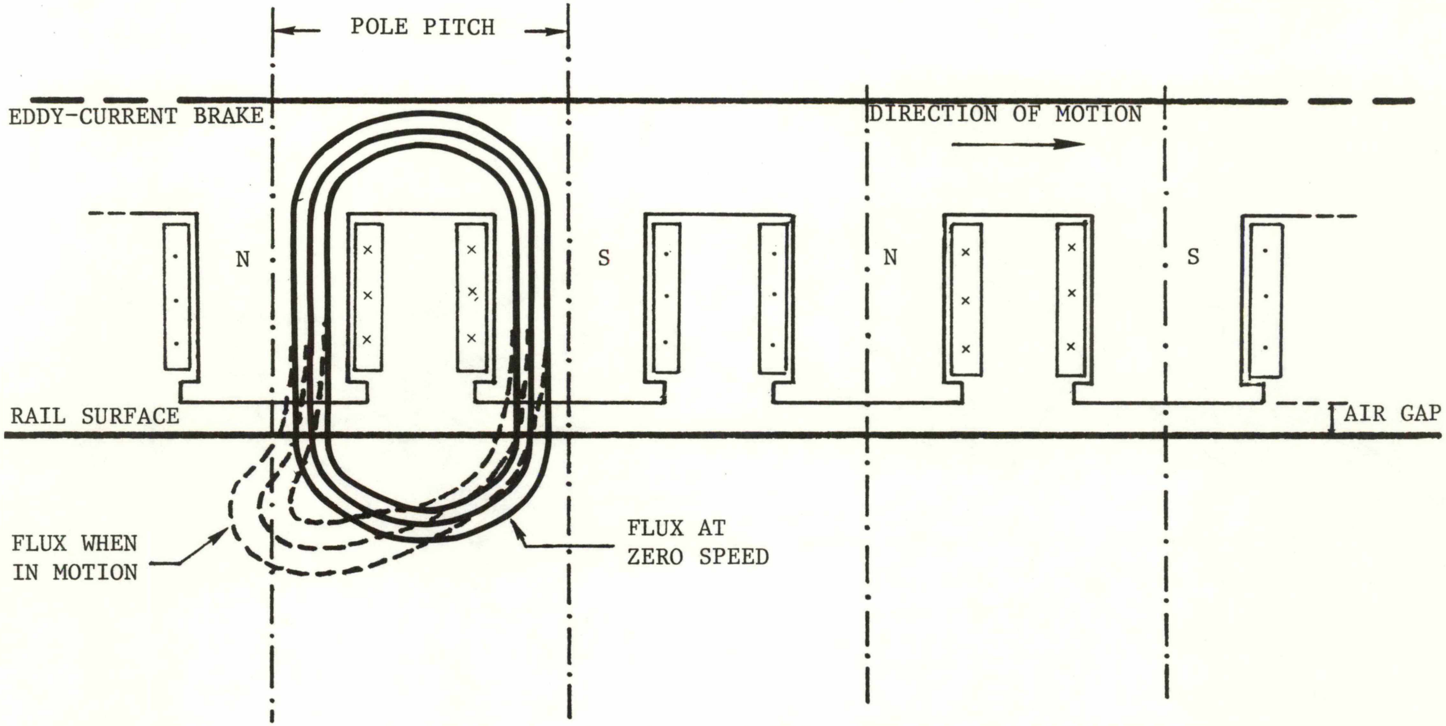


FIGURE 7
ALTERNATING POLES OF THE BRAKE

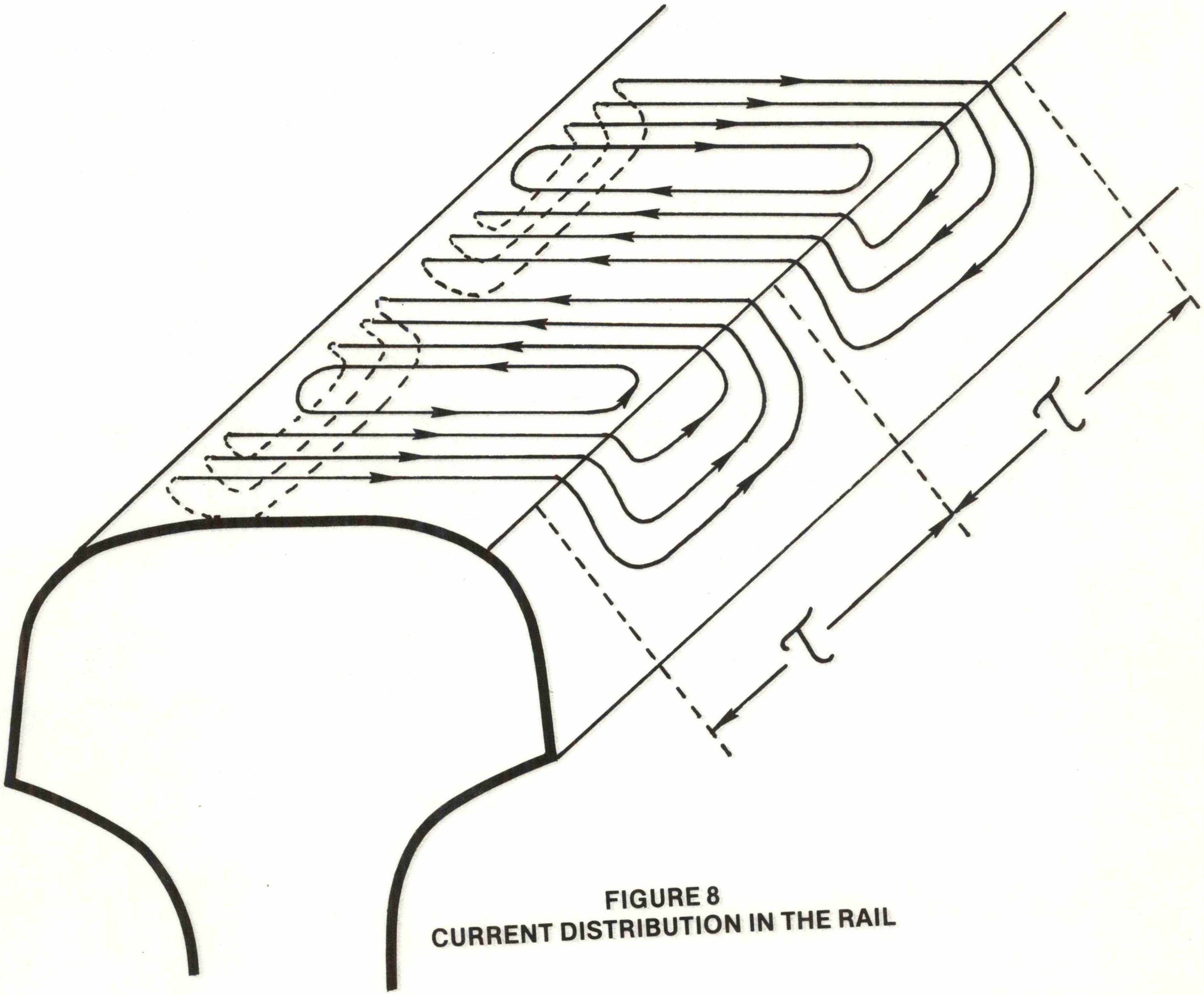


FIGURE 8
CURRENT DISTRIBUTION IN THE RAIL

a non-uniform airgap along the width of the rail because of the rail contour makes these edge effects more complex and difficult to analyse.

4.3 Performance Characteristics of Linear Brakes(5-11)

Linear eddy-current brake development started in the early 1970's and several prototypes have been tested in France, Germany, Switzerland and Japan. Some of the designs are compared in Table III. It should be noted here that the performance of the brake, in terms of braking force per unit length, is improved as the airgap is reduced; it also improves with higher excitation, which results in a heavier construction or a short duty cycle.

Some of the important characteristics of such a linear brake that must be evaluated are:

- Braking force as a function of speed and excitation
- Effect of airgap, rail width and pole face geometry on the braking force
- Normal force produced during braking action
- Temperature rise of the brake, as well as that of the rail

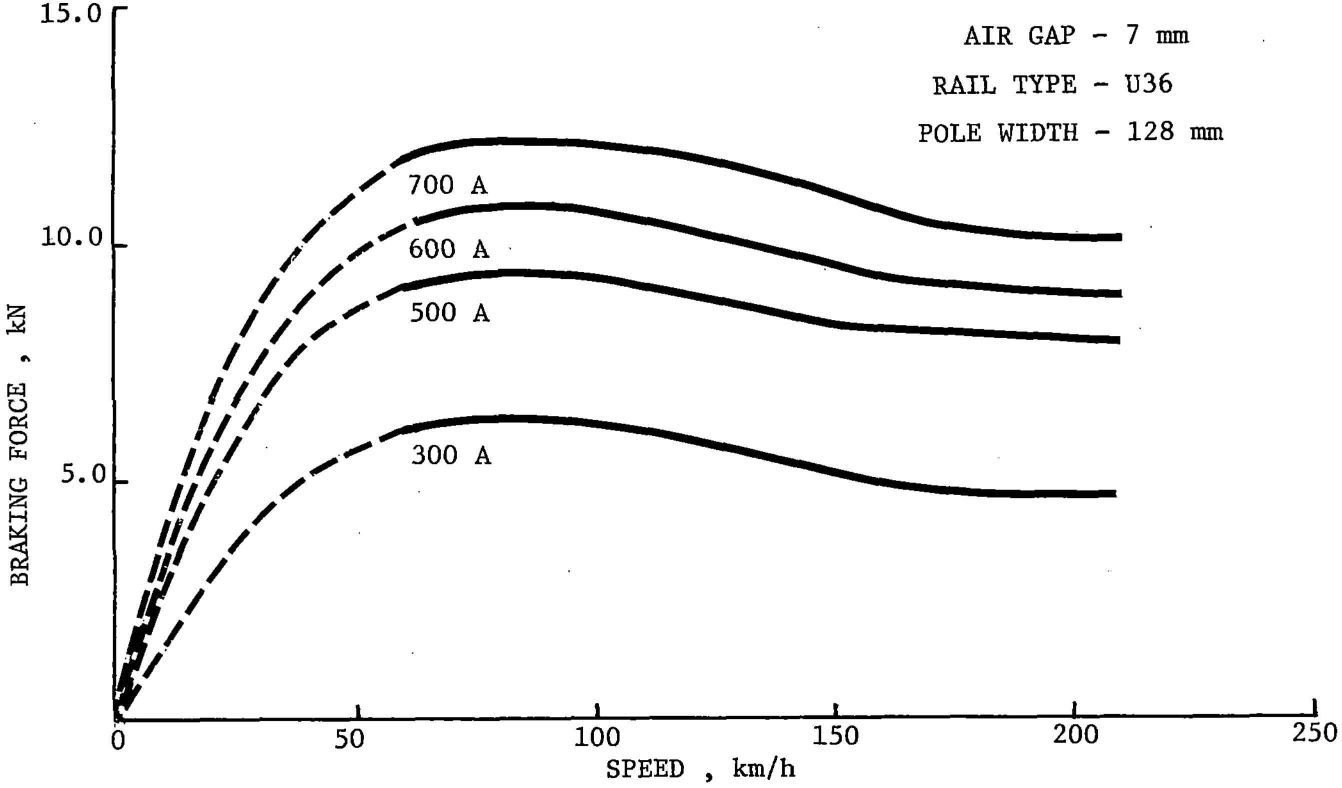
Other factors to be considered are the possible effects on signaling and communication systems, grade crossing equipment, increased unsprung mass, rail magnetization, etc. The performance characteristics described here are based on prototype testing done by SNCF in France and can be used to evaluate the possible advantages and limitations of such a braking system. This prototype unit was 2 m long, 0.13 m wide, 0.15 m high and operated with a gap of 7 mm.

Figure 9 shows the variation of the braking force with excitation and speed. From this data the effects of magnetic saturation are evident since the force/current^2 drops from approximately 7×10^{-5} kN/A^2 at 300 amperes to approximately 2.5×10^{-5} kN/A^2 at 700 amperes. It should also be seen that a fairly high braking force is obtained over

TABLE III

COMPARISON OF EDDY-CURRENT BRAKES

	Brake Unit Tested In		
	France	Germany	Switzerland
Length, mm	1900	1200	1200
Width, mm	57	130	80
Brake Force, kN	13.75	8.70	5.75
Excitation Power, kW	50	20	9
Brake Force/Length, kN/m	7.23	7.25	4.80
Excitation Power/Length, kW/m	26.3	16.7	7.5
Airgap, mm	7	7	5
Brake Force/Excitation Power, kN/kW	0.275	0.435	0.64
Thermal Load, kW/m^2	462	128	94



AIR GAP - 7 mm
RAIL TYPE - U36
POLE WIDTH - 128 mm

FIGURE 9
BRAKING FORCE AS A FUNCTION OF SPEED AND EXCITATION

a very wide speed range of 30-250 km/h and below 30 km/h the braking force rapidly falls to zero at zero speed.

Figure 10 shows the variation of the vertical force between the rail and the brake as a function of speed and excitation. It can be seen that this force is not uniformly distributed along the length and the ratio of the leading edge force to the trailing edge force increases with increasing speed. In other words, as the speed increases the airgap flux density distribution becomes increasingly non-uniform.

The degradation of the braking performance with increasing values of the airgap is shown in Figure 11. It can be seen that as the gap is changed from 7 mm to 15 mm the braking force is reduced by 25-30 percent and if the gap is increased to 30 mm the reduction is more than 60 percent. This loss of braking force increasing airgap is in fact the single most important factor which is going to influence the use of such braking systems in the U. S.

Figure 12 shows the effect of rail width on the braking performance. This data was obtained by using two different types of rail-- U 36 with 65 mm wide railhead and U 80 with 72 mm wide railhead. As can be seen the force is almost directly proportional to the width of the railhead under high excitation conditions.

Other important performance characteristics are the temperature rise of the excitation coil and the rise in the rail temperature. The excitation coil is designed with high thermal load to get a high braking force density. This, however, results in a short duty cycle as well as a short working life of the brake. The temperature rise of the excitation coil is shown in Figure 13 for different current levels. It can be seen that for a current between 650-700 amperes the duty

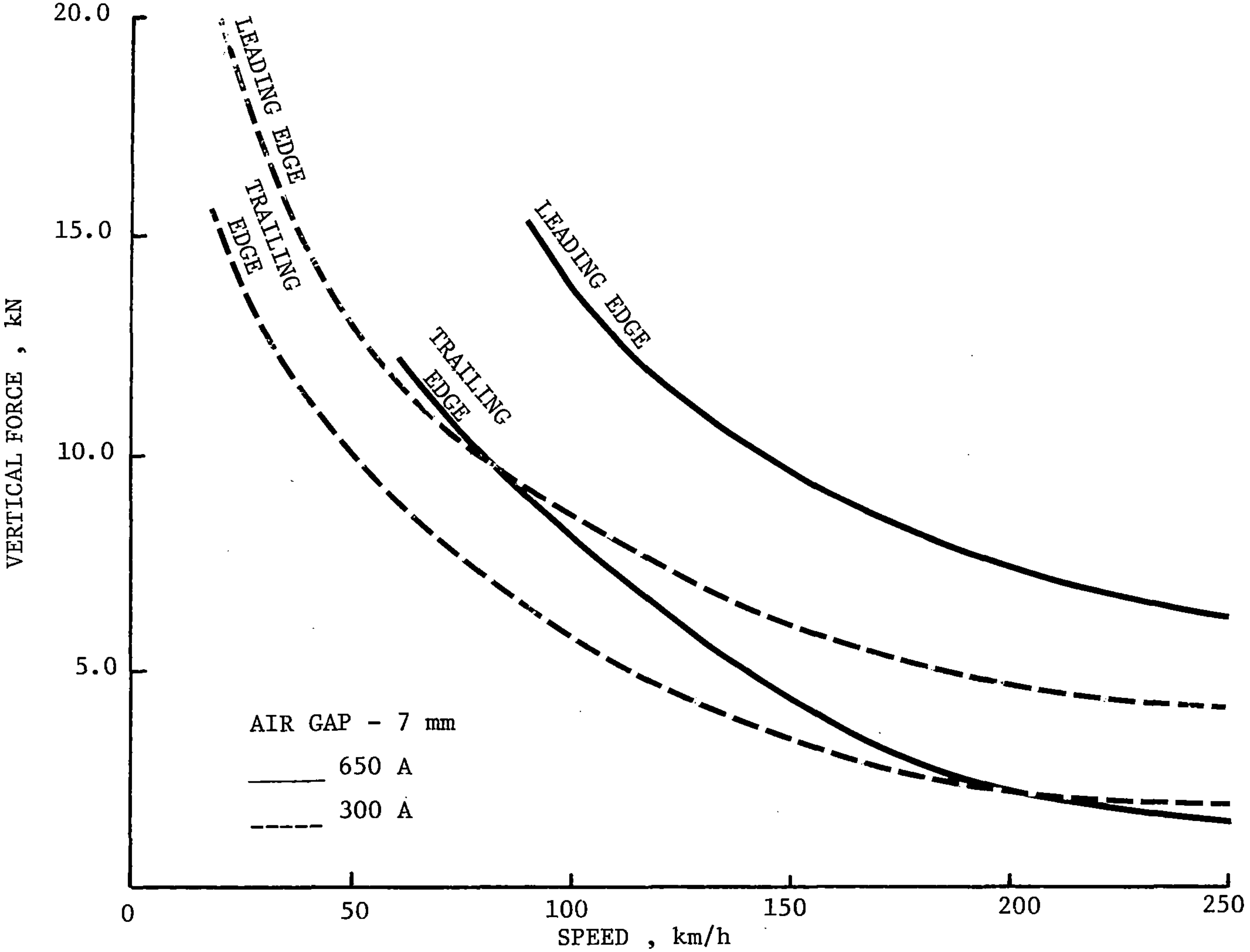


FIGURE 10
VARIATION OF VERTICAL FORCE

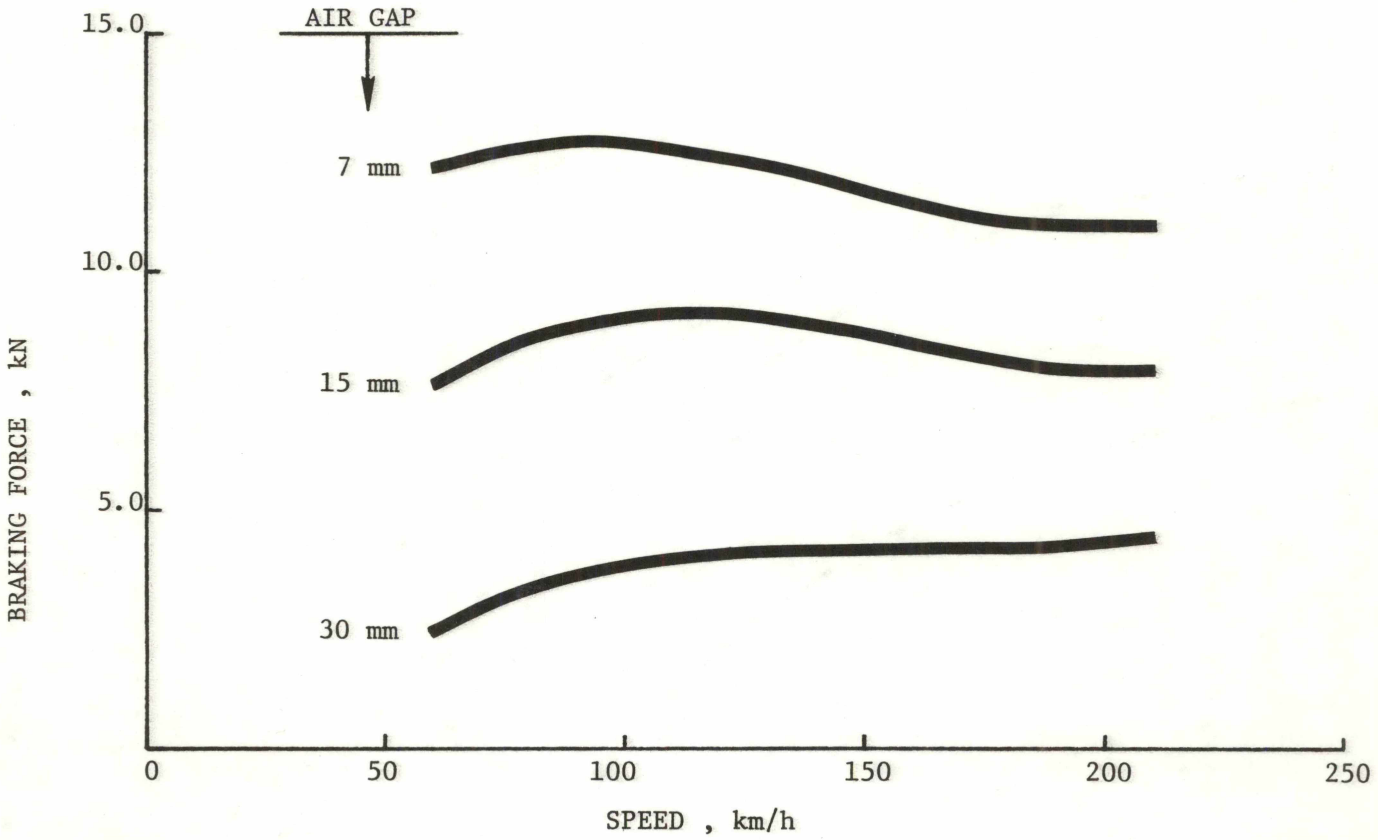


FIGURE 11
BRAKING FORCE AS A FUNCTION OF AIR GAP

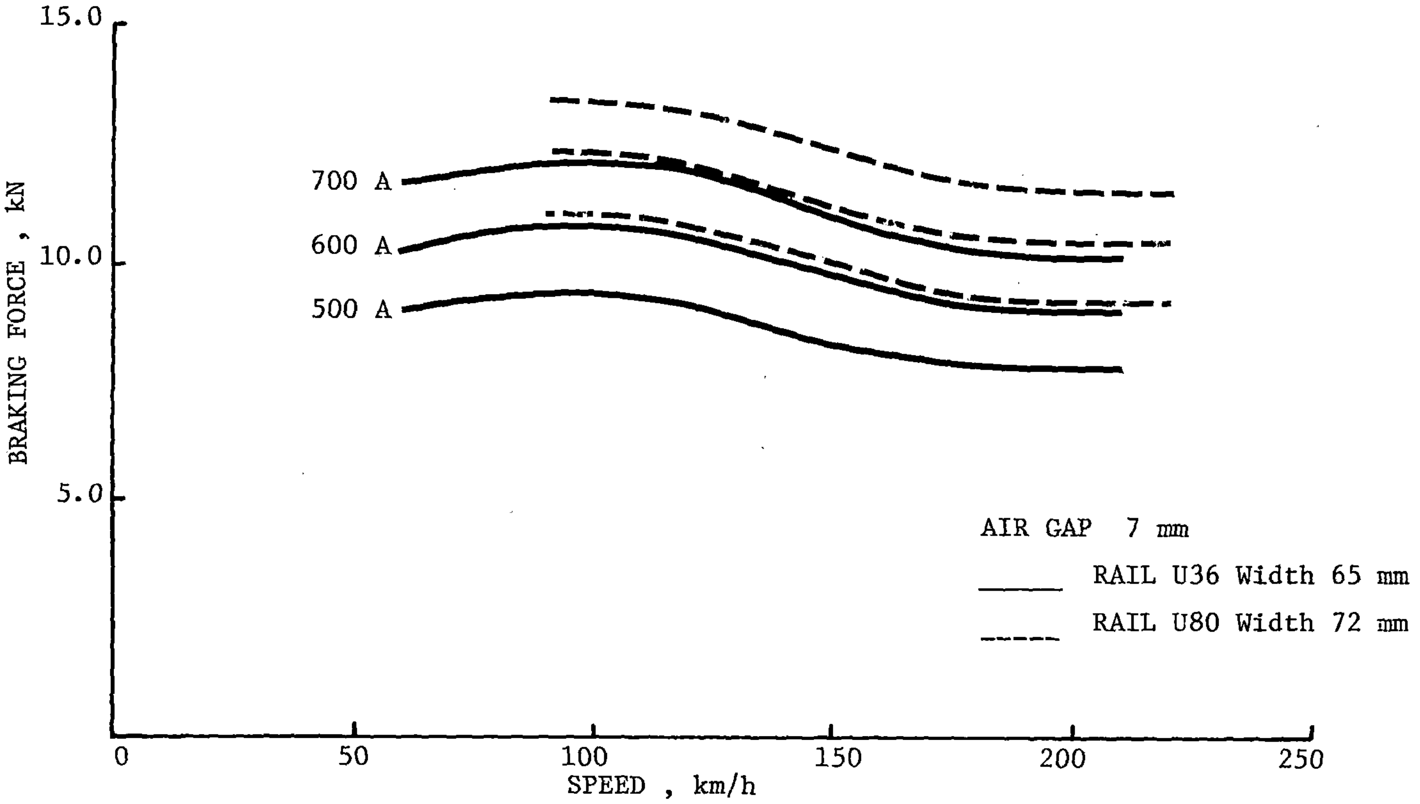


FIGURE 12
EFFECT OF RAIL WIDTH

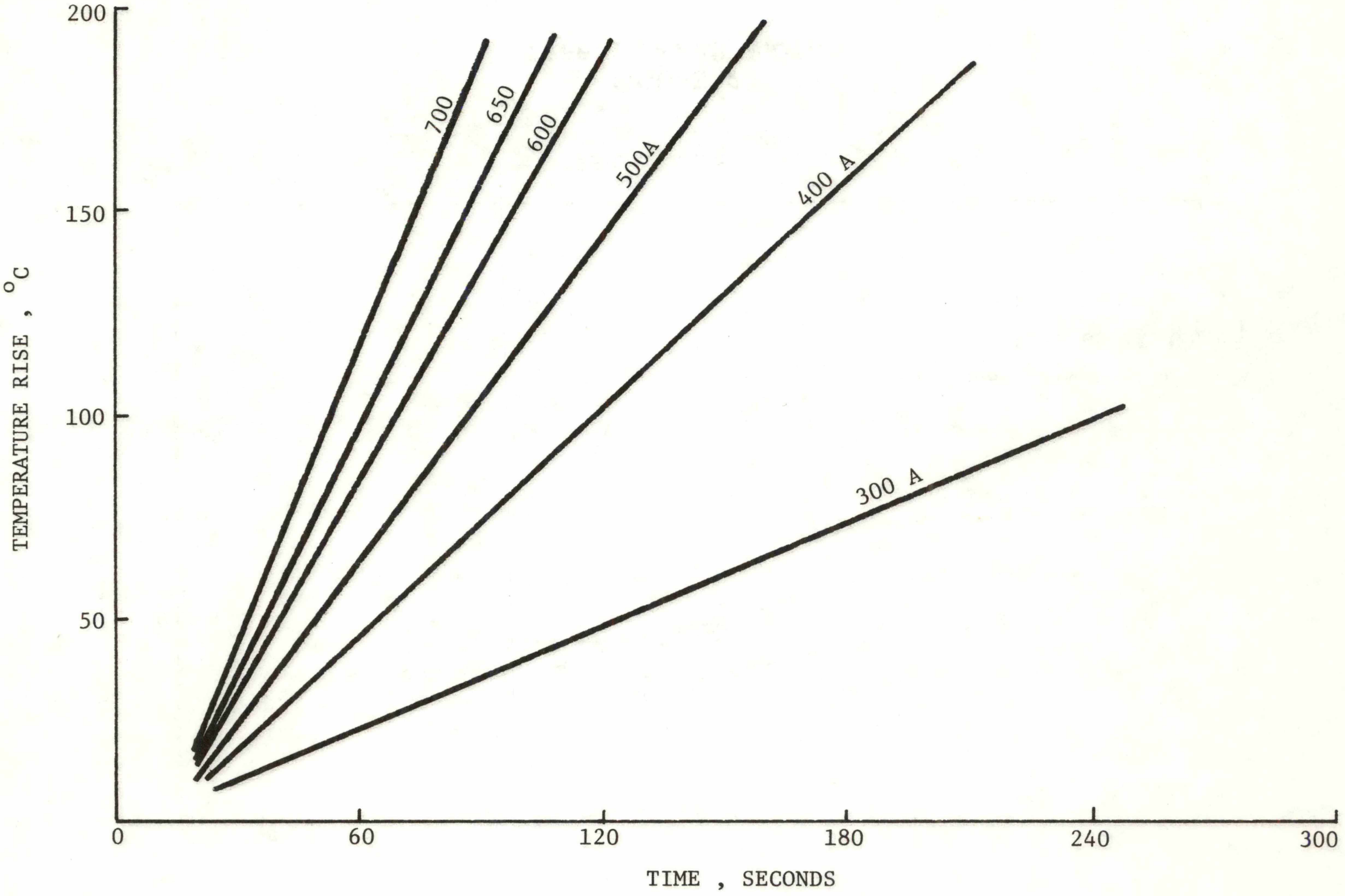
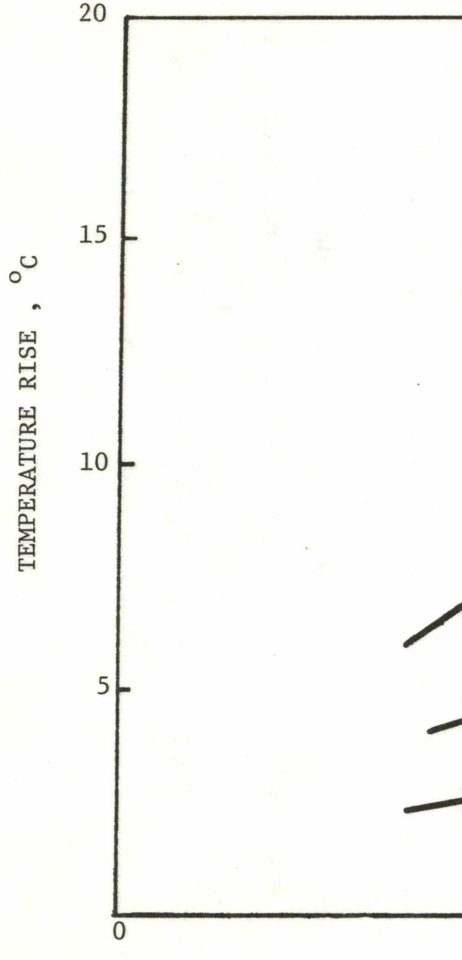


FIGURE 13
TEMPERATURE RISE OF THE EXCITATION COIL

cycle has to be limited to 100-85 seconds if the temperature rise is to be limited to 180° C. It can be recognized at once that under these thermal loads, although sufficient braking force is available, repeated application of these brakes as normal service brakes is impossible.

The rail temperature rise due to brake application was simulated in a laboratory test by Japanese National Railways (JNR). With a casual look at the problem, it appears that since the portion of the rail facing the brake is being continually replaced by new portions, the rail temperature rise should not be a problem of any significance. However, one has to understand that for a high passenger density corridor, long trains will likely be braked at short regular intervals on the same length of the rail and the rail temperature rise could very well be a major problem under some conditions. JNR, therefore, simulated a brake application of a 12-car train at speeds of 160 km/h. Simulated train headways were 5, 10 and 15 minutes. Figure 14 shows the ultimate temperature rise in the rail as measured close to the bottom of the rail. This data is presented here only to show representative values of expected temperature rise. For example, the data shows that a rail temperature rise of 20° C can be expected if the maximum braking force is applied with vehicle headways of about 5 minutes. For some regions where summertime rail temperatures could be as high as 70° C, this temperature rise is clearly unacceptable. However, realistically speaking of U. S. applications, the linear eddy-current brakes can be considered only for the Northeast Corridor. For this corridor, headways of less than 15 minutes are not envisioned for the forseeable future. With summertime high rail temperatures of about 55° C, an additional temperature rise of about 5° C because of brake application would create no problems at all.


TEMPERATURE RISE , °C
20
15
10
5
0

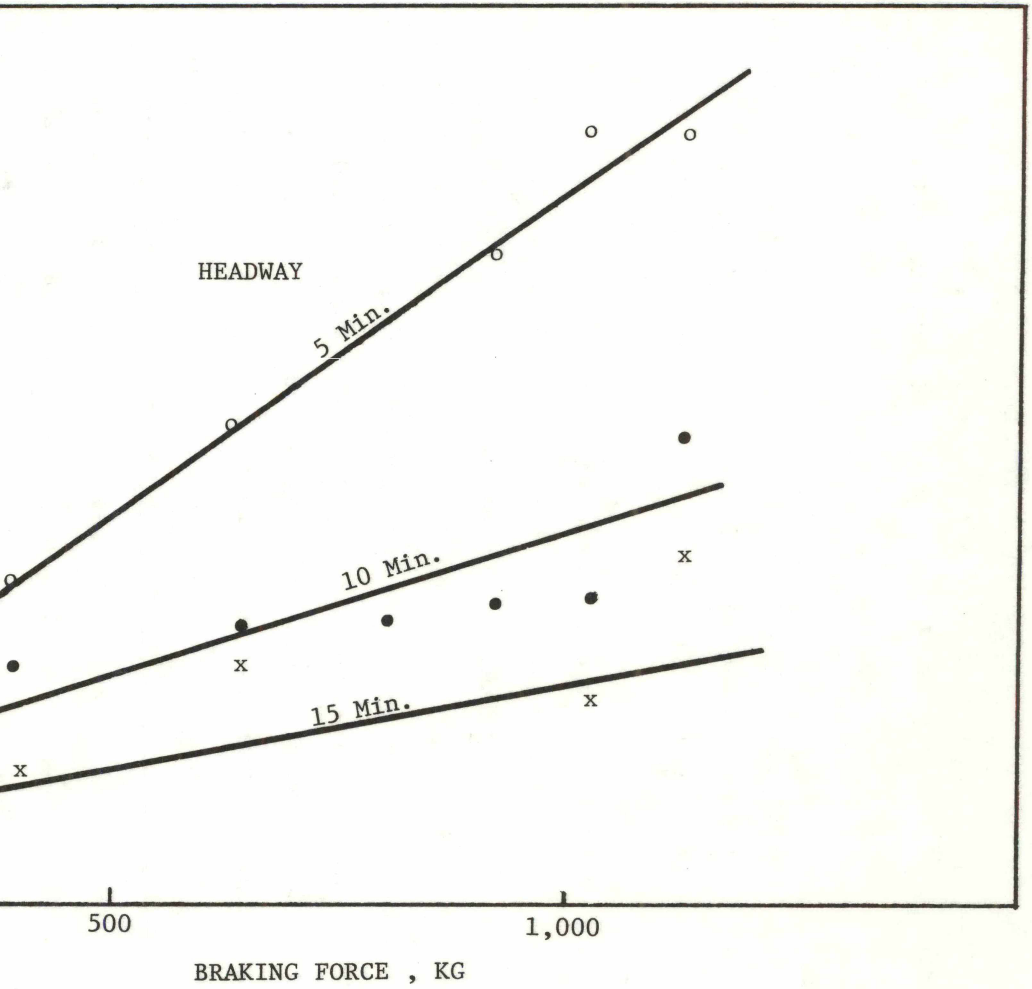


FIGURE 14
ULTIMATE TEMPERATURE RISE IN RAIL

In summary it can be said that linear eddy-current brakes offer a definite promise as a possible braking system for high speed vehicles. The braking action is consistent, predictable and independent of wheel-rail adhesion. It should also reduce the maintenance costs since there are no parts to wear.

4.4 Linear Eddy-Current Brake Application in the U. S.

The application of such brakes in the U. S. will ultimately depend on whether it can be economically justified under certain operating conditions. But before such an economic evaluation, the following technical issues will have to be addressed:

a. Small airgap: Eddy-current brakes have been operated usually with a 7 mm gap over the top of the rail although gaps as small as 4 mm have also been considered. For the present condition of U. S. tracks, these small gaps would pose severe problems and a 10-15 mm gap is more reasonable. At these gaps the braking force will be reduced 10-25 percent thus making the brakes less attractive and probably unacceptable. The issue of small airgap which is quite insignificant in the European railroad environment, thus becomes a major issue for the use of linear brakes on U. S. railroads.

b. Supply of Excitation Current: A single linear brake device requires a supply of approximately 20 kW. Hence one car using four such units would need 80 kW. For self-propelled equipment, the traction motors could be used in generating mode to supply this energy. For locomotive hauled trains, however, this scheme is highly impractical because this will require a transmission of almost 1 MW for a 12-car train via a train bus bar. This does not mean that the excitation supply is an insurmountable problem. Out of many possible solutions, two seem to be quite promising. First U. S. rail passenger cars have a significant "hotel load" capacity. During the brake application for short times, the excitation could possibly be obtained either by temporarily disconnecting the "hotel load" or by short-time over-loading of the system. Either of these schemes would require a redesign of hotel power system. Secondly, some of the linear brake units could be used in an induction generator mode to supply excitation to the other units. Or each unit can be made self-sufficient by using a part of the unit as a generator to supply the excitation to the rest of the unit. With recent advances in solid state controllers this should not be difficult.

5.0 OTHER APPLICATIONS

5.1 Urban Transit System(20,21)

In the urban transit systems SLIM propulsion offers many advantages such as:

- A simple bogie design is possible since propulsion equipment on the bogie is eliminated. A light, steerable design capable of negotiating tight curves is possible.
- A significant reduction in maintenance costs may result when SLIMs are compared to rotary systems with gears.
- Most of the system costs are in stations and guideways and hence motor inefficiency does not have a significant cost impact.

An example of SLIM propulsion for urban transit application is the Intermediate Capacity Transit System (ICTS) developed and tested by the Urban Transportation Development Corporation (UTDC) in cooperation with Canadair Ltd. In addition to SLIM propulsion, the concept is based on steerable action trucks, elevated right-of-way and moving block automatic train control. Although the information available on this system is limited, some features of the system and performance characteristics of the SLIM have been published. These are summarized below.

Each vehicle has a capacity for up to 70 passengers and a maximum mass of 19,00 kg. The vehicle is 12.7 m long and 2.5 m wide. There are two SLIM primaries per vehicle and each SLIM primary is fed by a transistorized variable frequency current source. The system was designed for headways of 1 minute, a maximum speed of 72 km/h (45 mph), and a capacity of 12-20,000 passengers per hour per direction.

One important consideration in selecting SLIM propulsion was the ability of the SLIM to provide braking independent of the wheel-rail adhesion characteristics.

The SLIMs on "Test Vehicle 1" were tested at the facilities of the Transit Development Center (TDC) over a period of 6 months (1978-1979). The oval track at TDC is 1.8 km long, has grades 3 and 6 percent, and has curves, switch points and other standard transit track equipment. The reaction rail is an aluminum sheet with back iron. The thickness of the reaction rail is 4.52 mm and the overhang (distance beyond the back iron) is 54 mm. The back iron has sections made of solid, laminated, and double-solid iron (the latter is made of two solid iron plates). The SLIM primary is 1.90 m long, 0.216 m wide, and is air cooled. The total mass of each SLIM is approximately 640 kg. This includes the mass of the iron laminations, copper windings and the frame. Some of the SLIM performance characteristics are presented in Table I. These characteristics are given at the nominal maximum speed of 72 km/h. During the test runs, the vehicle was accelerated up to 72 km/h at a maximum acceleration of 0.1 g.

A comparison of this motor with others in Table I indicates that its characteristics such as the normal force, the braking forces, etc. are within the range normally expected for such applications. The SLIM with laminated back iron rail produces from 10 to 20 percent (depending on speed and slip frequency) more thrust than either solid or double solid back iron. It is also reported that the dynamic gap control possible with the existing truck design, track and reaction rail installations is ± 3 mm for the nominal airgap setting.

The increase in propulsion force for laminated back iron suggests that it would be worthwhile to install this type of rail at stations in order to achieve the acceleration required without overheating the SLIM primary.

In conclusion, the reliability and ruggedness of the SLIM have been adequately verified by test results. The force densities seem to meet the specifications for reasonable parameter variations. However, there are still some questions about the ability of the SLIM to withstand more vigorous realistic duty schedules or if alternative cooling methods are necessary. Further tests are being planned to study smaller SLIM airgaps and alternative braking methods.

5.2 High Speed Rail Vehicles

Another possible application is a combined linear and rotary motor system for high speed rail vehicles. It is generally said that the limit of the running speed of wheel-on-rail vehicle is about 350 km/h (220 mph). At such high speeds wheel-rail adhesion and the hunting stability of carbody and/or truck are the two major problems. The problem of hunting stability or lateral guidance in general, can be solved or eliminated by using one of the several possible approaches such as active steering control, use of cylindrical and/or independently rotating wheels, etc. The problem of adhesion can be eliminated by using linear motors for propulsion along with rotating motors. Several types of linear motors can be used for such an application.

Alternative reaction rail configurations also exist for railroad applications. Limited reaction rail capability exists by using the running rails, as with the linear eddy-current brakes discussed previously in Section 4. The limited area, combined with the lower thrust density associated with a continuous duty motor cycle, would limit the available tractive effort, however. If additional structure is required for the reaction rail, there is a possibility of incorporating it into an unconventional running rail instead of using a separate reaction rail. Two such conceptions (B and C) are shown in Figure 15 along with the use of the existing running rails (D) or a separate reaction rail (A).

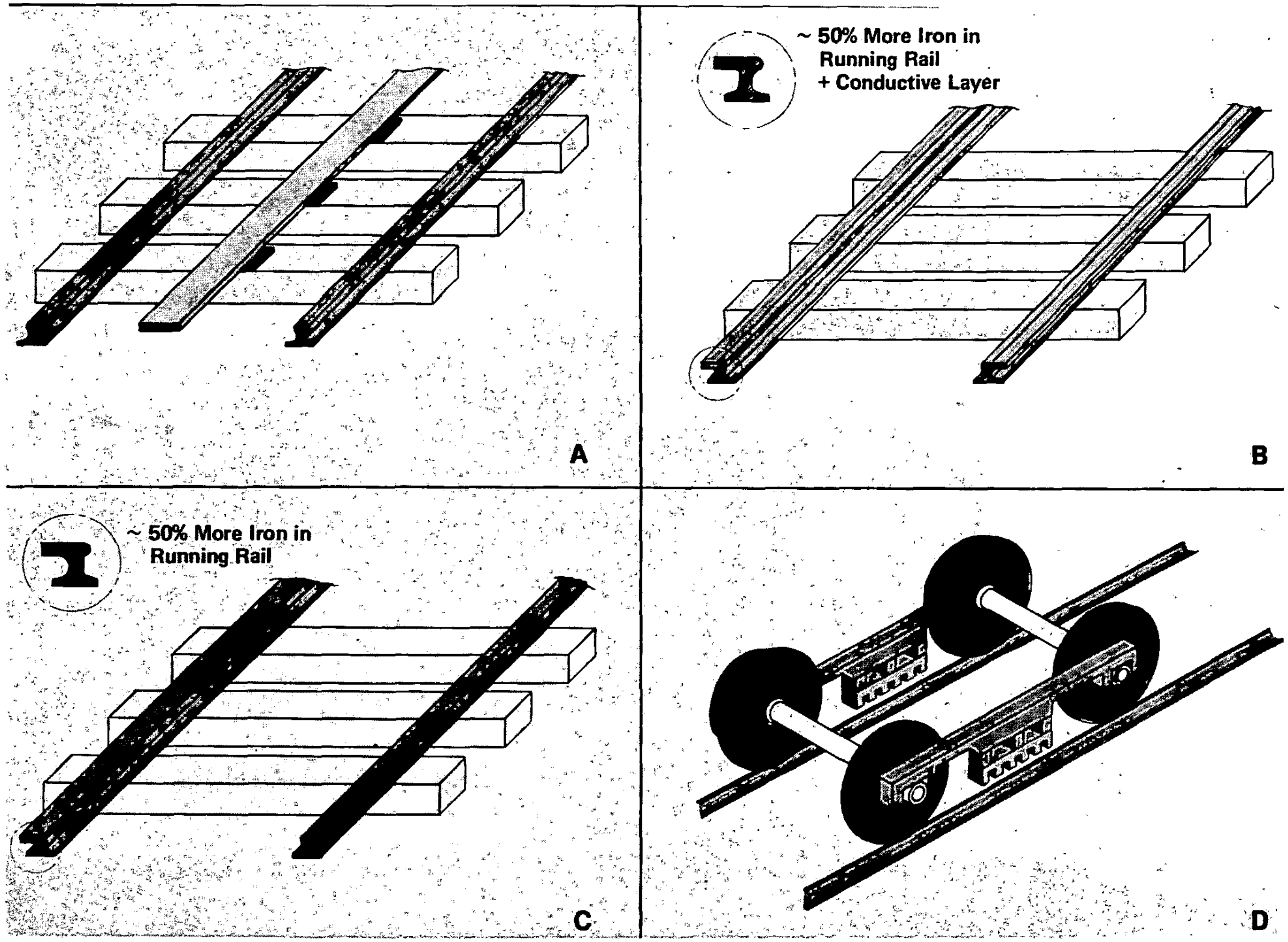


FIGURE 15
APPLICATIONS OF LINEAR MOTORS TO RAIL—
FOUR BASIC CONFIGURATIONS

Propulsion of trains with conventional motors is routinely handled up to speeds of about 250 km/hr (about 160 mph). The requirements of such systems can be used to help examine sizing requirements for linear motor propulsion of high speed trains. The tractive force available for two train configurations is shown in Figure 16.(22) The Metroliner (1) is a 6-car MU train. Using a reasonable adhesion limit, a constant tractive force of 250 kN (55,800 lb) is available at speeds up to 160 km/h (100 mph), at which point the motors are delivering the total maximum short term rating power of 11,100 kW (15,000 hp). Motor power decreases slightly as the train speed increases. This configuration has only moderate acceleration capability at low speed--0.05 g or 1.9 km/h/s (1.2 mphps)--but retains good acceleration capability at speeds beyond 200 km/h (125 mph). The train resistance for this configuration is also shown in Figure 16. At the continuous rating of 5400 kW for the motors, a balancing speed of 250 km/h (160 mph) is attained. The other example shown in Figure 16 is a 6-car Amcoach train pulled by an E60CP electric locomotive. This train has a high tractive force at low speeds and develops a maximum power of 7500 kW (10,100 hp) at 80 km/h (50 mph). The train has an acceleration capability of 0.07 g or 2.4 km/h/s (1.5 mphps). The maximum speed of this train at a continuous rating of 3700 kW (5000 hp) is 200 km/h (120 mph) since its resistance is slightly greater than the Metroliner.

These train characteristics can be used to size a linear motor propulsion system for a MU configuration. Providing the higher initial tractive effort of the locomotive would require a thrust of 56 kN (12,500 lb) per unit. The continuous duty thrust density of the TLRV SLIM, given previously in Table I, is 22 kN/m^2 (3.2 psi). Assuming the short term thrust density is twice as great, a reaction area of 56/(2 x 22) = 1.27 m^2 (1960 in^2) is required. The "A" rail configuration of Figure 15 is the only one that provides sufficient area.

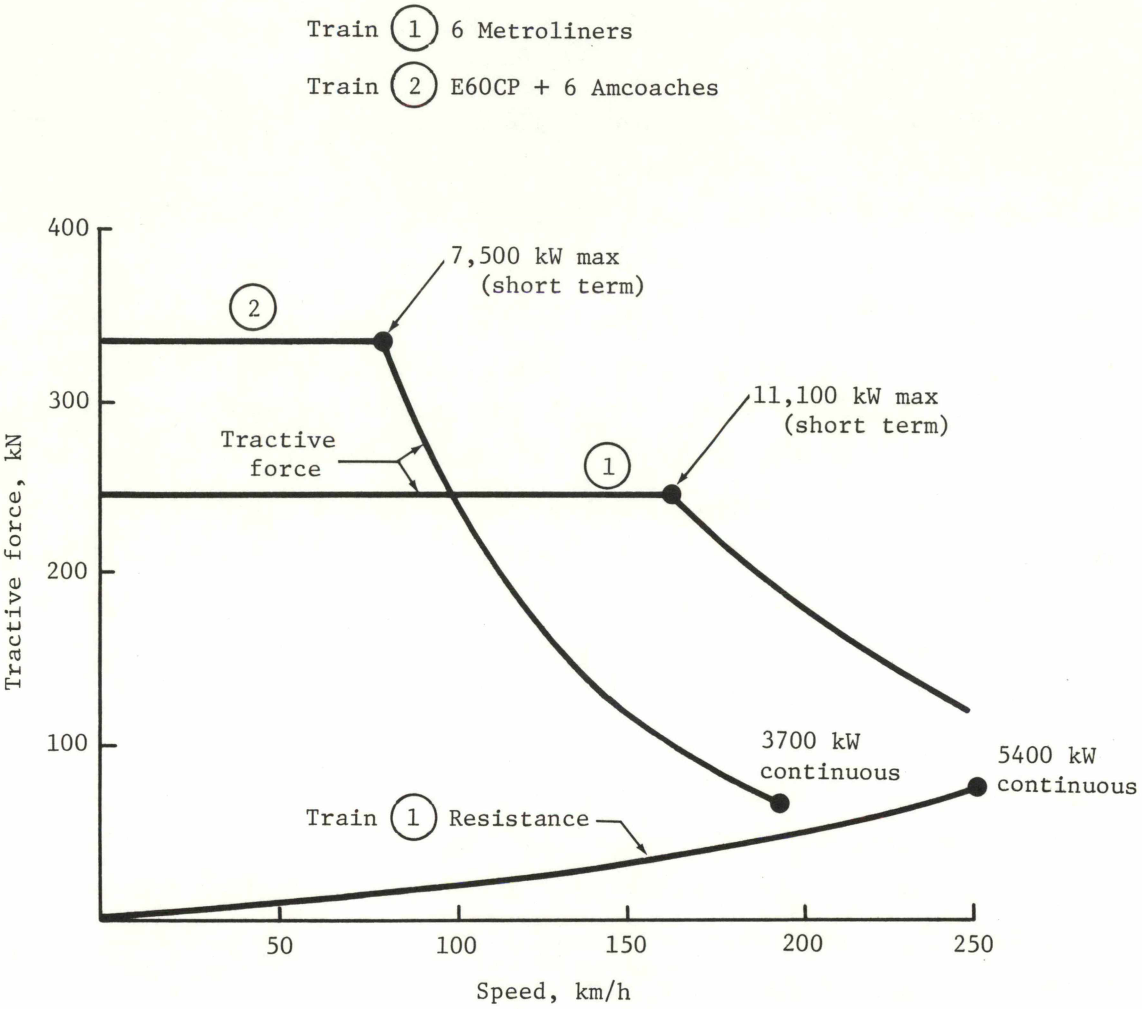


FIGURE 16
TRACTIVE FORCE AND TRAIN RESISTANCE

Assuming a length of 8 m (315 in) for the motor, the width must be 1.27/8 = .16 m (6.25 in). The normal force for this application, using the value for Table I doubled for the short term thrust rating, is of the order of 2 x 35 x 1.27 = 89 kN (20,000 lb). The power required to propel each unit, based on the Metroliner value, is in the order of 1850 kW. With an efficiency x power factor of .46, the inverter must be sized at 1850/.46 = 4020 kVA. The cost of a suitable inverter for this application is in the order of $150 kVA. Thus the cost is about 0.6 million dollars per unit.

The use of linear motors as the sole propulsion source of a car thus appears to have severe design and cost limitations. The use of linear motors in the helper mode has been suggested and appears to be more feasible. For an average rail car, about .456 m^2 are available using the conventional "D" rail configuration. This area would allow 22 x .456 = 10 kN of thrust (continuous rating) per unit. In terms of the Metroliner configuration, 60 kN of addition tractive effort on the train, applied at the upper speed range, would allow good acceleration capability to speed of 250 km/h (160 mph) and allow a top speed of 300 km/h (185 mph). The power requirement at this speed would be 850 kW per unit. Short term overload capacity would allow incremental tractive effort capability of 120 kN (27,000 lb) up to speeds of 150 km/h (95 mph) with this rating.

The numbers in this example point out that a booster configuration in combination with conventional rotory motors might provide the best all-around application for linear motors in high-speed railroads. Without a foreseeable application for 250 to 300 km/h railroads at this point, however, this concept has not been developed or evaluated further.

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